Star formation history written in spectra
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Introduction

Our subject in the past has been one in which the speculative mind could wander freely and far, with only the most general restraints imposed by demonstrable fact. We are always prepared for the existence of objects in the sky for which there seems to be no real theory; but I fear there are also theories for which no examples seem to exist. The volume of observational information is now so great, however, that I think it is time to make an effort to match up the domains of theory and observation in a more satisfactory manner.

– George. H. Herbig (1920 – 2013)

How did the stars form? This question has occupied inquisitive minds for thousands of years. In the Renaissance, two insights gradually became paradigms. First, the Earth and the other planets in our solar system revolve around the Sun; second, the Sun itself is a star, like the ones we see at night. Early theories of star formation were thus inspired by the appearance of our own solar system. In the 20th century, telescopes became so advanced that very young stars were discovered in the process of formation. Theory could finally be put to the test. From that point on, star formation matured as a scientific research area. The momentum brought about by observations resounds in the above words, written in 1969 by one of the field’s most eminent pioneers.

Star formation research has since evolved into a major discipline in astronomy. Great progress has been made in understanding the physics of young stars, aided by the growth of computer clusters and telescope mirrors, and their increased wavelength coverage. New observations continue to lead to many open questions which continue to propel the field. How did the stars form? has been rephrased into How do stars form?
In this thesis, the process of star formation is mapped from large to small scales, using the world’s most advanced observatories. Discoveries of several young stars with peculiar environments are reported. Dynamics of circumstellar gas and dust are analyzed in a diverse ensemble of intermediate-mass (2–10 solar masses, M⊙) young stars. The history of their formation process, impossible to probe directly, is revealed by spectroscopy.

This chapter gives an overview of star formation history and provides the scientific context for the results presented further on. Early models and observations are discussed. This is followed by a brief review of accretion, the process by which a young star grows. Three outstanding problems related to accretion are introduced: the origin of jets, the scaling of accretion with stellar mass, and the variability of the accretion process. The observational facilities featuring in this thesis are showcased. Finally, the contents of the remaining chapters are briefly summarized.

1.1 The nebular hypothesis

The first physical models for star formation were based on the structure of our own solar system. In the 18th century, the “nebular hypothesis” was formulated by the philosopher Emanuel Swedenborg (1734), and later adopted by Immanuel Kant (1755). Guided by observations of the polymath Maupertuis (1742), Kant hypothesized that the “fuzzy patches” that were sometimes seen with a telescope were not single stars, but conglomerates of stars (some of them were, indeed, galaxies). Building on this, he conceived that our own solar system had once been formed within such a “nebula”: a large, diffuse cloud of dust and gas. While from a physical point of view, the model was severely flawed (for instance, the system would start to rotate by itself), the idea was profound and audacious. It placed our solar system on par with the millions of stars we see at night. It introduced the dimension of time into astronomy. Stars could be seen as dynamical objects with a beginning and an end, rather than static and eternal beacons.

The nebular hypothesis was made into a physically more robust theory by Pierre-Simon Laplace (1796). He realized that upon cooling and collapsing under its own gravity, a rotating cloud will form a disk by virtue of the conservation of angular momentum. While in the center a star hatches, condensations in the disk eventually form planets. In this way, the combination of rotation and gravity naturally leads to a star and a planetary system. Sure enough, it had been known for centuries that the orbits of the planets are coplanar – an outcome naturally predicted by this theory.

Laplace’s model did have one fundamental problem: the initial angular momentum of the cloud cannot end up in the star, or it would shred itself apart. As often is the fate of a theory that cannot be tested by experiment, the nebular hypothesis fell out of grace. It was replaced by ever more exotic ones: the planets were formed by a nearby exploding star, or emerged after a grazing stellar collision. It was not until two centuries after its conception that the nebular hypothesis was dusted off and revived. To this day, our understanding of star and planet formation is based on it. Following astronomical tradition, observations paved the way.
1.2 Observations of star formation

The two main challenges that observational astronomers are faced with every day are to overcome distance and time. To study distant objects, we build ever larger telescopes to collect as much of their faint light as possible. To overcome time is perhaps an even more disheartening task. Most astrophysical processes of interest take place on timescales far exceeding an astronomer’s life expectancy. The ages of the universe, galaxies and stars span billions of years. The formation of a star takes only a fraction of its lifetime, but this can still be millions of years. In order to answer the question of a star’s origin, we need a way to trick time.

Being unable to go back to the beginnings of the solar system, our best option is to study stars equivalent to the Sun in the process of their formation. Joy (1945) was one of the first to identify such objects. He described a class of stars that were strongly variable in brightness, exhibited emission lines, and were associated with extended emission from a nebula. He named them after their prototype T Tauri. Ambartsumian (1947) realized that these objects were often located in the vicinity of (young) O- and B-type stars. He postulated that they must be very young low-mass stars. In the ensuing decade, more observational arguments supporting this hypothesis were found (Herbig 1962). T Tauri stars were discovered in large numbers in molecular clouds, which suggested that they formed out of these clouds not too long ago.

