Anton Pannekoek, Marxist astronomer

*Photography, epistemic virtues, and political philosophy in early twentieth-century astronomy*

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Chaokang Tai
Anton Pannekoek, Marxist Astronomer

Photography, Epistemic Virtues, and Political Philosophy in Early Twentieth-Century Astronomy
Anton Pannekoek, Marxist Astronomer
Photography, Epistemic Virtues, and Political Philosophy
in Early Twentieth-Century Astronomy

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Figure I.1: Anton Pannekoek in the library at Leiden Observatory, ca. 1916
Source: Archive of Laurence A. Marschall (LM)
Introduction

When Harvard University celebrated its tercentenary in 1936, it conveyed honorary degrees to 39 distinguished international scholars. Among the recipients was Dutch astronomer Anton Pannekoek (1873–1960), who was honoured for his 'contributions of high merit in many fields of astronomy'.¹ Among other things, Pannekoek had determined the distances to Milky Way clouds, providing early evidence of the eccentric position of the Sun in the stellar system; introduced a numerical method for calculating the astrophysics of stellar atmospheres; and produced drawings of the Milky Way that were featured in Zeiss Planetariums around the world for decades.²

There was also a very different side to Pannekoek. Prior to attending Harvard’s tercentenary conference, he addressed the members of the Workers’ Socialist Party of the United States: a small but active left com-


2. Carl Zeiss Jena to Anton Pannekoek, 25 Jul 1927, Archive of the Anton Pannekoek Institute, University of Amsterdam (API); Henry C. King, Geared to the Stars: The Evolution of Planetariums, Orreries, and Astronomical Clocks, in collaboration with John R. Millburn (Bristol: Adam Hilger, 1978), 70.
munist movement in Boston. Their members, who turned out in large numbers for the meeting, had a very different reason to be interested in Pannekoek. They knew him as the former party theoretician of the Sozialdemokratische Partei Deutschlands (SPD), the largest socialist party of its time, and as one of the contemporary theoretical leaders of the council communist movement, which they supported.

Throughout the twentieth century, few people have managed to be as influential as Pannekoek in such widely different fields as Marxism and astronomy. The fact that he managed to contribute significantly to both fields makes him a compelling case study for the history of science and the history of political thought. His life and work uniquely capture the fascinating connections between conceptions of nature, society, and their representations in the early decades of the twentieth century. Yet historical research on Pannekoek’s astronomy and its relation and connections with his socialism has been conspicuously lacking until very recently.

The goal of this thesis is twofold. The first is to analyse Pannekoek’s astronomy in relation to contemporary developments in the discipline. Such an analysis will increase our understanding of a crucial period in the history of astronomy when the field rapidly changed, not only in its description of the heavens, but also in its subject matter, approach, and methods of collaboration. The second is to explore the relations between Pannekoek’s astronomical research and his Marxist writings. This not only helps us better understand the methodological and epistemological choices he made in his astronomy, but will also inform us about the broader relations between science and political thought and provide a more unified picture of Pannekoek’s life. To achieve these goals, I will not only discuss Pannekoek’s scientific research but also investigate his ideas on proper scientific methodology, and use a framework of epistemic virtues to relate his scientific epistemology to his Marxist philosophy.

4. I mention ‘until very recently’ because a conference centred around this very subject was organized in 2016 by Jeronimo Voss, Edward van den Heuvel, Jeroen van Dongen, Bart van der Steen, Ralph Wijers, and myself. An edited volume containing selected papers from that conference has subsequently been published as Chaokang Tai, Bart van der Steen and Jeroen van Dongen, eds., Anton Pannekoek: Ways of Viewing Science and Society (Amsterdam: Amsterdam University Press, 2019).

Additionally, my own research on the relation between Pannekoek’s astronomy and Marxism has been published as Tai and Van Dongen, ‘Personae and the Practice of Science’; Tai, ‘Left Radicalism and the Milky Way’; ‘Milky Way as Optical Phenomenon’.
Anton Pannekoek

Pannekoek had an inconspicuous start of his career, quite similar to that of many Dutch scientists in the early twentieth century. He was born in 1873 in the small rural town of Vaassen in the eastern part of the Netherlands. For his secondary education, he attended the local Hogere Burgerschool (HBS) in nearby Apeldoorn, where he developed an interest in astronomy. At the instigation of his teachers, Pannekoek decided to pursue an academic career at Leiden University, where he studied physics and mathematics. He was hired as an observer at the Leiden Observatory in 1899 with the assignment to make precision measurements of stellar coordinates. He was also allowed time to work on his dissertation on the light variation of Algol, which he finished in 1902. Despite the auspicious start of his astronomical career, however, Pannekoek soon became disillusioned with his daily activities in Leiden. The work was tedious and irrelevant, the atmosphere stale and rigid, and he grew frustrated by the observatory director’s resistance to innovation. Pannekoek concluded that he was unsuited for the life of an astronomer and, in 1906, quit his position in Leiden to reconsider his career choices.

The opportunity to do something completely different came when he was invited to teach historical materialism at the Parteischule of the SPD in Berlin.

By this time, Pannekoek had built quite a reputation for himself as a Marxist thinker. He had converted to socialism in 1899 after reading

5. Anton Pannekoek, Herinneringen: Herinneringen uit de arbeidersbeweging; Sterrenkundige herinneringen, ed. Ben A. Sijes, Johanna M. Weelker and J. R. van der Leeuw (Amsterdam: Van Gennep, 1982), 229–231. The HBS was a form of secondary education for children from the upper middle class that strongly emphasized the natural sciences. Although it did not grant immediate access to the universities — HBS graduates were required to take additional courses in the classical languages, which took Pannekoek three additional years to complete — many prominent Dutch scientists of the late nineteenth and early twentieth century had graduated from an HBS. For a discussion on the role played by the HBS in the renaissance of Dutch science in the late nineteenth century, see Bastiaan Willink, De tweede Gouden Eeuw: Nederland en de Nobelprijzen voor natuurwetenschappen, 1870–1940 (Amsterdam: Bert Bakker, 1998); Ad Maas, “Tachtigers in de wetenschap: Een nieuwe kijk op het ontstaan van de ‘Tweede Gouden Eeuw’ in de Nederlandse natuurwetenschap”, *Tijdschrift voor Geschiedenis* 114, no. 3 (2001): 354–376; Maas, 'Civil Scientists: Dutch Scientists between 1750 and 1875', *History of Science* 48, no. 1 (2010): 75–103.


Introduction

socialist literature and becoming enthralled by utopian thinkers. He became actively involved in the socialist movement, co-founding the Leiden chapter of the Sociaal Democratische Arbeiderspartij (SDAP) and writing articles on Marxist theory. He established himself as a principled and orthodox Marxist on the left wing of the SDAP and often challenged and criticized the tactics of its leaders, which he perceived to be opportunistic and revisionist. Pannekoek’s activities impressed Karl Kautsky, the theoretical leader of the SPD, who had arranged the invitation to come to Berlin. Pannekoek’s time at the Parteischule was short-lived as he was soon prevented from teaching by the Prussian state, but he remained in Berlin to write socialist articles. In Germany, too, Pannekoek settled in the left opposition of the party, especially after his move to Bremen in 1910 where he was instrumental in organizing the radical Bremen left. He criticized the use of parliamentary tactics and the co-operation with trade unions, arguing that the only way to achieve a truly democratic socialist society was through a total revolution of the state, which could only be initiated by the workers themselves. This stance eventually led to a controversy with Kautsky but gained him the support of Lenin and the Bolsheviks.

The start of the First World War in 1914 forced Pannekoek to repatriate to the Netherlands, but he remained in close contact with both the Bremen left and the Bolsheviks. He was elated when he heard about the Bolshevik Revolution of 1917 and the German Revolutions of 1918–1919, although he stressed that the Soviet Union should not be ruled by the Communist Party but by the workers themselves. This criticism led him to be denounced by Lenin, who argued Pannekoek’s work was ‘particularly

8. See Klaas van Berkel, ‘Utopianism in Anton Pannekoek’s Socialism and Astronomy’, in Tai, Van der Steen and Van Dongen, Pannekoek: Ways of Viewing, 81–83. Van Berkel argues that both Pannekoek’s astronomy and his socialism emerged from ‘the utopian longing for wholeness and purity’ (85).
“solid” and particularly stupid’. For Pannekoek, it was clear that he occupied an increasingly isolated position within the communist movement. He terminated his membership of the Dutch Communist Party and aligned himself with the new council communist movement, which rejected any form of bureaucracy and instead championed complete self-organization by the working class. Pannekoek remained one of the leading theoreticians of council communism for the rest of his life, but the movement itself remained small and struggled to gain support or relevancy.

Despite his continued involvement with Marxism, the second half of Pannekoek’s life was primarily devoted to astronomy. Meetings with Karl Schwarzschild and Ejnar Hertzsprung of the Potsdam Observatory in 1909 had reignited his love for the subject and prompted him to engage in astronomical research once again. He became a lecturer in History of Astronomy at Leiden University in 1916 while the prospect of becoming a professional astronomer again came in 1918 when he was offered the position of assistant director at the reorganized Leiden Observatory. After a year of negotiations and delays, however, the Dutch government blocked the hiring, refusing to appoint an outspoken Marxist at a prestigious public university.


14. Pannekoek, *Herinneringen*, 241–242. A few years earlier, in 1907, Schwarzschild had put Pannekoek forward as a potential candidate for Professor of Mathematics in Göttingen, but this suggestion was rejected because Pannekoek was both a foreigner and a socialist. Karl Schwarzschild to Hendrik A. Lorentz, 9 Jul 1907, Lorentz, prof. dr. H. A., te Haarlem, Noord-Hollands Archief (NHA/HL), 69: 109; Schwarzschild to Lorentz, 15 Jul 1907, Nachlass Karl Schwarzschild, Niedersächsische Staats- und Universitätsbibliothek Göttingen (SUG/KS), Briefe 472.

15. A detailed account of Pannekoek’s rejection in Leiden is provided in David Baneke, “‘Hij kan toch moeilijk de sterren in de war schoppen’”. De afwijzing van Anton Pan-
The rejection in Leiden proved to be a blessing in disguise for Pannekoek: he was hired instead by the University of Amsterdam, a municipal rather than a state university, where he could found a new astronomical institute. Since he could not construct an observatory, he modelled the institute after the Astronomical Laboratory in Groningen and dedicated himself to measuring and reducing photographic plates taken by others. The initial focus of the institute was on the structure of the stellar system, which was an established topic in the Netherlands, primarily due to the contributions of Jacobus C. Kapteyn. Soon, however, Pannekoek redirected most of his attention to the newly emerging field of astrophysics of stellar atmospheres, becoming the first astronomer in the Netherlands to do so. He was appointed extraordinary professor in 1925 and ordinary professor in 1932. He also remained interested in the history of astronomy, which became a focal point of his writing during his retirement.

Pannekoek Scholarship

Plenty of historical literature has been written about Pannekoek, but this has almost entirely focused on his political career. Interest in Pannekoek’s Marxism had been revived following the protests of May 1968 and the Portuguese Carnation revolution of 1974, which led to the publication of books and anthologies that presented his socialist writings to a new public. Pannekoek became the subject of academic scholarship in the
late 1970s and 1980s, which resulted in several dissertations that traced the development of his political thought.19

The image of Pannekoek that emerges from these studies is one of a principled and orthodox Marxist who had a scientific approach to the subject. His Marxist philosophy, which he developed early in his career and from which he rarely strayed, was based not only on the writings of Karl Marx and Friedrich Engels, but especially on those of German-American self-taught philosopher Joseph Dietzgen. Following Dietzgen, Pannekoek emphasized that society developed through an interplay of both social and economic circumstances and mental factors like religion and education. He also concluded that any attempts by Marxists to predetermine or direct the political actions of workers would only serve to pacify them and diminish their revolutionary tendencies. Instead, he stressed that Marxism should be interpreted as a scientific method for studying society; indeed, he even used the term interchangeably with the terms ‘social science’ and ‘historical materialism’.20 The goal should be to study society and educate the workers so that they could formulate their own ideas on how the revolution should transpire and how society should be organized. This stance often placed him at odds with socialist leadership and is the reason why he constantly found himself in the left opposition.21


21. Tai and Van Dongen, ‘Personae and the Practice of Science’.
Introduction

Those who have studied Pannekoek’s socialism, however, have all but neglected his astronomical research. The lack of interest in finding the connections between his astronomy and Marxism can partially be attributed to his own attempts to keep his two careers separate. In his astronomical papers, there was never any mention of his political ideas, and he hardly ever discussed politics with colleagues. Likewise, in his political writings, he rarely mentioned his scientific background. Moreover, starting in 1918, he regularly wrote his socialist articles under various pen names to further compartmentalize his two careers. He even wrote two memoirs that separately discussed his careers in the workers’ movement and in astronomy. This strategy was successful in convincing both contemporaries and later historians that his two lives could indeed be kept apart. The British Marxist historian Eric Hobsbawm even used Pannekoek as an example to illustrate the apparent divide between political philosophy and the natural sciences in the early twentieth century. He argued that it was quite possible in [this] (or any) period to be both a distinguished astronomer and a revolutionary Marxist, like A. Pannekoek ..., whose professional colleagues doubtless thought his politics as irrelevant to his astronomy as his comrades felt his astronomy to be to the class struggle.

22. This is in stark contrast to those who have studied his two closest socialist compatriots, the poets Herman Gorter and Henriette Roland Holst. In their case, historians have actively searched for the connections between their socialism and literary work. For Gorter, see Herman de Liagre Böhl, Met al mijn bloed heb ik voor U geleefd: Herman Gorter, 1864–1927 (Amsterdam: Balans, 1996); Hub Zwart, ‘Poetry, Science and Revolution: The Enigma of Herman Gorter’s Pan’, Journal of Dutch Literature 10, no. 1 (2019): 24–49; for Roland Holst, see Elsbeth Etty, Liefde is heel het leven niet: Henriette Roland Holst, 1869–1952 (Amsterdam: Balans, 1996).

23. He was, for example, acquainted with Marxist physicist Léon Rosenfeld for years before they realized their shared Marxist conviction. See the Pannekoek–Rosenfeld correspondence, Léon Rosenfeld Papers, Niels Bohr Archive, University of Copenhagen (NBA/LR), box 1, folder 2.

24. Pannekoek, Herinneringen. The two memoirs were written in the winter of 1944 and were intended for his family. They were published together with introductions by Ben Sijes for the socialist memoirs, and Edward van den Heuvel for the astronomical memoirs. The choice to not attempt to write an introduction that encompassed both was criticized in Klaas van Berkel, review of Herinneringen, by Anton Pannekoek, BMGN — Low Countries Historical Review 99, no. 3 (1984).

Yet, as we have seen, Pannekoek did suffer the consequences of his political affiliation at various times in his astronomical career. His self-compartmentalization into two careers should be interpreted as an effort to minimize such conflicts. There were clear links between his socialism and astronomy, as Pannekoek himself asserted. When asked about their relation in 1957, he answered: ‘Interaction existed in so far, that the method of natural science, which I had learned thoroughly, helped me to discover the science of society in Marxism; and that has remained the foundation of my work.’ Accordingly, to appreciate Pannekoek’s idiosyncratic approach to Marxism, an analysis of his scientific methodology is indispensable. But here, we run into the problem that his contributions to astronomy have not received much attention from historians of science either. The literature on this subject is limited to short biographical articles and obituaries, and snippets included in more general histories of astronomy. These sources offer little more than a superficial indication of his methodology in astronomy. Taken together, this makes


clear that a detailed investigation of Pannekoek’s astronomical research is sorely needed. Not only because it will enable the comparison with his socialism, but also because it promises to provide valuable insight into the contemporaneous development of astronomy and astrophysics and how that was part of the larger history of knowledge in the early twentieth century.

The New Astronomy

The early twentieth century, when Pannekoek was active as an astronomer, was an exciting time in astronomy. It underwent several developments that transformed not only the content but also the practice of the field. Three of the most impactful transformations during this period were the widespread implementation of astrophotography, the overhaul of ideas on the size and structure of the universe, and the rise of astrophysics. Since Pannekoek was deeply involved in all three of these episodes, the study of his life and astronomy provides an excellent opportunity to study and appreciate this transformative episode in the history of astronomy.

Astronomy had been one of the first scientific disciplines to embrace photography in the mid-nineteenth century, but, as historians of astronomy and photography have shown, it was initially the domain of wealthy self-funded astronomers, who took the freedom to experiment with various photographic techniques. Many astronomers, especially

van de hemel: De Nederlandse sterrenkunde in de twintigste eeuw (Amsterdam: Prometheus Bert Bakker, 2015).
those working for large visual observatories, however, had genuine epistemic concerns about the trustworthiness and applicability of astrophotography in scientific research.\textsuperscript{31} Even in the depiction of visually striking objects, like nebulae, planetary and lunar surfaces, or the Solar corona, astronomers initially preferred drawings and diagrams based on visual observations over photography. Such observations were considered more accurate because the human eye was thought to be better at capturing large scale structures and evaluating differences in brightness. When photography was eventually applied to these subjects, toward the end of the nineteenth century, it was still rare for photographs depicting astronomical objects to find their way into professional publications. Instead, photographic plates were used mainly for precise measurement with the results being presented in the form of drawings and diagrams, similar to how visual observations had been used.\textsuperscript{32} Pannekoek’s use of astrophotography in representing the Milky Way a few decades later is interesting in comparison with these cases because it differed in a crucial way. Pannekoek did not wish to rely on regular photography to capture the Milky Way light, as that would resolve it into the individual stars that comprised it. Instead, he had to develop the method of extrafocal photographic photometry to mimic the workings of the human eye.


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Photography had one crucial advantage over visual observations: photographic plates could be taken in bulk and stored for later use.\textsuperscript{33} As such, they could be distributed to different locations, enabling a division of labour among astronomical institutions as part of the industrialization of astronomy.\textsuperscript{34} This division of labour was significant because extracting usable scientific information from photographic plates through measurement and calibration was very labour intensive.\textsuperscript{35} Many photographic observatories produced far more photographic plates than they could measure on their own, which made it possible to found astronomical institutes that lacked any kind of observatory. A ground-breaking example was the creation of the Astronomical Laboratory of Jacobus C. Kapteyn in Groningen in 1896. Kapteyn began a collaboration with David Gill of the Cape Observatory in which photographic plates taken in South Africa were shipped to the Netherlands where they were measured and reduced. The success of the resulting \textit{Cape Photographic Durchmusterung}, published 1896–1900, firmly established the value of astrophotography for positional astronomy and highlighted the advantages of dividing astronomical labour.\textsuperscript{36} It encouraged other institutes to follow the path of Kapteyn’s as-

\textsuperscript{33} The possibility to record observations for later use was useful for short events like Solar eclipses and Venus transits but also for creating photographic atlases that could be used as an archive for future astronomers, such as the \textit{Carte du Ciel}. For the former, see \textit{Empire and the Sun}; Canales, ‘Photogenic Venus’; Jessica Ratcliff, \textit{The Transit of Venus Enterprise in Victorian Britain} (London: Pickering & Chatto, 2008). For the latter, see Lorraine Daston, ‘The Immortal Archive: Nineteenth-Century Science Imagines the Future’, in \textit{Science in the Archives: Pasts, Presents, Futures}, ed. Lorraine Daston (Chicago: University of Chicago Press, 2017).


Pannekoek’s astronomical institute in Amsterdam was one of these, and the photographic projects initiated there serve to illustrate the versatile ways in which the distribution of photographic plates could benefit such institutions.

The Cape Photographic Durchmusterung was one of several comprehensive star catalogues that were produced in the second half of the nineteenth century. This large increase of data had a significant impact on theories on the size and composition of the universe, which were completely overhauled in the period 1900–1931. At the turn of the century, the generally accepted idea was that there was only a single rather small star system in which the Sun was located near the centre. By 1931, however, the Sun was thought to be located at the outskirts of a large rotating Milky Way galaxy that was only one of many galaxies in a vast expanding universe. These changes were the result of various developments and debates coming together in the 1920s. These included the question of the existence of external galaxies, the debate on the size and structure of our galaxy, and the discovery of interstellar absorption. These episodes, both individually and as a whole, have been extensively researched by historians of science. But these have focused almost exclusively on the developments as they took place in the United States, and often in the context of the 1920.


‘Great Debate’ on ‘The Scale of the Universe’ between Harlow Shapley, who argued for a single large galaxy, and Heber D. Curtis, who argued for a small galaxy that was one of many galaxies. As a result, these histories tend to ignore research conducted in other places. By investigating Pannekoek’s contributions to statistical astronomy, we get an impression of the debate as it played out in the Netherlands, which is particularly relevant because Dutch astronomers like Kapteyn, Pannekoek, Cornelis Easton, and Jan Oort contributed to the subject in important ways.

The final transformation concerns the rise of astrophysics as a topic of research in the mid-nineteenth century. Whereas astronomy had traditionally focused on the exact location of stars and movement of planets, the new astrophysics was concerned with the physical properties of the stars themselves. Like with astrophotography, this new field was initially explored by self-funded astronomers. These early astrophysicists explored spectroscopic techniques to investigate the spectra of the Sun and stars, which were classified and compared with spectra created in terrestrial laboratories in an effort to determine the chemical properties of the stars. As more and better stellar spectra were catalogued at the begin-
ning of the twentieth century, it became possible to correlate empirically various spectral properties of stars with one another, initiating what has been called “The Great Correlation Era”. 42 A more theoretical and quantitative approach to astrophysics became possible with the formulation of the ionization equation by Indian astrophysicist Meghnad Saha in 1920 and its subsequent further development. While historians of astronomy have certainly looked at many of these developments, much is still left unexplored. 43 Pannekoek’s astrophysics, for example, has received only a passing mention in many of these histories, which means the context and impact of his research have remained uncharted. This is regrettable because he made significant contributions to the subject for which he was praised by his contemporaries. 44 Moreover, he had a profound impact on the future of Dutch astronomy, as he effectively founded the ‘Dutch School of Astrophysics’ when he redirected his attention to the subject. 45 Thus, an investigation of Pannekoek’s contributions and approach to astrophysics is certainly warranted.

Science and Marxism

A close analysis of Pannekoek’s astronomical research can provide crucial insight into the transformation of astronomy and how this impacted its daily practice and methodology. Additionally, it also opens up new avenues to explore the connections between his astronomy and Marxism and situate both in the longer historiography of knowledge. Moreover, a study of their relation reaffirms how moral and political values mani-

44. See e.g. William Marshall Smart, ‘Address: Delivered by the President, Professor W. M. Smart, on the Award of the Gold Medal to Professor Antonie Pannekoek’, Monthly Notices of the Royal Astronomical Society 111, no. 2 (1951): 245–264; Bok, ‘Two Famous Dutch Astronomers’.
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vest themselves in scientific methodologies.\textsuperscript{46} Although excellent historical research exists on the interface of socialism and science, it has initially focused mainly on the context of communist state ideologies and its influence on scientists both within and outside of communist countries.\textsuperscript{47} Such scholarship has been effective in uncovering how communist politics interfered with the scientific process during the Cold War, but it has provided only a limited view of the various ways in which Marxism and science have been connected. Marxism encompasses more than just a political system and has been developed in places beyond the Soviet Union. Indeed recent scholarship has revealed a myriad of different ways in which science and Marxism were related throughout history that extended well beyond state influence alone.\textsuperscript{48} This raises the question of which connections between political thought and scientific work can be revealed.


in the case of Pannekoek. Can we get a better understanding of both Pannekoek’s astronomy and his Marxism if we investigate how they might relate to one another? And conversely and more broadly, what can the case of Pannekoek tell us about the relation between political philosophy and natural science in general?

One of the direct ways in which Marxism is reflected in the practice of science was through its use of analogy. Alexei Kojevnikov has shown, for example, how in condensed matter physics, the socialist concept of collectivism served as a powerful metaphor to explain the collective behaviour of electrons in metals, crystals and plasmas. The implementation of the metaphor depended on both the physical problem at hand and on the conceptions physicists had of collectivism. To appeal to a wider circle of physicists beyond socialists and leftists, however, these metaphors had to be purged of their overt political connotations and transformed into more neutral language.49 As Kojevnikov indicates: 'The effective invisibility so achieved suggests that more cases of this sort will be found .... It might prove to be a widespread common form of socialist legacy.'50 Thus it is worthwhile to search for similar hidden metaphors in the astronomical work of Pannekoek,51 since he too would likely have employed concealing tactics to maintain the outward separation between his political activities and his scientific career.52

Alternatively, aspects of science can be interpreted as dialectic materialism in practice. As Anja Skaar Jacobson has argued, this was the case in the work of Belgian physicist Léon Rosenfeld, who vehemently defended the Copenhagen interpretation of quantum mechanics because he conceived the concept of complementarity, which is central to the Copenhagen interpretation, as a practical implementation of the dialectic method. Notably, he mostly used this Marxist defence of complementarity against attacks from Soviet physicists who considered the concept to be ideal-

51. This has also been suggested in Kalshoven, *Marxistische economie in Nederland*, 218.
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ist and subjective instead of materialist and objective. Conversely, Pannekoek interpreted dialectical materialism primarily as a scientific method for studying the historical development of societies. He contrasted this method with the method of mechanical materialism, as was commonly used in the natural sciences. Mechanical materialism, he argued, was unsuited for analysing human society and behaviour because it failed to take into account how the human mind processed ideas and social circumstances. He was less outspoken, however, about whether dialectic materialism was preferable for the natural sciences as well. A close analysis of Pannekoek’s astronomical research can provide valuable insight into this question.

The study of the relation between science and Marxism as a philosophy has not yet received the attention that it deserves. As Michael Gordin reminds us: ‘In terms of scale and influence, [dialectic materialism] was one of the twentieth century’s most vigorous philosophies of science, and its history ought to be incorporated into the narratives of the history of philosophy of science that we now have.’ Gordin contributed to this cause by studying the life and philosophy of the Prague-born philosopher and historian of science Arnošt Kolman. A complicating factor with Kolman, however, was his deep involvement with Soviet Party politics, making it impossible to determine how sincere he was in many of his philosophical publications. Pannekoek, on the other hand, was an extremely principled Marxist who regularly gave up political influence for the sake of theoretical purity. He thus provides an excellent opportunity to study how dialectic materialism is reflected in scientific epistemology and practice.

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57. Ibid., 346–348.

18
Epistemic Virtues and Scholarly Personae

To explore the connections between Pannekoek’s astronomy and Marxism, we will focus on his ‘epistemic virtues’. Epistemic virtues, such as objectivity, thoroughness, and trained judgement, can be imagined as moral guidelines for the practice of scientific research. They are epistemic in that they indicate how knowledge should be extracted from the investigation of nature and what the role of the scientist is in this process; they are virtues because they provide a moral imperative for this. Although epistemic virtues are often implicit, they are always normative, and as such, they are present beneath the surface of scientific publications: in the assessment of other researchers, in the explanation of methodology, or in the representation of results. Likewise, traits ascribed to the scientific persona can be found by looking at how scientists and scholars praised or criticized their colleagues, but also in the way that they defended themselves against criticism.\(^{59}\)

Epistemic virtues and scientific or scholarly personae have been important topics of historical research in recent years as a way of exploring how scientific practice can be informed and directed by shared ideals, morals, and ambitions of researchers.\(^{60}\) In the case of scientific and scholarly personae, historians have described different but related ideas of how personae were envisioned and shown how investigating these can aid in understanding science and scholarship historically. Scientific personae have, for example, been construed as culturally shared scientific identities that provided a template for what it meant to be a scientist. By self-fashioning in relation to these personae, scientists could then delineate their personal identity, shape their public image, or indicate the scholarly tradition to which they wished to belong.\(^{61}\) They could even be deployed to justify characteristics that might otherwise be perceived as flaws. Gadi Algazi

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has shown, for example, how scholars in the early modern period cultivated the habitus of an absentminded and emotionally detached scholar to free themselves from the obligations of family life. For Pannekoek, the self-fashioning into two distinct identities can also be imagined an attempt to shield himself from the negative consequences of being a Marxist scientist or a bourgeois academic Marxist. By separating his Marxist activism from his scientific research, he intended to avoid astronomers seeing him as overtly political and socialists seeing his as elitist.

On the other hand, personae have been constructed as exemplars of how scientists or scholars ought to act and behave and how they should produce their work. Scientific personae, thus conceptualized, embody constellations of virtues and skills that can be contrasted against other practitioners adhering to competing virtues. Consequently, as Herman Paul argues: ‘Scholarly personae tend to remain invisible to researchers who focus exclusively on individual practitioners, without comparing their models of scholarly selfhood to those of practitioners committed to different constellations of goods.’ In the case of Albert Einstein, for example, his moralized conception of what it means to be a proper theorist becomes especially visible in his opposition to the convictions of the majority of his colleagues. As Jeroen van Dongen has shown, Einstein was well aware of his status as an exemplar in physics and beyond, and he actively used his status to influence the direction of theoretical physics.

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63. As we have seen, this was not always successful as his political beliefs at times hindered his astronomical career. Conversely, Pannekoek’s academic career was a vulnerable point of attack for his socialist critics. Communist activist Karl Radek called him an ‘astronomer gazing only at the stars, and never at a living worker’ after Pannekoek had criticized the direction of the Bolshevik Revolution. Quoted in Voerman, ‘Principled Theorist’, 68.


Crucially, he altered his recollection of his path to the general theory of relativity, the most important of his achievements, to reflect less how the theory was actually developed and more how the older Einstein believed theoretical physics should be conducted. Einstein re-imagined his past self in his recollections with the goal of changing the direction of theoretical physics research to find acceptance for his controversial new standards and virtues for the discipline.66

While studies on personae and epistemic virtues have often focused on specific disciplines or time periods, they also enable broader perspectives on how ideals in science shift over longer time periods.67 One of the most prominent examples is Lorraine Daston and Peter Galison’s seminal book *Objectivity*, which traces the development of various interpretations of objectivity as epistemic virtues. In particular, they argue that mechanical objectivity emerged as an epistemic virtue in the mid-nineteenth century as a reaction to the then-dominant epistemic virtue of truth-to-nature, which emphasized reason and active imagination to find universal truths hidden behind the appearance of nature. Steadily, this ideal was replaced by one where scientists were expected to operate in a machine-like manner to avoid the influence of their own subjectivity and to let nature speak for itself. This was the virtue of mechanical objectivity. Mechanical objectivity itself was supplanted as the dominant virtue in the early twentieth century by judgemental objectivity, or trained judgement, which called upon educated professionals to use their trained perception and intuition to search for structure and family resemblances in natural phenomena.68

According to Daston and Galison, epistemic virtues are closely tied to specific conceptions of selfhood and expressed in ways to discipline the self — to counteract its perceived weaknesses and emphasize its strengths. Mechanical objectivity, for example, was linked to a conception of the self that was active and always imposed its subjectivity on observations. This active self should be tamed by using mechanical techniques of representation and self-restraint. Truth-to-nature, on the other hand, was connected to the idea of a fragmented self wherein the human mind was seen as a


collection of faculties. To achieve truthfulness, scholars needed to use the faculties of reason and active imagination, while shutting out faculty of the passive imagination, which could lead to delusions and fanaticism. The interconnectedness of epistemic virtues and conceptions of the self make it a very promising perspective for investigating Pannekoek. In his astronomical work, Pannekoek paid much attention to the psychology and physiology of human sight and how this influenced observations of the stars and the Milky Way. This built upon an earlier tradition of scientists in the nineteenth century who became increasingly interested in the relation between human perception and scientific observation. In many cases, they actively used the act of observation to study their own psychology and physiology, in what Jutta Schickore has termed the ‘reflexive turn’ in science. Likewise, in his Marxist writings, Pannekoek extensively elaborated on the role of the human mind in dialectic materialism — an aspect that he felt was lacking in the writings of Marx and Engels. Many of his philosophical articles discussed how the human mind processed information and how it turned experience into general abstractions. These concerns make him an ideal subject to study how epistemic virtues are cultivated as technologies of the self.

The possibility of relating Pannekoek’s Marxist philosophy to his epistemic virtues in astronomy illustrate the potential merit of using this hist-


toriographical tool. But there are also other reasons to believe that a focus on epistemic virtues and scientific personae is fruitful when attempting to connect different aspects of a researcher’s biography. Matthew Stanley, for example, has shown how in the case of the Quaker and astronomer Arthur Eddington, many of his scientific virtues could be traced back to his religious Quaker values. Stanley termed these ‘valence values’ in analogy to valence electrons in chemistry, which ‘facilitate bonding through their ability to be, in a sense, shared between atoms. Similarly, I am interested in those values that facilitate interaction between science and culture.’

My approach will be slightly different. Instead of establishing virtues that crossed domains, I wish to argue that Pannekoek’s epistemic virtues in both Marxism and astronomy are connected precisely because they both emerged from a single conception of the self. At the same time, there can also be a tension between the idealizations captured by the scientific persona and the realities scientists faced in practice. In these situations, a focus on epistemic virtues and the scientific personae can illuminate how scientists navigated such contradictions by crafting a self-image that be-fitted their unique situation.

Pannekoek himself rarely discussed what he considered a virtuous approach to astronomy or how he envisioned an ideal scientist, but the contours of his epistemic virtues and persona are revealed in other ways. One way of uncovering his epistemic virtues is by analysing how he discussed his scientific practice. It is important to note that how he articulated his approach to science does not necessarily concur with what he actually did. As Schickore reminds us: ‘Historians have long warned that the study of scientific publications alone cannot give us an adequate picture of the activities involved in scientific research. Experimental reports are not a reliable source of information about what researchers really do in the laboratory.’

Scientific publications do not show what has actually

happened, but rather what scientists consider the most important aspects of their research. As a result, they are excellent sources to find out what researchers think ought to be done. In this way, the methodological sections of experimental reports have been examined by Schickore, who argues that: "method-related concepts, statements, and reflections as they are presented in experimental reports are significant because they reflect the author’s understanding of the structure and organization of good experimental research." Similarly, Daston and Galison have shown that the introductions of scientific visual compendia were a place where epistemological battles could be fought and where scientists could explicate what it meant to have a "scientific eye."

The fact that Daston and Galison focused their attention on visual compendia points toward another avenue way to investigate Pannekoek’s epistemic virtues: by focusing on the visual and aesthetic aspect of his astronomical research, we can explore his ideas on scientific observation and representation. For a long time, historians and philosophers of science had dismissed images as subsidiary tools intended to supplement knowledge that was mainly conveyed in words and equations. Similarly, they have traditionally treated observation as a passive process that was subservient to the construction of scientific theories and empirical laws. An increased interest in the visual aspect of science in the last few decades, however, has made it clear that scientific images are worth studying in their own right when trying to understand how science is practised. The aesthetic and technical choices scientists make in producing and reproducing images do not just reveal aspects of the knowledge that they wish to convey; they also reflect how scientists believe nature should be observed and which skills and epistemic virtues are required for this. This is certainly true for Pannekoek’s research on the visual appearance of the Milky Way, in

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which he was explicit about how human perception worked, what this meant for how the Milky Way should be observed, and the results of this research could best be represented in scientific publications.

Finally, we can investigate Pannekoek’s epistemic virtues through his assessment of other scientists. By looking at how he reacted to the work of contemporary astronomers, what he perceived to be their flaws, and how he suggested these could be corrected, we gain valuable insight into what he did and did not consider proper scientific conduct. Alternatively, we can also investigate how he described the contributions and virtues of other astronomers in his historical and biographical work. In such descriptions, the ideals of the author often shine through. As historians of science have shown, biographers can sculpt their biographical subjects into an exemplar of scientific behaviour by emphasizing certain virtues and practices. Therefore, Pannekoek’s historical writings, in particular, are valuable sources that will help us to further clarify his epistemic virtues and ideal scientific persona.

Scope and Structure

The following three chapters will provide a close analysis of Pannekoek’s astronomical research, with each chapter focusing on a different area of research. Throughout each chapter, there are three recurring historiographical themes: how did astrophotography impact Pannekoek’s astronomical research; what we can learn by investigating his epistemic virtues and scientific persona; and what relations existed between his astronomy and Marxism.


The first chapter will focus on Pannekoek’s efforts to depict the visual appearance of the Milky Way, for which he employed both visual and photographic techniques. In this research, Pannekoek elaborated extensively on his ideas of human perception and how this was altered by prior experience. He also developed photographic techniques to mimic the workings of the human eye freed from the influence of personal subjectivity. To fully appreciate his epistemic virtues in observing and representing the Milky Way, we must also explore his philosophy of mind.

The second chapter will discuss Pannekoek’s statistical astronomy, his contributions to the debates on the size and structure of the galactic system, and his unsuccessful attempt to develop a photographic method to determine stellar statistics. A notable difference between his approach and that of his contemporaries was how he investigated the statistical distribution of stars. Rather than relying on standardized methods to order this distribution, he emphasized the importance of using judgement to find stellar clusters. This led him to significantly different results despite relying on the same published catalogues. Both in the way that Pannekoek approached statistical astronomy and in the resulting models of the galactic system, there are clear analogies with his Marxist writings.

The final chapter provides an analysis of Pannekoek’s theoretical and observational contributions to astrophysics. One of the reasons why Pannekoek switched to astrophysics was because he believed it was eminently suited to benefit society. But as an astronomer without an observatory, he had to rely on photographic plates borrowed from other observatories for his observational research, which severely limited his possibilities. Therefore, he fashioned his methodology and his persona in such a way that he could manage the constraints of his institutional circumstances while following his conviction that scientific progress should lead to societal progress.

Together, these three chapters provide a thorough investigation of Pannekoek’s contributions to astronomy and their relation to both his own Marxist philosophy and the historical development of science in the first half of the twentieth century. In doing so, they not only provide a clear image of Pannekoek as a unified person, but also help us to understand the relation between science and political philosophy, and clarify what it means to a scientist.
Ever since they were first published in the 1920’s, the Milky Way images created by Anton Pannekoek have captured the imagination of astronomers and the public alike. Astronomers have used them as a definitive source for the distribution of galactic light, while the public got to know them through their inclusion in Zeiss planetaria and the Lund Panorama of the Milky Way.1 More recently, they inspired visual artist Jeronimo Voss in the creation of his exhibition ‘Inverted Night Sky’, which was displayed at the Stedelijk Museum Bureau Amsterdam.2 Joseph Ashbrook, editor of Sky and Telescope, even considered Pannekoek to be the ‘greatest of all naked-eye observers of the galaxy’.3 A striking feature of Pannekoek’s Milky Way research was that he used both visual observations and photographic methods to determine the distribution of galactic light, which he then represented using many different techniques, including naturalist

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1. **Milky Way Research**

   drawings, verbal descriptions, isophotic diagrams, and numerical tables. In this chapter, I focus on how these various representations were made and why they were made in the first place. By studying how and why Pannekoek employed such wide-ranging methods for observing and representing the visual aspect of the Milky Way, we gain crucial insight into the development of early twentieth-century astronomy. It illustrates the complex relation between naked-eye observations and photography during this period, reveals how astronomers coped with the characteristics of human psychology and physiology, and deepens our understanding of the connections between political philosophy and scientific epistemology.

