Anton Pannekoek, Marxist astronomer

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

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Astrophysics of Stellar Atmospheres

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.¹ 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, API. Translated from Dutch
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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 became 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. 

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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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. 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. According to historian of astronomy Robert W.

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11. See John B. Hearnshaw, *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.
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...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.

19. See e.g. Anton Pannekoek, *De evolutie van het heelal*, inaugural lecture, University of Amsterdam (Amsterdam: L. van Nijkerk Hzn. 1918).
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As they become denser, the contraction would slow down until, at one point, they started to cool down again.\(^{20}\) 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.\(^{21}\) 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.\(^{22}\) In a personal journal, he recorded his struggles:

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\(^{22}\) Anton Pannekoek, Herinneringen: Herinneringen uit de arbeidersbeweging; Sterrekundige herinneringen, ed. Ben A. Sijes, Johanna M. Welcker and J. R. van der Leeu (Amsterdam: Van Gennep, 1982), 235–237. Pannekoek was not alone in considering positional astronomy to be tedious and boring. As argued by Kevin Donnelly, boredom in positional astronomy was deliberate as it ensured the dispassionateness of the observers and emphasized the mechanical nature of the observations. Kevin Donnelly, ‘On the Boredom of Science: Positional Astronomy in the Nineteenth Century’, British Journal for the History of Science 47, no. 3 (2014): 479–503.
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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.23

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.24 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 Pannekoek


den der Astronomie und kosmischen Physik 10, no. 10 (1900): 117–152.

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

Pannekoek was keenly aware of Monck and Kapteyn’s work on this subject and he wanted to improve on their results by replacing \textit{proper motion}, the motion of a star relative to the Sun, with \textit{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:

\begin{quote}
I have not \ldots 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] \textit{c} stars show a very special behaviour; their proper motions and parallaxes are so much smaller than those of the [division] \textit{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.\textsuperscript{29}
\end{quote}

\textsuperscript{29} Ibid., 138.
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.

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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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In 1916, he was hired as *Privataadocent* 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’. 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.

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. Unsurprisingly, there was overlap between his approach and that of other Marxist historians like Léon Rosenfeld, Edgar Zilsel, and Boris Hessen. 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-

45. Pannekoek, Astrologie en hare beteekenis, 30. Translated from Dutch.
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


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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.\textsuperscript{51} 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.\textsuperscript{52} 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:

\textsuperscript{51} Pannekoek, ‘Astrology and Its Influence’, 174–175.
\textsuperscript{52} Tucker, ‘Popularizing the Cosmos’, 190–191.
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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

53. Pannekoek, Astrologie en hare beteekenis, 32, translated from Dutch.
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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

56. Pannekoek, Evolutie van het heelal, 8–17.
57. Ibid., 17–18. Translated from Dutch.
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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.'

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. 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.' 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.
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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 has the goal of making the lives of humankind better, happier, and richer.  

One of the practical uses of scientific research was as a foundation for technological advancement, as Pannekoek emphasized in his Marxist writings. 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. 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.

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. 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.

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, *Synthetisch denken: Natuurwetenschappers over hun rol in een moderne maatschappij, 1900–1940* (Hilversum: Verloren, 2008), 56.
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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. 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. With their hiring, the Astronomical Institute of the

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68. Pannekoek, Herinneringen, 283–284.
69. Stamboek van de leerlingen, Archief van de Vijfde HBS met Drie-Jarige Cursus, Stadsarchief Amsterdam (SA/5H), 5
3.3 Ionization Theory

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.\textsuperscript{70} 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.\textsuperscript{71} 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

\textsuperscript{70} Smith, ‘Astronomy in the Time of Pannekoek’, 121.
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

\begin{enumerate}
\item \textsuperscript{72} For an analysis of Saha as a peripheral scientist, see Dasgupta, ‘Stars, Peripheral Scientists, and Equations’.
\item \textsuperscript{73} Saha was highly critical of the Indian caste system and how it influenced science and technology in India. He was an outspoken advocate of egalitarianism, which was strongly tied to a trust in scientism, as argued in Abha Sur, ‘Scientism and Social Justice: Meghnad Saha’s Critique of the State of Science in India’, Historical Studies in the Physical and Biological Sciences 33, no. 1 (2002): 87–105.
\item \textsuperscript{74} DeVorkin, ‘Maghnad Saha’s Fate’, 158; Sur, Dispersed Radiance, 80-84.
\item \textsuperscript{76} Pannekoek had received Saha’s papers from Herko Groot, who was Pannekoek’s successor as cosmography teacher at a Bussum secondary school. Groot had written his dissertation on the theory of radiative pressure as it applied to the Sun, and sent a copy of it to Saha, who had done similar research. In return, Saha sent Groot his papers on ionization theory, which Groot passed on to Pannekoek. Pannekoek, Herinneringen, 251.
\end{enumerate}
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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.