From the 1970s onwards, the discovery of emission from CO (Wilson et al. 1970) and other molecules in the interstellar medium (ISM) allowed the mapping of the
giant molecular clouds in which stars form (e.g., Elmegreen et al. 1979; Blitz et al. 1982; Dame et al. 1986, 2001). Observations in the far-infrared became available with the introduction of several ground-based and space-born observatories (e.g., the Infrared Astronomy Satellite, IRAS, a joint project by the USA, the UK and the Netherlands). These opened up a spectral window which gave access to radiation produced by relatively cold gaseous and dusty clouds (Vrba et al. 1975; Elmegreen & Lada 1976; Wilking et al. 1989).

It was discovered that the nebulous regions where T Tauri stars abounded also harbored some bright, cold infrared sources, invisible to optical telescopes. These were hypothesized to represent an even earlier, embedded stage of star formation. The light produced by the infant star is absorbed by the dust surrounding it, and re-radiated at longer wavelengths. The birth nebulae hypothesized by Kant and Laplace had finally been observed with a telescope.

Star formation research has thrived on the ongoing advancement of observational techniques and facilities, many of which are used for this thesis. For an overview, see Sect. 1.7. Fig. 1.1 illustrates the development of observations over two centuries: from an ink drawing of the Orion Nebula by Charles Messier to a multi-band image by the National Aeronautics and Space Administration (NASA) Hubble Space Telescope (HST).

Based on the new observations, an empirical classification scheme for what had collectively become known as young stellar objects (YSOs, Strom 1972) was formulated by Lada (1987) and Adams et al. (1987), and later updated by Andre et al. (2000). The classification is based quantitatively on the infrared slope of the YSO's spectral energy distribution (SED): the amount of radiation received from a star as a function of wavelength. Its different classes represent the consecutive stages in the evolution from a cold cloud to a star and planetary system. The evolutionary sequence inspired by Lada’s classification scheme (Fig. 1.2) illustrates our current understanding of the star formation process.

The formation and early evolution of a Sun-like star progresses as follows (timescales are based on theoretical work; see, e.g., McKee & Ostriker 2007; Evans et al. 2009):

- A perturbed large-scale molecular cloud fragments into pre-stellar cores. These are cold (a few tens of Kelvin), gravitationally bound clouds which collapse under gravity, a process taking up to about 1 million years (Myr).

- In the center of the cloud a protostar or class 0 object is formed. By definition, a protostar generates its luminosity from the release of gravitational energy of infalling matter (Barsony 1994). From this stage onwards, a rotating accretion disk is detected (Tobin et al. 2012; Murillo et al. 2013) and bipolar outflows develop (Bachiller et al. 1990). This stage lasts for about $10^4 – 10^5$ yr.

- When the mass of the collapsing envelope roughly equals the mass of the protostar, the class I stage is reached. The system retains its disk and bipolar outflows; a large portion of the starlight is absorbed or scattered by the disk and dust envelope. Most of the envelope material settles into the disk in roughly $10^5 – 10^6$ yr.
Figure 1.2: Evolutionary sequence for low-mass star formation ($M_* \sim 0.5$ up to a few $M_\odot$). Time progresses from top to bottom, over roughly 100 Myr for a typical Sun-like star. From left to right: observational example, spectral energy distribution, schematic drawing. Image credits are listed at the end of this chapter.
In the class II stage, most of the envelope has disappeared, but the young star remains surrounded by a dust and gas accretion disk and – in some cases – collimated bipolar jets. Heating of the gas by the star causes the disk to “puff up” and re-radiate much of the stellar radiation, increasing the near-infrared excess emission (Kenyon & Hartmann 1987; Chiang & Goldreich 1997). Class II objects are more commonly known as T Tauri \((M \lesssim 2 \, M_\odot)\) or Herbig Ae/Be \((M \sim 2 – 10 \, M_\odot)\) stars. This stage lasts up to 10 Myr, depending on the mass.

Eventually, the disk mass decreases and accretion onto the star comes to a halt. Within the disk, planets are formed from large conglomerates of dust. Dust collisions may result in the production of a debris disk. This is the class III stage.

The typical outcome is a star surrounded by a planetary system. A statistical analysis of data from NASA’s Kepler spacecraft suggests that most Sun-like stars indeed have planets (Fressin et al. 2013).

Fig. 1.2 displays observational examples of each stage and also illustrates the evolution of the SED. The contributions to the SED from the star (shown in yellow) and its circumstellar material (shown in red) change over time. The radiation from the circumstellar material initially dominates; up to the class I stage, the (proto)star is embedded in an optically thick environment. Its radiation originates mainly from accretion and is absorbed by the dust envelope (Cardelli et al. 1989). Light escapes from the cloud surface at longer wavelengths. From the class II stage onwards, the emerging stellar radiation increases and eventually dominates the energy budget, while the disk becomes colder and fainter towards the class III stage.

The definition of these classes is somewhat ambivalent, as the appearance of a YSO depends on the observer’s line of sight. For instance, a class II source seen edge-on (high inclination) may appear as a class I or even a class 0 source, as the dust disk obscures the central star (Masunaga & Inutsuka 2000). The appearance of accretion bursts may also confuse the evolutionary state classification. As the accretion rate is expected to decrease with age, an older object experiencing such a burst may be mistaken for a younger one (see Sect. 1.6).