   To explain the co-existence of various representational methods in Pannekoek’s research, we must first examine the role he attributed to astronomers in observing the Milky Way; in particular, how he thought certain characteristics and limitations of human physiology and psychology combined to create the image of Milky Way. On this issue, it is informative to draw a parallel with late-nineteenth-century epistemic debates concerning the inherent differences between astronomical observers. Following the realization that well-skilled observers recorded different coordinates for the same star even when using the same instruments and diligently abiding by the same methods, astronomers had to reconsider the role of human perception in visual observation and develop strategies to either minimize or stabilize these differences. This reflexive inward look of astronomers was part of a greater ‘reflexive turn’ in observational science during the mid-nineteenth century, and it caused several astronomers to venture beyond their own field and participate in a cross-disciplinary exchange of ideas. More than half a century later, Pannekoek, too, was deeply concerned with the anatomy of the human eye and the psychology of the human brain when developing his method for visual photometry of


the Milky Way. He, too, ventured beyond astronomy to develop his ideas. In his case, however, it was not experimental psychology, but Marxism that he turned to.

There are clear advantages to actively considering Pannekoek’s Marxism when discussing his scientific methodology in representing the Milky Way. It is in his Marxist writings that Pannekoek developed his philosophy of the human mind: that humans have an innate ability to analyse and synthesize sense perceptions, but that this ability is implicitly influenced by prior experience. Historians of science Lorraine Daston and Peter Galison have argued that scientific epistemology is inextricably linked to conceptions of the self, as scientists seek to counteract the weaknesses of the self while emphasizing its strengths.6 Daston, in particular, has emphasized how the interaction between psychological-physiological concerns and scientific epistemology are especially prominent when considering the visual aspect of science.7 In Pannekoek’s Milky Way research, we find that he wanted to emphasize the innate capacity of the human mind to analyse sense perceptions while eliminating the effects of implicit bias. In doing so, he concurred with contemporary ideas on scientific collaboration. The late nineteenth century saw the emergence of large-scale scientific collaborations working on grand transnational projects. For the organizers of these projects, it was vital that participants showed self-restraint and followed predetermined methods. Subjective differences had to be minimized for individual contributions to be mutually compatible.8 Although Pannekoek’s Milky Way research was conceived on a much smaller scale, he advocated a similar ethos. In his case, he hoped to eliminate individual subjectivity while preserving collective subjectivity.

The question of how to observe and represent the Milky Way inevitably leads to a discussion on the role of photography in early twentieth-

1. Milky Way Research

century astronomy. When discussing the development of astrophotography, it is tempting to list vivid and increasingly detailed photographic images of visually striking astronomical objects, like nebulae, clusters, or the moon, produced by the latest technological innovations. Such an approach, however, would overlook that the acceptance of photography in astronomy was far from straightforward: it was accompanied by genuine epistemic concerns about the usefulness and trustworthiness of photography.9 Most historical research on this subject has focused on the second half of the nineteenth century, but these concerns persisted well into the twentieth century. When we look at Pannekoek’s Milky Way research, we find that drawing and visual observation still played a prominent role in his work precisely because he believed contemporary photographic images of the Milky Way were inadequate for his purposes. Moreover, it was rare for photographs depicting astronomical objects to find their way into professional publications at all. Rather, photography was used as a tool for gathering, storing, sharing, and measuring large amounts of observations without needing constant access to a telescope and clear skies.10 The information they contained was then usually presented in the form of large tables of numbers. Pannekoek’s use of astrophotography fits this profile. He was not interested in the way the Milky Way was depicted by photographic images, but in the measurement of its light intensity on photographic plates.


1.1. The Milky Way as Optical Phenomenon

This chapter will begin by investigating Pannekoek’s ideas on what the Milky Way actually was; how, as a phenomenon, it was shaped by the particularities of human physiology; and how astronomers could best take advantage of this physiology while counteracting its flaws. In doing so, it is vital to look beyond Pannekoek’s scientific writings and consider his Marxist philosophy. The next section will illustrate how these epistemic concerns were then translated into astronomical practice. It explores Pannekoek’s method of photometry through visual observations, how he combined observation from various observers, and the various ways in which he represented the final results. The final section will discuss his method of photographic photometry as a way of replacing visual observations and address the striking continuity between his visual and photographic programme.

1.1 The Milky Way as Optical Phenomenon

At a young age, Pannekoek was already interested in the visual appearance of the Milky Way. His early journals contain many observations of various features of the Milky Way. At times, these were accompanied by rudimentary drawings or even contour maps of sections of the Milky Way that represented areas of equal brightness through isophotic lines (Figure 1.1).\footnote{Pannekoek’s observational journals can be found in Archive of the Anton Pannekoek Institute, University of Amsterdam (API), except for the second one, which is located in Persoonlijk archief van Antonie Pannekoek, Museum Boerhaave (MB/AP), box 1. These journals also contain other astronomical and non-astronomical observations, such as of variable stars and of the plant life around the city of Apeldoorn where Pannekoek lived during this period.} Taken together, these observations suggest that he was already en route to developing a distinct method of representing the Milky Way before he started his formal education in astronomy.

One of the reasons why Pannekoek developed his own method for observing the Milky Way was because little research had been done in that area so far. As Pannekoek noted in his History of Astronomy many decades later:

> It is a remarkable fact that [after Ptolemy had written verbal descriptions of the Milky Way] in all later centuries no attempt was made to repeat and improve his work and to depict the phenomenon as it appeared to the eye. Star maps mostly

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showed a worthless picture of a uniform, sharp-bordered river. Probably the reason is that what always remains the same does not draw the attention.\textsuperscript{12}

It was thus unsurprising, so Pannekoek argued, that the first astronomer to publish systematic descriptions of the Milky Way, the British astronomer John Herschel, did so of a part of the sky that was unfamiliar to him. Herschel’s drawings, published in 1847, focused on the southern Milky Way and were based on observations made during his four-year trip to South Africa. It took three more decades before similar drawings were published for the northern Milky Way by Eduard Heis of the University of Münster in 1877, and by Jean-Charles Houzeau, director of the Brussels Observatory, in 1878. Houzeau’s atlas, \textit{Uranométrie générale}, was the first to represent the brightness of the Milky Way with isophotic lines.\textsuperscript{13}

In 1893, another drawing of the northern Milky Way was published; this was produced by Dutch journalist and amateur astronomer Cornelis

\begin{thebibliography}{9}
\bibitem{13} For an overview of Milky Way descriptions in the late nineteenth century, see \textit{History of Astronomy}, 474–475; Cornelis Easton, \textit{La Voie lactée dans l’hemisphère boréal} (Dordrecht: Blussé, 1893), 11–17.
\end{thebibliography}
Easton with the assistance of Pannekoek, who was then a student in Leiden. This publication is especially noteworthy because, in the introduction, Easton explicitly discussed the nature of the Milky Way and the problems associated with accurately drawing it. He contended that, due to its extreme faintness, it was not only very difficult to compare the brightness of different parts of the Milky Way, but also deceptively easy to exaggerate the contrast in drawings. Moreover, because the Milky Way was built up from the collective light of many faint stars, it was ultimately a visual phenomenon created by the observer; it could even be called an optical illusion. To make matters worse, the appearance of the Milky Way could be altered easily by observational circumstances or by foreground stars. It was therefore important not to assign too much value to its appearance. Nevertheless, Easton still believed it was important to keep drawing it, as drawings provided a valuable opportunity to track changes in the large-scale structure of the Milky Way over time.

Pannekoek’s ideas on the nature of the Milky Way phenomenon coincided with those of Easton, as Pannekoek stated in the introduction to his 1920 publication on the northern Milky Way:

The Milky Way image that we observe is an optical phenomenon, which is created by various optical, physiological and psychological conditions working together. Easton once referred to the Milky Way as an optical illusion; this expression may be even more true than the author himself had intended.

The Milky Way, according to Pannekoek, was not a real entity that existed in the external world; it was the result of the combined light of countless faint stars, as processed by the human eyes and brain. Even so, he still believed it was valuable to take this optical illusion seriously and investigate and represent it in detail, even more so than Easton did. To understand why, we will turn to Pannekoek’s Marxist philosophy, where he examined both the essence of scientific laws and the nature of the human mind.

15. Easton, La Voie lactée, 1–10.
16. Ibid.
According to Pannekoek, the task of the human mind was to analyse and abstract information that was provided from the sense organs. This intuitive abstraction was required to make sense of the external world, which Pannekoek conceived as a constant flow of infinitely varied and ever-changing phenomena. The mind turned these phenomena into stable objects and causal effects that we could understand. In his own words:

The mind is the faculty of generalization. It forms out of concrete realities, which are a continuous and unbounded stream in perpetual motion, abstract conceptions that are essentially rigid, bounded, stable, and unchangeable. ... The world is a unity of the infinitely numerous multitude of phenomena and comprises within itself all contradictions, makes them relative and equalizes them. Within its circle there are no absolute opposites. The mind merely constructs them, because it has not only the faculty of generalization but also of distinguishing.  

The human mind extracted information from the overwhelming amount of sense impressions of the outside world and organized and systematized this information into distinct categories and general laws. By abstracting the inflow of information, the mind could comprehend the world and predict future occurrences.  

Pannekoek’s theory of the human mind also extended to natural laws uncovered by science. These had no existence outside of the human mind, but were, in their essence, abstract rules extracted from our sense perceptions, formulated to bring structure and understanding to our observation of the external world of appearances. Natural laws did not refer to the properties of real objects but only talked about the properties of universal, abstract entities. By identifying concrete and singular facts with universals, they were crafted into natural laws. Both universal entities and natural laws only existed as abstractions in human thought; they were fabricated constructions that brought order to the overwhelming stream of sense perceptions. The aim of scientific research then should not be to search for the true structure of reality but to summarize knowledge. 

1.1. The Milky Way as Optical Phenomenon

and provide economy of thought.20 By organizing and systematizing natural phenomena into laws and models, it became possible to comprehend them.21 In light of this conceptualization of natural law, one can begin to understand why Pannekoek thought it worthwhile to investigate and represent the Milky Way. Even if it was not a real physical object as such, it was still valuable as a scientific object because it gave an intuitively created abstraction of the distribution of stars in the galaxy. This abstraction was useful for astronomers to track changes in the general distribution of stars, as Easton had also suggested, or as a comparison for the results of statistical astronomy, as will be discussed in the next chapter.

The Milky Way phenomenon is especially interesting in the context of Pannekoek’s philosophy of science because he explicitly discussed the various conditions that played a role in transforming the light of countless faint stars into the Milky Way as perceived by our eyes. He divided these conditions into three distinct types: the optical–anatomical, the psychological–physiological, and the purely psychological. Optical–anatomical conditions referred to the physical properties of the eye, such as the size and number of photosensitive nerves on the retina. The limited number of these retinal elements meant that the light of multiple stars, which might have been too faint to detect individually, was combined onto a single nerve. At the same time, the light of each star was not just detected by a single nerve but was spread out over multiple. The combination of these two effects obscured the individuality of stars in rich agglomerations and made their light appear to human eyes as a flat image of gradu-

20. On the topic of the essence of natural laws, Pannekoek agreed in broad terms with his contemporary Ernst Mach. At the same time, Pannekoek rejected what he considered Mach’s tendency toward subjectivism. He criticized Mach for prioritizing sense perceptions while stopping short of considering what caused them. This failure to take into account the external world made Mach an idealist rather than a materialist in Pannekoek’s opinion. For Pannekoek’s assessment of Mach’s philosophy, see Anton Pannekoek, Lenin as Philosopher: A Critical Examination of the Philosophical Basis of Leninism, repr. (1948; repr., New York: Breakout Press, 1975), 45–56. For more on Mach’s ideas on natural law, see Erik C. Banks, Ernst Mach’s World Elements: A Study in Natural Philosophy (Dordrecht: Kluwer, 2003), 123–135; Elske de Waal and Sjang L. ten Hagen, ‘The Concept of Fact in German Physics around 1900: A Comparison between Mach and Einstein’, Physics in Perspective 22, no. 2 (2020): 55–86, 64–66.
ally changing surface brightness. This flat image, Pannekoek identified as 'the theoretical Milky Way'.

The theoretical Milky Way was not how one actually perceived the Milky Way, however, as this image was further altered by psychological–physiological conditions. An example of such a condition was the visual stimulus threshold: the amount of light that was needed before a nerve would send a signal to the brain. This threshold was a function of both the size and brightness of an observed object. The smaller the object, the brighter it had to be to still be detectable. Additionally, small bright features were also blurred over a larger area, making them appear less distinct. Crucially, both optical–anatomical and physiological–psychological conditions depended on individual personal characteristics — like the number of retinal elements, visual acuity, or sensitivity to faint light — which meant that the Milky Way appeared differently to each observer.

It was impossible to discern the extent to which personal differences in physiology and anatomy affected the appearance of the Milky Way, however, as their effect was drowned out by the even more significant effect of purely psychological conditions. As Pannekoek explained it: ‘The personal Milky Way image is not objectively determined by the earlier mentioned conditions, but is subject to still other influences, which can best be described as purely psychological.’ Due to the elusive faintness of the Milky Way light, the brain inevitably created patterns where there were none. Unlike the other two classes of conditions, purely psychological conditions were largely random and not necessarily connected to the actual distribution of stars. Furthermore, because pattern creation was influenced by the observer’s prior investigations of the Milky Way, it was an effect that could not be lessened by further observations: ‘No repetition of the work, no matter how often, can help here; personal touch [Manier] will not be reduced, but will only impress itself stronger and clearer.’

Pannekoek’s views on human psychology and the role of prior knowledge in the creation of the Milky Way phenomenon resonated with his particular Marxist philosophy. The foundational principle of Marxist philosophy is that human consciousness is ultimately determined by ex-

22. Pannekoek, Nördliche Milchstrasse, 15.
23. Ibid., 15, n.1. Pannekoek explicitly referred to the work of physiologist Hans Edmund Piper, which later became known as Piper’s law.
24. Ibid., 14–16.
25. Ibid., 16. Translated from German.
26. Ibid., 16. Translated from German.
1.1. The Milky Way as Optical Phenomenon

ternal material factors. What exactly encompassed these material factors, however, remained a point of contention among Marxists. Pannekoek’s interpretation, which was based on the work of Joseph Dietzgen, was remarkably broad.\textsuperscript{27} He considered everything that was objectively observable to be ‘material’, including ideas, thoughts, and theories:

[T]he surrounding real world ... is not restricted to physical matter only, but comprises everything that is objectively observable. The thoughts and ideas of our fellow men, which we observe by means of their conversation or by our reading are included in this real world. Although fanciful objects of these thoughts such as angels, spirits or an Absolute Idea do not belong to it, the belief in such ideas is a real phenomenon, and may have a notable influence on historical events.\textsuperscript{28}

Crucially, the influence of all these material factors was a ‘subconscious spontaneous process in our minds’.\textsuperscript{29} The human mind was always involved in knowing the outside world, and because it worked instinctively, it was not always aware of the material factors that influenced its thoughts and ideas.\textsuperscript{30} In the case of the Milky Way, this meant that any knowledge of earlier observations, either through memory or by looking at drawings, would inevitably influence the perceived structure. The resulting image of the Milky Way would then mimic preconceived notions of how it should look. Escaping this influence of earlier knowledge was impossible, and so observations of the Milky Way were always altered by purely psychological conditions.\textsuperscript{31}

Although Pannekoek did not appear to be too concerned about personal differences due to optical–anatomical or physiological–psychological conditions, differences caused by purely psychological

\textsuperscript{27} Pannekoek greatly valued the work of Dietzgen and considered it an indispensable supplement to the work of Marx. In creating his Marx–Dietzgen synthesis, however, Pannekoek may have given a too narrow view of Dietzgen’s philosophy while overstating its originality and importance, as historians of socialism have suggested. See Tony Burns, ‘Joseph Dietzgen and the History of Marxism’, Science & Society 66, no. 2 (2002): 202–227; Jasper Schaaf, \textit{De dialectisch-materialistische filosofie van Joseph Dietzgen} (Kampen: Kok Agora, 1993), 242–253.


\textsuperscript{29} Ibid., 448.

\textsuperscript{30} Ibid., 451.

\textsuperscript{31} Pannekoek, \textit{Nördliche Milchstrasse}, 16.
conditions were a problem to him, precisely because they were both substantial and random. In 1897, he discussed various recently published Milky Way drawings and drew attention to the fact that, despite remarkable agreement on certain features, there were also substantial discrepancies in the structures they depicted. At times it was even hard to recognize that they were meant to represent the same object at all as a result of differences in the way observers recognized and recorded features, and differences in style and method of drawing.\textsuperscript{32} Pannekoek was not alone in noticing the discrepancies among Milky Way drawings. A few years earlier, for example, Edward Emerson Barnard, a pioneer in Milky Way photography, argued: ‘Eyes differ so much, and astronomers, as a rule, are such poor artists, that we may never expect to get anything like a fair delineation of the Milky Way by the human hand alone.’\textsuperscript{33} Pannekoek disagreed with this sentiment, however, primarily based on the comparison between the Milky Way drawings of Easton and the Irish astronomer Otto Boeddicker ‘which, though giving a very different representation of some parts, show in other parts a fair resemblance even of detail.’\textsuperscript{34} As we have seen, Pannekoek considered it valuable to create a representation of the Milky Way based on visual observations. The partial agreement between the drawings of Easton and Boeddicker gave him the confidence that such a representation could be constructed by combining the work of many different independent astronomers in such a way that eliminated personal biases while preserving the innate advantages of human perception.\textsuperscript{35}

This section has revealed some notable interrelations between Pannekoek’s scientific research and Marxist epistemology. By considering the latter, we can better understand methodological and epistemic choices he made in the former. It elucidates why Pannekoek believed it was important to capture the Milky Way as it was observed by the human eye, despite the fact that it was an optical illusion, and despite the considerable discrepancies among different observers. Intuitive abstraction was, after all, an


\textsuperscript{34} Pannekoek, ‘Existing Drawings of the Milky Way’, 41.

\textsuperscript{35} Ibid., 42.
inherent virtue of being human, and if the Milky Way aspect proved to be valuable for the investigation of the general structure of the distribution of stars, then it was worthy of scientific research. It also reveals why Pannekoek thought it was impossible to eliminating personal interpretation from visual observations. Since, as he explained in his Marxist writings, ideas and memories are material factors that determine human thought, subsequent observations of the Milky Way would only reinforce this interpretation, as they were unavoidably influenced by earlier impressions. It should be stressed, though, that neither belief was unique to Marxism and that Pannekoek had already begun to develop his ideas on the Milky Way before he had turned to Marxism. What the interrelations indicate, however, is that Pannekoek had a coherent epistemology that connected the practice of science with his political and ethical philosophy.

At the same time, we can relate Pannekoek’s extensive description of the various anatomical, physiological, and psychological circumstances that create the Milky Way phenomenon to how astronomers reflected on their own role in astronomical observations from the mid-nineteenth century onward. By this time, due to the increasing precision of astronomical observations, astronomers began to notice that different observers recorded different stellar coordinates when using the trusted eye-and-ear method in transit observations. These so-called ‘constant differences’ forced astronomers to acknowledge that even among the most skilled and educated observers, inherent differences could occur. Astronomers started to reflect on themselves as an intricate part of their astronomical instrumentation. They each had their own characteristics and variations that could be measured and had to be corrected for, as in the case of any systematic instrumental error.

Crucially, different beliefs on what caused constant differences led to different strategies to eliminate them. When it was believed that the effect was caused by psychological factors, the proposed solution was to minimize it by emphasizing discipline, skill, and education. When the effect was believed to be due to physiological factors, on the other hand, it became an inherent characteristic of the observer that could not be eliminated. It could, however, be standardized and accounted for by introducing mechanical methods and by keeping track of who made each measurement. This ultimately led to the measurement of each observer’s characteristics

36. The ear-and-eye method is a method of measuring the right ascension of a star by following its movement across reticles in the telescope while listening to a ticking clock.
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in order to calculate their so-called ‘personal equation’.\(^{37}\) According to Pannekoek, both psychology and physiology played a substantial role in creating the appearance of the Milky Way. Accordingly, we will see combinations of both strategies in his research. Psychological conditions could be reduced through proper method and collaboration. Physiological conditions, on the other hand, could only be eliminated through photography.

1.2 How to Represent the Milky Way

Pannekoek’s solution to the problem of providing a visual representation of the Milky Way that everyone could agree upon, was to make use of a collaborative effort. By combining various independent drawings and descriptions of the Milky Way, it would be possible to filter out random personal patterns, which were restricted to a single observer, while preserving those features that were present in the work of multiple observers. The resulting image, Pannekoek argued, would then be far more objective than any individual image.

Here, the importance of many independent works becomes apparent. Their differences give an impression of the objective uncertainties of faint particulars, which far exceeds the limits of subjective certainty. On the other hand, their agreement can secure faint details that each observer individually would be inclined to consider doubtful. In the average of various representations, the accidental-subjective, the style of each observer, disappears to a large extent. What is retained, is not an objective image of the Milky Way, but that which one could call the mean-subjective image \(durchschnittlich-subjektive Bild\), the objective image as it is altered by the general physiological–psychological observation conditions. The connection with an objective Milky Way image is then at least significantly easier to find.\(^{38}\)


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The method of combining the observations of multiple observers to create a single composite image was common in late nineteenth-century astronomy. Similar projects had been undertaken, for example, by William Parsons, the third Lord Rosse, in his drawings of nebulae, and by Arthur Ranyard and William Wesley in their depictions of the Solar corona. In both cases, the final image was extracted by a single astronomer whose task it was to determine the true shape of the astronomical object based on their careful visual inspection of the various observations. Pannekoek, as we will see, took a far more mechanical approach in his pursuit for what he termed the ‘mean subjective image’; an approach that was closely connected to his ideas of how the Milky Way should be represented in the first place.

A requirement for constructing a collaborative representation of the Milky Way was that there were observations by other astronomers in the first place. In 1897, when he was still a student in Leiden, Pannekoek published a series of articles in popular astronomy journals that encouraged amateur astronomers to record their observations of the Milky Way and outlined a method that they should follow. He also collaborated with Easton to create star charts that were specifically suited for observing the Milky Way. In calling amateur astronomers to contribute, he followed in the footsteps of Friedrich Argelander who, in 1844, had written an ‘appeal to the friends of astronomy’ to contribute by making easily conducted observations of the night sky, including of the Milky Way.

Before beginning their observations, Pannekoek asserted, observers had to take proper precautions. They had to ensure that there was no artificial illumination nearby and that the sky was clear and cloudless, but most importantly, they had to avoid learning about any previous research:

39. For nebula drawings, see Omar W. Nasim, Observing by Hand: Sketching the Nebulae in the Nineteenth Century (Chicago: University of Chicago Press, 2013), 38–65; for the Solar corona, see Pang, Empire and the Sun, 96–105.
41. Pannekoek owned a Dutch translation of Argelanders article: Friedrich Argelander, Handreiding voor vrienden der sterrekunde, tot het volbrengen van belangrijke waarnemingen, de groene werktenen vorderen, ed. Frederik Kaiser, trans. W. F. Kaiser (Zwolle: De erven J. J. Tijl, 1855), which is located at API.
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‘For [the Milky Way’s] great faintness makes it very easy to see what we expect to see, and preconceived ideas will soon vitiate the results.’ Here, we see a clear example of how Pannekoek believed thoughts and ideas could influence on scientific observations. It should be noted, however, that this epistemic fear of prior knowledge altering what was seen was quite common among astronomers of his time. When Irish astronomer Otto Boeddicker was working on his drawing of the Milky Way, which was published in 1889, he wanted to exclude the influence of prior knowledge to the point that he avoided looking at any earlier drawing—including his own—so that he could ‘remain as long as possible in ignorance of [the Milky Way’s] appearance as a whole’.

To record observations of the Milky Way, Pannekoek proposed a dual method that combined verbal descriptions with visual diagrams. When observing particular features, it was important to investigate only small parts of the Milky Way at a time and provide a detailed description of the position, boundaries, and interconnections of each Milky Way stream and cloud. Often, it was advantageous not to look directly at a bright spot but slightly next to it, as indirect vision could reveal details that were not seen by direct vision. Recording detailed features could best be done by written descriptions, as Pannekoek considered these to be much more intelligible and certain than drawings, for which it was never clear whether particular features were actually seen by the observer or the result of an inaccurate rendering by the draughtsman. To record the general distribution of brightness in the Milky Way, Pannekoek recommended the use of isophotes, lines of equal brightness, which could be produced as follows:

After having examined the region thoroughly, a boundary line is picked out, and its course is followed along the Milky Way, everywhere tracing the places of equal brightness. After having finished such a line, and after having marked its course

43. For example, among astronomers observing the surface of Mars, see K. Maria D. Lane, *Geographies of Mars: Seeing and Knowing the Red Planet* (Chicago: University of Chicago Press, 2011). Argelander also asserted that observers of the Milky Way should work independently from other observers. Argelander, *Handleiding voor vrienden der sterrekunde*, 78.
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upon the chart, another is chosen, shaping its course along a track of greater or lesser brightness.\textsuperscript{46}

The number of isophotes should be limited to only a few in order to avoid confusion. They also should be supplemented with systematic photometric estimates that had to be made by repeatedly comparing distant sections of the Milky Way to each other. This dual method had the advantage of catering to both astronomers who wanted to track changes in the visual appearance of the Milky Way, where minute details were important, as well as to those who wanted to use the Milky Way as a guide for researching the overall structure of the galactic system, for which the general distribution of light was more useful.

When Pannekoek was hired as observer at the Leiden Observatory in 1899, he abandoned his research on the appearance of the Milky Way. In 1910, he again picked up the subject, but he noticed that he had failed to cover the whole of the northern Milky Way in his observations. He attributed this to the fact that he had deliberately avoided looking back at his earlier observations during this research. From 1910 to 1913, he worked on the missing areas until he had finally covered the northern Milky Way in its entirety. The results of these observations were only published in 1920. Throughout this period, Pannekoek’s ideas on how to represent the Milky Way continued to develop, however. He concluded that the dual method of verbal descriptions and isophotic diagrams was insufficient; they had to be supplemented with naturalist white-on-black drawings that showed the Milky Way ‘as it appeared to [Pannekoek’s own] eyes’ (Figure 1.2).\textsuperscript{47}

This inclusion is significant as these naturalistic drawings would have been the most difficult and expensive to reproduce while serving no immediate scientific purpose, like the isophotic diagrams and verbal descriptions did. An isophotic diagram (Figure 1.3) could be used in comparison with statistical star counts in order to probe the three-dimensional structure of the star system, while verbal descriptions could be recorded over a prolonged period of time in order to track minute changes in particular features of the Milky Way.\textsuperscript{48} Instead, the naturalistic drawings were included because they had aesthetic value. Conveying this aesthetic value was important,\textsuperscript{46, 47, 48}

\textsuperscript{46} Pannekoek, ’Best Method of Observing the Milky Way’, 79.
\textsuperscript{47} Pannekoek, \textit{Nördliche Milchstrasse}, 11. These drawings were made with chalk on black paper.
Figure 1.2: Naturalistic drawing of a section of the northern Milky Way drawn by Pannekoek. Source: Pannekoek, *Nördliche Milchstraße*, plate 1.
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according to Pannekoek, because it was what often stimulated interest in astronomy in the first place: 'For modern man ... the aesthetic element undeniably helps to arouse love for the night sky, all the more because the pleasure that direct observation provides us, ... is further validated and enriched by knowledge.'

Pannekoek’s observations of the northern Milky Way prompted German astronomer Josef Hopmann to observe the southern Milky Way as part of his 1922 Solar eclipse expedition to Christmas Island. Hopmann explicitly followed Pannekoek’s method in making and recording his observations. He also presented his results in the form of an isophotic diagram, which he later supplemented with numerical values for the surface brightness. Pannekoek, however, was sceptical of Hopmann’s results. The latter’s photometric values for those areas that overlapped with the northern Milky Way were not consistent with the values that Pannekoek had found. Furthermore, Pannekoek doubted the veracity of the incredibly rich and detailed structure displayed in Hopmann’s southern Milky Way.

To extend the research himself, he first came up with the idea to travel to South Africa, but when the Dutch Royal Academy of Sciences organized an expedition to Palembang in the Dutch East Indies for the 1925 Solar eclipse, Pannekoek saw it as an ideal opportunity to observe the southern Milky Way on Java instead.

Before his expedition to the Dutch East Indies, Pannekoek had never been able to follow his own instructions in earnest as he had already been used the appearance of the Milky Way for his research on the statistical distribution of stars will be discussed in the next chapter.

53. Anton Pannekoek to Cornelis Easton, 19 Apr 1926, Correspondentie, aantekeningen Cornelis Easton, Museum Boerhaave (MB/CE) 427b.
54. Anton Pannekoek to Willem de Sitter, 22 Sep 1923, Leiden Observatory Archives, directorate Willem de Sitter, Leiden University Library, Special Collections (UBL/WdS), 45.2.
Figure 1.3: Isophotic diagram drawn by Pannekoek of the same section of the Northern Milky Way as depicted in Figure 1.2. The lines indicate areas of equal brightness while the numbers give a numerical value for the brightness at a specific point. Source: Pannekoek, *Nördliche Milchstraße*, plate 4.
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well acquainted with the appearance of the northern Milky Way prior to his first recorded observations. Now, with the southern Milky Way, he could truly start with a blank canvas. He soon discovered that there were practical problems to being unfamiliar with the area under investigation. It took him several days to get familiar enough with the stars of the southern hemisphere to be able to observe the southern Milky Way without constantly having to reorient himself. Moreover, he realized that even when looking at a completely unfamiliar sky, there were still ways in which implicit bias altered his observations. Increased knowledge of the importance of absorbing nebulae, for example, made him more inclined to mark dark features as real resolved objects. Nevertheless, he was satisfied with his method as it provided him with a systematic way of handling observational data, which in turn led to a more successful representation of the Milky Way.\(^{55}\) He also mentioned the valuable contribution of his wife, Anna Pannekoek-Nassau Noordewier, who acted as an observational assistant and penned down the verbal descriptions he dictated.\(^ {56}\) Significantly, one of the main conclusions of his research was that the richness of the southern Milky Way, which Pannekoek had dismissed in the work of Hopmann was indeed accurate. In a letter to Easton, he described how he had been stunned by the beauty of the southern Milky Way, further reinforcing the importance of the aesthetic aspect of the Milky Way for Pannekoek.\(^ {57}\)

Of course, presenting his own Milky Way observations was only the first step of the process for Pannekoek. His ultimate goal was to produce a collaborative mean subjective image. In 1920, Pannekoek did exactly that for the northern Milky Way, making use of the earlier observations of multiple independent observers, most prominently those by Otto Boeddicker, Cornelis Easton, and J.F. Julius Schmidt.\(^ {58}\) Pannekoek had initially intended to present the mean subjective image in the form of separate

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56. Pannekoek, *Südliche Milchstrasse*, 6. I have not found any other instance where Anna Pannekoek-Nassau Noordewier assisted Anton Pannekoek in his astronomical research.
57. Anton Pannekoek to Cornelis Easton, 19 Apr 1926, MB/CE, 427h.
Figure 1.4: The mean subjective image of the same section of the Milky Way as depicted in Figure 1.2 and Figure 1.3. This diagram is created by averaging over several drawings made by independent observers. Source: Pannekoek, *Nördliche Milchstrasse*, plate 7.
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reproductions of each individual drawing from which the readers could
draw their own conclusions about the structure of the Milky Way by com-
parison. By 1920, however, Pannekoek had grown more ambitious in his
plans for the mean subjective image. His new strategy was to make use
of the numerical properties of isophotic drawings. He wanted to mimic
the image that would emerge if these drawings had been made on trans-
lucent paper, placed on top of each other. He believed he could simulate
this effect numerically by measuring isophotic diagrams of the drawings
and calculating the arithmetic mean.

For his own observations and those of Easton, isophotic diagrams were
already available, but those of Schmidt and Boeddicker had to be specially
created from the original drawings. When these were done, however,
Pannekoek realized that the brightness estimates in the drawings of Boed-
dicker and Schmidt were far from systematic, making their absolute values
unreliable. Yet, at the same time, their drawings were often richer and bet-
ter in their finer structures than those of Easton and Pannekoek. To make
the most of the benefits of each drawing, Pannekoek attributed greater
weight to the work of Boeddicker and Schmidt in detailed features of the
Milky Way, while ignoring them to calculate the general structure — a
striking example of how he relied heavily on his own judgement in cre-
ating the mean subjective image. Pannekoek was pleased with the end
result, which he believed rose far above that of any one observer in depict-
ing the Milky Way structure, making it ideal for comparison with photo-
graphic results. The calculated mean subjective image was presented
both in the form of an isophotic diagram (Figure 1.4) and as a numerical
table. Additionally, for each section of the Milky Way, verbal descriptions
by multiple observers were placed side by side. All these different meth-
ods of representation were needed because, due to the intangible nature of

59. This strategy was later used by Fritz Goos in his depiction of the Milky Way. Fritz
61. Anton Pannekoek to Willem de Sitter, 21 Jul 1919; Pannekoek to De Sitter, 24 Jan 1920,
UBL/WdS, 45.1.
62. Pannekoek, Nördliche Milchstrasse, 90. In a review of Pannekoek’s publication, Ea-
ston remarked that Pannekoek had ‘sinned somewhat’ by being too modest and that the
result would have been even better if he had attributed double weight to his own estim-
ates, which would have been warranted because of his ‘impeccable method and precision’. Cornelis Easton, ‘De Noordelijke Melkweg’, review of Die nördliche Milchstrasse, by Anton
Pannekoek, Hemel en Dampkring 19, no. 5 (1921), 68–69. Translated from Dutch.
64. For an example of these descriptions, see Appendix A.
the Milky Way phenomenon, it was the only way to capture its appearance to the human eye.\textsuperscript{65}

Pannekoek’s strategy for constructing the mean subjective image from existing depictions of the Milky Way illuminates his views on the ethos of scientific investigation and collaboration. According to Pannekoek, the most important quality for Milky Way astronomers was not their excellent vision or innate genius. Indeed, such individual qualities were exactly what Pannekoek sought to eliminate in his creation of the mean subjective image. Instead, he implored astronomers to show self-restraint and follow the proper method in describing the Milky Way. Doing so would make their contribution to the combined image that much more valuable. And ultimately, this combined image, the mean subjective image, was much more trustworthy than the image that any individual observer could ever hope to produce.

1.3 Photography for Measurement

Pannekoek’s extensive work on visual observations of the Milky Way did not mean that he was not interested in photography. Quite to the contrary: from 1919 onward, he worked for decades on a photographic representation of the Milky Way. This photographic research was noteworthy because Pannekoek was not interested in wide-angle photography like his contemporaries. Instead, he used extrafocal photography, which meant that the photographic plate was intentionally placed outside the focal plane. Furthermore, the presentation of this research was remarkably similar to that of his visual observations. It was given in the form of isophotic diagrams and naturalistic drawings, and not, as one might expect, in the form of photographic reproductions. Analysing Pannekoek’s photographic method of representing the Milky Way provides crucial insight into the application of astrophotography in the early twentieth century and the impact it had on the daily practice of astronomy.

When photography was first introduced in astronomy in the second half of the nineteenth century, it was primarily the domain of wealthy self-funded astronomers, who had the freedom to experiment with photo-

\textsuperscript{65}. Historian of science Omar W. Nasim has recently argued that, in Pannekoek’s Milky Way research: ‘The active alternation of different media and techniques of representing — naturalistic and schematic — is certainly indicative of drawing used not for presentation but as tools for observing.’ Nasim, ‘Labour of Handwork’, 270.
1.3. Photography for Measurement

graphic techniques. Astronomers employed by large observatories, meanwhile, remained primarily focused on precision measurements using large visual refractors.66 Even in the depiction of visually striking objects, like nebulae, planetary surfaces, or the Solar corona, most astronomers generally preferred drawings based on visual observations over photography.67 These were considered more trustworthy because the human eye was considered better at capturing large scale structures and evaluating large differences in brightness.68 Photography did have one major advantage over visual observations, however: photographic plates could be taken in large numbers and then be stored for later use.69 By the early twentieth century, professional astronomers had started to embrace photography as new techniques and methods were developed that could work around its limitations. Meanwhile, drawing and visual observation increasingly became the domain of amateurs.70 The case of the Milky Way, however, illustrates that the epistemic concerns surrounding photography persisted well into the twentieth century.

The Milky Way provided an interesting challenge to astronomers wanting to study it photographically because telescopes — which were required to focus light onto the photographic plate — generally resolved the Milky Way into the many tiny individual stars that formed it.71 In the late nineteenth century, Edward Emerson Barnard found that he was able to capture unresolved Milky Way clouds on the photographic plate using a wide-angle lens. Although his first photographs were published in 1889,
1. Milky Way Research

the final work was only published posthumously in 1927. Around the same time, German astronomer Max Wolf used a similar lens to obtain photographs of Milky Way clouds and other extended bodies in the night sky. Pannekoek considered these photographs a ‘revelation’ because they had provided definitive evidence that the Milky Way was formed by the combined light of countless stars too faint to see with the naked eye. At the same time, the image these early photographic recordings revealed of the Milky Way was fundamentally different from what could be seen with the naked eye; it was much more detailed and irregular in structure. To some astronomers, this indicated that naked-eye observations should no longer be trusted. Barnard, in particular, believed in the inherent value of photography:

[N]o matter how erroneous the various theories concerning the constitution of the Milky Way, the photographs are supposed to tell their own story, from which the student can judge for himself how well the theories fit into the actual appearance of this wonderful zone of stars.

And Edward S. Holden, director of the Lick Observatory, stated that:

After taking into account all the advantages and disadvantages of the best possible representations of the Milky Way made by the eye and made by photography, it seems to be unquestionable that the latter process is the only one which should be employed in the future.

As we have seen, Pannekoek continued to value visual observations, but he was also impressed by the possibilities of Milky Way photography.

