Star formation history written in spectra
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One of the major questions in astronomy is: how do stars form? The answer is – literally – enshrouded in mystery. The dust and gas clouds out of which stars form hinder observations of the star formation process. A forming star radiates energy, which is reprocessed into infrared radiation by the surrounding cloud. In the past fifty years it has become possible to observe this radiation and to put theories of star formation to the test. Our knowledge of the process has increased tremendously, but many questions remain. Three of these play a central part in this thesis.

We study the formation of stars more massive than the Sun. These stars are important for the development of stellar populations because of their ionizing radiation and rapid evolution. Unfortunately, their accretion process is difficult to observe as they are small in number and form on a short timescale. A second question concerns jets, which are essential for the star formation process, but are only seen around a few young stars. These jets slow down the rotation of the collapsing cloud, enabling the formation of a central star. How they are launched is an important question. A third question is how the formation process of a star develops: does a star grow gradually, or in bursts?

Every day, a new star is born in the Milky Way, but a single stellar birth can take millions of years. As we will never be able to witness the entire process, we have to make do with snapshots. The challenge is to derive as much as possible about a star’s recent formation history from a stationary image. This history is hidden in the spectrum of the star.

This thesis maps the star formation process from large to small scale. First, we describe a typical birth environment: a star cluster. We then zoom in on a number of individual systems in this and other star formation regions. The components which make up these objects are the topics of the other chapters: the disk, jets, and finally the young star itself. Throughout, the direct environment of the star is treated as a crime scene. We use it to derive how the star was formed and which stage of its life (or evolution) it has reached. The goal is to describe the formation and evolution of stars as a function of their mass and their surroundings.
Summary

Spectra

The spectrum shows the amount of light radiated as a function of wavelength. This determines the color, which in turn depends on the temperature of the source. In our case, the light source is located at a large distance and in many cases cannot be spatially resolved. The spectrum is then the result of star and its direct surroundings.

At specific wavelengths, dark and bright lines appear in the spectrum. Here, light is absorbed or emitted in excess of the background. This is a consequence of the interaction of starlight with the surrounding dust and gas. Each atom, ion or molecule species in a gas has a unique “fingerprint” of spectral lines on different sets of wavelengths. The spectral lines shift if the source is moving. If the source moves away from the observer, a spectral line is observed at a longer wavelength; the wavelength of an approaching source is shorter. This is the Doppler effect. In an everyday example, an ambulance siren lowers its pitch as it rushes past, because sound, like light, is made up of waves.

Through its color, spectral lines, and Doppler shift, the spectrum contains a wealth of information on the composition and motions of the star and its surroundings. Many of the spectra presented in this thesis have been observed with X-shooter, a spectrograph with a broad wavelength coverage – from the ultraviolet up to the near-infrared. The instrument is mounted on one of the 8.2 m mirrors of the Very Large Telescope, operated by the European Southern Observatory in Chile.

A young and massive stellar population

In Chapter 2 a census is presented of a young stellar population named RCW 36. The stars are situated in the Vela Molecular Cloud, a gigantic dust and gas cloud spanning more than a hundred lightyears, located at a distance of 2300 lightyears from Earth. In the middle of this cloud a gap is visible of ten lightyears across. At this location, the cloud collapsed under its own gravity, resulting in a group (cluster) of hundreds of stars. The two most massive stars have a mass of about twenty solar masses each. Their radiation has blown out the surrounding dust and widened the gap, thus revealing the stellar “nursery”.

What is the formation history of this star cluster? The role of the massive stars may be crucial. Have these formed first and set the rest in motion by their radiation and stellar winds, or did the entire population form simultaneously? To answer this question, we determine the temperature and luminosity of as many stars in the cluster as possible. We compare these with theoretical stellar evolution models, which allow us to estimate the mass and age of the stars. Additionally, the size of the gap yields an estimate of the age of the massive stars. We have determined that the population, including the massive stars, has formed about a million years ago. At the edges of the region we have found a few stars which are probably younger than that. These are the subject of the next two chapters.
Disks and jets

The discovery of a disk and jets around the young star 08576nr292 was reported in Chapter 3. These are common features of a young star, which starts out as a cloud contracting through gravity. As the particles in the cloud are not stationary, they will not be drawn to the middle directly, but slowly rotate around it. The more the particles are drawn to the middle, the faster their rotation. Their angular momentum, the product of their momentum and the lever arm, is conserved. The same thing happens when one sits in an office chair and draws in two bricks: the chair will rotate faster. The cloud’s spin induces a centrifugal force perpendicular to the rotation axis. This force counteracts gravity only in the plane of rotation. As the material falls unhindered towards this equatorial plane, it settles and forms a flat disk.

Friction in the disk transfers momentum between particles on neighboring orbits. Particles do not remain in orbit, but spiral inwards, towards the middle of the disk, where a star forms. This growth process, which is driven by gravity, is called accretion. The largest part of the cloud’s angular momentum does not end up in the star, but is transported outwards. Part of it is carried away by a magnetic field perpendicular to the disk. The rotation slings the material away along the magnetic field lines. At the poles, two jets form: a flow of optically thin, hot gas, that propagates through the interstellar medium at supersonic velocities (hundreds of kilometers per second).
The star 08576nr292 is less than a million years old. Its mass is estimated at two to five solar masses. The spectrum contains many emission lines. Most of these originate in a dense gas disk, from which material accretes onto the star. On both sides of the star, two jets of approximately 0.15 lightyears are visible. This is rarely seen around the more massive stars. The jets also produce emission lines. By measuring their Doppler shift the velocity of the gas can be determined. We have thus established that the jets propagate in opposite direction with hundreds of kilometers per second. The results of this research drew the attention of the press (Fig. A).