### 1.3 Accretion: from cloud to star

The most fundamental problem of Laplace’s model is still unresolved, and has remained at the center of current star formation research. If a rotating cloud contracts, conservation of angular momentum dictates that inward moving material spins up, analogous to a ballerina drawing in her arms during a pirouette. The Sun contains 99.9% of the solar system’s mass. If it would contain the same fraction of its angular momentum, it would rotate so fast that it would break up. It could never have formed. Yet somehow most of the initial angular momentum of the Sun’s birth nebula did not end up in the Sun. Perhaps some of it even left the solar system altogether. All but a few percent of the solar system’s current angular momentum is contained in the orbit of Jupiter. To
better understand how the distribution of angular momentum is regulated, the theory of accretion is briefly reviewed.

The transport of mass through a young stellar system is governed by different physical processes in every stage of the formation sequence. These processes are collectively known as accretion: the growth of an object through gravitational attraction. The model by Shu (1977) describes the “inside-out” collapse of a cloud. The cloud’s central parts collapse faster than its outer shells. Material starts out in (roughly spherical) free fall until the inner part becomes optically thick and cannot cool efficiently: the “first core”. Several subsequent collapse phases are triggered by changes in the opacity and equation of state. Because of the cloud’s rotation, a net centrifugal force distributes the material in a plane perpendicular to the rotation vector: a disk is formed. If the disk material is to accrete onto the star, it must somehow shed its angular momentum. Two mechanisms may contribute to this: viscous spreading and external torques.

In the classic steady-state accretion disk model by Shakura & Sunyaev (1973), radial transport is induced by the differential rotation of the disk. Two particles on slightly different Keplerian orbits have slightly different velocities. If they interact, they exchange kinetic energy; one particle sinks into a lower orbit, while the other particle widens its orbit. This process is known as viscous spreading. It produces the desired outcome for star formation: it ensures a net influx of mass while angular momentum is transported outward (Lynden-Bell & Pringle 1974).

The efficiency of this mechanism depends on the coupling strength of gas with different velocities, analogous to the viscosity of a fluid. The effective viscosity \( \nu \) is expected to scale with the product of the sound speed \( c_s \) and the disk pressure scale height \( H \) (Pringle 1981):

\[
\nu = \alpha H c_s. \tag{1.1}
\]

The turbulent eddies in the disk are subsonic and if the turbulence is isotropic, also smaller than \( H \), which is the largest length scale in the disk. The dimensionless parameter \( \alpha \) is hence expected to assume values less than or equal to unity. Known as the turbulent mixing strength, \( \alpha \) describes the efficiency of viscous spreading. It does not represent a fundamental property of matter; its value is determined by local physical conditions in the disk (Armitage 2011). An effective value of \( \alpha \sim 0.01 \) is deduced from measurements of mass accretion rates and disk sizes of YSOs (Hartmann et al. 1998). Internal transport mechanisms thought to contribute to this value include self-gravity (Paczynski 1978) and the magneto-rotational instability (Balbus & Hawley 1991).

Angular momentum may also be removed from the disk by an external torque exerted by a magnetic field threading the disk. This process is known as magnetic braking (Mouschovias 1991). Angular momentum is carried away along the field lines in torsional Alfvén waves. As the field couples to the ionized gas, a rotating disk wind is launched which also carries a fraction of the accreting material and angular momentum (Blandford & Payne 1982; Königl & Pudritz 2000). This mechanism can explain the appearance of jets and outflows (see Sect. 1.4) and may even be the dominant driver of disk accretion, i.e., the transport of material through the disk towards the star (Königl & Salmeron 2011; Bai & Stone 2013).
Figure 1.3 displays the geometry of the inner disk. The accretion flow finally reaches the point where the disk interacts with the stellar magnetosphere. It is guided by stellar magnetic field lines and reaches the stellar surface at free-fall velocities (Camenzind 1990; Königl 1991). The gravitational energy released in the accretion shock is re-radiated at ultra-violet (UV) wavelengths (Calvet & Gullbring 1998). It also gives rise to broad emission lines in H$_{\text{i}}$ and other species (Muzerolle et al. 1998a,b). Because of the magnetic field configuration, the accretion shock most likely occurs close to the stellar pole. This gives rise to inverse P-Cygni shaped profiles: some of the line emission generated by the shock is absorbed at red-shifted wavelengths by the cooler outer flow (Hartmann et al. 1994). Measurements of the UV excess emission and the emission lines generated in the accretion shock are a quantitative diagnostic to measure mass accretion rates (e.g., Gullbring et al. 1998; Hartmann et al. 1998; Fang et al. 2009; Chapters 4 and 5). These provide constraints on the physical mechanisms that drive accretion.