1.3. Photography for Measurement

Pannekoek started his efforts to create a photographic representation of the Milky Way in 1919 while he was still refining his ideas on the mean subjective image, and many similarities exist between the two methods. The goal of both was to represent the large-scale distribution of galactic light. Wide-angle photography, as employed by Wolf and Barnard, was not suitable for this purpose because it emphasized minute structure over the general distribution of light. Pannekoek’s alternative was extrafocal photography. The method of extrafocal photography was developed primarily by Karl Schwarzschild for photographic photometry of individual stars. As plates were taken out of focus, the light of stars was spread over a larger area, which allowed more accurate photometric measurements. Pannekoek realized that this technique could be used to effectively produce the ‘theoretical Milky Way’—the Milky Way altered only by optical-anatomical conditions—as it would cause the light of the countless faint stars composing the Milky Way to overlap on the photographic plate.

If ... each starpoint is extended to a circle, the mean surface brightness of the sky over such a circle may be measured by the blackness of the plate; the scale being afforded by the extrafocal images of the bright stars on the plate. Such a picture will bear a much greater resemblance to the visual aspect of the Milky Way than an ordinary photograph.

While the mean subjective image could only eliminate the purely psychological conditions, extrafocal photography promised to eliminate personal physiological–psychological conditions as well.

Since Pannekoek lacked an observatory, he had to rely on the assistance of other astronomers for the implementation of his extrafocal photographic project, leading to logistical problems on top of the technical challenges associated with the project. The extrafocal plates of the northern Milky Way were taken by Max Wolf in Heidelberg, which took him several years to complete. One of the main delaying factors was the long

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Figure 1.5: Isophotic graph of the Scutum cloud derived from extrafocal photographic plates. The lines represent areas of equal brightness while the numbers indicate the brightness numerically. The white and striped dots indicate the location of bright stars located in front of the Milky Way. Source: Pannekoek, ‘Photographic Photometry of the Milky Way’, 21.

exposure time — three to six hours of continuous exposure — that the plates required. In case bad weather interrupted the exposure, the plate had to be discarded and the exposure started anew. Moreover, the first batch of these plates, which arrived in 1920, turned out to be unsatisfactory because they were not taken sufficiently out of focus. After receiving a more suitable batch of plates, Pannekoek decided to try out his method for a section of the Milky Way in Scutum. He encountered various minor issues with the reduction of these photographic plates. On the plates, stars

79. Anton Pannekoek, Photographische Photometrie der nördlichen Milchstrasse, Publications of the Astronomical Institute of the University of Amsterdam 3 (Amsterdam: Stadsdrukkerij, 1933), 2.
were not visible as uniformly dark circles, but had a small border ring which was darker than the rest of the disk. At the edges of the plates, they were stretched out to ellipses rather than circles. And the image was much fainter than a focal photographic image because the radiant energy had been diluted over a larger surface instead of a concentrated point. Finally, the darkening on the photographic plates had to be converted to a scale that correctly represented the visual brightness of the Milky Way. These problems, however, could all be overcome and the result was worth it, according to Pannekoek: the measurements from extrafocal plates managed to reflect the brightness distribution of the Milky Way light, and in more detail than drawn representations could. Like with the visual mean subjective image of the Milky Way, Pannekoek presented his results in the form of isophotic graphs supplemented with numerical values for the brightness of the Milky Way light (Figure 1.5).

In the extended programme, the quality of extrafocal photographic plates remained an issue; individual photographic plates were often found to have flaws and had to be replaced. Additionally, because Pannekoek had no access to the telescope himself, he was unable to experiment with the setup. He had to work with what he was given. All this meant that coverage of the northern Milky Way was not completed until 1928. For the southern part of the sky, it took even longer. In 1926, while Pannekoek was visiting the Bosscha Observatory in Lembang as part of his expedition to Java, he instructed the director Joan Voûte on how to take the extrafocal plates (Figure 1.6). Because the main telescope of the observatory was also used for other purposes, it took three years before Pannekoek received the plates. Again, many of the photographic plates were found to have flaws and had to be retaken in 1933 and in the winter of 1938–1939. An added complication was that the southern-most part of the sky was

81. Pannekoek, ‘Photographic Photometry of the Milky Way’, 22. Nasim argues that the manual labour associated with measuring and reducing photographic plates reflected the prominence that Pannekoek placed on the hand in both human and societal evolution — ‘Handwork is crucial to both sides of Pannekoek’s oeuvre.’ See Nasim, ‘Labour of Handwork’, quote is on 276.
82. Pannekoek, Photometrie der nördlichen Milchstrasse, 1–4; Pannekoek to Johan Stein, [ca. 1935], Archive of the Vatican Observatory (VO). See also the correspondence between Pannekoek and Max Wolf, UBH/MW, EP 7.
83. These plates included exposures of the Large and the Small Magellanic Clouds, which were measured and reduced by Gijsbert van Herk, then a student of the Astronomical Institute in Amsterdam, and published as Gijsbert van Herk, ‘Photographic Photometry of the Magellanic Clouds’, Bulletin of the Astronomical Institutes of the Netherlands 6, no. 209 (1930): 61–64.
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Figure 1.6: Extrafocal photographic plate of a portion of the southern Milky Way, taken at the Bosscha Observatory in Lembang by Joan Voûte. Source: API.

not sufficiently visible from Lembang. For that part, Pannekoek wanted to enlist the assistance of Willem Hendrik van den Bos at the Union Observatory in Johannesburg, but that location turned out to be unsuitable due to light pollution.\textsuperscript{84} On the suggestion of Van den Bos, Pannekoek

\textsuperscript{84} By this time the Second World War had started in Europe and communications with South Africa had been cut off, so Pannekoek corresponded with Van den Bos via Otto Struve, director of the Yerkes Observatory near Chicago. Anton Pannekoek to Otto Struve, 29 Jul 1940; Struve to Pannekoek, 18 Nov 1940, Otto Struve correspondence, Niels Bohr Library & Archives, American Institute of Physics (AIP/OS) reel 9.
turned to Harlow Shapley, director of the Harvard College Observatory, who agreed to have the plates taken at the Boyden Station in Mazelspoort, South Africa.\textsuperscript{85} These plates could only be taken in 1942 and only shipped to the Netherlands in 1945 after the war in Europe had ended. After they arrived, two of the Boyden-plates had to be rejected and retaken in 1946, finally completing the entire Milky Way.\textsuperscript{86}

Getting hold of photographic plates was only the first step of the process, however. The plates next had to be systematically measured using a microphotometer.\textsuperscript{87} These measurements then had to be corrected for both general systematic errors that resulted from the extrafocal method, as well as plate-specific systematic errors, which had to be determined empirically for each plate. To be able to combine the measurements and get a meaningful scale for the surface brightness, a reduction curve had to be derived separately for each individual plate.\textsuperscript{88} For most of the Milky Way, multiple plates overlapped, and the average value was calculated. All these measurements and calculations were conducted by Pannekoek’s long-time computer David Koelbloed.\textsuperscript{89} Pannekoek himself drew the isophotic diagrams, for which he used an episcope that projected the photographic plates onto paper. The isophotes were then drawn by tracing the features that the episcope had projected (Figure 1.7).

Throughout the entire measurement process, experience and expert judgement played a vital role. Pannekoek made this clear in a letter to Shapley that was sent only two days after the liberation of the Netherlands in the Second World War. In this letter, he requested that the remaining plates be sent as soon as safely possible, explaining that he had to finish the work himself ‘during the years that will be allowed to me’ as he was the only one with the skill and expertise needed to draw the isophotic diagrams (Figure 1.8). Similarly, he argued that only Koelbloed was capable of

\textsuperscript{85} Anton Pannekoek to Harlow Shapley, 11 Dec 1940; Shapley to Pannekoek, 17 Jan 1941, HUA/HCO box 45 folder 332; Pannekoek to Shapley, 20 Feb 1941, Papers of Harlow Shapley, Harvard University Archives (HUA/HS) box 22a.


\textsuperscript{87} A microphotometer is an instrument for measuring photographic plates that allowed both the coordinates and the blackening of the plate to be accurately determined.

\textsuperscript{88} The reduction curve is a formula that gives the relation between the incident light intensity of an object and the blackening it causes on the photographic plate.

1. Milky Way Research

Figure 1.7: Small part of one of Pannekoek’s working sheets for photographic photometry. On these working sheets, Pannekoek traced isophotic lines based on multiple photographic plates. The lines are supplemented with numerical measurements of the same plates. The different colours represent information from different photographic plates. Source: API.

conducting the required measurements and calculations for this project.\(^{90}\) Pannekoek’s emphasis on the importance of his own hand in drawing the isophotic lines underlines a crucial aspect of his method of photographic photometry: it was never meant to be objective in the sense that nature would represent itself. Not only should mechanical instruments mimic the human eye, expert judgement also remained crucially important.

90. Anton Pannekoek to Harlow Shapley, 7 May 1945, HUA/HCO, box 45, folder 332.
1.3. Photography for Measurement

Figure 1.8: Isoptic diagram made by Pannekoek of a section of the southern Milky Way. The diagram is based on photometric measurements of extrafocal photographic plates. Source: Pannekoek and Koelbloed, *Photometry of the Southern Milky Way*, chart 13.

In the presentation of the photographic research on the southern Milky Way, Pannekoek included naturalistic drawings of the Milky Way based on photographic photometry (Figure 1.9).\(^{91}\) This inclusion reinforces what we have noticed throughout Pannekoek’s photographic method:

\(^{91}\) Pannekoek, *Photometrie der nördlichen Milchstrasse*. 

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photographic plates were not intended to replace drawings as a way of depicting the Milky Way. Instead, they were meant to take over the role visual observations had played in Pannekoek’s construction of the mean subjective image. Pannekoek’s visual and photographic programmes displayed a clear continuity as they attempted to represent the Milky Way as it was seen by human eyes. This continuity from visual observations to photography was certainly not unique to Pannekoek; it can also be seen, for example, with astronomers using photography to depict spiral nebulae.\(^\text{92}\)

It is important to note, however, that photographic plates were never meant to supplant visual observations completely.\(^\text{93}\) Pannekoek worked on both projects simultaneously throughout the 1920s and their results were intended to be complimentary. This was made clear when he discussed the differences between the two methods. While visual observation was better at revealing the general structure of the Milky Way, individual minor features were more clearly visible using the extrafocal photographic method. As such, the results of the extrafocal method occupied the space between visual observations and focal photography:

We might describe the picture [produced by extrafocal photography] as the aspect the Milky Way would present to eyes that were far more sensitive to faint glares of light than ours and at the same time able to distinguish smaller details. A comparison with the focal photographs of Barnard and Ross shows a smoothing of all sharp detail, thus gaining a true representation of the surface intensity which is lacking there.\(^\text{94}\)

Comparing the visual observations with photographic exposures had an additional practical benefit. Because photographic plates were more sensitive to blue light than the human eye, the difference in surface brightness found through both methods made it possible to determine the colour index of Milky Way clouds. For the Scutum cloud, for example, this colour index was found to be 0.43, similar to an F-type star. Evidently, the Scutum cloud had a similar constitution to the surroundings of the Sun.\(^\text{95}\) Being


\(^{93}\) See also Hoel, ‘Measuring the Heavens’, 63.


\(^{95}\) Pannekoek, ‘Photographic Photometry of the Milky Way’, 23–24.
1.3. Photography for Measurement

Figure 1.9: Naturalistic drawing of the southern Milky Way by Pannekoek, based on measurements of extrafocal photographic plates. Source: Pannekoek and Koelbloed, *Photometry of the Southern Milky Way*, plate 3.
1. Milky Way Research

able to draw such conclusions illustrated the importance of providing both visual and photographic observations of the Milky Way light.

1.4 Conclusions

Although Pannekoek acknowledged the artificial nature of the Milky Way phenomenon as an optical illusion created by the nature of human physiology and psychology, he was convinced that an accurate description of the Milky Way was scientifically relevant. It showed how the eyes and the mind processed the light of many faint stars into a coherent image, which in turn could be used for further scientific research, for example in statistical astronomy. As he explained in his Marxist philosophy, usefulness, not truth, was his main criterium for scientific knowledge. The Milky Way image may have been a human construct, but then so were all scientific laws.

Because the Milky Way was intangible, many different representational methods were needed to capture all of its features. Pannekoek’s depictions of the Milky Way ranged from naturalistic drawings and verbal descriptions to isophotic diagrams and numerical tables of surface brightness. This variation also reflected the various ways in which the Milky Way image could be useful. Verbal descriptions could be used to track changes in minor features of the Milky Way over time, while isophotic diagrams and numerical tables could be used for comparison with statistical research on the distribution of stars. Finally, naturalistic drawings were meant to display the aesthetic value of the Milky Way. The latter was important because aesthetics often proved to be an important incentive to pursue scientific research, as was demonstrated by Pannekoek’s own career in astronomy.

Notably, photography was not one of the methods of depiction. Drawing and photography are often presented as distinct and competing methods of representation, but as Pannekoek’s research makes clear, this was not always the case. This is worth emphasizing since mechanically produced photographic images were often used by advocates of mechanical objectivity to argue that one should let nature represent itself without human intervention. According to Pannekoek, however, photography was

96. For more on photography and mechanical objectivity, see Daston and Galison, Objectivity, 161–173; cf. Alex Soojung-Kim Pang, "Stars Should Henceforth Register Themselves": Astrophotography at the Early Lick Observatory, British Journal for the History of
inherently incapable of representing the Milky Way without human intervention. Before photography could produce scientific results, measurement and expert judgement were required from the astronomer. The drawings that resulted from this critical engagement with photography were not the result of nature unveiling itself, but constructed images highlighting the structure of the system. Photography, in this case, replaced visual observation, but not drawing.

Both Pannekoek’s visual method and his photographic method of observing the Milky Way were developed to make optimal use of the desirable qualities of human perception. As he explained in his scientific writing as well as in his Marxist philosophy, human perception depended both on how information was received by the senses and on how it was transferred and interpreted by the human brain. Individual psychological conditions were undesirable here, but as in the case of constant differences, their effects could be minimized in visual observations. In the case of the Milky Way, this was achieved through a combination of adhering to proper methodology and combining the work of independent observers. The resulting mean subjective image was capable of presenting the Milky Way as it was seen by the average human eye, unaltered by purely psychological effects. The goal of Milky Way photography, in contrast, was to also remove physiological effects, much like mechanization had done in the case of the personal equation. By mechanizing observation, the image of the Milky Way would no longer be affected by personal physiological conditions like the strength of the eye’s stimulus threshold. Crucially, in both photographic photometry and the mean subjective image, Pannekoek sought to eliminate personal alterations of the Milky Way image while striving to preserve the shared optical-anatomical conditions; these he considered crucial for the way that humans interpreted the Milky Way. In isolation, such a dichotomy can be difficult to understand, but it becomes clearer in light of his Marxist philosophy of mind. Even if individuals could be led astray, without the interpretive and analytic abilities of the human mind, the Milky Way image would not exist at all.

The early twentieth century was one of the most exciting periods in the history of astronomy. During this period, the entire conception of the universe was overturned. While at the start of the century the prevailing belief was that the Sun was near the centre of a single small star system, by the 1930s the consensus was that the Sun was located in the outer regions of a vast rotating system that was only one of many such systems.\footnote{Robert W. Smith, \textit{The Expanding Universe: Astronomy’s ‘Great Debate’, 1900–1931} (Cambridge: Cambridge University Press, 1982).} These drastic changes in the conception of the universe were the result of several important breakthroughs in various subjects within astronomy occurring at around the same time. Measurements of the size of our galactic system indicated that it was much larger than previously thought, while distance measurements of spiral nebulae indicated they had to be separate galaxies independent from our own. The apparent contradiction of these results led to a prolonged discussion between astronomers about the shape and structure of the galactic system, exemplified by the public meeting at the National Academy of Sciences, held in 1920, that has become known as ‘The Great Debate on the Scale of the Universe’. This episode in the history of astronomy has received plenty of attention from historians, but primarily from the perspective of the United

2. Statistical Astronomy

While they have discussed the important contributions of Dutch astronomers like Jacobus C. Kapteyn and Jan Oort, the discussions occurring within the Netherlands during the 1920s have largely been ignored. This is unfortunate because there, too, the topic of the size and structure of the galactic system was lively debated, not only in professional scientific publications but also in popular magazines like *Hemel en Dampkring*, which inspired young readers like Bart Bok to study astronomy. Anton Pannekoek was a prominent figure in these discussions; through his research, we can investigate how the debate developed in other settings than the United States. In the case of the Netherlands, as we will see, the primary focus was on the size and structure of the universe, with much less attention being given to the potential existence of external galaxies.

Pannekoek had a peculiar and original approach to statistical astronomy. While he used the same statistical models as his nineteenth-century predecessors, Kapteyn and Hugo von Seeliger, he did not follow their example of developing all-encompassing smoothened models for the distribution of stars. Instead, he acknowledged the irregular and complicated character of the Milky Way and stressed the importance of investigating individual particularities. Marcel Minnaert described the difference as follows: ‘Kapteyn designed a general picture of the universe that surrounds us, a grand but smoothened picture. Pannekoek sought a more faithful representation of the complicated bright and dark patches, of the natural object as it truly manifests itself to us.’ Similarly, Edward van den Heuvel has suggested that ‘[Pannekoek] does not follow in the footsteps of Seeliger, who designed a strongly systematized mathematical model of our star

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system. Rather he responded to the call of Argelander to systematically observe the Milky Way.\(^5\)

Pannekoek’s rejection of idealized representations in favour of more complicated structures seems to coincide with how historians of science Lorraine Daston and Peter Galison describe an interesting aspect of the wider development of the sciences during the last two centuries, as we have discussed in the introduction. During this period, scientists shifted away from a focus on the universal, which was inherent to truth-to-nature science, and started to appreciate the particular and idiosyncratic. This changing perspective was tied to a change in epistemic virtues and scientific persona. Whereas, in the early nineteenth century, scientists were expected to rely on their intuitive genius and experience, by the late nineteenth century, the ideal was someone who suppressed their personal interventions to the extent that they may best be compared with a recording machine.\(^6\) Daston and Galison’s account is unapologetically mesoscopic as it tracks the \textit{longue durée} dynamics of epistemic virtues, their associated personae and their larger cultural and scientific reverberations.\(^7\) However, a focus on epistemic virtues can also be quite useful as a historiographical tool for studying individual cases because they make it possible to bridge the gap between the microscopic and the mesoscopic, by relating these case studies to wider developments in science.\(^8\)

Furthermore, a focus on personae enables us to look beyond the constraints of disciplinary boundaries in scholarship and thus contributes to a post-disciplinary approach to the historiography of knowledge. As historians have shown, epistemic virtues and ideal personae can be shared across disciplines and knowledge domains and then be adapted according to the specific needs of each discipline.\(^9\) This property makes it a promising perspective for investigating the relations between Pannekoek’s as-

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9. On how virtues and personae were shared across disciplines and knowledge domains, see e.g. Matthias Dörries, ‘Heinrich Kayser as Philologist of Physics’, \textit{Historical Studies in the Physical and Biological Sciences} 26, no. 1 (1995): 1–33; Matthew Stanley, ‘Religious
tronomical research and his Marxist philosophy. In the previous chapter, we have discussed how his philosophy of mind led Pannekoek to emphasize the importance of judgement in the representation of the Milky Way. As we will find in this chapter, judgement also played an important role in his statistical astronomy, where he used the distribution of Milky Way light as a guide in his statistical research on the distribution of stars. Judgement was an epistemic virtue because it warded against the pitfalls of a purely mechanical approach to stellar statistics. Likewise, in his Marxist writings, Pannekoek warned against a purely mechanical approach to studying societies and the limitations caused by ignoring human judgement.

This chapter will start with a historical survey of the field of statistical astronomy, which sought to investigate the structure of the galactic system through the statistical distribution of stars. Special attention is given to the research of Jacobus Kapteyn, which acted as a starting point for Pannekoek. The next two sections describe Pannekoek’s statistical research and the various debates he engaged in with contemporaries. These debates will be explored through the lens of epistemic virtues to highlight the differences in their various methodologies. The final section will discuss various aspects of Pannekoek’s Marxist philosophy to explore the intersections with his scientific methodology and epistemic virtues in astronomy. The goal is to situate Pannekoek’s statistical research in the context of both his own Marxist philosophy and contemporary developments in astronomy and science as a whole, and investigate how this, in turn, can provide a better understanding of Pannekoek’s particular approach to the subject.

2.1 Statistical Cosmology

In the early twentieth century, the question of the structure of the stellar system and its relation to the Milky Way was at the forefront of astronomical research. The predominant method of researching this topic through statistical analysis of the location, apparent magnitude, and proper motion of stars and clusters.\(^{10}\) Since many of the astronomers involved believed that through such methods, not just the stellar system, but the entire universe could be understood, historian of astronomy E. Robert Paul has argued that this research program can retrospectively be called 'statistical cosmology'.\(^{11}\)

One of the earliest examples of such research was conducted by William Herschel in his 1785 paper ‘On the Construction of the Heavens’.\(^{12}\) It is worth briefly discussing this paper as it serves well to illustrate the basic principles and goals of statistical astronomy. Herschel’s main goal was to determine the dimensions of the stellar system by simply counting the number of stars in each direction of the sky. He based his research on three assumptions: that all visible stars were contained in the stellar system, that stars were distributed roughly uniformly, and that his telescope could penetrate to the edge of the system. If these assumptions were valid, then the number of stars in a certain direction of the sky was a direct indication of the distance to the edge in that direction. The system he deduced using this method was roughly shaped like a flattened rhombus and can be seen in Figure 2.1. Further research made Herschel disavow his foundational assumptions in later life; his investigation of binary stars and star clusters indicated that stars were certainly not uniformly distributed, while his newly constructed 40-foot telescope indicated that the edges of the system were far more distant than he had anticipated.\(^{13}\) It was clear that to understand the structure of the stellar system, much more data

\(^{10}\) Apparent magnitude indicates the brightness of a star as seen from Earth. Lower magnitude indicates that a star is brighter. The brightest stars in the sky are about zeroth magnitude, and sixth-magnitude stars are the faintest ones that can be detected by the naked eye. Proper motion is the apparent movement of a star in the sky as seen from the Sun.


2. Statistical Astronomy

Figure 2.1: Herschel’s first attempt at a model for the stellar system. He assumed that he could see through to the edges of the system and that the stars were distributed randomly. Source: Herschel, ‘On the Construction of the Heavens’, 266.

were needed, and in the following century, many astronomers devoted their attention to counting and measuring the stars.

Statistical astronomy continued to be practised in the nineteenth century, most notably by William’s son John Herschel, German astronomer Friedrich von Struve, and his son Otto Wilhelm.14 The most important development for statistical astronomy, however, was the increasing amount of stellar data that became available during the century in the form of star catalogues, the pinnacle of which was compiled by Friedrich Argelander of the University of Bonn between 1852 and 1863. The resulting Bonner Durchmusterung contained the position and brightness of 324,198 stars in the northern hemisphere brighter than tenth magnitude.15

One of the first astronomers to make extensive use of this new data was Hugo von Seeliger of the University of Munich, who had worked as an assistant to Argelander in Bonn. Seeliger managed to derive an equation that could calculate the star density distribution as a function of distance from the Sun from the observed ‘star-ratio’, the ratio between the number of stars of a given apparent magnitude and the number of stars one magnitude fainter. In 1898, he determined this star-ratio for the stars in the Bonner Durchmusterung and found that it was lower than what would be expected for a uniform distribution of stars, especially in the direction of the galactic poles. From his investigations, Seeliger derived a model of


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the galactic system as a flattened ellipsoidal system, approximately 10,000 parsecs in diameter along the galactic equator and 1,800 parsecs in the direction of the galactic poles. The Sun was placed in the centre of this system, and the star density thinned out exponentially toward the edges of the system. Seeliger’s method relied heavily on complex mathematical manipulations and theoretical presuppositions. In particular, he required the luminosity function, which describes the relative number of stars as a function of absolute brightness, to be shaped like a Gaussian distribution. Only then was his mathematical analysis valid.

Seeliger’s approach to statistical astronomy was widely adopted by astronomers in the early twentieth century, including Carl Charlier, Arthur Eddington, and Karl Schwarzschild, who all developed different analytical methods to investigate the statistical distribution of stars in the stellar system. An alternative method for statistical astronomy was developed by Dutch astronomer Jacobus Kapteyn. Unlike Seeliger’s mathematical analysis, Kapteyn approached the topic empirically and numerically.

Kapteyn’s first goal was to determine the luminosity function, which he did empirically by analysing the distribution of absolute magnitudes for nearby stars. He published his first results of this research in 1901. By assuming that this luminosity was valid throughout the stellar system, he could then use it to compute the density distribution empirically as well. He developed his first model in 1908, for which he divided the night sky into three sections: the galactic plane, covering the sky from –20° to 20° galactic latitude; the galactic poles, covering the sky above 40° and be-

16. Parsec is a measure of distance, with one parsec being 3.26 lightyear
19. For a technical comparison between the methods used by Kapteyn and Seeliger, see Hans Kienle, 'Historical Development of Our Ideas Concerning the Structure of the Galaxy', in Structure and Evolution of the Galaxy, ed. Lyssimachos N. Mavridis (Dordrecht: D. Reidel, 1971). Although Kapteyn and Seeliger both worked in the same field, there was remarkably little interaction between the two. Kapteyn believed that Seeliger’s method depended too strongly on presuppositions, but he never expressed his criticism publicly. When his PhD student Willem J. A. Schouten strongly criticized Seeliger’s method in his dissertation, Kapteyn refused to have it published as part of the Groningen Publications because he considered it too polemical. Schouten then decided to publish the dissertation himself, which was predictably ill-received by Seeliger. Bok, interview by DeVorkin, AIP/OH; Paul, Milky Way Galaxy, 176–177.
20. Ibid., 94–99.
2. Statistical Astronomy

Figure 2.2: Kapteyn’s final dynamical model of the stellar system, published in 1922. The half ellipses indicate areas of equal star density. The small circle right of the centre indicates the location of the Sun in this model, which, according to Kapteyn’s calculations, was located at 650 parsec from the centre. Source: Kapteyn, ‘First Attempt’.

low –40° galactic latitude; and the transition zone in between those two sections. For each of these three sections, he determined the star-ratio separately and derived in the star density distribution from it. The results were very similar to those produced by Seeliger: Kapteyn’s model too was a flattened ellipsoid with gradually decreasing star density toward the edges. Kapteyn kept refining his results throughout the years, and by the end of his life, his model had become known as the Kapteyn Universe.

Kapteyn was initially skeptical of the fact that the Sun had such a central place in his system and suspected that this was caused by absorption from interstellar matter. He searched actively for evidence of the existence of this extinction until, in 1916, Harlow Shapley produced results that indicated space was indeed free of interstellar absorption. Knowing this result, Kapteyn continued his statistical approach and eventually came up with a dynamic model of the stellar system, seen in Figure 2.2, in which the stars had an orbital rotation and the Sun was located very near the centre of the system at only 650–parsec distance.

Kapteyn is still fondly remembered by astronomers for his numerical and open-minded approach to statistical astronomy. In the words of Dutch astronomer Adriaan Blaauw:

Kapteyn’s approach was basically different from that of contemporaries such as Hugo von Seeliger and Karl Schwarzschild. The latter proposed certain analytical expressions for the [density and luminosity] functions, as well as for the distribution of observed quantities, and then tried to solve for the parameters involved by means of integral equations. Kapteyn, on the other hand, preferred the purely numerical approach, allowing full freedom for the form of the solution.\(^\text{24}\)

Historian of astronomy Elly Dekker summarized:

[Kapteyn] never sacrificed clarity of treatment or exposure of essential details for elegance of presentation; and, although a mathematician himself by his early training, he strongly disliked treatises in which emphasis lay more on the form of the mathematical expression than on proper evaluation of the basic observation.\(^\text{25}\)

It is undeniably true that Kapteyn took a more inductive approach than Seeliger, one that prioritized the observational data over sophisticated mathematical techniques. This is especially evident in their different approaches to the luminosity function. Where Seeliger postulated an equation that allowed for easy mathematical manipulation, Kapteyn provided a table with observational data to allow the numbers to speak for themselves, in line with the virtue of mechanical objectivity.

At the same time, Kapteyn had his own preconceived ideas about the distribution of stars. Although he insisted that he was building up from below where others were building from the top down,\(^\text{26}\) he still prioritized the shape of the overall system over the existence of individual particularities. He felt confident that these could be ignored because they were only small deviations from the otherwise symmetrical distribution of stars.\(^\text{27}\)

This decision shows more in common with the ontological concerns of

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truth-to-nature and, as will be shown, had a crucial impact on the results of his research. It led to criticism from astronomers like Heber D. Curtis, who wrote: ‘While I am ready to worship Kapteyn’s methods ..., I can not, as most astronomers do, fall down and worship all the results which have come out of this mathematical mill.’ Likewise, Pannekoek also admired Kapteyn’s numerical methods, while believing his results were inaccurate because they did not reflect the visual appearance of the Milky Way. As we have seen in the previous chapter, Pannekoek spent considerable effort to obtain an accurate, reliable, and complete measurement of the distribution of Milky Way light. The following sections will indicate how he applied these results to his statistical astronomy.

2.2 Particularities in Statistical Distribution

One of the main reasons why Pannekoek valued an accurate representation of the distribution of Milky Way light was because it should guide statistical studies of the structure of the stellar system. He felt that this aspect was being ignored by Seeliger and Kapteyn. Pannekoek’s first paper on the statistical distribution of stars was a direct reaction to the symmetrical ellipsoidal distribution of stars presented by Kapteyn in his 1908 publication on the distribution of stars. In the introduction, Pannekoek explicitly mentioned the problem with this model:

[Kapteyn’s] conclusion ... is in direct opposition to the appearance of the galaxy. We see the galaxy as a belt of more or less circular masses, patches and drafts designating a totally different structure. ... The appearance of the galaxy shows ... that the zone between +20° and −20° galactic latitude should by no means be treated as one whole. In that way parts of the universe of really great diversity of structure would be mixed up .... It may be necessary to take all these different parts together for arriving at an average representation of the distribution of the stars in space, but this is obscuring the especially striking character of this distribution, which shows

2.2. Particularities in Statistical Distribution

in the aggregation of stars into clouds and drifts; and it is giving a false impression of the real Milky Way if the star-density is represented as a simple function of [distance] and [galactic latitude].

Pannekoek’s criticism was specifically aimed at the mechanical way in which Kapteyn had organized the stellar data at his disposal, rather than at his numerical methods. He argued that, by dividing the sky only according to galactic latitude, Kapteyn had already presupposed a symmetry in galactic longitude; the ellipsoidal shape of the resulting system was an artefact of this symmetry. His alternative was to assess the star density distribution separately for particular regions in the Milky Way, as a function of both latitude and longitude. This could be done by using the equation Seeliger had derived to determine the star density distribution of the entire system. From this equation, Pannekoek derived that clusters would reveal themselves in star counts through higher than expected star-ratios at a certain apparent magnitude; and that the apparent magnitude at which this happened directly correlated with the distance to the star cluster. Thus both the direction and distance of star clusters could be found by investigating star counts of specific locations of the sky.

To demonstrate his method, Pannekoek selected five regions to investigate, which he chose based on the visual aspect of the Milky Way. These were two particularly bright spots in Cygnus and Aquila, two faint parts directly adjacent to these clusters, and a fainter part of the Milky Way as a comparison. The star counts for these areas were taken from several sources: the Bonner Durchmusterung, the Carte du Ciel, and star gauges from William Herschel and Th. Epstein in Frankfurt. In the case of the two brighter regions, Pannekoek found that they had significantly more stars than one would expect from Kapteyn’s results, especially around ninth and twelfth magnitude. He concluded that this likely meant that there were indeed multiple star clusters in the directions of Cygnus and Aquila that caused those brighter regions of the Milky Way. Furthermore, in the case of Cygnus, he found that the higher star density was also present in the adjacent darker part, but only in the case of ninth-magnitude stars, not in the case of twelfth-magnitude stars. Apparently,

31. Ibid., 243–245.
32. Ibid., 245–248.
there was ‘no organic relation’ between the stars of ninth to eleventh magnitude and the Milky Way clouds, because the cluster of ninth-magnitude stars seemed to extend into the dark stroke in Cygnus where the Milky Way phenomenon was absent. Instead, the Milky Way light was probably caused by stars fainter than twelfth magnitude.  

Already from this first paper by Pannekoek, it is clear that there are stark differences between his approach and that of Kapteyn. One of the major differences was the perceived goal of sidereal astronomy. For Kapteyn, his research was a first step toward developing a grand scheme that would describe the general distribution of stars in the entire stellar system. In this scheme, the irregularities in the distribution could be discarded because they represented only small deviations from the mean distribution.  

Pannekoek, on the other hand, emphasized exactly those irregularities and argued that to understand the entire system, we first need to understand how particular areas of the stellar system corresponded with the visual appearance of the Milky Way. Another important difference was the role assigned to the astronomer. For Kapteyn, the astronomer had to minimize his own role in interpreting the data. This could be achieved by using systematically organized sections that allowed a mechanical way to sort the data and eliminated the need for interpretation. Pannekoek, on the contrary, constantly emphasized the importance of human judgement in organizing and analysing the data. Judgement was needed to choose which areas to investigate, and deciding on the relation between statistical data and the brightness distribution in the stellar system. Where interpretation was a vice for Kapteyn, it was a virtue for Pannekoek.

A problematic issue in statistical astronomy was the lack of complete and homogeneous data. Published star catalogues often registered only the position of stars, not their apparent magnitudes. That meant the actual number of stars of a certain magnitude had to be calculated by determining a limiting magnitude for each catalogue: the magnitude of the faintest stars still included in the catalogue. Even then, the limiting magnitudes were far from systematic because the star counts did not always cover

34. Kapteyn justified his decision to discard deviations in the star distribution in Kapteyn, *Number of Stars of Determine Magnitude*, 2–3.
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the entire area homogeneously.\textsuperscript{36} This was a significant problem because
the statistical method of Pannekoek and Kapteyn relied heavily on know-
ing the relative number of stars for various magnitudes. As a solution to
this problem, Pannekoek proposed a photographic method for obtaining
star counts. According to this method, multiple wide-angle photographs
had to be taken of a single region, using geometrically increasing exposure
times.\textsuperscript{37} By increasing the exposure times geometrically, the limiting
magnitude would increase by a constant number with each photograph.
The exposures could be taken on a single photographic plate with the plate
being slightly shifted in between exposures. This way, the magnitude for
each star could easily be determined by the number of times it appeared
on the plate.\textsuperscript{38}

Since Pannekoek had no photographic observatory of his own, he re-
quested photographic plates from Ejnar Hertzsprung at the Potsdam Ob-
servatory. He received photographic plates of the Aquila region in 1910–
1911. It took him close to a decade to reduce the plates, with the results
of this research being published in 1919. In processing these plates, Pan-
ekoek decided to divide the area into 100 squares, which were grouped
into five regions. As can be seen in Figure 2.3, these regions did not have
regular shapes. Instead, it seems that the squares were grouped according
to a combination of star density and location, with Sections I and II having
the most stars, while Section V was relatively poor in stars.

Although there were large differences in the total number of stars for
each section of the plate, Pannekoek found no significant difference in
the star-ratios. Denser sections had more stars at every magnitude, rather
than at a few magnitudes, as would be expected in the case of star clusters.
According to Pannekoek, this indicated that the number of distant stars
was actually consistent for the entire area. The relatively low number of
stars in Section V was probably caused by a triangle-shaped dark nebula,
rather than an actual deficiency of stars. This nebula had to be located
close enough to darken all but the brightest stars. Rather than forming an
‘organic’ connection with the distant clouds of the Milky Way, the neb-

\textsuperscript{36} Pannekoek, ‘Structure of the Galaxy’, 258.
\textsuperscript{37} The exposure times Pannekoek used were 6, 19, 60, 190, 600, and 1900 seconds, cor-
responding with limiting magnitudes of 9.0; 10.0; 11.0; 12.0; 13.0; and 14.0. See Anton
Pannekoek, ‘A Photographical Method of Research into the Structure of the Galaxy’, Pro-
ceedings of the Section of Sciences, Koninklijke Akademie van Wetenschappen 14, no. 2 (1912):
579–584, 584.
\textsuperscript{38} Ibid.
2. Statistical Astronomy

TABLE I. Number of stars.

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Source: Pannekoek, 'Galactic Cloud in Aquila', 1324.

Figure 2.3: This table indicates the star counts of the photographic plates taken of Aquila. The top number shows the number of stars visible at 1900 seconds exposure time, and the following numbers indicate the number of stars that were also visible with exposure times of 600, 190, 60, 19, and 6 seconds, respectively. The bold lines represent the division of the area into five equally large sections.

Source: Pannekoek, 'Galactic Cloud in Aquila', 1324.
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ula was ‘only accidentally projected’ in front of it.\textsuperscript{39} Despite these results, Pannekoek felt that the photographic method was inadequate. It proved impossible to penetrate much further than the fourteenth magnitude, as increasing noise levels made plates with even longer exposure times unreliable.\textsuperscript{40}

It is interesting to note that, even in a strictly systematic photographic scheme, Pannekoek felt the need to intervene with the organization of the stellar counts. He organized the field into intuitively determined sections following interesting features — dense clouds in Sections I and II, and a dark void in Section V — and decided that they should be investigated separately. This division allowed him to compare the different sections, which in turn led him to postulate the existence of a dark cloud in the region. This need to interfere with the organization of data can easily be understood in light of his epistemic virtues. If the data were simply organized mechanically, valuable information might be lost that the human mind could intuitively grasp and use to create structure.

The Great Debate

To make better use of the limited data available for stars fainter than the fourteenth magnitude, Pannekoek constructed a model of a single star cluster placed in an otherwise uniform system. For this model, he could compute a theoretical star count, which could be fitted to observed star counts by adjusting the distance and size of the theoretical cluster. This method had the advantage that a fairly precise measure of the distance could be provided with only a limited amount of data; the downside, however, was that small variations in the measured counts could have a significant effect on the final results. In 1919, he used this method to derive distances of 40,000 parsecs to the cluster that formed the Cygnus cloud.


\textsuperscript{40} Pannekoek, ‘Galactic Cloud in Aquila’, 1337.
and 60,000 parsecs to the cluster that formed the Aquila stream.\footnote{Anton Pannekoek, ‘The Distance of the Milky Way’, \textit{Monthly Notices of the Royal Astronomical Society} \textbf{79}, no. 7 (1919): 500–507, 504.} This result was especially significant because it firmly placed these branches of the Milky Way beyond the limits of both Seeliger’s and Kapteyn’s systems, which were both less than 20,000 parsec in diameter. Despite using the same basic numerical techniques, Pannekoek had now found results that directly contradicted the model of Kapteyn.