Jets: fossils of star formation?

In Chapters 4 and 5 we study three young stellar objects with jets (among which 08576nr292) in more detail. From the jet spectra we determine their mass loss rate and velocity. With this information, we disentangle the formation history of the star. The jets do not show a smooth flow, but consist of shock fronts. The position and velocity of a shock front are used to estimate its age. The further downstream a shockfront is located, the longer ago the material was ejected. This moment is possibly co-timed with a “grow spurt” of the star. This method may be compared to counting tree rings. The thickness of the ring indicates how much the tree has grown in a year. Similarly, jets contain a fossil record of the star formation process.

The shock fronts in the 08576nr292 jets are not symmetrical between both sides of the star. This provides the insight that the launch process is not synchronized between both sides of the disk. The shockfronts seem to be created every three hundred years. This implies the existence of cyclic physical processes in the disk which influence the jet outflow rate and possibly also the accretion rate. The second system in RCW 36 described in this chapter has a similar jet structure.

In Chapter 5 we present an analysis of the jet of HD 163296, a young star of more than two solar masses. The shock fronts in the jet are created on a regular interval of 16 years. We have also discovered that over the past 40 years, the star has experienced a number of fading episodes. During the longest of these, the star dimmed down to half its normal brightness level for more than six months. This was most likely caused by dust clouds which are launched above the disk plane and obscure the star like a curtain. The periodic appearance of shock fronts in the jet may be related to this dust launching. These studies show that the fossil information contained in jets traces dynamical processes that develop over a long time.

Two unusual stars

The last two chapters contain an analysis of two stars which look alike, but are different in nature. They have a comparable luminosity and surface temperature; both have a mass of five to ten solar masses. Both are surrounded by a large dust and gas disk. What sets them apart is their environment and possibly their evolutionary status.
One of these stars, B275 (Chapter 6), is located in the Omega Nebula, also known as Messier 17. This is a region in the Galaxy at a distance of 6500 lightyears from the Earth, harboring a large population of recently formed massive stars. From the X-shooter spectrum of the star we accurately determine its luminosity and surface temperature. From these we find that the star is very young: less than half a million years old. This can be understood by considering the early evolution of a star (see Fig. B).

Stars are born as gas giants. A young star contracts through gravity, which generates radiation. Initially, radiation from this process dominates the energy output. The luminosity and surface temperature change as a function of the mass and age of a star in the contraction phase. The star slowly heats, until the temperature in the core has reached the point where nuclear fusion of hydrogen into helium is ignited. An equilibrium is reached between the gravity, which compresses the star, and the outward gas pressure. This is called the main sequence phase. It remains stable for a long time; a Sun-like star lives on the main sequence for ten billion years.

A more massive star has a shorter main sequence age. This may be explained by the fact that the luminosity scales with roughly the third power of the mass. A star which is twice as heavy is brighter by a factor eight and will (approximately) run out of nuclear fuel four times as fast. The evolution before the stable main sequence phase also develops faster for massive stars. Our observations of B275 suggest that it has a mass of approximately six solar masses and is still in the process of contraction. Only a limited sample of these objects have been discovered so far. Additionally, it is peculiar that while the star is surrounded by a disk, the accretion rate seems to be low. We suspect that the star is in between two accretion episodes (“growth spurts”) and that the disk

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**Figure B:** Illustration of the evolution of a star more massive than the Sun (not to scale). *Left:* A disk and jets are visible; the accretion rate is high. *Middle:* The jets have disappeared, the disk gradually dissipates and the star shrinks. *Right:* The “naked” star has arrived on the main sequence. For a star like B275 the formation process takes up to half a million years.
gradually evaporates through the radiation of the star.

The topic of Chapter 7 is HD 50138, a star at a distance of about 1500 lightyears, which is still a mystery after nearly a century of research. Its luminosity and surface temperature are comparable with those of B275. Likewise, the star is surrounded by a hot dust and gas disk. Apart from young stars, some old stars also have disks, resulting from mass loss at the end of their main sequence lifetime. This star is not located in a cluster, which would have been a strong indication of a young age. The age therefore remains uncertain. Fluctuations in brightness level and spectral lines on timescales from days to years suggest the system has a complex geometry.

In this study, we use interferometry, an observational technique where the light beams from multiple telescopes are combined simultaneously. In this way the effective diameter of the telescope is increased and smaller details may be resolved. The observations are focused on Brackett-γ, a spectral line of hydrogen which is formed in the direct environment of hot stars. By mapping the Doppler shift of the line we have discovered a rotating gas disk. The disk radius is approximately equal to the orbit of the Earth around the Sun. It is the first time that this object has been observed in such spatial detail. Possibly, HD 50138 is a binary star: two stars which revolve around each other and – when they closely approach – may transfer mass through gas flows. This may produce a disk and also contribute to the variability of the spectrum.

The objects studied in this thesis are peculiar examples of stellar evolution. By using the best telescopes in the world in innovative ways, their surroundings and formation history is exposed. The clouds which enshroud young stars have lifted a little.