The role of the central star in the accretion process becomes increasingly important as it irradiates the envelope and disk. Stellar evolution in the pre-main-sequence phase, which precedes the hydrogen-burning or main sequence phase, is illustrated in the Hertzsprung-Russell diagram (HRD) in Fig. 1.5. On this diagram, the objects discussed in this thesis and a sample of other young stars are shown. A star becomes observable after the initial accretion phase; at this point, its luminosity and surface temperature are described by the *stellar birthline*. As the star contracts, it derives its luminosity mainly from gravitational contraction; as a result, its surface and interior heat. During their formation, stars are expected to move along the PMS evolutionary tracks overplotted in Fig. 1.5. This demonstrates that, in principle, it is possible to probe stellar evolution and age from instantaneous observables. The strong dependence of PMS evolution on stellar mass and accretion history complicates this; see Sect. 1.5.

The models for disk accretion described in this section are able to explain many of the observational characteristics of YSOs. Nevertheless, many questions remain. In the following sections, three of these are highlighted: the origin of jets and outflows, the scaling of accretion with stellar mass, and the variability of the accretion process.

### 1.4 Jets and outflows

Amidst the early development of T Tauri star research, Herbig (1950, 1951) and Haro (1952, 1953) discovered several nebulus objects in star forming regions, which were only visible in emission lines. Initially it was supposed that these *Herbig-Haro* (HH) objects harbored, or were related to embedded T Tauri stars (Ambartsumian 1957; Osterbrock 1958). More than a decade later, Strom et al. (1974) discovered an embedded YSO offset from an HH object. Herbig & Jones (1981) noticed that several HH objects were moving away from a YSO in different directions, at velocities of hundreds of km s$^{-1}$. It was eventually realized that HH objects were in fact manifestations of bipolar, collimated jets emanating from young stars (Dopita et al. 1982; Mundt & Fried 1983; Reipurth & Heathcote 1997). Slower moving molecular outflows are also seen around
Observational jet research has taken a flight in the past two decades, since the advent of HST. Apart from supplying beautiful images which popularized the field, HST has made it possible to study jet physics at high spatial resolution, revealing the complexity of the star formation process. This has greatly increased our knowledge of shock propagation, kinematics and proper motions, jet rotation, and the workings of the launch mechanism (Burrows et al. 1996; Reipurth et al. 1997b, 2002; Bacciotti et al. 2002; Hartigan et al. 2001, 2004, 2011; Hartigan & Morse 2007). Also, wide-field surveys have revealed that jets can attain parsec-scale lengths (Reipurth et al. 1997a). The catalog of HH objects currently contains more than 1000 entries (Reipurth 2000); the discovery of the new members HH 1042 and HH 1043 is reported in Chapter 3. These objects are studied in detail in Chapter 4.

The appearance of jets far from the source – namely, their collimation, velocity and knotted structure – is in some part determined by their launch process. According to what has become the canonical model by Blandford & Payne (1982), jets are launched and collimated by magneto-centrifugal forces. Charged particles are lifted from the system and travel along magnetic field lines. Possible geometries of the launch region include an X-wind, disk wind or stellar wind (Shu et al. 1994; Pudritz & Norman 1983, Matt & Pudritz 2005; for a comparison see Ferreira et al. 2006). As the poloidal velocity is predicted to scale with the Keplerian velocity at the launch radius, the inner parts of the flow are expected to move faster than those launched at larger radii. This is
also observed; in several objects a fast inner jet co-exists with a slower outflow with lower excitation conditions and a wider opening angle (see Chapter 5). At a few tens of AU from the disk, the flow is collimated, typically within a few degrees (Burrows et al. 1996; Hartigan et al. 2004). Collimation is most likely achieved by the hoop stress of the magnetic field (Blandford 1993).

The knotted structure of HH objects suggests that they are the remnants of episodic, FU Orionis-like eruptions (Dopita 1978; Reipurth & Aspin 1997). In some cases they have been associated with past accretion events (Benisty et al. 2010b; Caratti o Garatti et al. 2013). Shock fronts are generally not discrete ejecta, but disturbances in a continuous flow which may be enhanced by interaction with the ISM (Hartigan et al. 1994). However, their creation may still be enhanced by a variability in outflow velocity or mass-loss rate. The knotted structure of a jet thus contains a “fossil record” of the activity of the host system near the jet launch site. When shock fronts propagate uniformly, it is straightforward to reconstruct the outflow history at the source from their motions (Raga et al. 1990, 2012; Chapters 4 and 5).

The mechanism by which jets are launched intimately relates to the accretion process and the transport of angular momentum (Sect. 1.3). A correlation is therefore expected between the outflow and accretion rate; the value of their ratio differentiates jet launching models (Ferreira et al. 2006). Such a correlation is indeed observed (Cabrit et al. 1990; Hartigan et al. 1995; Chapter 4, Fig. 4.14). However, a direct comparison between the outflow rate (measured off-source) with the accretion rate (measured on-source) may not reflect their true ratio, as both can vary significantly in time (Fig. 1.4; see also Chapter 5).

Figure 1.4: Same as Fig. 1.3. The locations at which accretion and outflow rates are measured are highlighted in purple. A correlation between these rates is predicted from models, but a simultaneous measurement of both is difficult to achieve.
Spectroscopic observations with high spatial resolution have revealed rotation of material around the polar axis. Upon comparison with mass accretion rates, the observed rotation and mass-loss rates suggest that jets are the dominant carrier of angular momentum in the disk accretion process (Bacciotti et al. 2002; Woitas et al. 2005; Coffey et al. 2004, 2007).