Pannekoek was not the only one to challenge the models of Seeliger and Kapteyn. The previous year, in 1918, American astronomer Harlow Shapley had presented a model of the galactic system that was stretched some 100,000 parsec with the Sun located 20,000 parsec from the centre.\footnote{Harlow Shapley, ‘Globular Clusters and the Structure of the Galactic System’, \textit{Publications of the Astronomical Society of the Pacific} \textbf{30}, no. 173 (1918): 42–54, 54.} This model was based on his investigations on globular clusters. Shapley had found that these clusters were distributed symmetrically around the galactic plane (Figure 2.4), indicating that they outlined the galactic system, and located mostly in the direction of Sagittarius (Figure 2.5), which meant that the Sun was placed in the outer regions of the system. To determine the distances of the globular clusters, Shapley used a particular class of variable stars, known as Cepheids, as a yardstick. Cepheids showed a remarkable relation between their variation period and their absolute magnitude, as Henrietta Swan Leavitt of Harvard College Observatory had found a decade earlier. These distances turned out to be much larger than previously thought, which led Shapley to postulate his extended galactic system.\footnote{Ibid. See also Smith, \textit{The Expanding Universe}, 59–77; Paul, \textit{Milky Way Galaxy}, 191–202.}

Pannekoek recognized that his results were complementary to Shapley’s, as he stated in his paper:

> The results we have arrived at here are in accordance with [Shapley’s results], as they place some of the bright parts of the Milky Way at a distance of 40–60,000 parsec. So the starry masses of the galaxy are spread over space as far as the remotest clusters, and clearly both belong together to one system. In this system the dense agglomerations of stars are spread over a flat disc of about 2000 parsec thickness, and in the empty space above and below it the globular clusters are dispersed.\footnote{Pannekoek, ‘Distance of the Milky Way’, 507.}
2.2. Particularities in Statistical Distribution

Figure 2.4: Diagram by Shapley showing the distance of globular clusters from the galactic plane and projected on the galactic plane. Globular clusters tend to avoid the galactic plane, which is shaded grey. Source: Shapley, 'Globular Clusters', 47.

Figure 2.5: Diagram by Shapley showing the spatial distribution of globular clusters projected on the galactic plane. The solid circles show distance from the Sun in steps of 10,000 parsec, except the smallest circle, which indicates 1000 parsec. The dashed circles show the distance from the galactic centre. Source: Shapley, 'Globular Clusters', 53.
Besides the agreement in distance scales, there was another reason for Pannekoek to prefer Shapley’s model of the galaxy. He believed that it better reflected the appearance of the Milky Way. The eccentric position of the Sun explained why the Milky Way in Sagittarius — where the centre of Shapley’s system was located — was much brighter than in the opposite direction toward Perseus.45

Shapley’s expanded galactic system was a much-debated topic in the years following its publication. The most prominent challenge came from Heber Doust Curtis of the Lick Observatory. Curtis had done photographic research on novae in spiral nebulae and found that these novae, on average, appeared to be a hundred times more distant than novae located in the Milky Way. That would mean that these novae and the spiral nebulae in which they resided were located well outside the borders of the galactic system. Curtis concluded that these spiral nebulae were ‘island universes’, independent star systems that were similar in size to our own galactic system.46

Initially, these two results — the increased size of the galactic system and the existence of independent galaxies outside our own — seemed to contradict one another. Supporters of Shapley’s system believed that it was large enough to incorporate the entire universe including the spiral nebulae, whereas those who advocated for the island universe theory believed that Shapley’s extended galactic system was much too large in comparison with the size of the spiral nebulae. The discussions led to a public debate held at the National Academy of Sciences in 1920, which has become known as ‘The Great Debate on the Scale of the Universe’. During this meeting, Shapley and Curtis debated the merits of their respective theories. Curtis questioned the reliability of using Cepheids as a measurement tool, while Shapley argued the island universe theory was incompatible with the rotation measurements of spiral nebulae by Dutch-American astronomer Adriaan van Maanen.47 Van Maanen had taken photographs of spiral nebulae over a prolonged period of time and investigated how

stars moved within spiral nebulae over time. His conclusion was that stars rotated within the spiral nebulae far too quickly to believe they could be as large as the Milky Way system.\footnote{Van Maanen’s results were later shown to be false. For more on this episode, see Norriss S. Hetherington, ‘Adriaan van Maanen and Internal Motions in Spiral Nebulae: A Historical Review’, \textit{Quarterly Journal of the Royal Astronomical Society} 13, no. 1 (1972): 25–39; Richard Berendzen and Richard Hart, ‘Adriaan van Maanen’s Influence on the Island Universe Theory’, \textit{Journal for the History of Astronomy} 4, nos. 1–2 (1973): 46–56, 73–98.}

Despite Van Maanen’s role in the discussion over the island universe theory, this topic was not much debated in the Netherlands. Instead, the debate in the Netherlands mainly focused on the size of the galactic system, as this directly pertained to the status of the Kapteyn Universe.\footnote{In Germany, meanwhile, Seeliger rejected Shapley’s results in private correspondence but not publicly participate in the debate. Helge Kragh, \textit{Masters of the Universe: Conversations with Cosmologists of the Past} (Oxford: Oxford University Press, 2015), 46 and 60 n. 6.}


Kapteyn felt that, where Shapley was building from above, he was building from below.\footnote{Paul, \textit{Milky Way Galaxy}, 209–210.}

As we have seen in the previous chapter, Easton was keenly interested in the appearance of the Milky Way and had published detailed drawings...
2. Statistical Astronomy

Figure 2.6: Easton’s 1900 model of the Milky Way system Source: Easton, ‘New Theory of the Milky Way’, 157.

of them. Like with Pannekoek, these drawings played an important role in investigating the structure of the universe for Easton. In 1895, with the assistance of Pannekoek, he compared the brightness distribution of the Milky Way light in his drawings with the distribution of stars in the Bonner Durchmusterung. He found that the intensity of galactic light corresponded well with the distribution of stars and concluded that most likely a real connection existed between the distribution of faint and bright stars.\footnote{Cornelis Easton, ‘On the Distribution of the Stars and the Distance of the Milky Way in Aquila and Cygnus’, Astrophysical Journal 1, no. 3 (1895): 216–221.}

A few years later, in 1900, Easton extended his research in an effort to derive the shape of the whole galactic system using his own observations of the Milky Way light in combination with various star counts. From this comparison, he concluded that the most likely shape of the system was a ‘galactic spiral’ which ‘curiously resembles the spiral nebulae’.\footnote{Cornelis Easton, ‘A New Theory of the Milky Way’, Astrophysical Journal 12, no. 2 (1900): 136–158, 156.} The Sun was located close to the centre of the system, which he placed in the direction of Cygnus because of the high star density and bright Milky Way.
in that direction. The drawing that Easton made of this model can be seen in Figure 2.6. He insisted, however, that

\[\text{Figure 2.6 does not pretend to give an even approximate representation of the Milky Way. It only indicates in a general way how the stellar accumulations of the Milky Way might be distributed so as to produce the galactic phenomenon, in its general structure and its principal details, as we observe it.}\]

He revisited this model in 1913 when he used published photographic plates to test his hypothesis. Again he found that his spiral theory was perfectly capable of explaining the appearance of the Milky Way, although he stressed that this did not mean spiral nebulae were also independent galaxies.

While Pannekoek and Easton both used star counts in comparison with the appearance of the Milky Way, there is a stark contrast in how they approached this research. Pannekoek used the Milky Way image to locate areas of interest for which he then determined the individual characteristics. Easton, on the other hand, was interested in the Milky Way because it gave an impression of the general shape of the galactic system, without the necessity of accurately representing the actual distribution of stars. This difference in approach also played a prominent part in their discussion on the distance to the galactic clouds in Cygnus.

Easton’s criticism of Pannekoek’s distance measurements was founded on his earlier research on the correlation between the number of bright stars and the distribution of Milky Way light in Cygnus. In his reaction to Pannekoek, published in 1921, Easton stated that ‘it is obviously improbable that a real condensation of stars in the neighbourhood of the Sun and an extremely distant galactic cloud should be seen almost exactly in the same direction without their being physically related.’ It was much more likely that the brightest stars of the galactic clouds revealed themselves already at ninth magnitude, while the bulk presented itself only around twelfth magnitude. As evidence, Easton presented a comparison

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55. Ibid., 157. Emphasis in the original.
between star counts in the brighter sections and fainter sections of the Milky Way. Three aspects stood out in this comparison: in dense sections, there were more bright stars, a higher proportion of intrinsically bright B and A stars, and the average proper motion was lower. These results all pointed toward the conclusion that distant galactic stars revealed their presence among the brighter stars. Subsequently, the fact that, in the case of Cygnus, the effect was already noticeable at the ninth magnitude, indicates that these galactic clouds must then be much closer than Pannekoek had calculated.\textsuperscript{58}

Pannekoek felt Easton’s arguments were inconclusive at best. His main counterargument was that the correlation between the distribution of bright stars and galactic light was not as strong as Easton had presented. To illustrate his point, Pannekoek created a diagram (Figure 2.7) that compared the distribution of galactic light with star counts from the \textit{Bonner Durchmusterung}, representing the bright stars, and John Herschel’s star gauges, representing the faint stars. He argued that the diagram clearly showed that the distribution of the galactic light corresponded well with Herschel’s star gauges but not with the number of \textit{Bonner Durchmusterung} stars. He felt reinforced in his theory that there were two clusters—one nearby cluster within a few hundred parsecs of the Sun, which revealed itself in the \textit{Bonner Durchmusterung} stars, and one distant galactic cloud, which could be seen as galactic light and in John Herschel’s star gauges. One concession he was willing to make was that he had overestimated the distance to the galactic cloud, which he now calculated to be only 18,000 parsecs.\textsuperscript{59}

Pannekoek’s diagram, however, failed to convince Easton, who even felt attacked by Pannekoek’s paper. He demanded he should be allowed to publish a retort in the same journal, which was normally restricted to astronomers working at one of the astronomical institutes in the Netherlands. Although initially reluctant, Pannekoek was eventually persuaded to have the paper published under the auspices of the Amsterdam Institute.\textsuperscript{60} In his reply, Easton repeated his earlier argument that the correlation between \textit{Bonner Durchmusterung} stars and galactic light distribution

\textsuperscript{58} Easton, ‘Distance of the Galactic Star-Clouds’.
\textsuperscript{60} Anton Pannekoek to Willem de Sitter, [ca. May 1922], Leiden Observatory Archives, directorate Willem de Sitter, Leiden University Library, Special Collections (UBL/WdS), 45.2.
Figure 2.7: Pannekoek’s diagram of the Milky Way in Cygnus. The distribution of Milky Way light is indicated by isophotic lines, and the distribution of stars is indicated by shaded areas and dashed lines. Denser shading indicates a higher number of stars, and the shaded areas indicate fewer stars. Pluses and minuses indicate whether the star gauges by John Herschel revealed a high or a low number of stars. Source: Pannekoek, 'Distance of the Galaxy in Cygnus', 35.
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Figure 2.8: Easton’s diagrams of the Milky Way in Cygnus. The left diagram indicates the number of stars in the Bonner Durchmusterung, and the right diagram gives the numerical value of the brightness of the Milky Way. Source: Easton, ‘Correlation of Bright Stars and Galactic Light’, 239.

was too strong to be coincidental and presented his own chart (Figure 2.8) to illustrate this. In the discussion of the charts, Easton appealed strongly to the common sense of the reader: ‘We cannot of course expect a perfect agreement, but who could believe that these two diagrams represent two distinct and independent agglomerations of stars, situated respectively at distances of 400 and 18,000 parsec?’\(^{61}\) Pannekoek never reacted to this paper as he felt that Easton had simply rehashed his initial arguments, and that therefore the rebuttal was still valid.\(^{62}\) Easton, meanwhile, interpreted Pannekoek’s silence as his own victory, especially because he had managed to counter Pannekoek with his own data.\(^{63}\)

That same year, in 1922, Harlow Shapley visited the Netherlands after attending the first meeting of the International Astronomical Union in Rome.\(^{64}\) Pannekoek considered this occasion to be an ideal opportunity for the Dutch astronomical community to come together to discuss the size

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63. Cornelis Easton, Kort overzicht van mijn sterrenkundig en meteor. werk, Correspondentie, aantekeningen Cornelis Easton, Museum Boerhaave (MB/CE), 427g.
64. Harlow Shapley to Anton Pannekoek, 27 Dec 1921, Harvard College Observatory, Records of the Director, Harlow Shapley, Harvard University Archives (HUA/HCO), box 14, folder 108.
2.2. Particularities in Statistical Distribution

and structure of the galactic system because many Dutch astronomers had expressed their scepticism toward Shapley’s extended galactic system. Together with Willem de Sitter, he organized a special conference to debate this topic on 28 May. This meeting started with a talk by Shapley in which he presented his most recent results and expressed his confidence that, unless there was a fundamental source of error, his distance measurements could not be far off. To the disappointment of Pannekoek, however, there was little debate following this presentation. Both Schouten and Kapteyn were absent from the meeting, the latter because he was seriously ill, and Van Rhijn refrained from opposing Shapley’s result because he had already conceded by then that Shapley’s distance scale was correct and that the Kapteyn Universe was only a small subsystem of a larger Milky Way system. The only one who decided to challenge Shapley was Easton.

According to Easton, the system outlined by Shapley’s distance measurements was not reflected in the star counts nor in the appearance of the Milky Way. In Shapley’s system, the Sun is situated very eccentrically, near the edge of the system, so that a large asymmetry would be expected in both the statistical distribution of stars and the distribution of light in the Milky Way, so Easton argued. Although there was a slight decrease in both the number of stars and the brightness of Milky Way in the direction of Auriga, opposite to the centre of Shapley’s system, it was far less than was expected from the extremely eccentric location postulated for the Sun.

Shapley responded by stating that the Milky Way is ‘a dangerous place’ in which everything was a ‘mixture’ with dark rifts filled with ‘obscuring things’. He argued that Kapteyn’s Plan of Selected Areas, which Easton had used for his star counts, was not suited for investigating the galactic plane because the selected areas were distributed systematically without regard for the idiosyncrasies of the Milky Way. This mechanical way of

65. Anton Pannekoek to Harlow Shapley, 28 Jan 1922, HUA/HCO, box 14, folder 108; Pannekoek to Willem de Sitter, 28 Jan 1922, UBL/WdS, 45.2.
67. Anton Pannekoek to Willem de Sitter, 7 Jun 1922, UBL/WdS, 45.2.
68. Bok, interview by DeVorkin, AIP/OH.
70. Easton, Bezoek van Harlow Shapley, MB/CE, 427b.
choosing areas meant that selected areas were often located in dark spots or extraordinary areas, which meant they were not representative for the galactic plane as a whole. He disagreed with Easton about the distribution of galactic light as well, stating that the Milky Way showed more light, features, and special objects in the direction of Sagittarius, which was the centre of the Shapley’s system. Pannekoek also countered Easton’s criticism by stating that the star counts Easton had used did not penetrate far enough to already display the asymmetry in the distribution of stars in the galactic system. Pannekoek argued this asymmetry could only reveal itself at sixteenth magnitude and fainter. Easton conceded that this was a possible solution, but that it was by no means certain that it was actually the case.⁷¹

The discussions between Pannekoek and Easton illustrate how differences in epistemic virtues can influence observers in their research. For Easton, it was crucial that astronomers used common sense and guarded against misinterpretations of minor deviations leading them astray. In his models of the Milky Way system, he did not attempt to provide an accurate image, but one that showed the impression of the shape of the system. In his discussion with Pannekoek, he repeatedly emphasized how ‘remarkable’ a ‘chance coincidence’ of two superimposed clusters would be.⁷² From his diagrams of Cygnus, he expected the reader to recognize the rough similarities between the two distributions. In contrast, Pannekoek appealed to the active judgement of the observer while warning against predetermined ideas. His diagram of Cygnus allowed a more direct comparison of the data, and he left it to the reader’s own judgement to reflect on the differences in the distributions and determine that they are in fact not that similar. Implicit in this debate were the different roles of the astronomer. Where Easton expected the astronomer to use their creativity and common sense, in line with the epistemic virtue of truth-to-nature, Pannekoek expected the astronomer to be a consciously intervening, yet open-minded judge of empirical data.

### 2.3 Star Densities in the Local System

The period surrounding the Great Debate was a turning point for statistical astronomy. While there may have been disagreement between the pro-

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⁷¹ Easton, Bezoek van Harlow Shapley, MB/CE, 427b.  
⁷² Easton, ‘Correlation of Bright Stars and Galactic Light’.
2.3. Star Densities in the Local System

ponents of the island universe theory and those of the extended galactic system, they both agreed in assigning a reduced status to the Kapteyn Universe: it was either only one of many independent spiral nebulae or a small part of a vastly bigger system. Statistical astronomy had proven incapable of providing a cosmological model of the entire universe, leading to the decline of statistical cosmology as a major research program. But when we take a closer look at the situation in the Netherlands during the 1920s, we find that research on the structure of the galactic system remained an important topic here. Dutch astronomers remained invested in statistical astronomy; not to understand the cosmological universe, but to understand our local stellar surroundings. The work of Pannekoek is a clear example of this shift in focus.

Pannekoek continued using Kapteyn’s statistical methods because he never had the goal to derive a single model for the entire universe in the first place. His interest was always in how the collection of particular features, such as star clusters and dark nebulae, together formed the Milky Way phenomenon. He emphasized this difference in approach in his memoir:

I strongly sympathized with the work of Kapteyn, but always felt I viewed it differently. He treated the star density distribution only as a function of distance and galactic latitude, ignoring the variance in galactic longitude. Throughout my youth, I always watched the Milky Way and never perceived it as a gradually thinning ellipsoid, but rather as [a collection of] individual accumulations, similar and equally important as Kapteyn’s local system. I saw it as my duty to follow my own ideas and determine the structure of the Milky Way as a collection of corporal clouds and streams.

When statistical astronomy was understood to be fundamentally incapable of providing a cosmology, Pannekoek was not deterred, because it

could still provide insight into the structure of the galactic system, even if only on a local level.

Pannekoek believed that the structure of the galactic system should be researched using a variety of methods, which he outlined in a letter to Shapley after their meeting in 1922. He argued in this letter that different techniques were needed to find the density of stars at different distances. For the local system up to 1000 parsec it was still possible to make use of the techniques of statistical astronomy to determine the distribution of stars. For the area between 1000 and 10,000 parsec, however, matters were different. At these distances, it was almost impossible to distinguish bright distant stars from faint nearby stars. This problem could be circumvented by researching stars of each spectral type separately. For the intrinsically bright A and B-type stars, there was only a small window of absolute magnitudes, which meant that their apparent magnitude was an excellent indication for the distance of the star. Finally, for features in the galactic system beyond 10,000 parsec, like the galactic clouds in Cygnus and Sagittarius, the only visible stars had to be supergiants. Because photographic plates and the human eye detect colours differently, these supergiants were more readily detected in visual counts than in photographic counts.\textsuperscript{76} When Pannekoek wrote his letter to Shapley, on 1 July 1922, the first part of this research, the investigation of the star densities in the local system, was already underway.

Pannekoek’s first paper on the distribution of stars in the local system was a reaction to the PhD research of Utrecht astronomer Isidore Henri Nort, who had completed his dissertation in 1917. Nort had determined the distribution of stars down to the eleventh magnitude in all directions of the sky by counting the number of stars on the photographic \textit{Harvard Map of the Sky}. In line with Kapteyn’s results, he found that there were significantly more stars in the direction of the galactic plane than in the direction of the galactic poles.\textsuperscript{77} At the same time, he was also critical of Kapteyn’s model, especially the untested assumption that the stars were evenly distributed over galactic longitudes. Nort’s results, in contrast, showed that distribution of stars did vary with galactic longitude, especially in the galactic plane. The highest number of stars could be found in the direction of Centaurus, while the lowest number could be found in

\textsuperscript{76} Anton Pannekoek to Harlow Shapley, 1 Jul 1922, HUA/HCO, box 14, folder 108.
2.3. Star Densities in the Local System

the direction of Auriga. Like Easton before him, Nort also investigated
the correlation between the calculated number of stars and the brightness
of the Milky Way light. Contrary to Easton, however, he found that the
distribution of Milky Way light was not reflected in the stars down to the
eleventh magnitude. This conclusion, Nort stated, was ‘in harmony with
the results of Pannekoek’. For the local system as a whole, he found
an ellipsoid system with three unequal axes in which the Sun placed in a
slightly eccentric position.

Despite their shared assessment of the work of Easton and Kapteyn,
Pannekoek did not agree with Nort’s research either. His criticism was
aimed at two specific points. The first was aimed at how Nort had collec-
ted his data from the Harvard Map of the Sky. Pannekoek believed that the
numbers could be calibrated more harmoniously by comparing the areas
of the plates that overlapped with one another. His second point of cri-
ticism was directed at how Nort had constructed the system of stars as a
triaxial ellipsoid, which Pannekoek believed was ‘inadequate to represent
the irregularities of the star distribution’. A better way to represent these
features, according to him, was to create a diagram which showed the de-
viation of the measured number of stars from an averaged distribution
of stars. Such a diagram, Pannekoek believed, would make the detailed
structure of the distribution more pronounced.

Indeed, when Pannekoek created such a diagram himself (Figure 2.9), it
was immediately apparent to him that two opposite regions existed where

79. Ibid., 129. The disagreement between Easton and Nort was the main topic of a meeting
of the Nederlandse Astronomenclub in 1921. Easton made the argument that, although the
ninth-magnitude stars may not cause the Milky Way light, if was still very probable that
they were correlated with one another. And if that correlation exists, then there is no
reason not to believe there was not also a physical connection. For a report on this meeting,
see Hemel en Dampkring, ‘Verslag van de vergadering van de Nederlandse Astronomenclub
op 28 mei 1921 te Amsterdam’, Hemel en Dampkring 19, no. 3 (1921): 36–39.
criticisms was especially targeted at the English astronomer Henry Cozier Plummer, who
had cast Nort’s system in the shape of a three dimensional harmonic function in Henry
Crozier Plummer, ‘On the Distribution of the Stars’, Monthly Notices of the Royal Astro-
nomical Society 78, no. 9 (1918): 668–681. Nort rejected Pannekoek’s recalibration because
they were based on the poorest parts of the plates; and his correction of the stellar sys-
tem because they were based on the faulty calibration. I. Henri Nort, ‘On the Distribution
of the Stars down to the Eleventh Magnitude’, Monthly Notices of the Royal Astronomical
2. Statistical Astronomy

Figure 2.9: Diagram of the distribution of stars down to the eleventh magnitude, according to Pannekoek. These show the deviation in the number of eleventh-magnitude stars from an averaged stellar system through lines of equal density in the southern (left) and northern sky (right). Source: Pannekoek, ‘Stars of the 11th Magnitude’, 341.

the star count was much lower than expected: one in the direction of Ophiuchus and one in the direction of Aquila. Since these sparse regions were not reflected in the appearance of the Milky Way, Pannekoek once again concluded that the light of the Milky Way could not be caused by the light of stars of eleventh magnitude and brighter. Again, we recognize Pannekoek’s emphasis on judgement to detect and investigate individual idiosyncrasies in the distribution of stars, rather than ignoring them to find an overarching solution for the distribution.

A few years later, Pannekoek conducted his own extensive research on the structure of the local system based on the numbers in various Durchmusterung catalogues. As in his earlier statistical research, Pannekoek relied on the calculation of star ratios to determine the distances of star clusters. A marked difference in approach, however, was that he was not looking at specific clusters. Instead, he investigated the density distribution of the entire galactic zone between -20° and 20° galactic latitude as a function of both galactic longitude and distance. As we can see in Figure 2.10, he tried to accomplish this by dividing the galactic plane into twelve sections of 30° longitude each. The results, which extended to about

82. Pannekoek, ‘Stars of the 11th Magnitude’.

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2.3. Star Densities in the Local System

Figure 2.10: Diagram showing a top-down projection of the star density distribution in the galactic plane. The curved lines indicate areas of equal brightness. Source: Pannekoek, ‘Local Starsystem’, 62.

1,000 parsecs from the Sun, were presented through lines of equal star counts on a cross-section of the galactic zone. Notable features in the distribution were the condensations that appear in the direction of Cygnus, but especially those in the direction of Scorpio (around 315°–330°), where the density rose to 1.25 times the average density around the Sun at a distance of 100–200 parsecs.\(^{83}\)

Although Pannekoek was now looking at the entire galactic plane, he did not neglect his initial project of investigating specific irregularities of the Milky Way. Although he condensed large portions of the sky into a single section by dividing the sky into only twelve parts, he still determined the star count for each section separately without attempting to smoothen the distribution as Nort had done in his research. Pannekoek’s approach still focused on deviations from the mean and the particular

structure of the density distribution — aspects that would remain hidden in an approach that smoothed out the data.

Pannekoek’s methods were picked up by Egbert Albert Kreiken, who was preparing a PhD in Groningen, the following year. Kreiken had investigated the colour and magnitude of stars for various regions of the Milky Way, which drew his attention to the Scutum cloud where the density of stars was significantly higher than what would be expected from the Kapteyn Universe. Moreover, the stars in that region, especially the brighter stars, were much bluer than average. Kreiken decided to calculate the distance to the cluster responsible for the Scutum cloud, for which he found a distance of 1500 parsec. In other regions, he found no such a deviation from the Kapteyn Universe, which led him to conclude that ‘only in the case of the Scutum-cloud we may speak of a distinct group.’

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84. Later that year, Pannekoek found that the visual aspect of the Scutum cloud was bluer than the rest of the Milky Way as well, Anton Pannekoek, ‘Photographic Photometry of the Milky Way and the Colour of the Scutum Cloud’, *Bulletin of the Astronomical Institutes of the Netherlands* 2, no. 44 (1923): 19–24.
Kreiken’s background in Groningen gave him early access to the Plan of Selected Areas data, which were far more detailed and homogeneous than the catalogues that Pannekoek had used. Kreiken used this data to investigate the star density as function of galactic longitude and distance, first only in the galactic plane and later throughout the entire sky. To represent the results, he made diagrams that showed various cross-sections of the system (Figure 2.11) in a similar fashion to Pannekoek. Kreiken concluded that the star density was much higher in the southern sky — where Pannekoek’s results had been tentative — than in the northern sky, especially in the direction where Shapley had found the centre of his extended galactic system. He calculated a distance to the centre of the local system at a distance of 2270 parsec from the Sun. Although Kreiken recognized that many of the individual features of the local system were down to the clustering of stars and dark nebulae, he was certain that there was a strong dependence of the star density on both galactic latitude and longitude.

Third Approximation

Understanding the star densities in the galactic plane was not the end goal for Pannekoek; it was only the first step to providing a complete investigation of the local system that determined the distribution of stars as a function of latitude, longitude, and distance. In this way, it would be possible to ‘[treat] the different galactic features as special objects and [determine] the distribution functions separately for all these special regions in the sky’. This new research was not limited to the galactic equator alone but covered the entire sky. Pannekoek called this approach a ‘third approximation’ to the structure of the galactic system. With this term, he...
referred to the fact that he conducted a three-dimensional investigation of the density distribution, taking into account distance, galactic latitude, and galactic longitude, as opposed to Kapteyn’s second approximation which only used two, namely galactic latitude and distance.

It may seem as if Pannekoek simply wanted to add more detail to Kapteyn’s tried method, but that would neglect the significant differences in the fundamental goal of their research. Pannekoek was not looking for a single star density distribution that could capture the shape of the entire system; he was looking for specific features and irregularities that indicated the existence of star clusters in the Solar neighbourhood. Whether these clusters formed a complete system or were only a small part of a larger system was not of immediate concern. The acquired knowledge would be useful either way.\(^92\) This attitude, as we have seen, can be explained by his particular epistemic virtues that shunned the desire for grand schemes and instead called for structures to be created from the bottom up. In light of these goals, there was no reason for Pannekoek to abandon his research, despite the rapidly changing theories of the universe, and even when many other astronomers saw no benefit in continuing this line of research.

In practice, the third approximation meant that Pannekoek calculated the density distribution of stars in each direction of the sky by investigating the relative star-ratios for three different visual magnitudes, 5.7, 7.4, and 8.6. The results were represented as azimuthal projections of the northern and southern sky for each magnitude (Figure 2.12). Parts of the sky where the density distribution deviated strongly from the mean were highlighted in the diagram: red for relatively dense areas and blue for relatively sparse areas. The primary conclusion of this investigation was that no central condensation of stars could be found that acted as the centre of the system. Instead, he found multiple accumulations and clusters that were roughly comparable with each other, such as those in the directions of Cygnus, Monoceros, and Carina. For each cluster, the distance, size, and density were determined.\(^93\) The results were placed in a schematic top-down projection of the stars in the Solar neighbourhood that can be seen in Figure 2.13.

While Pannekoek, Kreiken, and Nort had all found reasons to doubt the Kapteyn Universe, the definitive rejection came in 1927 as a result

\(^92\) Pannekoek, \textit{Structure of the Universe} 1, 2.

\(^93\) Ibid.
2.3. Star Densities in the Local System

Figure 2.12: Diagram showing the density distribution of stars of visual magnitude 8.6 in the northern sky. Areas of relatively high density were indicated by increasingly darker shades of red, while fainter areas were indicated with blue shading. Source: Pannekoek, *Structure of the Universe* 1, Plate 3 North.

of Jan Hendrik Oort’s research on the differential rotation of the galactic system. Oort, the last of Kapteyn’s students, began his career conducting extensive research on the distribution of high-velocity stars. Early on, he found that these high-velocity stars were distributed asymmetrically throughout the galactic system, were almost exclusively intrinsically faint stars, and moved with the same speed and direction as the globular clusters.\(^{94}\) His initial theory for the Kapteyn Universe was as a local

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\(^{94}\) Jan Hendrik Oort, ‘Some Peculiarities in the Motion of Stars of High Velocity’, *Bulletin*
cluster of stars that moved with high speed through a larger collection of similar clusters, which was outlined by the globular clusters.\footnote{Jan Hendrik Oort, \textit{The Stars of High Velocity}, Publications of the Astronomical Laboratory at Groningen 40 (Groningen: Hoitsema Brothers, 1926).} Before long, however, Oort learned of the work of the Swedish astronomer Bengt Lindblad, who developed a mathematical theory of differential rotation to explain the fact that stars appeared to move in two preferential directions.\footnote{This was known as the star streaming and was first announced by Kapteyn in 1905. See Paul, \textit{Milky Way Galaxy}, 84–94; Smith, "Beyond the Big Galaxy", 314–315.}

The centre of this rotational system, Lindblad reckoned, was very near the centre of Shapley's system. Oort soon realized that his work on high-velocity stars provided immediate supporting evidence for Lindblad's theory. He constructed a model of a differentially rotating stellar system that made it possible to derive both the size and the mass of the galactic system.
2.3. Star Densities in the Local System

from observational data.\textsuperscript{97} Oort’s new system was an almost immediate triumph and, although it was smaller than Shapley’s model, it ended the debate on the eccentric position of the Sun and the location of the galactic centre.\textsuperscript{98}

For Pannekoek, Oort’s research confirmed his intuitions on the structure of the universe, and he immediately sought to find the central masses that could be responsible for the rotation.\textsuperscript{99} He also further investigated the distribution of stars in the local system by focusing on the distribution of specific spectral classes of stars. One major complication with statistical astronomy was always that the spread of absolute magnitudes in the luminosity function was much larger than the spatial spread of star clouds. This made it notoriously difficult to pinpoint the exact distance and size of star clusters because their presence was scattered throughout multiple magnitudes. By looking at specific spectral classes, however, this problem could be circumvented, as the spread of absolute magnitudes within a single spectral class was much smaller. The publication of the Henry Draper Catalogue in 1924, which not only contained the visual magnitude of every star down to the ninth magnitude but also their spectral class, provided Pannekoek with an excellent opportunity to derive the distance and size of star clusters with much greater accuracy than before.\textsuperscript{100}

For his investigation, Pannekoek focused on three star classes that were particularly bright: the B-type stars, the A-type stars, and the K-type giants. The B-type stars, which were very limited in number, could

\begin{itemize}
  \item \textsuperscript{97} Jan Hendrik Oort, ‘Observational Evidence Confirming Lindblad’s Hypothesis of a Rotation of the Galactic System’, \textit{Bulletin of the Astronomical Institutes of the Netherlands} 3, no. 120 (1927): 275–282; Oort, ‘Investigations Concerning the Rotational Motion of the Galactic System Together with New Determinations of Secular Parallaxes, Precession and Motion of the Equinox’, \textit{Bulletin of the Astronomical Institutes of the Netherlands} 4, no. 132 (1927): 79–89. See also\textsuperscript{xv–xvii}KatgertMerkelijn1997\textsuperscript{325–326}Smith2006\textsuperscript{181–200}vanderKruit2019
  \item \textsuperscript{100} Pannekoek, \textit{Structure of the Universe} 2, 1–69.
\end{itemize}
2. Statistical Astronomy

Figure 2.14: The location of clusters of B stars, as calculated by Pannekoek from the Henry Draper Catalogue, projected on the galactic plane. The circles represent distances of 300 and 1000 parsec from the Solar System, which is placed in the origin. Source: Pannekoek, *Structure of the Universe* 2, 65.
be individually placed on a map after their distance was calculated. Figure 2.14 shows the location of each projected on the galactic plane as derived by Pannekoek. The most distant B-type stars in the catalogue were located at a distance of 661 parsec from Earth. For the A-type stars and K-type giants, the number of stars was much greater, making it impossible to draw them individually on a map. The distributions of these two star classes were presented in an azimuthal projection that showed the density distribution of these stars up to 300 parsec (Figure 2.15). Pannekoek noticed some unexpected and interesting patterns that revealed how these stars were clustered. The A and especially B-type stars appeared to be strongly constrained to the galactic plane, while the K-type giants were much more evenly spread through the entire galactic system. B-type stars were also usually clustered near galactic clouds and irregular nebulae, and every cluster of B-type stars was associated with a cluster of A-type stars. Accumulations of K-type giants could also occasionally be found in the presence of A-type clusters, but they were never found in the presence of B-type clusters. From these patterns, Pannekoek argued that there might exist two stellar evolutionary tracks; one which included K-type giants and another which included B-type stars, with A-type stars featuring in both. He also suggested that, for the first evolutionary track, stars were created outside of the galactic zone as K-stars and slowly moved into the galactic zone as they evolved to A-stars. These suggestions were soon rejected as the theories of stellar evolution changed, but knowledge of the complicated structure of the local system remained vital for investigating the evolution of the galactic system. Nevertheless, it took astronomers a long time before they picked up the subject again in a similar fashion as Pannekoek; only in the 1950s did the study of O associations, as they came to be called, really take off.

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102. Ibid., 69.
104. In a 1964 review on O associations, Adriaan Blaauw mentioned: 'Of the early investigations of the space distribution of the early-type star groups, we mention only that by Pannekoek ..., the results of which show some striking resemblances to those of the modern investigations'. Adriaan Blaauw, 'The O Associations in the Solar Neighborhood', *Annual Review of Astronomy and Astrophysics* 2, no. 1 (1964): 213–246, 213.
In the preceding pages, we have seen how Pannekoek managed to adapt his research to the changing opinions on the structure of the universe. His focus was on how the stars were distributed throughout the universe, and not necessarily on the overall shape and size of this universe. When forced to choose, he stayed true to Kapteyn’s statistical method of deriving star densities from star counts rather than his goal of determining the size and shape of the entire galactic system, as the other Dutch astronomers did. Pannekoek’s focus on individual clusters could also lead to disputes, as we have seen in the case of Easton and Nort. Crucially, in these disputes, different methodologies related to different epistemic virtues, and vice versa.
2.3. Star Densities in the Local System

The rejection of a certain method could go hand in hand with the rejection of a persona, as illustrated by the assessment of Pannekoek and his approach to astronomy by Pieter van Rhijn, one of Kapteyn’s students and his eventual successor in Groningen. For Van Rhijn, individual features were useless for understanding the galactic system. Only by working systematically on the entire system could it be understood. When graduate student Bart Bok submitted his PhD thesis on the η Carinae region to van Rhijn, the latter initially dismissed it because it focused only on a single region in the sky rather than multiple regions distributed equally over galactic longitude, stating that: ‘it’s the sort of thing that that man Pannekoek would do’.  

The realization that statistical astronomy could only provide a model for a small portion of the universe did not diminish its value for Pannekoek, since it was still capable of uncovering the structure of the star distribution in our particular local system in high detail. This knowledge, in turn, could also have implications on the understanding of our entire system. In 1930, however, convincing evidence for the existence of interstellar absorption was provided by the American astronomer Robert Trumpler. The presence of interstellar absorption meant that Shapley had likely overestimated the distances to the globular clusters, and that the actual size of Shapley’s system was in line with the size Oort had measured for the rotational system. Moreover, the interstellar matter responsible for this absorption turned out to be irregularly distributed throughout the entire system, meaning that it was nearly impossible to correct for its effect in statistical studies, even for such a limited scope as the local system. Whereas the various larger systems of Shapley, Curtis, and Oort provided interpretive difficulties that were easily accommodated in Pannekoek’s methodology, the discovery of interstellar absorption provided a practical objection to sidereal astronomy to the point that it could no longer be defended. The features of the Milky Way that Pannekoek had been chasing turned out to be shadows. Nevertheless, in the final years of his professional career, he decided to chase these shadows for one last time with an extensive statistical investigation of the distribution of dark nebulae in the local system.

105. Bok, interview by DeVorkin AIP/OH.
2.4 Historical Materialism

While Pannekoek was exploring new methods to investigate the Milky Way system, he was also exploring methods to investigate the development of human society. Like with galactic astronomy, Pannekoek’s most active period as a Marxist was during the first few decades of the twentieth century when he formulated the philosophical foundations of his Marxism. While his conception of the socialist revolution and tactics changed over time, the underlying philosophy remained largely consistent. It is hardly surprising then that there are some meaningful connections between Pannekoek’s epistemic virtues in these different domains of investigation. As this section will illustrate, two recurring themes in his statistical astronomy also played a prominent role in his Marxist writings: the emphasis on thought and judgement over purely mechanical methods, and the rejection of a top-down approach to organization.

As has been discussed in the previous chapter, Pannekoek’s emphasis on the importance of judgement coincided with his Marxist philosophy of mind. The task of the human mind was to process sense perceptions and abstract this information and categorize them into concrete objects and ideas, something which happened constantly and could not be prevented. This ability to abstract was what set humankind apart from other animals; it allowed us to understand and eventually manipulate the external world. At the same time, the mind was susceptible to indoctrination and bias, as sense perceptions were not limited to impressions of physical objects alone according to Pannekoek; they also included information received from other people as well as one’s own memory. Judgement was an important epistemic virtue for Pannekoek because it emphasized the capabilities of the human mind to quickly categorize statistical information into something meaningful, while it could also detect biases and presuppositions.