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.

than assumed by Saha, consistent with earlier results that stellar atmospheres were dominated by radiative pressure.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{84}

\begin{thebibliography}{99}
\bibitem{80} DeVorkin and Kenat, 'Establishment of a Stellar Temperature Scale', 119–123.
\bibitem{81} Ibid., 123–124.
\end{thebibliography}
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
3.3. Ionization Theory

highest at 80 km, so Pannekoek concluded that the Heaviside layer in the Earth’s atmosphere could not be explained through photoelectric ionization.\(^{87}\) 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.\(^{88}\) 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.\(^{89}\)

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


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.\textsuperscript{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

\textsuperscript{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. 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. 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.

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. 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.

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

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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.


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.
3.4. Acquiring Photographic Plates

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.100

Plaskett was happy to oblige, as he had done for many foreign astronomers lacking their own observatories.101 The plates Pannekoek received over the years from Dominion Astrophysical Observatory sustained observational research in Amsterdam for many years.102 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.103 Such requests led Plaskett to lament that Pannekoek did not appreciate the effort

100. 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.
103. See e.g. Anton Pannekoek to John S. Plaskett, 9 April 1924, LAC/DAO vol. 49, file no. 4.
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Figure 3.3: Pannekoek during the Solar eclipse expedition in Gällivare, 1927.
Source: Archive of Laurence A. Marschall (LM)

involved in taking photographic plates or realize the practical difficulties of his requests.\textsuperscript{104}

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.\textsuperscript{105} 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.\textsuperscript{106}

\begin{enumerate}
\item[104.] John S. Plaskett to Anton Pannekoek, 15 December 1927, LAC/DAO vol. 49, file no. 4.; see also Broughton, \textit{Northern Star}, 38–39, 271.
\item[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 Jan van der Bilt et al., ‘Report on the Expedition to Sumatra for Observing the Total Solar Eclipse of 1926 Jan. 14th’, \textit{Proceedings of the Section of Sciences, Koninklijke Akademie van Wetenschappen} 29, no. 9 (1926): 1151–1164.
\item[106.] See Chapter 1
\end{enumerate}

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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.
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 spectrophotography. 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

110. J.S. Plaskett to Pannekoek, 15 Dec 1927, LAC/DAO vol. 49, file no. 4.
111. Pannekoek, Herinneringen, 261–263; Anton Pannekoek to Anna Pannekoek-Nassau Noordewier, 3 May 1929, Persoonlijk archief van Antonie Pannekoek, Museum Boerhaave (MB/AP), box 2.
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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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

\textsuperscript{112} Houziaux, ’Viewpoints on the Structure of Stellar Atmospheres’.
\textsuperscript{113} Hearnshaw, \textit{Analysis of Starlight}, 253.
\textsuperscript{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. 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.

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.

116. Ibid., 153.
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. 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. 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:

> 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.

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

**Figure 3.4:** Diagrams showing the theoretical contour of Calcium (Ca) and Hydrogen (H) absorption lines as computed by Pannekoek in 1930. The diagrams give the brightness of the line relative to the background radiation as a function of the difference in frequency from the centre of the line in Ångström. **Source:** Pannekoek, 'Theoretical Contours', 156–157.

... 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.\footnote{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.\footnote{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.’\footnote{124}

Continuous Absorption

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.\(^{125}\)

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.\(^{126}\)


\(^{126}\) Ibid., 5–6.
3. **Astrophysics of Stellar Atmospheres**

![Image of Table 1](image)

**Table 1. Ionization of a mixture of hydrogen and metal atoms.**

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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.
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. 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-

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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.
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

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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.
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

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3. **Astrophysics of Stellar Atmospheres**

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

In his reply to Unsöld, which was also published in *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.'\(^{131}\) 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.\(^{132}\)

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.\(^{133}\)

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:

> 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...

\(^{130}\) Unsöld, ‘Theoretical Colour Temperatures’.


\(^{132}\) Ibid., 382.

\(^{133}\) 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, *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.
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

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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 ‘protégé’ 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. 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. 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. 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:

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.

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

146. Pannekoek, Herinneringen, 265. Pannekoek mentioned the research of Sijtse 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.
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.\(^{150}\) 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.\(^{151}\) 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

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

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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, Analysis of Starlight, 145–146.

\textsuperscript{155} Théodore Walraven, 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.\(^\text{157}\)

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.

\(^{157}\) 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. 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’. 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

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

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<th>$\xi$ U. Mag. log A wt</th>
<th>Sun log A wt</th>
<th>$\xi$ Root. log A wt</th>
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3.7. Conclusions

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.  

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

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
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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.