Studies of jets at high spatial, spectral and temporal resolution lead to a better understanding of the star formation process. They help constrain the launch process, a vital constituent of the accretion mechanism. Mapping outflow histories can elucidate the variability of accretion disk physics. Also, studies of jets from intermediate-mass sources explore the limits of models for low-mass star formation. These topics are all relevant in the detailed analysis of three intermediate-mass jet sources in this thesis (Chapters 4 and 5).

1.5 Star formation towards higher masses

Massive stars ($M_\ast > 10 M_\odot$) evolve fast, produce ionizing radiation and stellar winds, and end their lives as supernovae and gamma-ray bursts. Being the dominant source of energy and momentum in the ISM, they influence the formation and dynamical evolution of stellar populations and change the large-scale structure of molecular clouds. Despite their significant impact on galaxy dynamics, the formation process of massive stars is poorly understood for both theoretical and observational reasons.

Forming a massive star is difficult from a theoretical point of view. The duration of the PMS phase is set by the Kelvin-Helmholtz timescale:

$$\tau_{\text{KH}} = \frac{GM_\ast^2}{LR},$$

which is the time it takes a spherical cloud of mass $M$, radius $R$ and luminosity $L$ to thermally adjust to its contraction. A lower limit on the time it takes the cloud to collapse is set by the free-fall timescale:

$$\tau_{\text{ff}} = \sqrt{\frac{R^3}{2GM}},$$

This timescale exceeds the Kelvin-Helmholtz timescale for masses $\gtrsim 10 M_\odot$, which implies that massive stars are still accreting while already on the main sequence. At the accretion rates required to form massive stars ($\sim 10^{-3} M_\odot \text{ yr}^{-1}$, Banerjee & Pudritz 2007), a strong radiation field emerges from the accretion shock and the subsequently bloated star. The resulting radiation pressure will cause the dust envelope to disperse before the star reaches a high mass (Wolfire & Cassinelli 1987). Note that these are rather simplified estimates (assuming, e.g., a homogeneous density, spherical symmetry and an a pressure-free collapse) of timescales governed by complex physical processes.

Despite this problem, gravitational collapse is very likely a common mode of massive star formation (Krumholz et al. 2005; Bonnell & Bate 2006; Krumholz & Bonnell 2009). Simulations show that dispersion by radiation pressure is circumvented when matter
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Figure 1.5: Hertzsprung-Russell diagram of a selection of Galactic pre-main-sequence objects. Gray symbols represent T Tauri stars in the Taurus-Auriga cloud (open circles, Kenyon & Hartmann 1995), Herbig Ae/Be stars in various locations (filled circles, van den Ancker et al. 1998), and OB stars with infrared excess in M17 (filled triangles, Hoffmeister et al. 2008). Black symbols represent objects studied in this thesis; the circle indicates the supposed location of 08576nr292. PMS evolutionary tracks are overplotted; non-accreting models (Siess et al. 2000; Da Rio et al. 2009, dotted lines) and accreting models with $\dot{M}_{\text{acc}} = 10^{-4} \, M_\odot \, \text{yr}^{-1}$ (Hosokawa & Omukai 2009, dash-dotted line). Solid lines are the birthlines for these models.

accretes in a disk. The radiation escapes through the polar regions (Yorke & Sonnhalter 2002; Kuiper et al. 2010). Because of the influence of accretion on stellar structure, the location of the star in the HRD depends strongly on its accretion history (see Fig. 1.5; Hosokawa & Omukai 2009; Hosokawa et al. 2010). It is therefore difficult to establish whether massive stars have an observable PMS phase at all. Alternative birth scenarios that circumvent the radiation pressure may also be at work, like competitive accretion (Bonnell et al. 1998).
The observed large fraction of close binaries towards higher stellar masses implies that binarity plays an important role already in the formation process (Blaauw 1991; Kouwenhoven et al. 2007; Sana et al. 2012). Gravitational fragmenting of the massive circumstellar disk may be an important channel towards massive binary formation (Krumholz et al. 2009).

The observational record of forming massive stars is limited because of their rarity (and therefore, large distance), their short formation timescale, and their obscuration by dust in their birth cloud. Disks and outflows have been observed around several embedded objects with estimated masses exceeding 10 M\(_\odot\): massive YSOs (MYSOs; see references in Sect. 3.1). In most of these objects, radiation from the photosphere of the central star cannot be detected as it is absorbed by the circumstellar envelope. We are missing an essential probe of stellar evolution during cloud collapse. Mass estimates of MYSOs are in general derived from their bolometric luminosity. The work presented in this thesis partly builds on a survey of Galactic massive star-forming regions by Bik (2004), from which a sample of MYSO candidates was retrieved (Bik et al. 2006).

Lacking direct observations of massive star formation, our understanding of this process can be improved by several strategies. One of these is to study the signatures of the impact of young massive stars on their cloud and stellar environment (Chapter 2 and references therein). Alternatively, the scaling of the star formation process to higher masses may be studied in young intermediate-mass stars (2–10 M\(_\odot\)). These objects are less troublesome to observe than MYSOs and provide a limiting case for low-mass star formation.