Translated to the science of astronomy, the emphasis on judgement meant astronomers should interpret their results and counteract presuppositions where needed, whereas with a strict adherence to mechanical objectivity such presuppositions would remain undetected. In the case of statistical astronomy, judgement meant that astronomers had to acknowledge particular features that they noticed in the distribution of stars and
needed to constantly compare their statistical result with the visual appearance of the Milky Way. This was especially true because, even if it were somehow possible to prevent the human mind from interfering with the registration and collection of phenomena, then it would still only lead to a multitude of particularities without structure or order. Such an unsorted collection of events would have no value in helping to understand the world. Not only was human intervention inevitable — it was desirable.

Pannekoek’s criticism of proponents of mechanical objectivity in natural science strongly resembles his criticism of mechanical materialism in his Marxist writings. To illustrate this, we must understand how he interpreted Marxism. For Pannekoek, Marxism was not a political theory but a scientific research method that was specifically designed for analysing society. In fact, he used the terms ‘Marxism’, ‘social science’, and ‘historical materialism’ interchangeably.\footnote{110} This tendency can already be found in his first major philosophical paper, published in 1901, where he wrote: “The materialist conception of history is not a fixed system, or a certain theory; it is a method of research, a method, that asks for the causes of all historical occurrences; that searches for a plausible explanation of social developments.”\footnote{111}

Of course, Pannekoek was far from unique in believing that historical materialism was a research method; many Marxist theorists agreed with him on this point. They also agreed that this meant that the historical development of society should be studied through an analysis of material factors. The exact nature of these material factors, however, has been a source of constant debate. Often, the focus was on economic factors such as ownership of the means of production, labour relations, and the distribution of capital. Pannekoek, on the other hand, distinguished himself by strongly emphasizing the importance of the human mind in interpreting these material factors. This emphasis on the role of the mind, he argued, was what differentiated historical materialism from mechanical materialism — or ‘bourgeois’ materialism as he called it — which, according to him, reduced the entire world to the deterministic movement of particles.\footnote{112}

To explain the differences between the two kinds of materialism, Pannekoek often referred to their historical development. As Pannekoek argued, mechanical materialism as a way of understanding nature was developed in the late eighteenth century when the bourgeoisie started their struggle with the aristocracy for political power. It served the needs of the rising bourgeoisie because it could act as an ideological weapon in that struggle. By eliminating the need or even the possibility of divine intervention, it undermined the traditional foundations of absolutism, such as the divine right of kings.

Mechanical materialism also served as the philosophical foundation of natural science and provided a method for investigating the physical world. It was not, however, without its flaws, according to Pannekoek. In reducing everything to the movement of matter and energy, it failed to describe the dynamics of human society or the function of the human brain. The inevitable result was that mechanical materialism contained a strict demarcation between mind and matter. Where natural science could, in principle, completely explain the realm of physical matter, it had nothing to say about the realm of the mind. Consequently, bourgeois scientists would invariably fall back on mysticism in order to make sense of the latter. Either this mysticism could come in the form of a return to religion and the reintroduction of divine intervention; or it could come in the form of absolute principles, like causality and natural law, and bourgeois ideals, like personal and economic freedom.

Pannekoek’s emphasis on Marxism as a scientific method also reflected on the role he believed Marxists should play in society. Pannekoek believed it was important to differentiate between Marxists, who researched society, and the members of the working class, who were responsible for changing society. According to Pannekoek, the sole responsibility for initiating and leading the revolution should lay with the latter group.


114. About mysticism in causality and natural law, Pannekoek wrote: 'Unaware of their origin and nature, physicists see [causality and natural law] as independently existing beings or powers. Thus their entire worldview, which is based on causality and natural law, eventually becomes as narrowly mystical as the old one: instead of one God that rules everything, there are countless mysterious demons, forces, who manipulate everything. Instead of one will, nature must obey natural laws that prescribe what is allowed and what is not.' Ibid., 304.
the working class had found the right revolutionary spirit, they would organize themselves and through spontaneous mass actions slowly weaken the foundation of the existing state. When this finally collapsed, the working class would create a new, truly democratic society that was organized from the bottom up according to the principles and methods that they had developed as they lived through the struggle.\textsuperscript{115} Since the new society had to be developed by the workers themselves, Marxist scholars had to play a part on the side-lines. They should avoid trying to dictate the direction of the social revolution from the top down and instead focus on educating the workers and helping them understand why they took certain courses of action. Marxists had to analyse the revolution as it happened, devoid any theoretical presuppositions, as an open-minded yet trained expert.\textsuperscript{116}

Pannekoek’s ideal of the Marxist persona as a detached scholar led him to play a passive role in the labour movement. Even in Germany during his most active period, he focused on writing opinion pieces and teaching historical materialism rather than participating in political action himself. By the mid-1910s, Pannekoek had completely rejected parliamentarianism and trade unionism as paths toward the new society. He believed that any top-down organization would inevitably turn its leadership into a labour aristocracy, who would benefit from perpetuating the status quo within the existing government.\textsuperscript{117} Instead, the workers should organize themselves from the bottom up, by congregating into factory councils that together formed the new council communist government.\textsuperscript{118} From the 1920s onwards, Pannekoek was no longer an official member of any socialist organization and focused primarily on theoretical and philosophical discussions on the nature of historical materialism. Although his retreat into theory was partially the result of his isolation from the working class, the fear of influencing their revolutionary spirit would no doubt also have played an important role.\textsuperscript{119} On this point, we can find an analogy with

\begin{itemize}
\item \textsuperscript{115} Gerber, \textit{Pannekoek and Workers’ Self-Emancipation}, 95–99.
\item \textsuperscript{116} Tai and Van Dongen, ‘Personae and the Practice of Science’, 68.
\item \textsuperscript{118} Anton Pannekoek [pseudonym P. Aartsz], \textit{De arbeidersraden}, 2nd ed. (1946; repr., Amsterdam: De Vlam, 1971), 35–41.
\item \textsuperscript{119} Unsurprisingly, Pannekoek’s analytic yet expectantly observant and academic persona was seen as a vulnerable point for the attacks of his opponents. He became known as a perpetual critic who lacked political pragmatism. Karl Radek called him an ‘astronomer gazing only at the stars, and never at a living worker’, while Willem van Raven-
his astronomical research. His bottom-up conception of the ideal society is reminiscent of the bottom-up method he applied in sidereal astronomy, where individual stars congregated into clusters and the combination of clusters formed the Milky Way system. In both cases, there was no need for an overarching, top-down system to control the basic structure.

2.5 Conclusions

We started this chapter by asking whether an investigation of the epistemic virtues and scholarly personae of Pannekoek would lead to a deeper understanding of his Milky Way research in the context of contemporary developments in science, and in relation to his Marxist philosophy. Throughout the chapter, we have seen that both the astronomical persona and the Marxist persona, as conceptualized by Pannekoek, had to be actively involved in systematizing and analysing information. How this worked in practice depended on the specific field of research. The galactic astronomer had to look for the structure in the Milky Way and determine how this coincided with the clustering in the distribution of stars. The Marxist theorist had to analyse how material factors — social, economic, or ideological — determined the behaviour of social classes, and develop tactics that would optimize the odds for creating a truly democratic society.

In both cases, these personae needed to be open-minded; they should not let themselves be guided by preconceived ideas about how the structures should look or how the revolution should play out, because such preconceptions would alter their perceptions and would lead them to see what they expected to see. Rather than there being some fundamental disconnect, Pannekoek’s conception of the ideal scientist and the ideal Marxist were both rooted on the same epistemic concerns, each adapted to suit its specific field of research. This, of course, should hardly be surprising because they were ultimately created by the same person: Pannekoek.

Although this study has revealed a strong relation between Pannekoek’s epistemic virtues in his approach to socialism and science, their
relation was certainly not limited to these virtues alone. It is also possible to draw an analogy between his model of the local system and his model for council communism. In both cases, he rejected a predetermined top-down strategy that emphasized the overarching system as a meaningful entity. Instead, he promoted a bottom-up strategy that emphasized the way in which individual persons or stars congregate into larger systems. The collection of these individual clusters provides sufficient structure for the system as a whole without requiring an additional overarching layer. Similarly, his rejection of mechanical materialism shows some striking parallels with his rejection of mechanical sorting schemes in astronomy. In both cases, by neglecting the potential role of the human mind, crucial information was overlooked or misinterpreted.

The focus on Pannekoek’s epistemic virtues also helped considerably with the other goal of this chapter, which was to situate his astronomical research within the greater developments of contemporary science. Here, Daston and Galison’s mesoscopic narrative provides a useful context for Pannekoek’s novel methods. We have seen that Pannekoek was involved in lively discussions on the construction of the universe with other Dutch astronomers like Kapteyn, Easton, and Nort. In the Netherlands, these discussions focused primarily on the question of the size and structure of the galactic system, rather than on the nature of the spiral nebulae. Pannekoek’s rejection of the methods of Kapteyn and Nort can be understood in light of typical rejections of both truth-to-nature and mechanical objectivity. He argued that Kapteyn’s mechanical method of sorting star counts according allowed no way of correcting preconceived structures that were built into the sorting scheme. By doing so, Kapteyn could find no other shape for the system than the one he already had in mind. He believed that by idealizing a fully mechanical approach to science, the most defining aspect of human beings—their ability to analyse—would be lost.

Instead, Pannekoek can be seen as one of the earliest adepts of the twentieth century epistemic virtue of trained judgement. He was part of a growing movement of scientists who increasingly emphasized the need for interpreted structure and systematized data. His ideal astronomer was actively involved in systematizing and analysing the information provided by instruments or sense perceptions. His task was to recognize characteristic or distinguishing features of particularities and highlight them for other astronomers. This strongly reminds us of his socialist philosophy of mind. The very nature of the human mind is to organize and distinguish sense perceptions; this ability to make sense of the infinitely varied
external world is its greatest strength. If scientists are to understand the
world, they ought to use this strength.

Yet — obviously — upon closer inspection, there are also ways in which
this story reveals that Daston and Galison’s narrative needs to be nuanced.
Kapteyn is difficult to place as he seems to occupy a position that floats
somewhere in between truth-to-nature and mechanical objectivity, and
Pannekoek is hardly the archetypical trained judgement expert, since he
assigned no specific importance to the role of professional training in de-
veloping scientific intuition. Of course, this is a common occurrence when
grand historical schemes are applied to specific case studies; strict cat-
egories of these schemes fall apart in a sea of context. The overwhelm-
ing complexity within the history of science refuses to be captured in a
single big picture. This does not mean, however, that these grand schemes
are without value. Despite its flaws, the narrative of objectivity as an
epistemic virtue, as described by Daston and Galison, helped to situate
the development of Pannekoek’s astronomy within the broader historical
context. It helped to highlight the differences between him and Kapteyn,
which led them to contradictory results despite their use of the same math-
ematical methods and statistical data. It helped to understand why Pan-
nekoek continued to contribute to a field of research that was essentially
declared dead several years earlier.
When Pannekoek founded the Astronomical Institute in Amsterdam, he had planned for statistical astronomy to be the main topic of research. Soon, however, his attention was drawn to the astrophysics of stellar atmospheres. This turned out to be a successful move because, of all natural-scientific endeavours that Pannekoek engaged in, his contribution to astrophysics was most highly regarded by his professional colleagues in astronomy. This raises two pertinent questions that this chapter seeks out to answer: Why did he make the switch to astrophysics, and how did he contribute to the field? As this chapter aims to illustrate, Pannekoek’s choice for astrophysics was effectuated by a combination of conviction and circumstance. On the one hand, astrophysics satisfied his desire for socially relevant research, on the other, it was particularly well suited for the type of institution that he had founded, an astronomical laboratory without an observatory. These two factors also impacted his methodology, as they coalesced into the virtue of thoroughness as a guiding principle in both his observational and theoretical research.

Pannekoek entered the field of astrophysics during a period of rapid changes. The last few decades of the nineteenth century saw the institutional implementation of astrophotography, which had a profound impact on the daily practice of observational astronomers. It led to the founding of large, high-altitude, photographic observatories in Western North America, which shifted the centre of astrophysical research away from the smaller city-based visual observatories found in Europe. This change in observational practice was accompanied by a major breakthrough in


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theoretical astrophysics. After decades in which astrophysics could only be studied qualitatively, the formulation of an ionization equation by the Meghnad Saha in 1920 had made it possible to investigate the physical conditions in stellar atmospheres in a quantitative manner. This research unlocked a wealth of opportunities for interpreting photographic spectra that had not been possible before. The combination of these developments enabled someone like Pannekoek, who was willing to put in hard work but lacked resources, to become a trailblazer in the new astrophysics — one who came to be seen as the ‘founder’ of modern astrophysics in the Netherlands by his contemporaries. He did so by pursuing virtues that allowed him to make use of the opportunities astrophotography and large photographic observatories provided for isolated astronomers like him — virtues such as persistence, meticulousness, and especially thoroughness.

Pannekoek’s emphasis on thoroughness as an epistemic virtue becomes clear when we look at how he is remembered by his close collaborators. When Marcel Minnaert was asked to summarize Pannekoek’s contributions to astronomy, he wrote:

One cannot say that Pannekoek introduced important new physical effects in order to explain the stellar spectra. His merit is that he did not hesitate to take into account all physical factors already known, not deterred by mathematical complications or laborious numerical calculations.

Gale Bruno van Albada, who was not only a doctoral student of Pannekoek but also a fellow council communist, noted:

Pannekoek was never satisfied with a theory that represented phenomena only roughly, or with observations that only

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globally tested a theory. Ever again, it had to be sharper and more refined, because the contradictions between theory and observations help to deepen our insight.4

When interpreting such descriptions, it is important to realize that individual epistemic virtues have meant different things to different people at different times.5 To appreciate the meaning and impact of an epistemic virtue like thoroughness, it is necessary to investigate what it meant in practice.6 Thus, we will analyse Pannekoek’s theoretical models in astrophysics to discover what sort of research he considered thorough.

Pannekoek’s methodology and his pursuit of thoroughness were influenced by his particular position as the lone professional astronomer working at an astronomical institute that had multiple calculators but lacked an observatory. The most straightforward way to make use of his resources would have been to delve deeply into steadfast calculation of theoretical models. Yet, Pannekoek wanted to contribute to observational research as well. For this purpose, he equipped his institute with measuring instruments and borrowed photographic plates and observation time from the new photographic observatories. With these photographic plates, he and his students could then conduct observational research. Since the number of available plates was always limited, Pannekoek made sure that he got as much information from them as he could, as Elsa van Albada-van Dien recalled

[According to Pannekoek] Every observation was unique and not repeatable. That is why every spectrum was studied to its fullest extent. ... His belief that as much as possible should be extracted from each observation also formed the foundation for this institute. P[annekoek] once told me: at large observatories, they do not have time to measure out everything in detail, that is why we do this in Amsterdam.7

5. See e.g. M. Norton Wise, ed., The Values of Precision (Princeton: Princeton University Press, 1995), for an indication of various meanings the virtue of precision could have.
7. Elsa van Albada-van Dien, Niet-letterlijke weergave van toespraakje over Pannekoek [non-literal rendition of lecture on Pannekoek], 18 May 1982, AFI. Translated from Dutch
While astrophysics allowed Pannekoek to overcome his lack of observatory access, it also provided him with the opportunity to satisfy his desire for social relevance, which he considered a crucial aspect of scientific research. One of the reasons why he had given up positional astronomy to pursue socialism in 1906 was because he failed to see the social relevance of his research. He believed that astrophysics was much more likely to lead to societal progress than positional astronomy. Pannekoek’s thoughts on the relation between scientific and societal developments and his own potential role in this process become clear in his three inaugural lectures: the first in 1916 as an unpaid lecturer in history of astronomy at Leiden University; the second in 1918 as a lecturer in astronomy and mathematics at the University of Amsterdam; and the third in 1925 as professor extraordinarius in astronomy, again at the University of Amsterdam. In the lectures, Pannekoek made clear that he valued astronomy not only for the theories about the universe it could provide, but also because it instilled a scientific way of thinking in those who studied it.

One of the goals of this chapter is to investigate the epistemic virtues Pannekoek pursued in his astrophysics research and to see how these were constrained by the tension between his circumstances as an astronomer without an observatory on the one hand, and his conviction on how science ought to be pursued on the other. The juxtaposition between virtues grounded in social ideals and those resulting from practical concerns can provide valuable insight into how scientific personae are constructed. This has been demonstrated, for example, by Jessica Wang in her analysis of the scientific persona of American physicists Merle A. Tuve and Robert R. Wilson during the Cold War. Both Tuve and Wilson struggled to reconcile their protestant ideals of austerity and self-reliance with the practical reality of large-scale state-controlled Cold War physics; and, as Wang shows, they navigated these contradictory realities by crafting a self-image that befitted their unique situation.8

Of course, social ideals and practical constraints are not necessarily in conflict with one another. A clear example of how they could reinforce one another is Arthur Eddington’s effort to measure the deflection of starlight due to the Sun’s gravity during the 1919 Solar eclipse, which provided the

empirical evidence for Albert Einstein’s General Theory of Relativity. Eddington was strongly motivated by his desire to restore the ideal of scientific internationalism — an ideal that coincided with his professed Quaker beliefs — during the aftermath of the Great War. The 1919 eclipse provided an ideal opportunity because it allowed him to both verify a controversial theory by a pacifist German physicist and push the limits of observational astronomy by using the latest technological improvements in astrophotography.\(^9\)

This chapter will delineate and analyse Pannekoek’s contributions to the astrophysics of stellar atmospheres, and establish the goals, methodology, and virtues of his research. Since Pannekoek’s astrophysics has hitherto received little attention from historians, it is valuable to give a global overview of his contributions to the field and place these within the historical context already established by historians of astronomy. This overview should give an indication of the main problems Pannekoek was concerned with and the impact it had on the development of contemporary astronomy. The focus will be on his efforts to determine the physical properties and conditions of stellar atmospheres through the analysis of spectral lines, which encompassed both theoretical and observational research. In particular, we will focus on Pannekoek’s approach to this subject and how he saw his role in the astrophysics community. Ever present in Pannekoek’s research were two competing forces. On the one hand, there was the ideological incentive to practice astronomy in such a way that it may benefit society. On the other hand, there were the practical constraints of being an isolated astronomer on the periphery without an observatory. What this chapter will show is how these forces shaped Pannekoek’s approach to astrophysics and the virtues he pursued in this research.

The chapter will begin with a discussion of the background of astrophysics in the first two decades of the twentieth century and Pannekoek’s own role in the development of the spectrum-luminosity diagram. Then we will discuss how Pannekoek pictured the growth of scientific knowledge and the social relevance of astrophysics as explained in his three inaugural lectures; and how these ideas were reflected in the founding of the Astronomical Institute of Amsterdam. The final four sections of the chapter will discuss in detail Pannekoek’s theoretical and observational

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\(^9\) Matthew Stanley, “”An Expedition to Heal the Wounds of War”: The 1919 Eclipse and Eddington as Quaker Adventurer”, \textit{Isis} 94, no. 1 (2003): 57–89.
research on stellar atmospheres from the 1920s to the early 1950s and explore how these reflected the ideals he delineated in his inaugural lectures within the practical constraints of his position.

3.1 Spectrum, Luminosity, and Colour

Pannekoek’s first two papers on astrophysics were published in 1906 and discussed the relation between the spectrum, luminosity, and colour of stars. These papers were embedded in contemporary discussions on the classification and evolution of stars, and they give an early impression of the recurrent themes and strategies in Pannekoek’s research. To contextualize them properly, we will first look at the state of astrophysics around the turn of the century.

Astrophysics only became established as an academic discipline in the late nineteenth century. Although astronomers had begun to investigate the physical properties of the stars, as opposed to just their visual properties, in the early nineteenth century, this was primarily done by self-funded astronomers who were not constrained by the responsibilities of professional astronomy. The most influential of these early explorers was John Herschel, who managed to convince the astronomical community of the benefits of treating the stars as physical objects with his measurement of stellar masses through binary star systems, among other things.\(^{10}\) The major breakthrough for astrophysics, however, came in the mid-nineteenth century with the development of spectroscopy and the realization that each chemical element had a unique spectrum. This meant that spectral lines in the Sun could be matched with spectral lines created in terrestrial laboratories, allowing an investigation of the chemical properties of stars.\(^{11}\) According to historian of astronomy Robert W. Case, \(\text{Making Stars Physical: The Astronomy of Sir John Herschel}\) (Pittsburgh: University of Pittsburgh Press, 2018). John Herschel refused to take a professional position in astronomy because he wanted to keep full control over his own research topics. For a general discussion of the role of amateurs in early astrophysics, see John Lankford, ‘Amateurs versus Professionals: The Controversy over Telescope Size in Late Victorian Science’, Isis 72, no. 1 (1981): 11–28; Lankford, ‘Amateurs and Astrophysics: A Neglected Aspect in the Development of a Scientific Specialty’, Social Studies of Science 11, no. 3 (1981): 275–303; Karl Hufbauer, ‘Amateurs and the Rise of Astrophysics, 1840–1910’, Berichte zur Wissenschaftsgeschichte 9, no. 3 (1986): 183–190; Nall, News from Mars: Mass Media and the Forging of a New Astronomy, 1860–1910, 12–15, 179–181, 192 n. 25.

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\(^{11}\) See John B. Hearnshaw, \(\text{The Analysis of Starlight: Two Centuries of Astronomical Spec-\)
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Smith, this development in rough qualitative analysis of the chemical composition of stars can be seen as the first of three stages in the development of astrophysics.\textsuperscript{12}

The introduction of mass photographic spectroscopy in the late nineteenth century enabled large research programmes that could catalogue vast numbers of stellar spectra, which induced the second stage in the development of astrophysics, the systematic matching of various observational properties. The most significant of these programmes was the large-scale classification project of photographic spectra set up at the Harvard College Observatory, led by its director Edward C. Pickering. The scale of this project required an internal division of labour with workers located at different physical sites. While the photographic plates containing the spectra of the northern hemisphere were taken at Harvard College Observatory itself, those of the southern hemisphere were taken at the remote high-altitude Boyden Station in Arequipa, Peru, and transferred to Harvard for measurement.\textsuperscript{13} These measurements — the most significant and laborious part of the process — were performed by women computers who were formally tasked to conduct machine-like labour in order to create an objective classification.\textsuperscript{14} In the process, however, they set critical standards for the classification process and developed the foundation of classification systems that still persist today.

The first catalogue produced by the Harvard College Observatory was the \textit{Draper Catalogue of Stellar Spectra}, published in 1890, for which the majority of spectra were measured by Wilhelmina Fleming. For this cata-


\textsuperscript{12} For a concise summary of the three-stage development of astrophysics, see Smith, ‘Astronomy in the Time of Pannekoek’, 121.

\textsuperscript{13} The Boyden Station was founded in Peru in 1889 and was moved to South Africa in 1927. For more on the Boyden Station in Peru, see Catherine Nisbett Becker, ‘Professionals on the Peak’, \textit{Science in Context} 22, no. 3 (2009): 487.

\textsuperscript{14} Pickering explained in the preface of the catalogues that strict automated procedures were set up, which allowed the employment of unskilled, replaceable hard-working female assistants. Their lack of training in astronomy was considered a virtue as it discouraged them from speculations on the nature and meaning of the their classification, which may contaminate the results. Annie J. Cannon, in particular, was praised for her total abstinence from theoretical speculation, see Lorraine Daston and Peter Galison, \textit{Objectivity} (New York: Zone Books, 2007), 341–342.
logue, a lettered system was developed that was based primarily on the strength of hydrogen lines. A more complex scheme was developed by Antonia C. Maury for her 1897 catalogue, *Spectra of Bright Stars*. She introduced an additional subdivision within each class depending on the relative shape of the spectral lines. Stars with regular spectral lines were placed in division a, those with wide spectral lines in division b, and those with exceptionally narrow lines in division c. Many of her colleagues, however, worried that Maury’s divisions could perhaps be caused by instrumental errors. For the subsequent *Spectra of Bright Southern Stars*, published in 1901, Annie J. Cannon reverted back to the Pickering–Fleming classification but rearranged the placement of the A and B class stars and placed the O stars, whose spectra closely resembled the spectra of nebulae, at the beginning of the sequence. The resulting sequence O, B, A, F, G, K, M, which is still in use today, was implicitly an evolutionary sequence, although Cannon never explicitly stated this to be the case. This same classification scheme was also used for the extended *Henry Draper Catalogue*, published between 1918 and 1923.

Astronomers were keenly interested in spectral classification because they hoped it could reveal information about the constitution and evolution of stars. According to the prevailing belief in the early twentieth century, stars got their energy from converting potential energy into heat. Stars were thought to begin their life as large gaseous nebulae that contracted under their own gravity, heating up as a result and becoming stars.

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19. See e.g. Anton Pannekoek, *De evolutie van het heelal*, inaugural lecture, University of Amsterdam (Amsterdam: L. van Nifterik Hzn. 1918).
3.1. Spectrum, Luminosity, and Colour

As they become denser, the contraction would slow down until, at one point, they started to cool down again. The prominence of this theory is reflected in the fact that even today the hotter O and B type stars are called early-type stars while the cooler K and M stars are known as late-type stars.

It was hoped that observational evidence for theories of stellar evolution could be provided through investigating the relation between the spectrum and luminosity of stars. This research was taken up by, among others, William H. S. Monck and Jacobus C. Kapteyn toward the end of the nineteenth century. They had both determined the average proper motion for stars of each spectral type. Since it was assumed that, statistically, the proper motion of stars was inversely proportional to the distance of stars from the Sun, the average proper motion of a spectral class was also inversely correlated with the average luminosity of stars of that spectral class. What these investigations revealed, however, was that the spectral types with the highest average proper motions, the faintest stars, were the yellow stars like the Sun and not the late red type stars as they had expected. Pannekoek, too, was keenly interested in this subject, even though it was not part of his professional research at the time.

When Pannekoek wrote his papers on the spectrum and luminosity of stars, he was working as a positional astronomer at the Leiden Observatory. His task was to record stellar coordinates using the observatory’s meridian circle. It was precise work, but also tedious and dreary, and it exasperated Pannekoek, who failed to see the relevance of his research and began to feel increasingly that he was unsuited for astronomy. In a personal journal, he recorded his struggles:

While everyone contributes their part to the improvement of [social] conditions, I am reducing meridian positions. Science is surely the only thing that persists and progresses with the change of people and conditions. It has to prepare the better future; it is the reason that humankind progressed to where it can imagine becoming free and happy, again through science. But what a work of thought is necessary to follow, in all its twists and turns, the connection between societal happiness and reducing stellar coordinates.  

To satisfy his desire for more socially relevant research, Pannekoek engaged with topics beyond positional astronomy. In 1900, for example, he wrote a remarkable article on the colours of stars, in which he not only discussed visual colour estimates of stars but also analysed how the perception of colour was formed through physiological and psychological conditions. Pannekoek was also interested in physics and had a strong background in the subject. When he was a student in Leiden, he left a lasting impression on Hendrik A. Lorentz, who considered Pannekoek to be one of his best students, not just in astronomy but also in physics. During one of Lorentz’ classes, Pannekoek pointed out a flaw in how Lorentz had derived the quadruplet for the Zeeman effect, thereby solving a problem that Lorentz had been struggling with for some time.


25. Hendrik A. Lorentz to Karl Schwarzschild, 11 Jul 1907, Nachlass Karl Schwarzschild, Niedersächsische Staats- und Universitätsbibliothek Göttingen (SUG/KS), Briefe 472; Pannekoek’s contribution was mentioned in Hendrik A. Lorentz, ‘Considerations Concerning
also wrote a short paper on the foundation and interpretation of statistical mechanics, which was communicated to the Royal Netherlands Academy of Arts and Sciences by Lorentz.\(^\text{26}\) The new astrophysics that explored the relation between spectrum and luminosity provided an ideal opportunity for Pannekoek to combine his interest in the colour of stars with his background in physics.

In his first paper on stellar astrophysics, ‘The luminosity of stars of different types of spectrum’ (1906), Pannekoek was primarily concerned with the question of stellar evolution. After a comparative analysis of various spectral classification schemes, he discusses how, according to ‘the most widely spread opinion’, a star moved through all the spectral types in its development.\(^\text{27}\) They started as large masses of gas that heat up as they contract, reaching maximum temperature before cooling down as they contracted even further. Studying the relation between the luminosity and the spectrum of the stars, he argued, could provide a test for this theory:

This development of a tenuous mass of gas into a dense and cold body, of which the temperature first increases and then decreases is in harmony with the laws of physics. In how far, however, the different spectral types correspond to the phases of this evolution is a mere hypothesis, a more or less probable conjecture; for an actual transition of a star from one type into the other has not yet been observed. The hypothesis may be indirectly tested by investigating the brightness of the stars. To answer to a development as sketched here the brightness of a star must first increase then decrease; the mean apparent brightness of stars, reduced to the same distances from our Solar System must vary with the spectral class in such a

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way that the maximum is reached where the greatest brightness is found while the apparent brightness decreases in the following stages of development.28

Pannekoek was keenly aware of Monck and Kapteyn’s work on this subject and he wanted to improve on their results by replacing proper motion, the motion of a star relative to the Sun, with parallactic motion, the apparent motion of a star that resulted from the motion of the Solar System through the stellar system. Pannekoek argued that a statistical analysis of parallactic motions provided a better indication of the average distance of stars than proper motion because it excluded the intrinsic motions of stars themselves. Indeed, he found that by using parallactic motion the results were improved but not enough to alter the general conclusions earlier astronomers had found significantly. The adjusted results showed that the luminosity of stars decreased from B-type stars down to G-type stars, but that it then increased again for K-type and M-type stars. This would mean that the G-type stars were the faintest stars, with both the hotter and colder stars being brighter.

Monck had proposed that the red M-type stars could be intrinsically brighter than the yellow G-type stars but Pannekoek rejected this suggestion, referring to recent work of physicist Wilhelm Wien, who had derived that intrinsic brightness directly correlated with colour for unattenuated radiation. This meant that blue stars had to be intrinsically brighter per unit area than red stars. A more plausible explanation for why K and M-type stars were brighter than G-type stars, according to Pannekoek, was that they were physically larger. That conclusion, however, stood opposed to the theory that stars evolved from G-type to M-type through contraction. A solution to this conundrum was provided by the recent work of Ejnar Hertzsprung, as Pannekoek indicated:

I have not ... used [the initial computations], but have modified them first, because it was not until the computation was completed that I became acquainted with Hertzsprung’s remark that the [Maury’s division] c stars show a very special behaviour; their proper motions and parallaxes are so much smaller than those of the [division] a stars of the same classes that they must be considered as quite a separate group of much greater brilliancy and lying at a much larger distance.29

29. Ibid., 138.

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Hertzsprung had investigated the proper motion of stars using Maury’s catalogue and found that for red stars, those that Maury had categorized in division a had much higher proper motions than those that she had categorized in division c. This meant that, statistically, stars in division c were much further away than those in division a, and were thus probably much brighter. In his research, Hertzsprung was mainly interested in finding the empirical relation between spectral class, proper motion, and absolute magnitude; in other words, his work was driven by observational and positional concerns. Pannekoek, on the other hand, was keenly interested in what the relation between these quantities could reveal about the physical properties and evolution of stars.

One of the physical properties that Pannekoek investigated, for example, was the relative mass of stars. Using data from binary systems, he computed that A-type and B-type stars were much more massive than equally bright K-type stars in Maury’s division c. From the combination of high luminosity and low mass in these division c stars, Pannekoek concluded that they had exceedingly low densities compared to other stars.

As David DeVorkin has argued, the early development of stellar classification was closely connected with the development of stellar evolution theories, with the latter being an important impetus to the former. In Hertzsprung’s work, this connection is nearly absent, but for Pannekoek, stellar evolution was a fundamental concern. His attempts to determine

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the volume of stars were driven by a desire to establish how the temperature of stars changed as a result of their contraction.

In his next paper, published later that same year, Pannekoek went a step further and also investigated how stellar spectra were related to the colour of stars as perceived by the human eye — a subject that we have seen he took an interest in a few years earlier. By comparing colour estimations from Heinrich Osthoff with the spectral measurements from Maury, Pannekoek found that the colour of stars did not directly correlate with the spectrum of stars. The bluest stars were not found in type I–III (equivalent to Cannon’s O-type and early B-type stars) but in type IV–V (equivalent to late B-type and early A-type stars). Pannekoek welcomed this unexpected result as it solved some of the discrepancies he had found in the relation between spectrum and luminosity before.33

When we discussed Pannekoek’s Milky Way research, we saw that he valued human perception as a supplement to measurements made from photographic plates. In his early astrophysics, too, human perception played an important role. In this case, photographic catalogues were supplemented with the visual estimation of the colours of stars. In both cases, he was concerned with how perception was formed through physiology and psychology.34 This striking combination of human perception and photography was a defining feature of Pannekoek’s research, as has also been noted by Bruno van Albada: ‘In his early publications, we fully recognize the later Pannekoek. We find him here as a meticulous and critical observer, who fully takes into account physiological and psychological phenomena that influence perception.’35

These two papers in 1906 were the last Pannekoek wrote on astrophysics for more than a decade. Disillusioned by his experience at the Leiden Observatory, he decided to pursue a career in the labour movement in Germany, where he was hired to teach historical materialism at the Parteischule of the Social-Democratic Party of Germany (SPD) and write philosophical and theoretical articles for socialist journals. Hertzsprung, too, was unable to continue his research, but for very different reasons. The classification scheme of Maury, on which his work was founded, was dismissed by Pickering and Cannon for being too complicated and, as a

34. See Pannekoek, ‘Farben der Gestirne’.
result, new catalogues produced by the Harvard College Observatory no longer included the classification scheme that Hertzsprung required for his research.\(^{36}\)

A few years later, however, Henry Norris Russell from Princeton, who had initially been unaware of Hertzsprung’s research, found the same distinction between giant and dwarf stars of the same spectral type. Unlike Hertzsprung, Russell had access to the original spectra and was able to find the distinction not only in the late-type stars but in every spectral class. He visualized this information by plotting it in a diagram with the spectral class on one axis and the luminosity on the other: the spectrum-luminosity diagram — now known as the Hertzsprung–Russell diagram.\(^{37}\) The spectrum-luminosity relation was one of many empirical relations between astronomical quantities that were found during 1860–1920, which DeVorkin has termed the ‘Great Correlation Era’.\(^{38}\) Similar empirical correlations established during this period included the period-luminosity relation of Cepheids, discovered by Henrietta Swan Leavitt, and the mass-luminosity relation, discovered, among others, by Jakob Halm, and the establishment of spectroscopic parallax by Walter S. Adams and Arnold Kohlschütter.\(^{39}\)

### 3.2 Growth and Relevance of Astronomy

Pannekoek returned to the Netherlands at the onset of the First World War and began working as a cosmography teacher at secondary schools.

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3. *Astrophysics of Stellar Atmospheres*

In 1916, he was hired as *Privaatdocent* in History of Astronomy at Leiden University. During this period, history of science was not established as a professional field in the Netherlands, and those who lectured on the subject were either active or former scientists. Outside of the Netherlands, too, many of the best-known historians of science, like William Whewell, Ernst Mach, and Pierre Duhem, were also active scientists. For many of these scientist-historians, their target audience did not consist of specialized historians but fellow scientists; their main goal was to understand how science developed and progressed over time, in an effort to either educate contemporary scientists in the methods they are to follow or to clarify the nature of specific scientific concepts.

Pannekoek shared these goals and ideals, and it is worthwhile to take a closer look at his inaugural lecture in Leiden as it reveals his ideas on how science developed and how scientists should practice scientific research. This is especially relevant because we can compare these with Pannekoek’s own approach to astrophysics during the following decades.

The subject of Pannekoek’s 1916 lecture was the historical development of astrology and how this influenced the development of astronomy. In the lecture, he stressed that scientific developments should always be considered in their historical and cultural context, stating that ‘the development of science [*wetenschap*] is not an accumulation of abstract truths, but the struggle of thinking, living people’. The pre-modern belief in astrology can be understood, so Pannekoek argued, when we take into account the cultural context in which it was developed. The prevailing world view was anthropocentric; the Earth and humankind were located in the centre of the universe. In such a worldview it was entirely plausible that the movement of the celestial bodies directly reflected events on Earth. When the heliocentric worldview replaced the

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anthropocentric worldview, these astrological theories were rejected because they no longer made scientific sense. But that did not mean that they should also be dismissed when considering the history of science. Just because astrological theories had been proven false did not mean that it had been wrong for past astronomers to pursue them.

Pannekoek explicitly contrasted this way of looking at the history of science to the approach of (unnamed) earlier historians of science, whose goal had been ‘to discern the growth of truth, ... to honour the champions of science, to discover which thinkers and researchers were the first to have the right insight into a problem ..., and against which forces of darkness ... had to be fought’.45 This, he considered to be an ‘ahistorical mindset’. Historians should not judge past theories by comparing them to what present theories believe to be true. Rather, they should investigate how they developed within their historical and cultural context. Scientific growth should not be seen as linear but had to be imagined as ‘a succession of incarnations’, each of which was adjusted to the cultural worldview in which it was embedded.46

Pannekoek’s approach to history of science, in particular his attempts to explain scientific developments through its societal context, was unequivocally Marxist; he even considered it a ‘natural outcome’ of his Marxist readings.47 Unsurprisingly, there was overlap between his approach and that of other Marxist historians like Léon Rosenfeld, Edgar Zilsel, and Boris Hessen.48 Pannekoek, however, published his historical research exclusively in (popular) astronomical or socialist journals and, as a result, his early papers went unnoticed by historians of science. In the Anglo-

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46. Ibid., 30. Translated from Dutch.
47. Anton Pannekoek to Léon Rosenfeld, 19 Jul 1949, Léon Rosenfeld Papers, Niels Bohr Archive, University of Copenhagen (NBA/LR).
sphere, for example, Marxist history of science did not take off until the 1930s, when it was introduced by the Russian delegation to the International Congress for the History of Science and Technology, held in London in 1931, some 15 years after Pannekoek had held his lecture on the history of astrology. Pannekoek’s work, meanwhile was picked up only in 1949 when Rosenfeld invited him to contribute to a collection of essays by mainly Marxist historians, which became the special issue ‘Essays on the Social History of Science’ in *Centaurus* volume 3, number 1. This essay and his subsequent book *De groei van ons wereldbeeld* (1951), which was translated as *A History of Astronomy* (1961), firmly established Pannekoek’s name as a historian of astronomy.