In search of high-mass T Tauri star analogs, Herbig (1960) defined a class of A- and B-type stars exhibiting emission lines and associated with nebulosity. The current catalog of Herbig Ae/Be (HAeBe stars), as they became known, runs in the hundreds (Thé et al. 1994; Bjorkman et al. 2005; Carmona et al. 2010). They are intermediate-mass class II PMS stars surrounded by large amounts of circumstellar dust (for a review, see Waters & Waelkens 1998). For some objects, the classification as a young star is uncertain as they appear in isolation, and have characteristics that are also seen in evolved systems (see Chapter 7).

HAeBe stars can be seen as the more massive equivalent of T Tauri stars, but essential differences exist between these two types of YSO. First of all, HAeBe stars are scarcer than T Tauri stars. As outlined above, this is because more massive stars are fewer in number and evolve faster. Secondly, heat transport in the stellar envelopes of intermediate-mass stars is dominated by radiation rather than convection. This has consequences for their thermal structure and evolution, which will be strongly dependent on the accretion history (Palla & Stahler 1993). This is reflected by a changing stellar birthline as a function of accretion rate (Palla & Stahler 1990). The HRD displayed in Fig. 1.5 illustrates the difference between accreting (intermediate-mass) and non-accreting (low-mass) models for PMS evolution.

Lastly, the physical conditions in the inner disk region are different in stars more massive than the Sun. Because of their radiative envelopes, intermediate-mass stars are expected to have weaker magnetic fields. This calls into question whether the magnetospheric accretion model is appropriate (Hartmann 1999). Also, the high luminosity
and ionizing power of HAeBe stars implies there is a relatively large (AU-scale) inner region where no equilibrium population of dust can exist. This has consequences for the structure of the inner gas disk. At the observed accretion rates, the high density in the inner disk renders it optically thick (Hartmann et al. 1993). The disk structure is difficult to determine because of the different sources of opacity which are present (e.g., bound-free and free-free processes, H−, molecular lines; Muzerolle et al. 2004).

Even with an optically thick inner gas disk, the “inner rim” of the dust disk will be irradiated by the star, heat up and presumably increase in scale-height (Natta et al. 2001; Dullemond et al. 2001). HAeBe stars show a near-infrared excess component peaking at ~ 3 μm, well-fitted by a blackbody of ~ 1300 – 1800 K, which is in the same range as the evaporation temperature for typical silicate dust compositions. Many scenarios have been put forward to explain this excess, including dust emission from the inner rim, a dust halo, the inner gas disk, and a dusty disk wind. In a few objects, the apparent origin of this radiation is within the dust sublimation radius (Tannirkulam et al. 2008a), which disfavors the inner rim scenario (for a review see Dullemond & Monnier 2010; also see Chapter 5).

The differences between T Tauri and HAeBe stars are illustrated in Fig. 1.3. In spite of their different inner disk composition, signs of magnetospheric accretion are observed in HAeBe stars (Muzerolle et al. 2004). The accretion rate increases with stellar mass roughly as \( \dot{M}_{\text{acc}} \propto M_{\ast}^{2} \) (Muzerolle et al. 2003; Natta et al. 2004). This relation scales up to the intermediate-mass regime (Calvet et al. 2004; Garcia Lopez et al. 2006; Mendigutía et al. 2011; Donehew & Brittain 2011). Interestingly, a correlation between disk physics and stellar parameters is not a priori apparent, although some explanations for this observed correlation are given in the literature (Natta et al. 2006; Dullemond et al. 2006).

While molecular outflows are often seen around intermediate-mass and massive YSOs, only a handful of objects have been associated with atomic emission from a jet (Corcoran & Ray 1998; McGroarty et al. 2004; Grady et al. 2000, 2004; Carrasco-González et al. 2010; Chapters 4 and 5). This scarcity may be a bias effect due to the distance and luminosity of intermediate-mass objects, which makes it a challenge to observe HH objects in their vicinity. It is an intriguing question how accretion and jet launching are achieved in different inner disk environments.

Fig. 1.5 displays all the objects studied in this thesis in the HRD. The intermediate-mass objects span a wide range of stellar parameters and evolutionary states. To illustrate this, a selection of Galactic PMS stars and evolutionary models for low- and intermediate-mass stars is overplotted. The selection runs across the stellar mass range: T Tauri stars, HAeBe stars, and OB stars with infrared excess (which may represent the PMS phase for massive stars).
1.6 Accretion variability

A last aspect of accretion relevant for this thesis is its long- and short-term variability. Non-steady state accretion is a consequence of the complex interplay of rotation, magnetic fields, non-axisymmetric structure and gravitational torques in disk-jet systems. Episodic accretion, i.e., the occurrence of intense and relatively short-lived accretion bursts, is expected to manifest itself at all stages of the star formation process (Hartmann & Kenyon 1985; Hartmann et al. 1998; Hartmann 2009; Vorobyov & Basu 2010). For this reason, studying accretion also involves studying its variability, which is often difficult to achieve due to practical constraints.

Based on mostly circumstantial evidence, Fig. 1.6 displays a tentative picture of the evolution of the accretion rate over the formation process of a solar-mass star. The bulk of the mass is accumulated in the class 0/I stages; the accretion rate gradually decays towards the later stages as the mass reservoir empties. Observationally, the most extreme example of accretion variability presents itself in the class of FU Orionis objects (FUor). These objects show a sudden (within ~ 1 yr) brightness increase of 5 mag or more that decays slowly (over decades). These events are attributed to thermal disk instabilities and probably occur more than once over the formation time of a star. Material from the gas and dust envelope slowly piles up in the disk, and is finally released in an outburst, during which the accretion rate increases by several orders of magnitude. Despite their rarity, a significant portion of a star’s final mass is expected to be accreted...
through these events (Herbig 1977; Hartmann & Kenyon 1996; Zhu et al. 2007).

Another class of objects which show similar bursts of accretion are the EXor objects (named after the prototype EX Lupi, Herbig 1989). EXor bursts fade much more quickly (within less than one year) than FUor outbursts; in some cases, multiple events have been recorded (e.g., Ábrahám et al. 2009; Hillenbrand et al. 2013). Both the accretion and the ejection of dust clouds have been found to contribute to the variability (Kóspál et al. 2013). It may well be that like in FUors, thermal and gravitational instabilities cause the outbursts in EXors. In various other objects, less intense modulations of the accretion rate are observed on shorter timescales, allowing for a better coverage in the time domain (see references in Sect. 4.5.1).

Variability of accretion and outflow appears in various contexts in this thesis. Variability may be probed by the “jet fossil record” as described in Sect. 1.3. This hypothesis is explored in Chapters 4 and 5. The system described in Chapter 6 is thought to be in the process of clearing its disk, or in a phase between accretion episodes. Chapter 7 describes a system which frequently undergoes outbursts.

1.7 Observations: the new generation

Signatures of star formation can be observed across the entire spectral domain: from the radio and far-infrared (cold cloud and disk material), through the near- and mid-infrared (warm gas and dust in disks), up to the optical, UV and X-ray domain (stellar photospheres, winds and accretion shocks). Multi-wavelength data from a broad selection of observatories is presented in this thesis. A prominent role is reserved for the spectrograph VLT/X-shooter.

X-shooter is mounted on the Cassegrain focus of the Unit Telescope 2 of the Very Large Telescope (VLT, Fig. 1.7) on Cerro Paranal, located in the Chilean Atacama Desert and operated by the European Southern Observatory (ESO). The light collected by the 8.2 m mirror is split and dispersed in three separate echelle spectrographs or “arms”. These cover the near-UV (UVB, 300–590 nm), the optical (VIS, 550–1020 nm) and near-
infrared (NIR, 1000–2480 nm). The length of the slit is 11′′; its width can be set individually in each spectrograph arm (D’Odorico et al. 2006; Vernet et al. 2011). This results in a typical resolving power ($\lambda/\Delta\lambda$) of ~5000 (UVB) up to ~11,000 (NIR).

Designed as a multi-purpose spectrograph (its name refers to “object X”), X-shooter is particularly well-suited to study accretion and outflow in star formation. The unprecedented spectral range catches many signatures of both the star and its circumstellar material in one “shot”. Diagnostics across the spectral range can be compared simultaneously. Continuum emission from star and disk and emission lines from disk, jet and accretion region are all simultaneously mapped. Every chapter in this thesis features results from X-shooter, which were observed as part of the Dutch Guaranteed Time Observations.

A variety of other state-of-the-art instruments and facilities have been utilized for the work presented in this thesis. Two of these are VLT instruments which operate in the near-infrared. VLT/SINFONI is well suited to study stellar populations, jets and the nebulous regions in which they are embedded (Chapters 2 and 3). With VLTI/AMBER (the I stands for Interferometer), which combines the light of multiple 1.8- or 8.2-meter telescopes, it is possible to study small (milli-arcsecond) scale circumstellar environments, as demonstrated in Chapter 7.

Space-born observatories provide a window on spectral ranges unaccessible from the ground. Data from optical and infrared space telescopes are therefore of great value to studying star formation and are also featured in this thesis. The NASA Hubble Space Telescope UV and optical images and spectra of a jet are featured in Chapter 5. The NASA Spitzer Space Telescope provides images and spectra in the mid-infrared (Chapters 2 and 6). The Herschel Space Observatory, operated by the European Space Agency, imaged the large-scale cluster environment presented in Chapter 2 in the far-infrared.

A new generation of high-precision instruments have recently become available or will see first light in the following years. One of these is the Atacama Large Millimeter/submillimeter Array (ALMA), a joint project of Europe, North America, East Asia and Chile. Located at 5000 meters altitude in the Atacama Desert, it is an interferometer which consists of more than sixty antennae. It provides images and spectra of the cold gas and dust (key in star formation) at very high spatial resolution and sensitivity. Data from ALMA and VLT/X-shooter are for the first time combined in Chapter 5.