Embedded in Pannekoek’s view of scientific development was the belief that scientific knowledge displayed a clear growth even as theories were rejected or overthrown. He illustrated this through the example of astrology, which he argued played a vital role in the growth of astronomical knowledge. The perceived social relevance of astrology in pre-modern times was the leading motivation for priests and astronomers to study the stars. To correctly interpret celestial events, it was necessary to track the...
movements of celestial bodies closely. These elaborate observations, Pannekoek argued, were crucial for the development of astronomy. This can be best be seen in the work the Danish astronomer Tycho Brahe, who was driven by his belief in astrology and became famous for his precise and elaborate observations of the movements of the planets. These observations were made under the assumption of a planetary system that we now consider to be wrong, but they nevertheless proved to be invaluable for the development of astronomy. When Johannes Kepler compared these observations with his thorough computations of planetary orbits from eccentric circular orbits, small differences became apparent. It was only because of the high accuracy of Brahe’s observations that these differences were not disregarded but instead prompted Kepler to try different types of orbits instead, which led him to conclude that they had to be elliptical rather than circular.\footnote{Pannekoek, ‘Astrology and Its Influence’, 174–175.} Kepler, too, had worked hard to come to his theory and Pannekoek praised him elsewhere for not hiding the effort that he put into developing and calculating theories.\footnote{Tucker, ‘Popularizing the Cosmos’, 190–191.} And so the observations of Brahe, motivated by his belief in astrology, led to Kepler’s laws of planetary motion and ultimately to Newton’s law of universal gravity, according to Pannekoek.

From Pannekoek’s discussion of sixteenth-century astronomy, we get a good impression of how he envisioned the growth of scientific knowledge. Science progressed through the interplay between theoretical developments and observational improvements. Theoretical models were created in order to account for all observational data and formed the foundation for new observations. These observations, in turn, tested the validity of existing theories and pointed in the direction of new theories. The goal of science was to improve this correspondence between scientific theories and observational facts. In this process, thoroughness in both observations and calculations was of vital importance. Without Brahe’s extensive observations or Kepler’s elaborate calculations, it was unlikely that theoretical dogma could have been challenged.

In line with this view of scientific development, Pannekoek contended that progress in scientific research meant improving the correspondence between observation and theory. This was the property on which past theories could be judged in their historical context. He stated that that:
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In a certain timeframe, the right scientific theory is the one that gives the most concise and comprehensive summary of all known facts. This foundational epistemological statement holds the key to proper judgement of past theories and concepts. We should not measure them to our subjective standards of what we now consider to be the best and truest theory. We should understand them as part of the entire worldview of their time, and thus understand the development of science through, and as part of, the development of humankind.\(^53\)

While working as a historian of astronomy, Pannekoek published a few articles on Babylonian astronomy.\(^54\) Soon, however, he was provided with the opportunity to return to astronomy proper when the University of Amsterdam hired him as lecturer in mathematics and astronomy in 1918 and the Leiden Observatory offered him a position as assistant director the same year. That latter position, however, was withdrawn after a long and arduous process in which the prime minister personally stepped in to prevent an outspoken Marxist from getting a teaching position at a state-funded university.\(^55\) This proved to be a blessing in disguise for Pannekoek, as the University of Amsterdam — then a municipal university rather than a national university — enabled him to found a new astronomical institute in Amsterdam.

Pannekoek’s inaugural lecture in Amsterdam, which was held in late 1918, reveals that he was still interested in astrophysics and theories of both stellar and universal evolution even though he had not published on the subject since 1906. The 1918 lecture focused primarily on contemporary theories of stellar evolution. According to these theories, stars evolved from large nebular clouds that contracted under their own gravitational

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attraction. In contracting, stars heated up enough that they started to shine. At a certain point, depending on their mass, stars would reach their maximum temperature as the radiative pressure inside the star started to counterbalance the gravitational attraction. From that point onward, stars started to cool off as they slowly contracted further. In that regard, not much had changed since Pannekoek wrote about stellar evolution in 1906. Pannekoek argued that the significance of stellar evolution theories extended beyond the understanding of the stars themselves. They pertained directly to the broader fundamental question of the formation and future of the universe. Although stars lost their energy through radiation, this radiation would eventually be captured again by nebular clouds, thereby triggering star formation anew. In this way, Pannekoek argued, the evolution of the universe was ultimately circular.\(^{56}\)

Pannekoek was quick to caution that the theories of stellar evolution he described in his inaugural lecture were still tentative and under development. But this lack of certainty was not a blemish on scientific research — it was an inherent aspect of scientific development. That was the main message he sought to bring across:

> It has been my goal today to illustrate the incompleteness of our knowledge, the many unsolved questions, to make you see that contemporary astronomy is a process of development and growth, of finding new paths and opening new avenues. Because to study a science, it is not sufficient to learn ready results; to really know it, one has to actively and practically participate in its construction.\(^{57}\)

In his 1918 inaugural lecture, Pannekoek also explained why he believed astronomy to be socially relevant. On the one hand, it could provide a rational theory of the nature and development of the universe that combined empirically grounded knowledge from many different disciplines. As he emphasized in his Marxist writings, such a rational alternative to religious dogma was a crucial ideological weapon in the social struggle.\(^{58}\)

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57. Ibid., 17–18. Translated from Dutch.
On the other hand, the very practice of scientific research was indispensable for the education of future generations. By seeing and learning how science actually progressed, they could learn how to participate in the construction of new scientific knowledge themselves. With these goals in mind, Pannekoek believed he could make a real difference by teaching astronomy in Amsterdam, despite the limitations in available resources. 'For this purpose, it is not necessary to have giant instruments and a large observatory; there are numerous researches that require only modest equipment while still being of great importance for the progress of science.\textsuperscript{59}

The two social virtues that Pannekoek ascribed to astronomy — its value as ideological weapon and its educational value — remained important motives for him. They are clearly present in 1925 when he held his third inaugural lecture on the occasion of his appointment as Professor of Astronomy in Amsterdam. By this time, the theories of stellar evolution that Pannekoek had explained in 1918 had been rejected. The theories that had replaced them provided much more details on the physical conditions of both the outer layers and the interior of stars, even if they could no longer explain the source of stellar energy.\textsuperscript{60} This, however, did not dishearten Pannekoek, who enthusiastically proclaimed: 'A new, almost unforeseeable field of practical astrophysical research lies before us and we should not doubt that precise quantitative intensity measurements in the spectra of all celestial bodies will deliver new and important results.'\textsuperscript{61} But to Pannekoek, it was not just the promise of new results that made astrophysics so enticing. It was the way that it brought separate fields together and in doing so opened up new avenues for research:

The modern development of astrophysics, due to its intimate cooperation between physics and astronomy, brought a revolution in our knowledge of the nature of stars. And this is not due to the problems it has solved, as much as it is due to the problems it has raised.\textsuperscript{62}

\textsuperscript{59} Pannekoek, \textit{Evolutie van het heelal}, 18. Translated from Dutch.
\textsuperscript{61} Anton Pannekoek, \textit{De astrophysica en hare moderne ontwikkeling}, inaugural lecture, University of Amsterdam (Amsterdam: J. H. de Bussy, 1925), 19. Translated from Dutch.
\textsuperscript{62} Ibid., 30. Translated from Dutch.
To conclude the lecture, Pannekoek reiterated how he envisioned the social relevance of astrophysics:

One may wonder: the problems of astrophysics may be very interesting, but how do we humans benefit from this knowledge about the nature of distant stars? Can this science ever be of practical use? We will not pass off this question by singing the praise of abstract knowledge; even science must serve life. We do not consider ... practical use to be inferior to pure science. We believe that science \[\text{wetenschap}\] has the goal of making the lives of humankind better, happier, and richer.\(^{63}\)

One of the practical uses of scientific research was as a foundation for technological advancement, as Pannekoek emphasized in his Marxist writings.\(^{64}\) For this purpose, astrophysics was especially relevant because of its search for the stellar energy source, which could lead to the development of new energy sources on Earth.\(^{65}\) But even more important, according to Pannekoek, was the role of astrophysics for the unity of science. As sciences continuously exchanged ideas and techniques developed in their own respective fields, they also trained the human mind, forming it into a tool uniquely adapted to investigating the whole of nature. This was the spiritual value of pure science for the advancement of humankind.\(^{66}\)

Pannekoek considered observational research a crucial aspect of being an astronomer and he believed that, in order to receive a proper education in astronomy, his students needed hands-on experience in reducing observations. Yet, in Amsterdam, he was confronted with the reality of not having an observatory, after efforts to have one constructed in an old water tower had failed.\(^{67}\) The recent emergence of professional astrophotography provided a solution to this conundrum. As mentioned above, photography allowed observations to be stored onto photographic plates, which could be exchanged over large distances in both time and space.

\(^{63}\) Pannekoek, \textit{Astrophysica en hare moderne ontwikkeling}, 30. Translated from Dutch.
\(^{64}\) See e.g. Pannekoek, ‘Twee natuuronderzoekers’, 301–302.
\(^{65}\) Other astronomers, such as Willem de Sitter, were more skeptical about this prospect, or feared that the research could be abused to create weapons. See David Baneke, \textit{Synthetisch denken: Natuurwetenschappers over hun rol in een moderne maatschappij, 1900–1940} (Hilversum: Verloren, 2008), 56.
\(^{66}\) Pannekoek, \textit{Astrophysica en hare moderne ontwikkeling}, 31–32.
\(^{67}\) Pannekoek, \textit{Herinneringen}, 248–249.
Because photographic observatories producing many more photographic plates than they could comfortably measure and reduce on their own, this not only led to a division of labour within astronomical institutions but also encouraged a global division of labour among astronomical institutes, as exemplified by the collaboration between David Gill and Jacobus C. Kapteyn discussed in the introduction.

Faced with the prospect of founding an astronomical institute without an observatory, Pannekoek decided to follow the example of Kapteyn’s laboratory and build an institute that specialized in measuring imported photographic plates.\(^{68}\) He ordered specialized instruments for measuring photographic plates (Figure 3.1) and, in 1921, hired two secondary school graduates — David Koelbloed (aged 16) and Hendrik Reus (aged 15) — to work as computers.\(^{69}\) With their hiring, the Astronomical Institute of the

\(^{68}\) Pannekoek, *Herinneringen*, 283–284.
\(^{69}\) Stamboek van de leerlingen, Archief van de Vijfde HBS met Drie-Jarige Cursus, Stadsarchief Amsterdam (SA/5H), 5
University of Amsterdam was officially founded and equipped to conduct observational research, despite the lack of an observatory.

### 3.3 Ionization Theory

The initial focus of the Astronomical Institute in Amsterdam was on statistical astronomy but this soon changed with the rise of quantitative theoretical astrophysics in the 1920s, the third stage in the development of astrophysics. The new field had been effectively established in 1921 when Meghnad Saha formulated an ionization equation that established the relation between temperature and the ionization rate of elements. His theoretical result was an accumulation of various strands of contemporary research coming together. By this time, the Hertzsprung–Russell diagram had been firmly established and astronomers like Karl Schwarzschild and Hans Rosenberg had made the first tentative measurements of stellar temperatures. Meanwhile, the development of atomic quantum theory in physics suggested how spectral lines were related to the structure and ionization of atoms. Saha had been educated in both thermodynamics and quantum theory in India when, in 1920–1921, he travelled to the UK to visit Alfred Fowler at Imperial College London and Germany to visit Walter Nernst and John Eggert in Berlin. Especially his visit to Berlin proved to be a crucial influence for Saha as Nernst and Eggert were working on a thermodynamic theory of chemical equilibrium. Inspired by their work, Saha realized that by substituting the chemical potential in those equations with the ionization potential found in Bohr’s atomic theory, he could calculate the ionization equilibrium inside stars as a function of temperature and pressure. This was a major breakthrough as it finally allowed astronomers to make meaningful calculations on the physical conditions of stars based on spectroscopic observations.

An intriguing aspect of Saha’s research is that he worked from an isolated position for most of his career, and not only because he worked in a

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country on the scientific periphery.\textsuperscript{72} In India, too, he was looked down upon because he was a member of a lower caste.\textsuperscript{73} This had an important influence on how he presented his research, as Saha suppressed his speculative tendencies and was very tentative in presenting results of which he was not absolutely certain.\textsuperscript{74} Despite his relative isolation, Saha’s work was quickly picked up by astronomers in the centres of astrophysics, in particular by Henry Norris Russell at Princeton and Edward Arthur Milne at Cambridge, who both quickly latched on to the new subject and began to develop various aspects of Saha’s research further.\textsuperscript{75} Pannekoek also became aware of Saha’s research early on and was immediately intrigued by its potential.\textsuperscript{76} He soon began to calculate various applications and consequences of Saha’s theory and published his explorations in 1922 in a paper called ‘Ionization in Stellar Atmospheres’.

One of the striking aspects of Pannekoek’s 1922 paper is the wide range of topics that he discussed. Rather than focusing on a single analysis, the paper presented a varied collection of calculations that were intended to explore the potential of Saha’s ionization theory to clarify the physical conditions in the outer layers of stars, where especially the role of pressure was still poorly understood. Pannekoek began his paper by constructing a diagram that could quickly illustrate the relation between different quantities in the stellar atmosphere. This diagram, which had temperature and pressure as its axes, contained two types of curves, the ionization curves and the atmospheric curve (Figure 3.2). The ionization
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curves represented curves of constant ionization and indicated for various elements under what temperature and pressure they were either ionized or neutral. In conditions located above the ionization curve, where the temperature was higher and the pressure lower, more atoms were ionized, while below the curve more atoms were neutral. The atmospheric curve, on the other hand, described the relation between temperature and pressure inside the stellar atmosphere under the approximation of radiative equilibrium. Its shape was fixed and indicated that, in the inner layers, there was a nearly linear relation between \( \log P \) and \( \log T \), but in the outer layers, pressure quickly dropped while the temperature remained nearly constant. Pannekoek called the point where this change occurred the 'boundary temperature'.

This diagram formed the foundation for further explorations by Pannekoek into various physical processes in stellar atmospheres.

Some of the topics that Pannekoek wanted to explore were: the gravitational distribution of elements in the interior of stars, the optical depth where the stellar spectrum found its origin, the contribution of scattering to total absorption, and the origin of the chromospheric spectrum. On these topics, Pannekoek’s calculations were suggestive and his conclusions tentative. He pushed his calculations as far as he could to explore what could be learned from this and constantly compared his theoretical results to published observational results to check their validity. Of all his tentative conclusions, the most significant was the realization that the location of the atmospheric curve on the temperature-pressure diagram only depended on two physical quantities of the star: the effective temperature and the surface gravitation. This meant that for stars of the same spectral type, for whom the effective temperature was the same, the difference in the relative strength of spectral lines was solely due to differences in the surface gravity.

We have seen that, in 1906, Pannekoek had concluded that stars with narrow spectral lines were very large stars with exceedingly low densities. Now, he was able to provide a physical explanation for how this difference in density could lead to differences in the relative strength of spectral lines. In doing so, he offered an early theoretical discussion of the effects of absolute magnitude on the stellar spectrum.

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78. Ibid., 110–115.
When Saha presented his work on ionization theory in stars, he provided a rough estimate of the stellar temperature scale by determining at what temperature spectral lines would become visible using the ionization potentials of the elements that caused those lines. This method of ‘marginal appearance’ faced a few practical problems: it was difficult to determine exactly when a spectral line first became visible and some elements appeared in a far wider spectral range than others. These difficulties could be avoided, as Edward Arthur Milne and Ralph H. Fowler showed, by using the maximum intensities of spectral lines instead of their marginal appearance. The added advantage of this technique was that the maximum intensity only relied on temperature and pressure, and not on the abundance of the element. From their calculations, Milne and Fowler found that the pressure inside stellar atmospheres was significantly lower.

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than assumed by Saha, consistent with earlier results that stellar atmospheres were dominated by radiative pressure.80

Milne and Fowler’s method was taken up two graduate students in Harvard — Donald H. Menzel, who was a PhD student of Russell in Princeton, and Cecilia Payne, who came from Cambridge University — who went to test the stellar temperature scales of Saha and Milne–Fowler with the incomparable amount of spectroscopic sources available there.81 Menzel derived a method for determining ionization potentials from these spectra and managed to show that Milne–Fowler theory was in quantitative agreement with the behaviour of line intensities as a function of spectral class.82 Payne went even further and managed to provide a coherent theory for the temperature scale underlying the spectral classes. She thus finally provided convincing evidence for what had been suspected but could not be proven in the preceding years: that the differences between spectral classes were caused solely by a difference in temperature and not by a difference in chemical composition. Moreover, she came to the startling conclusion that stellar atmospheres consisted almost entirely of hydrogen, rather than having a chemical composition similar to Earth.83 This result was quite unexpected, and her calculations failed to convince her supervisors Harlow Shapley and Henry Norris Russell. Following the advice of Shapley, she de-emphasized this conclusion in her dissertation. It was only after supporting evidence was provided in the following years, among others by Russell himself, that the result was finally accepted.84

81. Ibid., 123–124.
Another improvement upon Saha’s theory came from a theoretical perspective. In 1922, Milne suggested that the assumption of thermodynamic equilibrium, an important condition for Saha’s formula, was untenable in a stellar atmosphere. According to contemporary models of stellar interiors, radiation from the internal energy source perfectly balanced the gravitational attraction of the star. For this to be stable, there had to be a strong temperature gradient inside the star with the interior being much hotter than the outer layers. This meant that, instead of a thermodynamic equilibrium, there was a radiative equilibrium inside stars. Saha collaborated with Ramanikanta Sur to update his original theory and formulate an ionization function that was valid under the assumption of radiative equilibrium and the same was done by the Leiden theoretical astronomer Jan Woltjer Jr. Their work formed the starting point for Pannekoek’s next paper on the ionization in stellar atmospheres. In this paper, Pannekoek analysed Woltjer’s ionization function and concluded that the temperature used to determine the intensity of spectral lines should not be the surface temperature. Instead, the effective temperature from the layers underneath the layer responsible for the spectral line should be used. This meant that for each spectral line, a different temperature had to be used depending on the optical depth of that line.

Pannekoek realized that this method of determining the ionization rate could be extended to calculate the ionization rate in the upper layers of the Earth’s atmosphere as a result of incoming Solar radiation. Using Woltjer’s ionization function, Pannekoek calculated that, if Solar radiation was the primary source of ionization, the ionization rate should increase going down from space to about 130 km and then sharply decrease due to increased absorption of Solar radiation by the Earth’s atmosphere. These results did not coincide, however, with observations that ionization was...
highest at 80 km, so Pannekoek concluded that the Heaviside layer in the Earth’s atmosphere could not be explained through photoelectric ionization.\textsuperscript{87} This paper was Pannekoek’s only excursion into geophysics, but, as Saha concluded in 1938, Pannekoek’s method was not all that different from the later and more successful work by geophysicist Sydney Chapman.\textsuperscript{88} In any case, it is a remarkable illustration of Pannekoek’s belief that all the sciences are connected, and that research in one field can bring insights to another, as he had discussed in his 1925 inaugural lecture.

Meanwhile, Pannekoek’s work on stellar atmospheres was criticized by Kharkiv and Harvard astronomer Boris Gerasimovich, who argued that atmospheres not in thermodynamic equilibrium were far too complicated to be solved analytically. Pannekoek’s reaction makes clear his pragmatic attitude toward such complications. Because even though he greatly valued meticulousness and thoroughness, that did not mean that simplifications could not be made for the sake of improvement.

Of course [Gerasimovich] is right that the simple suppositions, from which the formula was deduced, cannot be strictly true. But they will be nearer to the truth than the first approximation of the supposition of thermodynamic equilibrium. When we consider the valuable and important results that have been obtained with Saha’s formula, which strictly holds only for isothermal gases, there is no reason to reject a second approximation because it does not exactly represent the complicated conditions in a stellar atmosphere.\textsuperscript{89}

The early years of Pannekoek’s engagement with quantitative theoretical astrophysics reveal that he combined a pragmatic attitude toward theories and models with extensive calculations of their potential implications. He did not necessarily require his calculations to have positive outcomes; in cases with negative results, he concluded his calculations indicated that the model failed in giving an adequate explanation. Although such conclusions were not always satisfactory, he did not hesitate

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to embrace and publish them because they exposed flaws in the theory and pointed toward directions of future research.

3.4 Acquiring Photographic Plates

So far, we have discussed Pannekoek’s contributions to theoretical astrophysics, but his contributions were not limited to theoretical calculations alone. He also contributed through observational research. We have seen that Pannekoek attributed great importance to the comparison between theoretical and observational results in his theoretical analyses. This required that not only the theoretical derivations were thorough, but the observational measurements too. In what follows, we will examine Pannekoek’s observational astrophysics, how it was constrained and shaped by the lack of his own observatory, and how it reflected his epistemic virtues.

In the previous chapter, we have seen that one of the major programmes in Amsterdam was the measurement of extrafocal photographic plates of the Milky Way, which had been recorded by observatories in Germany, the Dutch East Indies, and South Africa following his specific instructions. The other major observational programme at the Amsterdam Institute was the detailed measurement of photographic spectra, for which Pannekoek received photographic plates from Lick Observatory and Dominion Astrophysical Observatory. A major incentive for this programme was the observational training of his students.90

How Pannekoek organized the observational education of his students and which virtues he wanted to instil in them can be illustrated by the training of Jacobus Josephus Maria Reesinck, who was his first doctoral student. Reesinck was tasked with measuring the absorption lines of several photographic spectra that Pannekoek had received from Lick Observatory. Because they had not yet received the mechanical measurement devices Pannekoek had ordered, Reesinck had to determine the strength of these lines through visual estimates. To increase the accuracy of the results, each spectrum was measured three times. To ensure that he did not know at which spectrum he was looking, because that might influence the estimates, he was given the spectra in random order and combined

90. For the role of education in instilling epistemic virtues, see Ten Hagen, ‘History and Physics Entangled’, 115–197.
3.4. Acquiring Photographic Plates

the measurements only after all the estimates had been recorded.\textsuperscript{91} Additionally, to gain some hands-on experience in observational astronomy, Pannekoek arranged for Reesinck to spend a summer at Leiden Observatory to take photographic plates himself and observe binary stars.\textsuperscript{92} This became a common theme for Pannekoek, as he also tried to arrange positions at astronomical observatories for later students, such as Elsa van Dien and Fjeda Walraven.\textsuperscript{93}

Reesinck’s doctoral research built upon his visual estimates of photographic spectra, which included those of the Cepheid variables α Ursae Minoris, ζ Geminorum, and δ Cephei. Reesinck analysed how the strength of absorption lines in the spectra of these Cepheids varied between when the star was at the maximum and at the minimum brightness.\textsuperscript{94} But to say something meaningful about the change in physical conditions in the stellar atmospheres of Cepheids throughout their period, it was essential to measure the spectrum at more points in the period than just at the minimum and maximum brightness. The plan for Reesinck was to do that for the star δ Cephei. By measuring the shape and strength of absorption lines at different points in the variation, he would be able to compute the variation of temperature and surface gravity throughout the period.\textsuperscript{95}

Acquiring the additional spectra needed for this research proved problematic, however. When Pannekoek asked for plates taken during intermediate stages of the period, William H. Wright and Robert Aitken of Lick Observatory were reluctant to send them because they were already being


\textsuperscript{92} Anton Pannekoek to De Sitter, 6 Jun 1923, 6 Jul 1923, 13 Jul 1923, Leiden Observatory Archives, directorate Willem de Sitter, Leiden University Library, Special Collections (UBL/WdS), 45.1.

\textsuperscript{93} Anton Pannekoek to Harlow Shapley, 22 Sep 1945, Harvard College Observatory, Records of the Director, Harlow Shapley, Harvard University Archives (HUA/HCO), box 76; Anton Pannekoek to Otto Struve, 29 Jul 1948, Otto Struve correspondence, Niels Bohr Library & Archives, American Institute of Physics (AIP/OS), reel 9.


used by one of their own students. Pannekoek eventually did receive the spectra he requested, which included two original plates for the ascending branch of variation and several enlarged copies of plates for the descending branch. This was sufficient for Reesinck to conduct his research on the variation of δ Cephei. His main conclusion was that temperature tended to be higher and ionization rate lower in the ascending branch of the period (where brightness increased) than with the same brightness in the descending branch.

Although Pannekoek was grateful for receiving plates from Lick Observatory, he was also quite surprised by the difficulties surrounding his request:

> In the case of spectral changes I thought that new negatives might be taken with the same instrument without too much trouble; thus sufficient data might be provided for himself by an astronomer having access to such beautiful instruments as are present at your observatory. That is the reason that I thought I did not really deprive the Lick astronomers by my requests, because they are always able to complete their stock by new negatives. But perhaps I underestimate the trouble involved in this work.

This episode illustrates the dependent position of Pannekoek as an astronomer without an observatory and his naivety with regard to photographic research. The latter was likely a result of his lack of hands-on experience with astrophotography. His observational experience had been limited to the meridian circle of Leiden Observatory and naked eye observations of variable stars and the Milky Way. He was simply not accustomed to the intricacies of spectroscopic photography.

A similar picture emerges from his exchange with John S. Plaskett of the Dominion Astrophysical Observatory in Victoria, BC. Pannekoek first wrote to Plaskett in 1921 to request photographic plates for his research on

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96. Anton Pannekoek to William H. Wright, 10 Jul 1923; Wright to Pannekoek, 30 Jul 1923, Lick Observatory Records: Series 1 Correspondence, University of California, Santa Cruz, Special Collections & Archives (UCSC/LO), box 112.
97. Anton Pannekoek to William H Wright, 17 Aug 1925; Wright to Pannekoek, 4 Sep 1925, USCS/LO, box 112.
the ionization in stellar atmospheres. He explained his vision for the division of astronomical labour and the merits of the Astronomical Institution in Amsterdam:

Though as a rule the investigation of these spectra will be best taken up at your own observatory there are cases, on the other hand, that an astronomer, who has no spectrograph himself, wishes to test new ideas or methods, for which a small quantum of experimental data is necessary. On the other hand such a great deal of time as we are spending in investigating each single plate will not be available at an observatory where every night new masses of material may be accumulated. Thus cooperation will prove most profitable for science; and I trust that by this method of working new ways of research will come out in the line of work your observatory has chosen with so much success.\footnote{Anton Pannekoek to John S. Plaskett, 9 Feb 1924, Dominion Astrophysical Observatory, Office of the Director, Library and Archives Canada (LAC/DAO) vol. 49, file no. 4.}

Plaskett was happy to oblige, as he had done for many foreign astronomers lacking their own observatories.\footnote{R. Peter Broughton, *Northern Star: J. S. Plaskett* (Toronto: University of Toronto Press, 2018), 271.} The plates Pannekoek received over the years from Dominion Astrophysical Observatory sustained observational research in Amsterdam for many years.\footnote{See e.g. Reesinck, ‘Spectral Parameters of δ Cephei’; Anton Pannekoek and Gale Bruno van Albada, *A Photometric Study of Some Stellar Spectra (δ Cephei, ζ Cygni, π Cephei, δ Equulei): Part 1. Catalogue of Line Intensities*, Publications of the Astronomical Institute of the University of Amsterdam 6, pt. 1 (Amsterdam: Stadsdrukkerij, 1939); Pannekoek and Van Albada, *A Photometric Study of Some Stellar Spectra (δ Cephei, ζ Cygni, π Cephei, δ Equulei): Part 2. Discussion of the Results*, Publications of the Astronomical Institute of the University of Amsterdam 6, pt. 2 (Amsterdam: Stadsdrukkerij, 1946).} Nevertheless, the collaboration between Plaskett and Pannekoek was not always smooth. At times Pannekoek received photographic plates that were unsuited for his research, even though they had been made according to his specific instructions. He then had to request a new batch of photographic plates of the same objects made according to updated instructions.\footnote{See e.g. Anton Pannekoek to John S. Plaskett, 9 April 1924, LAC/DAO vol. 49, file no. 4.} Such requests led Plaskett to lament that Pannekoek did not appreciate the effort.
3. Astrophysics of Stellar Atmospheres

Pannekoek was eventually given ample opportunity to conduct photographic research in the second half of the 1920s, first as part of Solar eclipse expeditions organized by the Royal Netherlands Academy of Arts and Sciences. During the winter of 1925–1926, Pannekoek led an expedition to Palembang on the island of Sumatra in the Dutch East Indies to record the total Solar eclipse of 14 January 1925. The photographic observations of this eclipse failed because clouds passed in front of the Sun precisely during the eclipse, but for Pannekoek the journey was fruitful nonetheless because he had also arranged to make visual observations of the Southern Milky Way and initiated the extrafocal photographic observations at Bosscha Observatory in Lembang, Java.

104. John S. Plaskett to Anton Pannekoek, 15 December 1927, LAC/DAO vol. 49, file no. 4.; see also Broughton, Northern Star, 38–39, 271.
105. The other members of the expedition were the Utrecht astronomers Marcel Minnaert, Jan van der Bilt, Willem J. H. Moll, and doctoral student Johanna Cornelia Thoden van Velzen. The report was published as J:: van der Bilt et al., ‘Report on the Expedition to Sumatra for Observing the Total Solar Eclipse of 1926 Jan. 14th’, Proceedings of the Section of Sciences, Koninklijke Akademie van Wetenschappen 29, no. 9 (1926): 1151–1164.
106. See Chapter 1
3.4. Acquiring Photographic Plates

A second eclipse expedition was planned the following year to Gällivare in the Lapland region of Sweden (Figure 3.3). This time, the expedition managed to take several photographic recordings of the flash spectrum and chromosphere of the Sun. The latter recordings became the research subject of another doctoral student of Pannekoek, Nicolaas Wilhelmus Doorn, who had also been part of the expedition. The Lapland expedition was a smaller expedition that was primarily intended to gain practical experience for the 1929 eclipse over the Dutch East Indies, which would be more favourable because of a much longer period of totality. Pannekoek withdrew from that expedition, however, to spend the summer of 1929 as a visiting astronomer at the Dominion Astrophysical Observatory.

The invitation to visit the Dominion Astrophysical Observatory came in 1927 when Pannekoek made yet another request for specific photographic plates. This time, Plaskett replied that due to the complicated nature of Pannekoek’s request and the lack of experienced staff for this specific task, he was unable to deliver the plates. He noted, however, that observational time was available and that, if Pannekoek so desired, he could come to Victoria for six months to take the required plates himself. The only compensation required was that some of the results would have to be published in the Publications of the Dominion Astrophysical Obser-

107. The flash spectrum is the spectrum of the Sun taken just before the total eclipse.
109. The plates Pannekoek had received so far were taken by Henry H. Plaskett, John S. Plaskett’s son, but he had accepted a professorship at Harvard where he started in January 1928. Pannekoek, *Herinneringen*, 257.
3. **Astrophysics of Stellar Atmospheres**

This was a golden opportunity for Pannekoek, who often felt he was hampered by the lack of photographic plates while other astronomers explored avenues and solved problems that he had also wanted to tackle. Now he finally had the chance to collect a good number of plates that were specifically catered to his own research.

The six months that Pannekoek spent at the Dominion Astrophysical Observatory made him appreciate the practical intricacies of spectroscopy. In letters to his wife during his stay in Victoria and in his memoirs, Pannekoek reflected extensively on the practice of photographic observation and how it differed from visual observation. One of the most enduring sentiments Pannekoek expressed was the monotonous, mechanical, and boring nature of photographic observation. Unlike when observing with a visual telescope, there was no actual research done during photographic observation; the only task was to ensure that the light of the star remained focused on the spectroscope, while the actual measurements of the observations came later. Moreover, it was exhausting and lonely labour; in the late summer, Pannekoek worked until 8 in the morning to record not only stellar spectra but also calibration spectra. Despite the monotony and long hours, he did enjoy the experience, which he had not expected after his time as positional astronomer in Leiden. The mechanical nature of the work that made it so monotonous also allowed his mind to wander and imagine the potential results of his research and its place within the greater scientific enterprise. During his time at the Dominion Astrophysical Observatory, Pannekoek recorded several dozen photographic spectra, which were shipped back to the Netherlands. These were intended to provide the Astronomical Institute measurement work for a couple of years. In fact, as we will see below, they formed the basis of much of the research conducted in Amsterdam for decades to come.

Pannekoek’s efforts to collect photographic plates for the Astronomical Institute serve to illustrate both the opportunities and constraints of an astronomical institute without observatory in the first half of the twentieth century. The increasing reliance on astrophotography brought with it the option to record photographic observations elsewhere that could be stored and measured over an extended period or bring in photographic plates from other places. At the same time, these resources were severely

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110. J.S. Plaskett to Pannekoek, 15 Dec 1927, LAC/DAO vol. 49, file no. 4.
3.5 Model Stellar Atmospheres

limited compared to the resources of large photographic observatories, who engaged in an arms race to see who could construct the biggest telescopes and be the first to make new observational discoveries. To remain relevant in such an environment, Pannekoek decided that the best way to move forward was to focus on thoroughness in his measurements to get as much information as possible for each individual plate, as we will see later in this chapter.

3.5 Model Stellar Atmospheres

In theoretical astrophysics, too, thoroughness remained an important virtue for Pannekoek. The clearest example of this are the theoretical models of stellar atmospheres he developed in an effort to reproduce the observed contours of absorption lines. Because of the complexity of these models, many of the differential equations they contain could not be solved analytically. To still get meaningful results, Pannekoek introduced the technique of numerical integration instead. This section will explore his efforts to construct model atmospheres to see what this meant in practice.

Efforts to model stellar atmospheres and learn more about the physical processes inside them began early in the twentieth century. In 1905, Arthur Shuster introduced a model for a so-called ‘foggy atmosphere’, in which all radiation originated in the stellar interior, and the atmosphere only acted as a ‘reversing layer’ that scattered the radiation at specific wavelengths, thus creating spectral lines.112 This model was further developed by, among others, Karl Schwarzschild, who used it to investigate limb darkening in the Sun and demonstrated that the main source of energy transport from the stellar interior to the stellar surface was through radiation rather than convection.113

This model, which became known as the Shuster–Schwarzschild model, formed the basis of Albrecht Unsöld’s research in the late 1920s on the contours of Fraunhofer lines.114 Although his method was reasonably successful in predicting the general shape of the absorption line, it failed for the central intensity of the line. In observational measurements absorption lines always contained at least some residual intensity, no matter how strong they were. Unsöld’s model, however, predicted that the

114. Houziaux, ‘Viewpoints on the Structure of Stellar Atmospheres’. The contours of absorption lines are later called the line profiles of absorption lines.
3. Astrophysics of Stellar Atmospheres

line would become entirely dark if there were enough absorbing material. Pannekoek considered this an important flaw in Unsöld’s approach.\textsuperscript{115} A better way to model an atmosphere, he argued, was to take into account that radiation was, in fact, produced by the atmosphere itself:

In Unsöld’s treatment of the problem … the simplifying assumption is made of a continuously emitting black surface at the bottom with an overlying absorbing atmosphere. In reality the continuously emitting matter is composed of the very atoms that by their absorption produce the Fraunhofer lines, and all the atmospheric layers contribute to both the continuous emission and the line absorption.\textsuperscript{116}

Pannekoek’s alternative model was primarily based on the work of Milne, who in 1928 had investigated the various ways in which radiation interacted with atoms in the stellar atmospheres. Milne concluded that besides line absorption and emission, other processes played a vital role in creating continuous absorption and emission, such as continuous scattering from free electrons and inelastic collisions, where atoms were either ionized or ionized atoms captured free electrons. Spectral lines in Milne’s model were not caused by a single reversing layer that absorbs radiation coming from the stellar interior. Instead, the outer layers of the stellar atmospheres produced their own radiation, and spectral lines were caused by differences in opacity for various frequencies. When the opacity was higher, only the outer layers of the atmosphere could be seen; when the opacity was lower, deeper layers could be seen. Since the temperature inside the atmosphere increased further into a star, those parts of the spectrum where the deeper layers could be seen were brighter than those where only the outer layers could be seen. Because Arthur Eddington had developed the equation that was used to establish the local temperature inside the stellar atmosphere, this model became known as the Milne–Eddington model.\textsuperscript{117}


\textsuperscript{116} Ibid., 153.

3.5. Model Stellar Atmospheres

A major problem with the Milne–Eddington model was that it was notoriously difficult to calculate with because of the many mutually dependent quantities that played a role. Moreover, to make the model work, many assumptions and simplifications had to be made that already presupposed the validity of other parts of the model. Because of this, many of Pannekoek’s contemporaries believed it was better to construct simplified models instead, from which general conclusions about the physical processes working inside stellar atmospheres could be derived. Pannekoek disagreed with this sentiment, as he explained in the introduction to his first attempt at constructing a model atmosphere. There, he stressed the importance of considering more complicated models and computing their full consequences to investigate the merits of the approximations that go into them:

Eddington expressed strong doubts whether, through the complications of the problem in its physical as well as its mathematical and astronomical foundations, the results obtained by these approximations so far have any real value. To remove such doubts it will be necessary to work out exactly the consequences of strictly defined suppositions; only when the lack of harmony with observation cannot be ascribed to the approximate mode of treatment, shall we be able to trace its origins back to the physical and astronomical foundations. Therefore an attempt is made in this paper to find an exact solution of the equations representing existing conditions, though simplified, as nearly as possible.\textsuperscript{118}

The model Pannekoek constructed was a plane-parallel model in which energy radiated in two directions, outward or inward. This radiation exchanged energy with the matter that constituted the atmosphere. Matter interacted with radiation in various ways in the model. At a specific wavelength corresponding to the difference between the two energy levels, atoms could simply absorb or emit photons of that exact energy. In other cases, they could exchange energy with the radiation through inelastic or hyperelastic collisions, in which some of the energy of the photon was exchanged with the kinetic energy of the atom. Finally, energy could be transferred through free–free transitions, a continuous absorption and emission from the direct translation of radiation into kinetic

\textsuperscript{118} Pannekoek, "Theoretical Contours", 139–140.
energy, which was independent of the specific energy levels of atoms.\textsuperscript{119} According to the model, continuous absorption was responsible for the background radiation — or continuous radiation — of the spectrum, while the element-specific absorption caused the spectral lines. While continuous absorption could be determined exactly in this model, individual absorption lines could not. Because of the intricate interplay of various processes in those parts of the spectrum, their differential equations ‘cannot be integrated in a finite form’ and Pannekoek had to rely instead on ‘simple mechanical integration’, i.e. numerical computation, as the most efficient way to proceed.\textsuperscript{120} With these numerical calculations Pannekoek could determine the relative effect of various causes of absorption and the influence of physical properties like the electron pressure and the surface gravitation, which could then be used to compute the profiles of absorption lines for various models.

Pannekoek used his models to compute the theoretical contours of calcium and hydrogen absorption lines for various scenarios, which he illustrated using diagrams, such as can be seen in Figure 3.4. These diagrams show absorption lines profiles computed for varying concentration of the element. They illustrate that, as the concentration increased, the absorption line would first deepen without broadening much. When the line became saturated, the total strength of the line only increased marginally with concentration until finally, the wings of the line became prominent. This effect can be seen at a concentration of $\log C = -6.4$ for hydrogen and $\log C = -6.8$ for calcium. This investigation of how the contours change with increased temperature also formed the foundation of Pannekoek’s later research on the ‘curve of growth’, which will be discussed in the section of observational astrophysics below.

Despite the ‘more exact computations’ Pannekoek had used, his model failed to provide a theoretical solution for the observed residual intensities in the centres of strong absorption lines. He concluded that:

\begin{quote}
There is a marked difference between the observed contours of absorption lines and the theoretical results derived here on the basis of the assumptions [used for this model]. Whereas for strong lines we find the center of the line practically dark, such a dark center is an exception among the observed lines.
\end{quote}

\textsuperscript{119} The specifics of the models are detailed in Pannekoek, ‘Theoretical Contours’, 140–141.
\textsuperscript{120} Ibid., 144.
3.5. Model Stellar Atmospheres

... The often-quoted influence of collisions of atoms and electrons in the Solar atmosphere is, as we have seen now, unable to explain these high central intensities, so we have to look for other influences that may change the contours of the lines.121

This inability to provide a solution, however, did not mean that the computations were a failure for Pannekoek. They did, after all, provide a clear answer: collisions were not the cause for residual intensities in absorption lines, and so another cause had to be found. This result could only be established by his more complicated model, which took the effects of collisions into account. This episode coincided with how Pannekoek believed research should be conducted. When theoretical explanations were postulated, they had to be put to the observational test, and if they failed to deliver, this indicated the explanation was inadequate and provided an incentive for further theoretical research.

121. Pannekoek, 'Theoretical Contours', 158.
The quest to explain the discrepancy between theoretical calculations of the central intensities of spectral lines and their observational measures occupied much of Pannekoek’s theoretical work in the following years. He computed the effects of the various physical processes that had been proposed as solutions, including resonance broadening, cyclic transitions, and fluorescence, but found that they were all insufficient in explaining away the discrepancy.\(^{122}\) Throughout his attempts to find a physical solution for the puzzle of the central intensity of absorption lines, Pannekoek also continued to improve his model. In a follow-up paper on the contours of theoretical absorption lines in 1931, for example, he replaced one of the core assumptions of his 1930 model: that the atmosphere has a constant composition throughout the layers of the atmosphere. This assumption was only valid if the ionization rate of the chemical element responsible for the absorption line under consideration did not strongly correlate with temperature and pressure. In many cases, however, this ionization rate increased as temperatures rose further into the atmosphere, meaning that deeper layers consisted of more ionized atoms and fewer neutral atoms.\(^{123}\) Pannekoek considered the consequences for both increasing and decreasing concentration deeper into the atmosphere and found that, in the former case, absorption lines would be shallower while in the latter case the lines would be steeper. In both cases, however, ‘The difference is not pronounced, and it is questionable whether in the present state of photometry of absorption lines in stellar spectra it can be discerned with certainty.’\(^{124}\)

### Continuous Absorption

Pannekoek’s most comprehensive calculations of model atmospheres were published in 1935 in Volume 4 of the Publications of the Astronomical

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123. This can also be extended to double ionization where an increase in ionization rate increased the number of doubly ionized atoms and decreases the number of singly-ionized atoms, and so forth.

3.5. Model Stellar Atmospheres

Institute in Amsterdam, *Theoretical Intensities of Absorption lines in Stellar Spectra*. There he reflected on the fact that prior investigations on Milne–Eddington atmospheres often ‘only provide a first approximation, by means of simplifying assumptions’. He believed that more complex calculations were needed even if the theoretical foundations of the model were still uncertain. Such calculations could be useful for testing the validity of these foundations.

It may be asked whether it is not premature to go to further more exact approximations, since there are outstanding discrepancies between theory and observation, indicating that in our fundamental conceptions there remain uncertainties. On the other hand these theories give a good qualitative and often even a quantitative explanation of the wings of the lines, their half width and their equivalent width. An exact quantitative test will be possible only if the theory is worked out to a greater degree of approximation. The test of a theory is not complete until, numerically, its consequences have been worked out to the limit imposed by the accuracy of observation.\(^\text{125}\)

The first approximation of a Milne–Eddington model, which Pannekoek mentioned above, entailed that absorption lines were modelled by deriving the limiting optical depth for each part of the spectrum. The layers below that optical depth were neglected while the layers above were assumed to have constant values of absorption and diffusion. The first approximation thus ignored the variation of physical conditions throughout those layers. Pannekoek decided to improve the accuracy of the model by taking into account the variation within different layers. To calculate this variation, Pannekoek considered two main sources of continuous absorption for this model: inelastic scattering and free–free transitions. For both the physical conditions of the stellar atmosphere played an important role: the amount of absorption due to inelastic scattering depended on the number of atoms that could be ionized while the amount of free–free transitions depended on the number of electrons already released.\(^\text{126}\)

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\(^{126}\) Ibid., 5–6.
Figure 3.5: Table showing the absorption of metals, hydrogen, and both as a function of temperature and pressure. The thick lines indicate various domains where the continuous absorption in stellar atmospheres is dominated by metals (upper right), hydrogen (lower left), or both (centre). Source: Pannekoek, Theoretical Intensities, 11.

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Table 3.1: Ionization of a mixture of hydrogen and metal atoms.
3.5. Model Stellar Atmospheres

Another important factor for continuous absorption was the chemical composition of the atmosphere; metals, like magnesium and iron, had a significantly lower ionization potential and thus contributed more to continuous absorption at lower temperatures than non-metals, like hydrogen and especially helium. Although the exact chemical composition of stars was still unknown, it had been firmly established they consisted primarily of hydrogen.\(^ {127}\) Consequently, Pannekoek decided to distinguish his model atmospheres between those for low-temperature stars, where continuous absorption was primarily the result of interactions with metals and the electrons they had released, and high-temperature stars where absorption is dominated by hydrogen (Figure 3.5). In between those two groups of stars, there was a group of stars where both effects were dominant.

In addition to continuous absorption as a function of wavelength, the ‘mean absorption coefficient’, which is the average absorption for all wavelengths, also played an important role in Pannekoek’s models because it indicated the total amount of energy that was absorbed and radiated by each layer of the atmosphere. To calculate this mean absorption coefficient, Pannekoek had to integrate over the continuous absorption with some corrections for strong monochromatic lines. But to compute the continuous absorption, the mean absorption coefficient had to be known because it partially determined the change in pressure and ionization in each layer. To solve these differential equations, Pannekoek once again relied on numerical computation methods. With the continuous absorption and mean absorption coefficient computed, he could then calculate the shape and strength of individual absorption lines as a function of temperature and surface gravity (see Figure 3.6).

The computation of these model atmospheres was a massive undertaking that required an enormous amount of labour from Pannekoek and his computers. It led to results that managed to describe the behaviour of absorption lines with changing temperature reasonably well, at least qualitatively. Additionally, Pannekoek used these calculations of continuous and mean absorption to derive the colour temperature of stars as a func-

\(^ {127}\) Much of the debate on the chemical composition revolved around the question of how much more abundant hydrogen was compared to the other elements. Russell, for example, had calculated that the hydrogen to metal ratio in the Sun was 61.5 but using that same data, Pannekoek calculated a much higher ratio of 1000 to 5000. Pannekoek, *Theoretical Intensities*, 10.
3. Astrophyics of Stellar Atmospheres

Figure 3.6: Diagram showing the variation of absorption line strength computed by Pannekoek as function of temperature and gravity. The horizontal axis indicates temperature on a logarithmic scale, the vertical axis, which has no explicit scale, the strength of the line. The various lines show lines of the indicated materials at different surface gravities. Source: Pannekoek, *Theoretical Intensities*, 71.

As we have seen earlier in the chapter, the relation between the colour and temperature of stars was an important topic in Pannekoek’s early astrophysics research. Now, decades later, he was finally able to explain the relation between two quantitatively.

For most of his theoretical astrophysics research, Pannekoek worked on his own problems isolated from other astronomers. This caused him to overlook at times the contributions of his contemporaries. This was, for example, the case in his research on the relation between the colour temperature and effective temperature of stars. In Germany, Ludwig Biermann and Albrecht Unsöld had tackled the same problem in the preceding

128. Anton Pannekoek, 'Theoretical Colour Temperatures', *Monthly Notices of the Royal Astronomical Society* 95, no. 6 (1935): 529–534. The colour temperature is the temperature of a star determined by fitting its spectrum along a Planck function for blackbody radiation; the effective temperature is the temperature determined from the total energy output of a star.
3.5. Model Stellar Atmospheres

years, but Pannekoek had neglected to mention their work at all. This provoked Unsöld, who wrote a letter to the astronomy journal *The Observatory* to air his grievances. In the letter, he stated that he had already derived some of the same conclusions as Pannekoek and published results that were 'identical in almost every detail'.

He then chastened Pannekoek for not mentioning this work:

Prof. Pannekoek, however, does not consider it necessary even to mention these papers at all. I am afraid that this method of neglecting research done by others, which has recently become common in some quarters, will necessarily lead to severe dangers to scientific co-operation. It is only that

care — and not the question of priority as such — which has induced me to clear up the historical facts.\textsuperscript{130}

In his reply to Unsöld, which was also published in \textit{The Observatory}, Pannekoek conceded that ‘Dr. Unsöld … is right in remarking that in my paper on “Theoretical Colour Temperatures” his paper … should have been quoted as well as Dr. Biermann’s papers.’\textsuperscript{131} He explained that he was so engrossed in his research and so eager to publish the results that he had neglected to search for similar investigations. He disagreed with Unsöld, however, that such neglect was always problematic.

It is certainly desirable, in general, to give close attention to all current literature; but with the enormously increasing productivity of science, this can be done only at the cost of time which should be spent on one’s own research work. It is often easier and more efficient to attack a problem in one’s own way than to follow another’s development of the same problem. Independent treatments of the same problem are more often no waste of scientific energy.\textsuperscript{132}

This particular conflict is illustrative of Pannekoek’s single-minded approach, as well as his relative isolation in Amsterdam, where he lacked close colleagues who kept up with astrophysical literature.\textsuperscript{133}

Despite his peripheral location in the astrophysics community and his sometimes insular approach, Pannekoek’s astrophysics research was well appreciated by his contemporaries. Harlow Shapley, for example, invited him as one of the lecturers at the inaugural Harvard summer school in astronomy, noting that:

\begin{quote}
You have for a long time been at the head of our list of men whom we would like to join this summer group. Your activities in astrophysical, photometric, and stellar statistical fields
\end{quote}

\textsuperscript{130} Unsöld, ‘Theoretical Colour Temperatures’.
\textsuperscript{131} Anton Pannekoek, ‘Theoretical Colour Temperatures’, Correspondence to the Editors, \textit{The Observatory} 58, no. 738 (1935): 328, 328.
\textsuperscript{132} Ibid., 382.
\textsuperscript{133} Pannekoek worked in the same building as the physicists at the University of Amsterdam, but for the most part, they did not keep up with the latest developments in theoretical physics. Moreover, of these physicists, only Pieter Zeeman was concerned with spectroscopy and quantum physics. See Kox, ‘The Zeeman Effect’, 143–144; Ad Maas, \textit{Atomisme en individualisme: De Amsterdamse natuurkunde tussen 1877 en 1940} (Hilversum: Verloren, 2001), 198–204.
3.5. Model Stellar Atmospheres

would make you, if you will pardon my saying it, the most important astronomer of Europe for the kind of conferences we have in mind.\(^{134}\)

Pannekoek was happy to attend but offered to lecture only on stellar astrophysics as that had been his main research subject for the past years.\(^{135}\) This request was granted by Shapley, although it meant that he had to shuffle around with the subjects of the other speakers to ensure that the summer school did not focus too much on astrophysics over other astronomical topics.\(^{136}\) One of the participants of the summer school, James G. Baker, recalled how Pannekoek together with Harlow Shapley and Cecilia Payne-Gaposchkin would often dominate the discussions: 'They were the experts, they knew hundreds if not thousands of stars and their characteristics'.\(^{137}\) In his diary, Baker wrote about Pannekoek: 'I certainly admire this astronomer of about 65. He is probably the best lecturer here and has done an enormous amount of work.'\(^{138}\)

In addition to the 1935 summer school, Pannekoek was also invited for the Harvard Tercentenary celebration the following year, where he received an honorary doctorate for his 'contributions of high merit in many fields of astronomy, notably in fundamental astrophysical investigations'.\(^{139}\) Pannekoek dedicated his symposium lecture to the question of the stellar temperature scale, discussing whether it was possible to establish the effective temperature of various spectral classes conclusively. He considered this only possible for stars of spectral type cm0 and A0.

\(^{134}\) Harlow Shapley to Anton Pannekoek, 8 Nov 1934, HUA/HCO, box 45, folder 332. Other invited lecturers were Jan Oort, Ira S. Bowen, and Otto Struve, of which only Oort was unable to attend. David H. DeVorkin, 'The Harvard Summer School in Astronomy', Physics Today 37, no. 7 (1984): 48–55, 50. Shapley had also invited Pannekoek for an earlier summer school in 1932, but that time Pannekoek had to decline due to scheduling conflicts. Anton Pannekoek to Harlow Shapley, 10 Feb 1932, HUA/HCO, box 45, folder 332. Shapley eventually had to postpone his plans to 1935.

\(^{135}\) Anton Pannekoek to Harlow Shapley, 27 Dec 1934, HUA/HCO box 45, folder 332.

\(^{136}\) Bart J. Bok to Otto Struve, 6 Feb 1935, AIP/OS, reel 1.

\(^{137}\) James Baker, interview by David H. DeVorkin, 9 Jun 1980, Oral History Interviews, Niels Bohr Library & Archives, American Institute of Physics (AIP/OH)

\(^{138}\) DeVorkin, 'Harvard Summer School', 52.

which were firmly established at 3300 K and 10500 K respectively. For other stars, the effective temperature depended on too many unknown conditions in the stellar atmospheres to be certain. But that did not mean that the calculated effective temperatures were useless; they could still be used to study the physical conditions in stellar atmospheres and to test theories about them:

[T]he temperature now established may enable us to make a decision between different assumptions made in the discussion of energy gradients and line intensities. With the progress of the theoretical treatment of stellar atmospheres and their absorption coefficients, an increasing accordance may be expected. But this degree of accordance will serve rather as a test of the theories and as a source of knowledge concerning stellar atmospheric conditions than as a determination of temperature.

Ultimately though, Pannekoek’s numerical model atmospheres failed to reproduce the full spectrum of stars accurately, leaving astronomers puzzled at what caused the discrepancy between Pannekoek’s predictions and the observed spectra. The solution was found a few years later in the form of the negatively charged hydrogen ion. In fact, Pannekoek had already included the effect of electron absorption by neutral hydrogen in his calculations in a later addendum, based on new results for the transition energies by Donald H. Menzel and Chaim L. Pekeris. However, in these calculations, he found the influence to be negligible compared to absorption by metals. In the following years, however, developments

141. Ibid.
142. Laurence Aller, Interview by David H. DeVorkin, 18 Aug 1979, AIP/OH.
143. Anton Pannekoek, Addendum to 'Publications of the Astronomical Institute of the University of Amsterdam, No 4' (Amsterdam: Amsterdam University Press, 1935). Pannekoek noted that he received the results of Menzel and Pekeris’ calculations before they were published. Menzel and Pannekoek were quite fond of each other. Menzel considered Pannekoek one of his ‘great favorites’ and attested that ‘he had more influence on my career than any astronomer’. Donald Menzel autobiography, Niels Bohr Library & Archives, American Institute of Physics (AIP/DM), 29; Menzel to Antonie Johannes Pannekoek, 12 May 1960, MB/AP. Pannekoek, meanwhile, spoke of Menzel as his ‘pronégo’ and was impressed by his work. Menzel, autobiography, AIP/DM, 29; Cecilia H. Payne to Menzel, 4 Jul 1933, Papers of Donald Howard Menzel, Harvard University Archives (HUA/DM).
in physics indicated that the electron affinity of hydrogen could be much higher than previously thought, making it a much more significant source of opacity.\textsuperscript{144} Rupert Wildt amended the calculations Pannekoek had made in 1935 to include the new values of absorption by hydrogen, and found that this significantly improved the correspondence with observed spectra.\textsuperscript{145} Thus, while Pannekoek did not find the solution himself, his thorough models played a crucial role in its development.

Pannekoek was disappointed when he realized that his calculations were based on faulty physics. In his memoirs, he lamented that, as a non-physicist, he had taken as true, results from physics that were only accepted provisionally. With the physics still so uncertain, his advanced methods were not yet needed. When the physics proved to be wrong, his thorough calculations had become worthless. Still, Pannekoek did not believe that all effort was wasted because it had at least provided substance for his doctoral students.\textsuperscript{146} Ultimately, this was the role that Pannekoek saw for himself in astrophysics; not as someone who explored new pathways and developed new theories, but someone who was put in hard labour and paved the way for others:

\begin{quote}
I always believed my contribution to astrophysics was not to solve problems (for which I lacked the intuitive and inner knowledge of physical topics; so this was done by Unsöld, Struve, and others), but to develop the consequences of theories numerically if this required a lot of computational work, and I knew therefore that it would not be done by others. Even if this let to monastic work at times, the methods might yet be able to serve others.\textsuperscript{147}
\end{quote}

Pannekoek’s own recollection and assessment of his research coincide with the general impression we get when we consider his theoretical re-

\begin{footnotesize}
146. Pannekoek, \textit{Herinneringen}, 265. Pannekoek mentioned the research of Sijtze Verweij on the Stark effect of A-type stars and to research that is still in progress but delayed due to the war. This probably refers to the research of Bruno van Albada (graduated in 1945), Elsa van Dien (graduated in 1947 at Radcliffe College, Cambridge, MA.), and Johan Weenen (graduated in 1949).
147. Ibid.
\end{footnotesize}
search on stellar atmospheres. Pannekoek rarely came up with pivotal insights that significantly changed the direction of research. He nevertheless remained at the forefront of cutting-edge astrophysics by latching on to important theoretical developments and putting these to the test of thorough computations. The goal of these calculations was not to focus on minute details or exact results, but on incorporating the complexity of the stellar atmosphere and exploring the correspondence between theory and observation. Knowing his limitations as a creative theorist, Pannekoek devoted himself to thoroughness and hard labour. The persistence that he had praised in the work of Tycho Brahe was on full display in his own work. As a result, he was capable of pursuing the goals he set out when he started in Amsterdam: to contribute to the development of astrophysics despite limited means, and to give his students the education and tools necessary to do the same.

As we will see in the following section, this was true not only for his theoretical astrophysics but also for his observational astrophysics.

3.6 Curve of Growth and Equivalent Widths

Pannekoek’s theoretical research on stellar atmospheres directly influenced the direction of observational astrophysics in Amsterdam. It drove Pannekoek to emphasize getting the most out of limited observations even further. With the improvement of theoretical analysis, thoroughness in observational measurements became an even more vital virtue to pursue. The primary source of photographic plates at the Amsterdam Institute during the 1930s and 1940s were those taken by Pannekoek during his visit to Victoria. These were used by Pannekoek, his students, and his computers to study the physical conditions in stellar atmospheres, in particular by measuring the ‘equivalent widths’ of absorption lines and using them to compute the ‘curve of growth’ of a star. As we will see in this

148. Elsa van Albada-van Dien recalled how, when she went to Harvard in 1945, her education equalled that of the local students, despite all her astronomy classes being taught by Pannekoek alone: Elsa van Albada-van Dien, interview by Laurence A. Marschall, 1982, LM. This required Pannekoek to keep up not only with astrophysics but also quantum mechanics and atomic physics. Since he was the only professor in Amsterdam who studied and taught these subjects, his classes often attracted physics students. Edward P. J. van den Heuvel, ‘Anton Pannekoek’s Astronomy in Relation to his Political Activities, and the Founding of the Astronomical Institute of the University of Amsterdam’, in Tai, Van der Steen and Van Dongen, Pannekoek: Ways of Viewing, 42.
149. For a list of Pannekoek’s astronomy students, see Appendix B
section, this newly developed method provided an excellent opportunity for Pannekoek to combine his focus on thorough measurements with his numerical calculations on stellar atmospheres.

The most important quantity in Pannekoek’s observational research was the equivalent width of an absorption line. This equivalent width indicated the total absorption of the line. The concept was introduced in 1927, independently by Marcel Minnaert at Utrecht University and Harald von Klüber at Potsdam, as a way to circumvent the observational limitations of stellar spectroscopy.\textsuperscript{150} As we have seen in Pannekoek’s theoretical research, the strength and shape of absorption lines were directly related to the physical conditions and processes inside stellar atmospheres. In practice, however, these lines were blurred on the photographic plate due to certain unavoidable observational effects, which exacerbated observational errors and made it impossible to get exact measurements of absorption line profiles. Instead of measuring the exact shape of absorption lines or using measures of line strength that relied on the intensity of specific parts of the spectrum, as had been common at the time, Minnaert and von Klüber suggested measuring the total absorption instead, thereby sidestepping the problem of line blurring. The equivalent width is the width that a completely dark line would need in order to absorb the same amount of light that the actual line did.

Although a more convenient observational method, the equivalent width alone did not reveal as much about the conditions in the stellar atmosphere as line profiles could. To still be able to investigate the physical conditions and processes inside stellar atmospheres responsible for absorption lines, Minnaert introduced the concept of the curve of growth: a diagram that related the equivalent width of a spectral line to the amount of absorbing material responsible for the line. As the name indicated, this relation effectively showed how an absorption line ‘grew’ as the absorbing material was increased.\textsuperscript{151} In essence, the curve of growth was an observational tool, but it required significant theoretical input since the absolute concentration of absorbing material in stellar atmospheres was of course unknown. When the spectral lines originated from the same chemical element, however, the relative concentration of absorbing material responsible for each line could be calculated theoretically from the

\textsuperscript{150} Hearnshaw, \textit{Analysis of Starlight}, 143.
\textsuperscript{151} Ibid., 142–144. It was also Minnaert who, in 1934, came up with the term curve of growth, being familiar with the biological meaning of the term from his days as a biology student.
3. Astrophysics of Stellar Atmospheres

ionization rate and the quantum numbers associated with each absorption line. Thus, a curve of growth could be constructed for each chemical element individually by calculating the relative concentrations for each of its absorption lines.

According to Pannekoek, valuable information could be deduced from the shape of the curve of growth about the physical processes responsible for the deepening and broadening of absorption lines. Based on his theoretical model of absorption lines, described above, Pannekoek suggested three different parts of the curve of growth could usually be distinguished. In the first part of the curve, where the concentration was low, only the central part of the line deepened and the equivalent width increased proportionally to the concentration. Then when the central intensity of the line reached its minimum, the deepening of the line came to a stop and the equivalent width increased very slowly with concentration. Finally, the resonance wings started to appear and the equivalent width increased proportionally to the square root of the concentration. ‘In this way the study of the dependence of the equivalent width on the concentration may furnish the same information as the study of the contours give.’

The first empirical curves of growth were constructed in 1929 for the Sun by Minnaert and his students, B. van Assenbergh and Gerard F. W. Mulders. One of the more surprising conclusions from these curves of growth was that the middle section was steeper than had been anticipated. From this, Minnaert concluded that the effect of dampening in the Sun was considerably stronger than previously thought. Based on his theoretical models, Pannekoek thought that the likely cause for this stronger than expected damping was absorption due to free–free transitions. He decided that the best way to test this hypothesis was to construct the curve of growth for a supergiant star. Because the surface density of supergiant stars was much lower than that of dwarf stars like the Sun, he anticipated that the dampening would also be much lower. Pannekoek also had a perfect candidate for his research, the A-type supergiant α Cygni (Deneb), of which he had taken the spectrum during his visit to Dominion Astrophysical Observatory (Figure 3.8). Pannekoek measured the equivalent widths for three elements in the spectrum, ionized titanium, ionized iron, and ionized chromium, and plotted them against the concentration, which he had

153. Hearnshaw, Analysis of Starlight, 144.
3.6. Curve of Growth and Equivalent Widths

Figure 3.8: Photographic reproduction and diagram of the spectrum of α Cygni. On the left is an enlarged reproduction of the spectrum, which was photographed by Pannekoek in Victoria. On the right is a tracing of the spectrum where one division corresponds to 0.1 mm in the spectrum. Source: Pannekoek, ‘Influence of Collisions’, between 758 and 759.
calculated using quantum multiplet rules. The resulting curve of growth, the first of a star other than the Sun, was shaped differently than he expected, however (see Figure 3.9). The middle section was even steeper than in the curve of growth of the Sun, which meant that dampening in α Cygni had to be stronger too, contrary to what was expected. Thus, Pannekoek concluded that free–free transitions did not play a perceptible role in stellar atmospheres after all.\textsuperscript{154}

The construction of the curve of growth of α Cygni is emblematic for Pannekoek’s observational research. It required only a single photographic plate that had to be measured in excruciating detail. These measurements were then combined with theoretical considerations in an effort to test a possible explanation for an astrophysical problem. The conclusion that was drawn was also typical for Pannekoek: when the results turned out to be different than he anticipated, he did not hesitate to accept them and quickly came up with an alternative theoretical explanation that better fitted the result.

The curve of growth proved to be a valuable and versatile method for Pannekoek. Another topic where he and his students employed the method was on the variability of δ Cephei, which had earlier been the subject of Reesinck’s research. Pannekoek had dedicated several observing nights in Victoria on recording the spectrum of δ Cephei at different stages in its period, taking a total of eleven usable photographic plates of the star. These plates were measured by Pannekoek’s doctoral student Fjeda Walraven, who used these measurements to compute separate curves of growth for each plate. He could then determine the variation in temperature and electron pressure of the star throughout its period.\textsuperscript{155}

Walraven’s observational research allowed Pannekoek to reflect on theoretical models that had been formulated to explain the variation of δ Cephei. In particular, he wanted to test the suggestion by Martin Schwarzschild (Karl Schwarzschild’s son) that the variation was caused by a radial pulsation caused by a progressive wave. But when Pannekoek computed the variation of gravity from Schwarzschild’s model and compared it to the values found by Walraven, they did not correspond. As can be seen in Figure 3.10, the measured values for the gravity were much lower through-

\textsuperscript{154} Pannekoek, ‘Influence of Collisions’, 763. See also Hearnshaw, \textit{Analysis of Starlight}, 145–146.

\textsuperscript{155} Théodore Walraven, \textit{The Line Spectrum of δ Cephei}, Publications of the Astronomical Institute of the University of Amsterdam 8 (Amsterdam: Stadsdrukkerij, 1948).
3.6. Curve of Growth and Equivalent Widths

Figure 3.9: Curve of growth of α Cygni, computed by Pannekoek based on a photographic spectrum he had taken in Victoria. The horizontal axis indicates the relative concentration of absorbing material on a logarithmic scale while the vertical axis indicates the equivalent width. The points show the measurements of absorption lines with each symbol indicating a different quantum transition. The line fitted through the points is the curve of growth. Source: Pannekoek, ‘Influence of Collisions’, 762.

As an alternative explanation, Pannekoek suggested that the variability of δ Cephei could be caused by periodic outflows of material from the star, which alternated with periods of rest. When material flowed out from the hotter interior of the star, the observed temperature was higher, while in periods of rest the temperature was lower. This outflow also accounted out the entire period than the theoretical values and the minimum value for the gravity occurred when the model predicted a maximum.156

for the lower than expected surface gravity. Pannekoek conceded that it was difficult to provide a fully accurate model, but he was nevertheless satisfied with the results that Walraven’s measurements were able to give:

Thus it appears that the amount of material and the accuracy of our spectra is insufficient to give clear decisions. That this small dozen of not first-rate plates could give important indications about the problems connected with the variation of this star, is due only to the skilful and minute reduction and discussion to which they were subjected.\footnote{Pannekoek, ‘Line Spectra of Delta Cephei’, 766.}

This statement by Pannekoek about the merits of the thoroughness pursued in Amsterdam encapsulates what we have seen throughout his observational research. Knowing that he lacked access to a great number of spectra to conduct his research, he focused instead on making the most of the few he was able to obtain.

\footnote{157. Pannekoek, ‘Line Spectra of Delta Cephei’, 766.}
3.6. Curve of Growth and Equivalent Widths

Although Pannekoek had found alternative uses for some of the plates he had taken in Victoria, the main intended purpose was always to provide full catalogues of the absorption lines and their equivalent widths for these spectra between the wavelengths of 4000–5000 Å. The publication of these catalogues was delayed or cancelled for various reasons. In the case of the B-type stars, which had relatively few absorption lines, more comprehensive catalogues had already been published in the meantime, leading Pannekoek to focus on F, G, and K stars, which were more time-consuming as they had many more lines.\footnote{158} For these stars, the results were delayed ‘because the methods of measurement and discussion had to be devised at the same time, and often led to side-tracking and theoretical studies’.\footnote{159} The main practical issue that Pannekoek had to overcome in his measurements was that especially for the late-type stars he investigated, spectral lines were not neatly defined and tended to overlap. To still determine the equivalent width of each individual line, it was often necessary to estimate what part of the absorption belonged to which spectral line. The results of these measurements were provided in tables covering a total of 58 pages, 24 for the supergiant spectra and 34 for the dwarf stars. An example of one of these tables can be seen in Figure 3.11. Besides the wavelength of each line and its measured equivalent width, Pannekoek also provided the chemical element responsible for the line and indicated how well-defined the spectral lines were and thus how reliable the measurements. The full catalogue of F and G-type stars that he produced as the end product of his 1929 visit to the Dominion Astrophysical Observatory was published only in 1950, more than two decades after the photographic plates had been taken.

The catalogue of F and G-type stars may seem like the least representative of all the publications that resulted from Pannekoek’s trip to Victoria. We do recognize his thoroughness, diligence, and hard labour in the catalogue, but it lacks the theoretical interpretation of the results that typified his observational research. Pannekoek was always interested in what measurements and observational results could tell us about the physical conditions in stellar atmospheres and the theories about them. In that approach — in bringing together observation and theory — we recognize his ideas on how science progresses: theories had to model observations and suggest new avenues for observational research while observations

\footnote{158} Pannekoek, \textit{Herinneringen}, 266.  
### Figure 3.11: Table listing the equivalent widths for absorption lines of various F and G stars. Source: Pannekoek, *Spectra of Advanced Type*, 179.

<table>
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<tr>
<th>Wave-length</th>
<th>Identification</th>
<th>( \alpha ) C. M. ( \log A ) wt</th>
<th>( \xi ) U. Mag. ( \log A ) wt</th>
<th>Sun ( \log A ) wt</th>
<th>( \xi ) Brot. ( \log A ) wt</th>
<th>( \eta ) Drac. ( \log A ) wt</th>
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</thead>
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<td></td>
<td>2-44 4</td>
<td>2-46 5</td>
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<td>Fe I</td>
<td>2-01 3</td>
<td>2-20 3</td>
<td>2-31 1</td>
<td>2-31 0</td>
<td></td>
</tr>
<tr>
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<td>1-55 0</td>
<td>2-34 1</td>
<td>2-71 2</td>
<td></td>
</tr>
<tr>
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<td>2-30 2</td>
<td>2-38 2</td>
<td>2-34 2</td>
<td>2-91 2</td>
<td></td>
</tr>
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3.7 Conclusions

Throughout our analysis of Pannekoek’s astrophysics, we find two recurring characteristics that defined his research. The first was the thoroughness with which he approached both the measurement of photographic plates and the computation of model atmospheres. The second is his constant emphasis that observation and theory should go hand in hand. Observational research had to test theory and suggest improvements, while theoretical models had to model observational results as accurately as possible.

Pannekoek’s focus on thoroughness is exemplified in his observational research by the considerable amount of time and effort he spent on the detailed measurements of only a limited number of photographic plates. Similarly, in his theoretical research, Pannekoek did not shy away from laborious numerical calculations to investigate the consequences of overlooked physical effects in models of stellar atmospheres. Thoroughness for Pannekoek did not mean getting the most precise number possible from a theory or an observation. Instead, it meant not sparing effort to

had to test theories and suggest new theoretical developments. Indeed, we have seen that Pannekoek often used already published observational results for his own theoretical explorations. With that in mind, the lack of theoretical interpretation in the catalogue of F and G stars makes more sense. Even if Pannekoek himself did not interpret his measurements, the catalogue still enabled others to do so instead.

For the K-type stars, the publication of the final results took even longer. These had become the subject of the doctoral research of David Koelbloed, who had initially been hired as a computer in 1921 when he was only 16 years old. In addition to his job as computer, he started an education in astronomy, which cumulated in a PhD degree in 1953 with a dissertation on the spectra of the K-type stars. In his catalogue, Koelbloed went beyond what Pannekoek provided in the catalogue of F and G-type stars. Besides measuring the equivalent widths of the spectral lines, he also used these measurements to construct curve of growths for each star, which he then used to analyse the physical conditions of the star.160

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get as much as information as possible from a single plate so as not to waste anything that was captured; it meant taking into account as many parameters as possible in a theoretical model so that the results were more secure. Thoroughness was an epistemic virtue for Pannekoek because it facilitated the close comparison between observation and theory.

Thoroughness was also a practical virtue for Pannekoek: it allowed him to make the most of his particular situation and conduct as much research as possible with his limited resources. Astrophotography offered a way for Pannekoek to acquire observations despite the absence of an observatory, but his possibilities were still limited because he had to rely on others in order to obtain the material. The focus on thoroughness in measurement enabled Pannekoek to contribute in a meaningful way as he strove to get more information from these plates than those who had access to a great number of plates would. He thus carved out his niche in observational astrophysics. Likewise, thorough calculations allowed Pannekoek to contribute to theoretical astrophysics, even though he believed he lacked the theoretical aptitude to come up with new visionary ideas of his own. By doing what few others were willing to do, he contributed significantly to the development of astrophysics.

Pannekoek’s focus on thoroughness was not always voluntary. At times Pannekoek decried his relative isolation on the periphery of astrophysics and his lack of resources. His ambitions in astrophysics were frustrated in part because of this, as others were better placed to pursue the most fruitful avenues of research. Despite this disappointment, he ventured forth because he believed in the social value of his scientific research, as he discussed in his inaugural lectures. For Pannekoek, science in general, and astrophysics in particular, were inherently progressive forces that would ultimately improve the lives of humankind. When contributing to astrophysics meant that he had to spend the final years of his active career calculating the minute consequences of physical theories and measuring spectral lines in excruciating detail, for which others lacked the time, that was exactly what he did.

It was not just resignation at his peripheral position that led Pannekoek into this path of thoroughness, however. He genuinely believed that thoroughness was an epistemic virtue and that it was of educational importance to display it in his daily practice. Pannekoek believed that science did not progress only through genial insights or ground-breaking discoveries. These breakthroughs were precipitated by the hard labour of many, often unheralded scientists, who further developed extant theories
and made meticulous observations. Such labour was crucial, according to Pannekoek, because it allowed critical comparison between observational results and theoretical consequences that pointed the way forward. It is clear from his own research that Pannekoek envisioned himself as part of this unheralded but indispensable group of scientists. And it was the sort of approach that he wanted to instil into his students so that they too could contribute to the progress of science. Scientific research was most effective when conducted thoroughly. Thus, we can conclude that Pannekoek’s focus on thoroughness was the result of a combination of conviction and circumstance; a carefully constructed strategy that allowed him to contribute to the growth of astrophysics within the practical constraints of his particular situation.
Conclusion

The goal of this thesis has been to investigate Anton Pannekoek’s contributions to astronomy and how these relate to both his own Marxist philosophy and the historical development of science in the early twentieth century. As indicated in the introduction, we have focused on three pertinent historiographical themes in doing so: how did astrophotography impact Pannekoek’s astronomical research; what epistemic virtues did he pursue and how did these impact his research; and what connections can be found between his astronomy and Marxism.

The prevailing image of Pannekoek that comes forward in this thesis is one of an incredibly productive and versatile astronomer. Throughout his career, he successfully latched onto various upcoming fields — research on the distribution of Milky Way light, statistical research on the structure of the galactic system, and the astrophysics of stellar atmospheres — and contributed significantly to their development. Unfortunately for Pannekoek, many of the methods and theories he helped to develop and refine have since been superseded and, as a result, his contributions are now largely overlooked. As this thesis has illustrated, however, his astronomical career provides crucial insights into the development of astronomy in the first half of the twentieth century and what it meant to be an astronomer during this time.

Photography

Pannekoek’s astronomical career makes the significant impact that astrophotography had on the development of twentieth-century astronomy abundantly clear. By investigating his photographic research, we ar-
Conclusion

rived at valuable insight about both the practical and epistemological consequences of the implementation of astrophotography. The most important practical consequence of photography for Pannekoek was that it enabled him to conduct observational research without having an observatory. We have seen that astronomers greatly valued photography because it allowed them to record observations onto photographic plates, which could be transferred to different locations where they could be measured at length. Because the large photographic observatories often produced many more photographic plates than they could measure themselves, this led to a division of labour among astronomical institutes. Astronomers with no access to an observatory, like Pannekoek, could conduct observational research by requesting these plates from remote photographic observatories. Therefore, when he was provided with the opportunity to found the Astronomical Institute in Amsterdam, Pannekoek furnished it with measuring instruments designed for photographic plates to be able to exploit these new opportunities. The photographic plates that were measured in Amsterdam came from all over the world, ranging from the Dutch East Indies and South Africa to the United States and Canada.

At the same time, Pannekoek’s reliance on remote photographic observatories for his photographic plates created an imbalanced situation, which led to various practical problems. He could not always immediately obtain the photographic plates that he wanted, for example. When he required photographic plates for J. J. M. Reesinck’s research on the variation of δ Cephei from Lick Observatory, he had to wait for the astronomers there to finish their own research on the subject. On the other hand, when Pannekoek developed his own photographic projects, he had to rely on remote astronomers, like Max Wolf in Göttingen and John S. Plaskett Victoria, to implement his method correctly without having the flexibility to make immediate adjustments. Only after the first batch of the plates arrived could he alter his instructions and wait for a new, improved batch to arrive. Thus, while astrophotography provided opportunities for astronomers without observatory, it also placed them in a subordinate position.