Planned facilities that astronomers studying star formation (and all other astronomers, for that matter) look forward to include colossal optical and near-infrared telescopes like the European Extremely Large Telescope, the Giant Magellan Telescope, and the Thirty Meter Telescope, and the giant radio telescope Square Kilometer Array. In space astronomy, all eyes are on big projects like the James Webb Space Telescope (infrared) and Gaia (optical astrometry).
1.8 This thesis

In this thesis, cutting edge observational facilities and innovative methods are combined to better understand the dynamical process of star formation. The general strategy is to determine a system's history and evolutionary state by mapping its circumstellar gas dynamics. The objects under scrutiny are young (< 5 Myr) intermediate-mass stars (roughly 2 to 10 M⊙, see Fig. 1.5 for their location on the HRD). These stars are special for several reasons. Firstly, their higher mass implies a high accretion rate and fast evolution. Secondly, because of their high luminosity and different stellar structure, the physics of their formation process is expected to deviate from their low-mass counterparts.

This work presents a view on star formation from large scales: the cluster environment where most stars form, to small scales: the dynamics of the gas close to the surface of a young star. In every chapter, the main question concerns the history of the system. Throughout, X-shooter plays a crucial role in the spectral diagnosis of the young stellar systems.

We attempt to probe processes that take place on timescales that exceed a human lifetime by many orders of magnitude, where sometimes only a single measurement is available. We are looking for a clock hidden in the data.

In Chapter 2, the clock is provided by the cluster environment. A census is presented of the young stellar population of the embedded cluster RCW 36. By carefully comparing their stellar spectra with pre-main-sequence evolutionary models, we attempt to reconstruct the star formation history. The clock is mass-dependent: low-mass stars are less evolved than high-mass stars. About 1 Myr ago, two 20 M⊙ stars have formed. Their intense radiation pressure probably shaped the nebula around them. They co-evolve with a low and intermediate-mass stellar population, that has not yet arrived on the main sequence. An even younger generation is forming on the outskirts of the nebula. The analysis illustrates the progression of star formation in the proximity of massive stars, a common circumstance for stars in the Galaxy.

In Chapter 3, the discovery of two Herbig-Haro jets (subsequently dubbed HH 1042 and HH 1043) in RCW36 is reported. One of these, HH 1042, is driven by a very young intermediate-mass star, 08576nr292, in an extreme state of accretion. A heuristic analysis of the spectral diagnostics is made: lines originating in the disk, the outflow and the accretion column can be distinguished based on their line profile. While the photospheric spectrum is veiled by continuum emission from the disk, clues to its evolutionary stage can be found in its circumstellar material. This chapter demonstrates the diagnostic potential of X-shooter to study these extreme objects.

The two jets HH 1042 and HH 1043 are studied in detail in Chapter 4. The emission lines in the spatially resolved X-shooter spectra of these objects are used to diagnose the physical conditions along the jet in great detail. The nearby massive stars seem to be contributing to the anomalously high excitation conditions in the jets. In the second part of the chapter, the kinematics of the HH 1042 jet are used as a clock to map the outflow history of the system. From this, we deduce a typical timescale of 300 yr for the outflow variability. This method shows that the history of highly variable systems can...
be reconstructed up to thousands of years, using only a single observation.

The same method is applied to the X-shooter spectrum of the jet from the Herbig Ae star HD 163296 (Chapter 5). This object, like 08576nr292, belongs to the small group of intermediate-mass stars that are associated with Herbig-Haro objects. The jet has a regularly spaced knotted structure, suggesting a history of periodic outbursts. Although the lobes are asymmetric in terms of velocity and physical conditions (just like HH 1042), their outflow history seems to be synchronized. The historic lightcurve of the source displays episodic optical fadings and near-infrared brightenings. We conclude that these are caused by dust ejections, possibly caused by the same mechanism responsible for the jet structure. This analysis provides new constraints on jet launching and its variability in young intermediate-mass systems, while also introducing a novel method to study variable phenomena.

In Chapter 6, another rare species of YSO is investigated: the Herbig Be-like star B275 in the Omega Nebula (M17). The sensitivity of X-shooter facilitates an unprecedentedly accurate spectral classification, while the well-known distance to M17 constrains its luminosity. The star has an early-B luminosity but a relatively cool surface temperature and low surface gravity; it is located above the main sequence in the HRD. B275 is one of the most luminous stars known which are still in the PMS phase. Such massive stars are expected to have very high accretion rates and evolve quickly through the HRD; it is debated whether they have an observable PMS phase at all. Although a circumstellar disk is present, B275 does not show any signs of active accretion. Its discovery challenges PMS evolutionary models: either the star has just emptied out part of its inner disk in an accretion episode, or the disk is currently being photo-evaporated.

In Chapter 7, we zoom in further on the circumstellar material of a star that quite literally does not show its age. The object under scrutiny is HD 50138, a so-called B[e] star. Its appearance is very similar to B275: a B-type star with low surface gravity, surrounded by a copious amount of circumstellar dust in a disk or envelope. Its evolutionary status is a mystery; it bears characteristics which are seen in both pre- and post-main sequence systems. Spectro-interferometric observations at milli-arcsecond spatial resolution constrain the kinematics of the circumstellar gas of this system at unprecedented scales. We find strong evidence of a rotating gas disk at the sub-AU scale. These findings help to constrain the evolutionary path which has lead to such a peculiar system.

Image credits for Fig. 1.2


The opening quote for this chapter is from Herbig (1970).