Pannekoek’s photographic research illustrates the tremendous amount of labour that went into measuring and reducing photographic plates; a characteristic he was able to use to his advantage. His dependent position meant he had access to far fewer photographic plates than the photographic observatories themselves, but he coped with this situation by focusing on work that could utilize the plates he did have to the fullest.
Each individual plate was extensively measured in minute detail to extract as much information as possible. As a result, he was the first to publish a comprehensive catalogue of spectral lines in F and G-type stars in 1951. While similar catalogues of B-type stars had been published decades earlier, the sheer amount of lines in F and G-type stars meant that none of the better equipped astronomical institutes had taken on the daunting task of measuring them all. Pannekoek thus saw the opportunity to contribute to astrophysics by doing what other astronomers were unwilling to do.

On an epistemological level, we found that Pannekoek valued photography for its ability to reduce the human aspect of observation. Unlike many of his contemporaries, however, he did not want to eliminate it entirely. This is best illustrated by the photographic method he developed for representing the visual aspect of the Milky Way. Here, the advantage of photography was that it could record the brightness of Milky Way light without being influenced by personal differences like human observers were. At the same time, he wanted photography to capture the Milky Way clouds as could be seen by the human eye. Regular photography was insufficient for this purpose because it resolved these clouds into individual stars. Instead, Pannekoek turned to the method of extrafocal photographic photometry, which he argued could mimic the anatomical and physiological structure of the human eye. Through this method, he could thus eliminate personal subjectivity while preserving collective subjectivity. Even in the photographic method, the human aspect of observation remained vitally important for Pannekoek.

Additionally, human interpretation was also needed to extract meaningful information from photographic plates, according to Pannekoek. This was an essential feature in his photographic method for statistical astronomy. Pannekoek hoped that photography could provide a more uniform distribution in the limiting magnitudes of various observations, which would make it easier to determine the distances to star clusters. In choosing how to divide the star counts measured on the photographic plate into different sections, however, he relied on the appearance of the Milky Way to guide him, rather than following a predetermined scheme. This way, he could group together parts of the sky that he believed belonged together. This method further reinforces what we have seen throughout the thesis: photography for Pannekoek was not merely a way of letting nature represent itself. Photographic plates were material objects that could be exchanged between people and institutions, and that
Conclusion

had to be handled, measured, and interpreted to be valuable for scientific research.

Epistemic Virtues

While investigating Pannekoek’s contributions to astronomy in this thesis, we have focused on the epistemic virtues he pursued in his research. This has led to a deeper understanding of his scientific methodology, how it compared to that of his contemporaries, and how it related to his philosophy of mind and ideas on scientific progress. As I have argued, two epistemic virtues, in particular, stood out in the work of Pannekoek: judgement and thoroughness.

The importance that Pannekoek placed on the virtue of judgement is evident in his research on the statistical distribution of stars. Judgment was required to determine how statistical data had to be clustered to provide meaningful results. This was not only the case for photographic plates, as discussed above, but also when it came to reducing data from published catalogues. By looking at the appearance of the Milky Way, Pannekoek used his judgement to find specific features, like clouds and clusters, to investigate in more detail. This could have a considerable impact on the results of his research, for example when Pannekoek determined the distances to the star clusters in Cygnus and Aquila and found them to be located at 40,000 to 60,000 parsec from the Sun, well outside the boundaries of the widely-accepted star system that had been derived by Jacobus C. Kapteyn. Pannekoek was thus one of the first astronomers to provide supporting evidence for Harlow Shapley’s extended galactic system.

The contrast between the statistical research of Pannekoek and that of Kapteyn is especially compelling because they both used the same statistical methods. The main difference was that Kapteyn provided a uniform sorting method in which the statistical data was used to derive the parameters for an all-encompassing model of the entire galactic system. Kapteyn valued a mechanical application of his statistical method as he believed it would ensure that astronomers remain focused on the larger system and would prevent them from getting distracted by idiosyncrasies in the system. Pannekoek, conversely, argued that Kapteyn’s scheme already presupposed the shape of the system and warned that his reluctance to intervene meant that there was no way to counteract this predetermined structure. The model of the galactic system that Pannekoek constructed
instead was built up from individual clusters that together formed the sys-

tem. What we have uncovered by focusing on epistemic virtues is that judg-

ement was crucial for Pannekoek because it allowed him to detect and cir-

cumvent this bias in the methodology. Moreover, we can now un-

derstand how he could derive results that directly contradicted Kapteyn’s model despite using the same statistical methods.

Pannekoek’s emphasis on judgement can be understood in light of his ontology and philosophy of mind, which he explicated in his socialist writings. According to this ontology, the external world was a continuous and infinitely varied stream of phenomena. This external world could only be accessed through impressions received by the senses, and so the human mind could never fully access or understand it. Accordingly, that should not be the goal of science. Instead, he argued that the focus should be on how information from the senses was ordered, systematized, and interpreted by the human mind. This ability to analyse sense impressions and turn them into a coherent and comprehensible conception of the world is what set humans apart from other animals. Pannekoek’s idea that science should look for structure in the sense perceptions explains why he developed various methods of representing the visual appearance of the Milky Way. These various representations provided different methods of structuring the distribution of star light; they represented independent research objects that highlighted different aspects of this distribution. The fact that these structures did not exist outside of the human mind was irrelevant if they could help us understand the phenomenon of the Milky Way. By using their judgement, astronomers would be applying one of humankind’s most unique and powerful attributes.

While Pannekoek considered judgement was an essential virtue for all astronomers, this thesis has indicated that thoroughness was a virtue more catered to his personal circumstances. We have seen that thoroughness was an important virtue in his observational astrophysics, where it drove him to extract as much information as possible from each individual photographic plate. But it was a prominent feature of his theoretical astrophysics research as well. Pannekoek contended that he lacked the theoretical insight to contribute to astrophysics by developing new astrophysical theories. Rather, he worked within theoretical frameworks developed by others and investigated their consequences, possibilities, and weaknesses. In this process, thoroughness was a vital asset.

The role of thoroughness in Pannekoek’s theoretical astrophysics can be most prominently seen in his theoretical models of stellar atmospheres.
Conclusion

There, he rejected the commonly-used simplified Schwarzschild–Shuster model and instead constructed complex versions of the Milne–Eddington model that accounted for the variation in ionization rate inside stellar atmospheres. Although such models required much more calculating work, they enabled him to conduct a thorough investigation of the physical processes occurring inside stellar atmospheres. These models, however, consistently failed to reproduce observed stellar spectra accurately, with Pannekoek unable to pinpoint exactly where the problem lied. The solution was eventually found by Rupert Wildt, who adjusted Pannekoek’s models with new data from physics and managed to show that they had underrepresented the influence of the negative hydrogen ion. Thus, while Pannekoek failed to find the solution himself, he did manage to contribute significantly to the development of theoretical astrophysics through his thorough computations of complex models.

Thoroughness was not just a practical virtue for Pannekoek, however. He also considered it a truly epistemic virtue vital for scientific progress. According to his ideas on scientific development, scientific knowledge grew through the dialectic of theory and observation; observation tested theories and suggested improvements, while theories modelled observational results and indicated the direction of new observational research. In this process, thoroughness was crucial because meticulous measurements and complex calculations allowed for a more exact comparison between theory and observations. Therefore, Pannekoek’s adherence to the virtue of thoroughness can be interpreted as a consequence of both circumstance and conviction.

Science and Marxism

As has been noted in the introduction of this thesis, historical literature on Pannekoek has so far largely neglected the connections between his astronomy and Marxism. But as evidenced in the preceding chapters, this separation into two distinct careers is misleading as there were numerous ways in which the two intersected. Moreover, by considering his Marxist philosophy and theories, we get a much better insight into some of the methodological and practical choices Pannekoek made in his astronomical career.

One of the most profound connections between Pannekoek’s astronomy and his socialism was through his Marxist philosophy of mind. As we have seen, this philosophy led him to emphasize the importance of
judgement in his astronomical research. It also impacted his conceptualization of dialectic materialism as the scientific method for socialist research. According to this method, the Marxist theorists had to analyse how material factors — whether social, economic, or even ideological — determined the behaviour of social classes. For astronomers and Marxists alike, open-mindedness was imperative; they should not let themselves be guided by preconceived ideas about how the stellar systems should look or how the revolution should play out. Such preconceptions would alter their perceptions and would lead them to see what they expected to see. This suggests that, rather than there being some fundamental disconnect, Pannekoek’s conception of the ideal scientist and the ideal Marxist were both rooted on the same epistemic concerns, each adapted to suit its own field of research.

Although this study revealed strong relations between Pannekoek’s epistemic virtues in his approach to socialism and science, they are certainly not limited to these virtues alone. There is also a clear analogy between his model of the galactic system and his model for council communism. In both cases, he rejected the top-down model that emphasized the overarching system as a meaningful entity. Instead, he advocated a bottom-up method that emphasized the way in which individual persons or stars congregate into larger systems. The collection of these individual clusters provides sufficient structure for the system as a whole without requiring an additional overarching layer.

Finally, by considering Pannekoek’s Marxist writings, we can understand why he remained in astrophysics even when he believed he lacked the theoretical aptitude to contribute on a fundamental level. There, Pannekoek explained that scientific progress was an important prerequisite for social progress, for example, through technological advancements that derived from scientific development. Astrophysics was an especially promising field for this purpose because it searched for the stellar energy source, which could perhaps lead to useful energy sources on Earth. Even more important, however, was the educational value of scientific research. For the education of the next generation of scientists, it was necessary to illustrate the proper scientific method through example and show the importance of virtues such as judgement and thoroughness. For the wider public, too, these were virtues that they required to challenge received wisdom and assess for themselves their social, economic, and cultural circumstances.
Conclusion

By looking beyond the separation that Pannekoek himself had created between his astronomical and socialist career, we have found numerous ways in which his astronomy and Marxism were interconnected. The fact that we have found these connections re-emphasizes that science should not be detached from its cultural and political context. We have seen that, by studying Pannekoek’s astronomy in the context of his political philosophy, we gain a deeper understanding of the practical, methodological, and epistemological choices he made during his research. Moreover, in doing so, we have arrived at a more unified and complete description of his entire professional life — a description that recognizes that behind Pannekoek-the-astronomer and Pannekoek-the-Marxist there was a single person with the same convictions, the same virtues, and a consistent worldview.
Verbal Descriptions of the Milky Way

The following is an extract from Pannekoek’s *Die nördliche Milchstrasse* (pp. 66–67). It gives a verbal description of the mean subjective image of a small section of the Northern Milky Way. This is created by combining descriptions from direct visual observations for some observations with descriptions of features seen in the drawings of others. The names indicate who made the observations. All these descriptions cover the same part of the Milky Way where the constellations Camelopardalis, Lynx, and Auriga meet.

Pannekoek:

§ 51. In these areas, between 10 H and 10 Camelopardali, where the triangle of light reaching towards γ Persei also connects with the northern stream, the column becomes unnoticeable and bright patches from ε and ι Cassiopeiae come together. They become gradually fainter eastward and run in a wide weak stream from 10 – 11 over 31 Camelopardali towards the stars in the head of Lynx. On clear nights this light can be followed as a faint offshoot up to the head of the great bear. Towards the southern the light goes from 10 Camelopardali over δ Aurigae, while getting gradually brighter, towards β Aurigae; a dark area α–β Aurigae separates this stream from the mainstream.
A. Verbal Descriptions of the Milky Way

Easton:

21) With E[aston] the column remains visible, past the brightening 1 H–7 H it becomes darker again (E. XXXIII) and extends itself past 10 and 11 Camelopardali to a dark area between δ–α–β Aurigae.

22) E[aston] 122, narrow stripes 11 Camelopardali – δ–41 Aurigae, come through in the stream from 18 Lyncis towards β Aurigae. Everything is very faint, therefore the is[ophotic] m[ap] is hardly indicated.

Schmidt:

§ 51. In the border areas only a few spots are visible: from 9 to 10–11 Camelopardali an isolated distinctly elongated spot (on I; On II the stars lay on the faint border of light), around 2 Lyncis a round spot on I, and n[orth] of 1 Lyncis a faint glimmer on II. A narrow light-stripe starts at ξ–δ Aurigae and goes on towards β Aurigae.

Boeddicker:


Backhouse:

Pannekoek’s Astronomy Students

During Pannekoek’s time the director of the Astronomical Institute in Amsterdam, a number of students studied astronomy there as their main subject. The following is a list of the students who went on to obtain a doctoral degree in astronomy, whether in Amsterdam or elsewhere, sorted by their date of graduation.1

Jacobus Josephus Maria Reesinck (1902–1984) Reesinck was the first PhD student to study astronomy at Amsterdam. His doctoral research combined observational measurements and theoretical calculations on the period variation of δ Cephei.2

Nicolaas Wilhelmus Doorn (1901–1955) When Doorn was an astronomy student in Leiden, he joined Pannekoek and Marcel Minnaert as part of the 1927 Solar eclipse expedition to Gällivare. He finished his doctoral research at the University of Amsterdam in 1929 with a thesis based on the photographic plates of the chromosphere taken during that expedition.3

1. For the entire list, the dates of birth and death are taken from the Album Academicum of the University of Amsterdam: albumacademicum.uva.nl.
B. PANNEKOEK’S ASTROLOGY STUDENTS

Sijtze Verweij (1894–1979) Verweij graduated in 1936 with a PhD thesis on theoretical computations of the Stark effect in hydrogen lines.¹⁴

Gijsbert van Herk (1907–1999) Van Herk studied astronomy in Amsterdam where he finished in 1930 with a master’s thesis on the photographic photometry of the Magellanic Clouds.⁵ He obtained his doctoral degree in 1936 in Leiden, where he remained the rest of his career. Up until 1957, one of his main tasks there was to observe with the meridian circle that had once been used by Pannekoek.⁶

Gale Bruno van Albada (1912–1972) Before the start of the Second World War, Van Albada measured the equivalent widths of several stars ranging from A to G-type. Anton Pannekoek and Gale Bruno van Albada, A Photometric Study of Some Stellar Spectra (δ Cephei, ζ Cygni, π Cephei, δ Equulei): Part 1. Catalogue of Line Intensities, Publications of the Astronomical Institute of the University of Amsterdam 6, pt. 1 (Amsterdam: Stadsdrukkerij, 1939). These measurements formed the basis of his PhD thesis, for which he constructed curves of growth and analysed the physical conditions of those stars.⁷ He was director of Bosscha Observatory in Lembang from 1949 to 1958, where he married Elsa van Dien in 1950 (his second marriage), and director of the Astronomical Institute in Amsterdam from 1959 to 1972.⁸ He was also an active member of the council communist movement.⁹

Elsa van Dien (1914–2007) As an astronomy student in Amsterdam, Van Dien investigated the limb darkening in YZ Cassiopeiae, which led to an early publication. She was awarded a scholarship to finish her doctoral research at Radcliffe College in 1939 but had to go into hiding during the Second World War. She finally went after the war ended and graduated in 1948 with a thesis on the Stark effect in Balmer lines; the topic had been suggested by Pannekoek. She spent two years at Dominion Astrophysical Observatory in Victoria, BC before moving to Bosscha Observatory. She married Bruno van Albada in 1950, after which she stopped publishing research. She returned to Amsterdam in 1958 where she published a few papers in the 1980s and 1990s.


Johan Weenen (1916–2005) Weenen graduated in 1949 with a PhD thesis on theoretical calculations of the structure of Wolf-Rayet stars. He wrote the first part of his thesis before the Second World War super-

B. Pannekoek’s Astronomy Students

vised by Pannekoek and finished the second part after the war supervised by Herman Zanstra.16

David Koelbloed (1905–1977) At the age of 16, Koelbloed was hired as computer at the newly-founded Astronomical Institute in Amsterdam. He assisted Pannekoek in his Milky Way and statistical research and was co-author in the publication of the photographic photometry of the southern Milky Way.17 He also assisted many of Pannekoek’s students. He started following astronomy classes and obtained his master’s degree in 1948 and eventually graduated in 1953 on a doctoral thesis on the line spectra of K-stars.18 He was lecturer of astronomy in Amsterdam from 1963 to 1974.

Archives

AIP  Niels Bohr Library & Archives, American Institute of Physics, College Park, MD.
AIP/DM  Donald Menzel autobiography, 1974 [MB2013-1167].
AIP/OS  Otto Struve selected correspondence, microform [MI78].
API  Archive of the Anton Pannekoek Institute, University of Amsterdam.
HUA  Harvard University Archives, Cambridge, MA.
HUA/DM  Papers of Donald Howard Menzel [HUG 4567].
HUA/HCO  Harvard College Observatory, Records of the Director, Harlow Shapley, 1921–1956 [UAV 630.22].
HUA/HS  Papers of Harlow Shapley [HUG 4773].
IISH  International Institute of Social History, Amsterdam.
IISH/AP  Archief Anton Pannekoek [ARCH01030].
LAC  Library and Archives Canada, Ottawa.
LAC/DAO  Dominion Astrophysical Observatory, Office of the Director [R214-254-4-E].
LM  Archive of Laurence A. Marschall [in possession of author].
MB  Museum Boerhaave, Leiden.
MB/AP  Persoonlijk archief van Antonie Pannekoek [a 631].
MB/CE  Correspondentie, aantekeningen Cornelis Easton [a 427].

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Anton Pannekoek (1873–1960) was both an innovative astronomer and influential Marxist thinker. While historians have extensively discussed his socialist career, his astronomical career has received much less attention. This thesis provides a comprehensive overview of Pannekoek’s astronomical research both in the context of the historical development of astronomy in the twentieth century and the in context of his own Marxist philosophy. Throughout the thesis, the focus is on three pertinent historiographical themes: the impact of photography on astronomy, Pannekoek’s epistemic virtues, and the connections between his astronomy and Marxism.

Chapter 1 discusses Pannekoek’s efforts to create a complete representation of the distribution of Milky Way light. The visual appearance of the Milky Way was an optical illusion, according to Pannekoek, created by how the eye recorded the light of innumerable stars in the Milky Way and how the mind interpreted this information. Nevertheless, he argued that it was important to study the appearance of Milky Way because it provided valuable information on the distribution of stars. Such an assessment was consistent with his Marxist philosophy, which emphasized the role of the human mind in understanding the external world. According to Pannekoek, the external world was a continuous and infinitely varied stream of phenomena. This external world could only be accessed through impressions received by the senses, and the role of the human mind was to order, systematize, and interpret these sense impressions. This ability
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is what set humans apart from other animals. Whether or not the Milky Way existed outside of the human mind was thus irrelevant if it could help us understand the world.

Pannekoek used both visual and photographic observations to observe the Milky Way. In the former case, he combined the observations of multiple independent observers to create what he called the 'mean subjective image'. In doing so, he wanted to eliminate individual subjectivity while preserving collective subjectivity, thus creating the Milky Way as the average human would see it. In the case of photographic observations, Pannekoek used the technique of extrafocal photography to mimic the physiological characteristics of the human eye while avoiding the psychological characteristics of human observers. The photographic plates required for this research were brought in from Germany, the Dutch East Indies, and South Africa, and measured in Amsterdam. The resulting image of the Milky Way was represented using various techniques: verbal descriptions (only in the case of visual observations), numerical tables, isophotic diagrams, and naturalistic drawings.

Chapter 2 studies Pannekoek’s statistical research on the distribution of stars in the galactic system. Rather than searching for the general shape and size of the entire galactic system, like Jacobus C. Kapteyn, Pannekoek focused on individual clusters and investigated them in detail. In this research, the epistemic virtue of judgement played a crucial role. Judgement was needed to select specific features in the stellar distribution to investigate, and it was needed to interpret the results of this research by comparing them to the visual appearance of the Milky Way. Although Pannekoek used the same statistical methods as Kapteyn, their difference in approach led to contradictory results. The distances Pannekoek found to the Milky Way clouds were much larger than Kapteyn’s entire system and instead concurred with Harlow Shapley’s extended galactic system.

Pannekoek’s main objection against Kapteyn’s method was that the shape of his system was predetermined by the way he organized the statistical data. Moreover, Pannekoek argued, the mechanical way in which Kapteyn applied his scheme prevented him from detecting and correcting this bias in his model. Pannekoek’s alternative method for constructing a model for the galactic system was not to start from a predetermined scheme for the entire system but instead to build the system up from individual clusters.

There are clear parallels between Pannekoek’s statistical astronomy and his Marxist philosophy. His model of the local system is analogous
to his model for council communism. In both cases, he rejected a predetermined top-down strategy that treated the overarching system as a meaningful entity. Instead, he promoted a bottom-up strategy that explored how individual persons or stars congregated into larger systems. The collection of these individual clusters provided sufficient structure for the system without requiring an additional overarching layer. Similarly, his rejection of mechanical materialism shows striking parallels with his rejection of mechanical sorting schemes in astronomy. In both cases, by neglecting the ability of the human mind, crucial information was overlooked or misinterpreted.

Chapter 3 focuses on Pannekoek’s research on the astrophysics of stellar atmospheres and how they related to his ideas on scientific and social progress. Pannekoek faced with several practical constraints in his astrophysics research. In the case of observational research, Pannekoek faced with the circumstance of not having an observatory. To still conduct observational research, he had to rely on photographic plates that were borrowed from other institutions or recorded by himself during research expeditions. As a result, he had access to far fewer photographic plates than observational researchers working at large photographic observatories. To make the fullest of the plates he did have, Pannekoek focused on the virtue of thoroughness. He decided to measure every plate in as much detail as possible, for which other astronomers often lacked the time, thereby establishing his niche in observational research.

In the case of theoretical astrophysics, Pannekoek believed he lacked the theoretical insight to develop new theories or make significant breakthroughs. Here, too, thoroughness became an essential virtue. He decided to focus on investing and further developing already existing theories, like Meghnad Saha’s ionization formula, and constructing detailed theoretical models of stellar atmospheres. Pannekoek believed he could best contribute by thoroughly computing the exact consequences of theoretical assumptions and physical conditions in his models so that these could be assessed through a comparison with observational results. To do so, he used the method of numerical integration to solve complicated differential equations, instead of simplifying the models so that they could be calculated analytically as many of his contemporaries did.

Thoroughness was not just a practical virtue for Pannekoek, however. He also considered it an epistemic virtue vital for scientific progress. According to his ideas on scientific development, scientific knowledge grew through the dialectic of theory and observation; observation tested theor-
Summary

ies and suggested improvements, while theories modelled observational results and indicated the direction of new observational research. In this process, thoroughness was crucial because meticulous measurements and complex calculations allowed for a more exact comparison between theory and observations. Therefore, Pannekoek’s adherence to the virtue of thoroughness can be interpreted as a consequence of both circumstance and conviction.

The thesis as a whole illustrates the significant impact photography had on Pannekoek’s astronomical research. On a practical level, photography allowed him to conduct observational research even though he lacked an observatory. On an epistemological level, it enabled him to reduce the human aspect of observation, although he was careful not to eliminate it entirely. What becomes clear from Pannekoek’s photographic research is that it was not merely a way of letting nature represent itself. Photographic plates were material objects that could be exchanged between people and institutions, and they required significant labour to measure and interpret them before they became valuable for scientific research.

The focus on Pannekoek’s epistemic virtues in astronomy leads to a deeper understanding of his scientific methodology and how it compared to that of his contemporaries. Two epistemic virtues, in particular, stood out in the work of Pannekoek: judgement and thoroughness. Investigating the role of judgement in his statistical astronomy highlights the main difference between his approach and that of Kapteyn. The focus on the role of thoroughness in Pannekoek’s astrophysics explained how he adapted his methodology according to the constraints of his personal situation and his ideas on scientific and social progress.

Finally, by investigating Pannekoek’s astronomy in relation to his political philosophy, we have found numerous ways in which these were interconnected. These existed through his philosophy of mind, in analogies between the systems created in astronomy and socialism, and in the goal of scientific research. Through these connections, we better understand the practical, methodological, and epistemological choices he made during his research. Moreover, in doing so, we have arrived at a more unified and complete description of his entire professional life — a description that recognizes that behind Pannekoek-the-astronomer and Pannekoek-the-Marxist there was a single person with the same convictions, the same virtues, and a consistent worldview.
Anton Pannekoek, marxistisch astronoom. Fotografie, epistemische
deugden en politieke filosofie in vroegtwintigste-eeuwse sterrenkunde.

Anton Pannekoek (1873-1960) was een innovatief astronoom en een in-
vloedrijk marxistisch denker. Zijn carrière in de arbeidersbeweging is uit-
gebreid onderzocht door historici; zijn sterrenkundige carrière daarente-
gen heeft een stuk minder aandacht gekregen. Dit proefschrift bespreekt
Pannekoeks astronornisch onderzoek zowel in de context van de histori-
rische ontwikkelingen in de sterrenkunde tijdens de eerste helft van de
twintigste eeuw, als in verhouding met zijn eigen marxistische filosofie.
Hierbij legt het proefschrift nadruk op drie relevante geschiedkundige the-
ma’s: de invloed van fotografie op de sterrenkunde, Pannekoeks epistemis-
sche deugden, en de dwarsverbanden tussen zijn sterrenkunde en marxis-
me.

Hoofdstuk 1 beschrijft Pannekoeks inspanningen om de verdeling van
het licht in de Melkweg volledig weer te geven. Hij stelde hierbij dat het
visuele voorkomen van de Melkweg een optische illusie was, die werd ge-
vormd door de werking van het oog, dat het licht van ontelbare sterren
verzamelde en registreerde, en de geest, die deze informatie vervolgens
verwerkte. Desondanks vond Pannekoek het belangrijk om dit voorko-
men te bestuderen omdat waardevolle informatie gaf over de verdeling
van sterren aan de hemel. Deze manier van redeneren kwam overeen met
zijn marxistische filosofie, waarin hij de rol benadrukte die de menselijk
geest speelt in het begrijpen van de externe wereld. Pannekoek concep-
tualiseerde de externe wereld als een constant veranderende en eindeloos
gearrigeerde stroom verschijnselen. Informatie over deze externe wereld

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kon enkel verkregen worden via de zintuigen en het was de taak van de menselijke geest om deze zintuiglijke indrukken te ordenen, systematiseren, en interpreteren. Hiermee onderscheidden mensen zich van andere dieren. Of de Melkweg ook buiten de menselijke geest bestond was niet relevant voor Pannekoek, zo lang het concept maar kon helpen om de wereld beter te begrijpen.

Pannekoek gebruikte zowel visuele als fotografische technieken om de Melkweg te onderzoeken. In het eerste geval combineerde hij de observaties van verschillende onafhankelijke waarnemers om een collectief beeld te creëren, wat hij het ‘gemiddeld subjectief beeld’ noemde. Hiermee hoopte hij individuele subjectiviteit uit te kunnen sluiten terwijl collectieve subjectiviteit bewaard zou blijven. Daarmee kon een Melkwegbeeld gecreëerd kunnen worden zoals een gemiddeld persoon het zou zien. In het geval van fotografische waarnemingen gebruikte Pannekoek de methode van extrafocale fotografie, waarbij het beeld bewust onscherp werd genomen waardoor het licht van verschillende sterren kon overlappen. Hiermee wilde hij de fysiologische eigenschappen van het menselijk oog nabootsen zonder dat deze beïnvloed konden worden door de psychologische eigenschappen van menselijke waarnemers. De fotografische platen voor dit onderzoek werden opgenomen in Duitsland, Nederlands-Indië, en Zuid-Afrika, en volgens naar Amsterdam gebracht alwaar ze werden uitgemeten. Het resulterende Melkwegbeeld werd op verschillende manieren weergegeven: door middel van verbale beschrijvingen (enkel voor de visuele observaties), numerieke tabellen, isofotische diagrammen, en natuurgetrouwe tekeningen.

Hoofdstuk 2 bestudeert Pannekoeks statistisch onderzoek naar de ruimtelijke verdeling van sterren in het Melkwegstelsel. In tegenstelling tot voorgangers als Jacobus C. Kapteyn, die vooral op zoek waren naar de algemene vorm en grootte van het gehele stelsel, had Pannekoek meer oog voor individuele clusters en bestudeerde hij deze in detail. Hierbij was een belangrijke taak weggelegd voor de epistemische deugd beoordelingsvermogen. Dit was bijvoorbeeld nodig om specifieke bijzonderheden in de sterverdeling te selecteren voor onderzoek, maar ook om de resultaten van dit onderzoek vervolgens te interpreteren door middel van een vergelijking met het visuele voorkomen van de Melkweg. Hoewel Pannekoek dezelfde statistische methodes gebruikte als Kapteyn, leidde hun verschillende benaderingen tot tegengestelde resultaten. De afstanden die Pannekoek vond naar Melkwegwolken waren significant groter dan Kapteyn had berekend voor zijn totale stelsel. Pannekoeks afstanden kwamen beter
overeen met het uitgebreidere Melkwegstelsel van de Amerikaanse sterrenkundige Harlow Shapley.

Pannekoeks belangrijkste bezwaar tegen Kapteyns aanpak was dat de vorm die het systeem kon hebben al van tevoren was vastgelegd door de manier waarop Kapteyn zijn statistische data verwerkte. Bovendien zorgde de mechanische manier waarop Kapteyn zijn programma uitvoerde ervoor dat hij dit vooroordeel in zijn model niet kon ontdekken en corrigeren, aldus Pannekoek. In plaats van het gehele Melkwegsysteem volgens een van te voren bepaald systeem te onderzoeken, stelde hij voor om het lokale sterrensysteem van onderaf op te bouwen vanuit individuele clusters.

Er zijn duidelijke parallellen zichtbaar tussen Pannekoeks statistische sterrenkunde en zijn politieke ideeën. Zijn model voor het lokale sterrenstelsel is overeenkomstig met zijn model voor het radencommunisme. In beide gevallen wees hij een van bovenaf bepaalde strategie die betekenis gaf aan een overkoepeld systeem af. In plaats daarvan benadrukte hij dat gekeken moest worden naar hoe systemen van onderaf werden opgebouwd vanuit individuele personen of sterren. Deze opbouw, stelde hij, gaf voldoende structuur waardoor een extra overkoepelende laag overbodig was. Op een soortgelijke manier vertoont Pannekoeks afwijzing van het mechanisch materialisme een opvallende parallel met zijn afwijzing van mechanische methodes om statistische data te analyseren. In beide gevallen beargumenteerde hij dat het negeren van het menselijk denken ervoor zorgde dat cruciale informatie verloren ging.

Hoofdstuk 3 richt zich op Pannekoeks onderzoek naar de astrofysica van steratmosferen in relatie tot zijn ideeën over wetenschappelijke en maatschappelijke vooruitgang. Pannekoek werd in zijn astrofysica geconfronteerd met enkele praktische beperkingen. Zo beschikte hij niet over een eigen sterrenwacht. Om toch observationeel onderzoek uit te kunnen voeren leende hij fotografische platen van andere instituten en ging hij op onderzoekreizen om zelf ook platen op te nemen. Het gevolg hiervan was wel dat hij veel minder platen tot zijn beschikking had dan observationele sterrenkundigen die werkzaam waren bij grote fotografische sterrenwachten. Om optimaal gebruik te maken van de platen die hij wel had, benadrukte Pannekoek de epistemische deugd *grondigheid*. Hij besloot om elke plaat tot in het fijnste detail uit te meten, iets waarvoor andere sterrenkundigen vaak simpelweg de tijd niet voor hadden. Hiermee wist hij alsnog zijn eigen niche te creëren binnen dit onderzoeksveld.
Met betrekking tot de theoretische astrofysica meende Pannekoek dat hij het theoretisch inzicht miste dat nodig was om nieuwe theorieën te ontwikkelen of lastige problemen op te lossen. Ook in dit geval werd grondigheid een essentiële epistemische deugd in zijn onderzoek. Hij besloot zich te richten verder uitwerken van al bestaande theorieën, zoals Meghnad Saha’s ionisatievergelijking, en het maken van gedetailleerde modellen van steratmosferen. Pannekoek beschouwde het als zijn taak om de exacte gevolgen van theoretische aannames en fysische omstandigheden in zijn modellen zo grondig mogelijk uit te rekenen, zodat ze beoordeeld kunnen worden aan de hand van een vergelijking met waarnemingsresultaten. Hiervoor maakte hij gebruik van numerieke integratie om gecompliceerde differentiaalvergelijkingen uit te rekenen, in plaats van zijn modellen te simplificeren zodat ze analytisch op te lossen waren, zoals veel van zijn tijdgenoten deden.

Grondigheid was echter niet alleen praktische deugd voor Pannekoek. Hij meende dat het ook een epistemische deugd was dat cruciaal was voor wetenschappelijke vooruitgang. Volgens zijn ideeën over wetenschappelijke ontwikkelingen groeide wetenschappelijke kennis door de dialectiek tussen theorie en waarneming; waarnemingen testen theorieënen en suggereren theoretische ontwikkelingen, terwijl theorieënen waarnemingsresultaten modelleren en de richting van nieuw observationeel onderzoek bepalen. In dit proces speelde grondigheid een cruciale rol omdat zorgvuldige metingen en complexe berekeningen exactere vergelijkingen tussen theorie en waarneming mogelijk maken. Het nastreven van grondigheid door Pannekoek kan dan ook gezien worden als het gevolg van zowel omstandigheid als overtuiging.

Het proefschrift als geheel illustreert de aanzienlijke impact die fotografie had op Pannekoeks sterrenkundig onderzoek. Op praktisch vlak zorgde fotografie ervoor dat hij observationeel onderzoek kon uitvoeren ondanks dat hij geen sterrenwacht had. Op kennistheoretisch vlak zorgde het ervoor dat hij het menselijk aspect van het waarnemen kon reduce- ren, hoewel hij er wel voor waakte het niet volledig uit te bannen. In Pannekoeks fotografisch onderzoek komt duidelijk naar voren dat fotografie niet enkel gebruikt werd om de natuur zichzelf te laten weergeven. Fotografische platen waren materiële objecten die uitgewisseld werden tussen mensen en instanties en waarvoor veel arbeid nodig was om ze nuttig te maken voor wetenschappelijk onderzoek.

De nadruk op Pannekoeks epistemische deugden leidt tot een beter begrip van zijn wetenschappelijke methodologie en hoe dit zich verhoudt
tot dat van zijn tijdgenoten. Twee epistemische deugden in het bijzonder springen hierbij in het oog: beoordelingsvermogen en grondigheid. Door de rol van beoordelingsvermogen in Pannekoeks statistische sterrenkunde te belichten wordt het contrast tussen zijn aanpak en dat van Kapteyn duidelijker zichtbaar. De focus op de rol van grondigheid in Pannekoeks astrofysisch onderzoek maakt duidelijk hoe hij zijn methodologie had aangepast aan zijn persoonlijke omstandigheden en zijn ideeën over wetenschappelijke en maatschappelijke vooruitgang.

Het onderzoek naar de raakvlakken tussen Pannekoeks sterrenkunde en zijn politieke filosofie tenslotte, laat meerdere manieren zien waarop ze met elkaar verbonden waren. Dit was bijvoorbeeld terug te vinden in zijn filosofie van de geest, in parallellen tussen de systemen die hij ontwikkelde in de sterrenkunde en het radencommunisme, en in wat hij zag als het doel van wetenschappelijk onderzoek. Door deze dwarsverbanden te onderzoeken ontstaat een beter beeld van de praktische, methodologische, en kennistheoretische keuzes die hij maakte in zijn onderzoek. Bovendien geeft het een beter geïntegreerd en completere beschrijving van zijn gehele professionele carrière — een beschrijving die erkent dat achter Pannekoek-de-astronoom en Pannekoek-de-marxist één enkel persoon schuilt met dezelfde overtuiging, dezelfde deugden, en een consistent wereldbeeld.
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For the past decade, Anton Pannekoek played a significant part in my life. First as the subject of my master’s thesis and later as the subject of my PhD research. In 2012, when I applied for a scholarship to fund a PhD project on Anton Pannekoek, I was asked the question ‘Don’t you think it will be boring to spend four years researching a single person?’ Now, having gone through the process, I can wholeheartedly answer that it was never boring. The life and work of Pannekoek has intrigued and captivated me throughout my research and I expect that I will keep coming back to the subject for many years to come. The social context of my research also ensured that it was never boring, as I have met many remarkable people and discussed with them many fascinating aspects in the history of science.

This dissertation would not have existed without the contributions of my supervisor Jeroen van Dongen. In 2011, when I was still a History and Philosophy of Science student at Utrecht University, Jeroen suggested that, for my master’s thesis, I should investigate Pannekoek’s astronomy in the context of epistemic virtues. Soon, we both realized that there was far more to investigate and discover than could possibly fit within the constraints of a master’s research. We started looking for opportunities to expand my research into a PhD project and, thanks to Jeroen’s persistence, managed to manufacture a PhD position with the financial support of the Institute of Physics, the Anton Pannekoek Institute, the Descartes Centre, and the Pieter Zeeman-Fonds. Jeroen has guided me throughout my master’s and my PhD, allowing me to make my own decisions in my research while reminding me (not always successfully) to stay focused at the task at hand and not lose sight of the ‘rode draad’. His supervision and critical
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Ralph Wijers was brought in as second supervisor to clarify astrophysical matters and ensure that my description of Pannekoek’s scientific research was sound. I enjoyed our meetings very much as he brought in a contagious enthusiasm for the history of astronomy and often assured me that I was on the right track when I was doubting whether what I was doing made sense. Moreover, Ralph gave me the confidence to prioritize my life as I saw fit and showed by example that you can be a great scientist without neglecting your family.

During the final four and a half years at the University of Amsterdam, I was joined by my fantastic colleagues, Sjang ten Hagen, Emma Mojet, and Jaco de Swart. I loved our many meetings, coffee breaks, and lunches, in which we had inspiring discussions about our research and general conversations on all aspects of life. It was amazing having them around as we grew together as historians of science. It is a great shame that the pandemic greatly reduced our opportunities for informal collaboration and quick interaction during the final year of projects.

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One of the things I am most proud of during my PhD is the international conference we held on the science and socialism of Pannekoek at the Royal Academy of Arts and Sciences in 2016. It was an amazing experience to discuss the life and work of Pannekoek with so many great scholars who delved deeply into the subject. I want to thank Jeronimo Voss for initiating this project and for our many conversations about Pannekoek; Jeroen, Edward, Ralph, and Bart van der Steen for co-organizing the conference; and all the speakers for their contributions.
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Throughout my research, I often relied the increasing number of online databases that provide digital access to public domain sources that would be very difficult to obtain otherwise. Often, these databases provide direct access (in the form of digital facsimilia) to the original sources and therefore do not appear in explicitly my bibliography. Their services, however, are greatly appreciated. The databases I relied on most were the SAO/NASA Astrophysics Data System (adsabs.harvard.edu); KNAW Digital Library (dwc.knaw.nl/toegangen/digital-library-knaw/); and Association Archives Anton Pannekoek (aaap.be).

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