Doctoral Thesis

Accretion variability in low-mass young stellar objects

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“Éjszaka majd folnézel a csillagokra. Az enyém sokkal kisebb, semhogy megmutathatnám, hol van. De jobb is így. Számodra az én csillagom egy lesz valamerre a többi csillag közt. Így aztán minden csillagot szívesen nézel majd... Mind a barátod lesz.”

Antoine de Saint-Exupéry: A kis herceg

“And at night you will look up at the stars. Where I live everything is so small that I cannot show you where my star is to be found. It is better, like that. My star will just be one of the stars, for you. And so you will love to watch all the stars in the heavens... they will all be your friends.”

Antoine de Saint-Exupéry: The Little Prince
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The formation of Sun-like stars has been in the interest of astronomers for a long time. In the past decades, the available telescopes and instruments have significantly improved, which allowed astronomers to study young stellar objects in detail never seen before. The Konkoly Observatory in Budapest hosts researchers focusing on star formation and young stellar objects for decades, and the Konkoly Space Astronomy, Planet and Star Formation Group is continuously increasing. The researched subjects cover a wide range of topics, including young eruptive stars, interferometric studies of the circumstellar environments, examination of debris disks, compilation of catalogs of young stars, and also modeling of planet formation.

I got in contact with the examination of young stellar objects during my MSc studies, when I applied for the “Piszkéstető Demonstrator Program” started by Konkoly Observatory, which allowed university students to join the scientific research at the observatory under the supervision of one of the institute’s researchers. Thanks to this program and Ágnes Kóspál, who became my supervisor, I gained insight to a research field that was completely new to me: star formation. I was immediately involved in several projects, including working on data from the observatory’s Piszkéstető Mountain Station but also had the opportunity to analyze space telescope data from the Kepler and Spitzer space telescopes. Moreover, I regularly carried out observations at the Piszkéstető Mountain Station with the 1 m class telescopes. I learned how to operate the telescopes, how to reduce their data, and after some time, I became responsible for writing the telescope time proposals for the Piszkéstető observatory on behalf of our research group. During this time, I discovered how much I enjoy observational work (despite – or rather thanks to – the sleepless nights by the telescopes), and how fascinating the world of young stars is. I realized that these systems that form before our eyes are just like the Solar System at its youth, and by studying them, we might gain information on how our Solar System formed. This experience led to design the PhD project with my supervisor of studying star formation – on the basis of which this thesis was prepared.
When starting the PhD, I joined the SACRED ERC group led by Ágnes Kóspál, thanks to which I became part of a thriving community of international researchers from the field of star formation. First, I studied multifilter light curves of young stellar objects obtained by both ground-based and space telescope observations. The Transiting Exoplanet Survey Satellite (TESS), which started operating in 2018, gave a great opportunity to continue this aspect, because we quickly realized that despite it is aimed to study exoplanets, it will also visit star forming regions. But by studying the light curves of young stars, I realized how much additional information is available if one could obtain spectra for them. Besides TESS, another instrument that became available for the astronomer community in 2018, around the time I started my PhD, is the ESPRESSO high resolution spectrograph on the Very Large Telescope at the European Southern Observatory. For this reason, my supervisors and I wrote a successful DDT proposal to monitor the spectroscopic variability of certain young stars contemporaneously with the TESS observations. This prompted my attention to work more closely with ESO instruments, therefore, I applied for the ESO Studentship Program. Thanks to my successful application, I was able to spend one year at the headquarters of ESO in Garching (Germany) and worked on a project under the supervision of Gaitee Hussain and Carlo Manara.

After coming back from ESO, I continued to work on high-resolution spectroscopic and multifilter photometric studies of young stars, where I took great advantage of all the knowledge I gained during this year abroad. In the future, I am continuing to study the accretion process of young stars, however, I am going to explore later some new directions as well. The accretion process is observed not only during the star formation process, but it occurs in several other astrophysical systems from accreting black holes to forming planets. Thanks to a postdoc position offer, I am joining a research group at the University of Leicester which will study the accretion disks of various astrophysical systems.
Chapter 1

Introduction

Stars are continuously being born in star forming regions across the Milky Way with a star formation rate of around $3 - 5 \, M_\odot/\text{yr}$. They form in groups, within interstellar molecular clouds, mainly in giant molecular clouds. The most well-known star forming regions include the Taurus, Chamaeleon, Orion, Lupus, Scorpius, which regions accommodate a large number of low-mass young stellar objects (YSOs). In this Chapter, I summarize the mechanism of low-mass star formation following Ward-Thompson & Whitworth (2011). I then focus on the magnetospheric accretion process, introduce YSOs with various levels of accretion rate, and describe the observational signatures of the accretion process and its accompanying physical mechanisms, such as winds and outflows.

1.1 Formation of low-mass stars

Stars form in interstellar molecular clouds through gravitational collapse. These cold (T≈10K) clouds mainly consist of molecular hydrogen and contain dust to smaller extent, with a dust-to-gas mass ratio of approximately 1:100. The mass of the clouds range from a few thousand solar masses up to a million solar masses, and they have a size ranging from 0.1 pc to 100 pc. Their average density is 100 – 1000 particles per cubic centimeter, however, the distribution of the gas and dust is not uniform within the cloud. Over time, the cloud fragments, and regions with higher density ($n \sim 10000 – 100000 \, \text{cm}^{-3}$) can form: these are the cloud cores, which are the sites of star-formation. The Jeans criterion describes the stability of a molecular cloud against fragmentation and collapse: the smallest clump which can collapse is characterized by the Jeans radius $R_J \simeq \left( \frac{15}{4\pi G \rho_0} \right)^{1/2} a_0$ and the Jeans mass $M_J \simeq \left( \frac{475}{4\pi} \right)^{1/2} \frac{a_0^3}{G^{3/2} \rho_0^{1/2}}$, where $G$ is the gravitational constant, $\rho_0$ is the initial density of the medium, $a_0$ is the
isothermal sound speed. When $M_0 > M_J$, the molecular cloud becomes gravitationally unstable and starts to contract, then to fragment. As its density is increasing, the Jeans mass is decreasing, which causes smaller regions (the fragments) of the original cloud to contract themselves. The fragmentation can occur repeatedly and hierarchically, until the gas is no longer isothermal.

The contraction can be triggered by an external effect, such as a shockwave of nearby supernova explosions or a gentler tide caused by a star passing by; and the collapse occurs on the free-fall timescale: $t_{ff} = \left(\frac{3\pi}{32G\rho_0}\right)$. However, the turbulence and the magnetic field of the medium contributes to the deceleration of the collapse. When no mechanism is maintaining the turbulence, it slowly dissipates, and the cloud core is able to slowly form, which collapses further due to the gravitational contraction. The object becomes unstable as the contraction proceeds, and the core collapses on the free-fall timescale. Initially, the cloud core is radiating the heat away faster than it is released due to the collapse, since it is transparent to its own thermal radiation. This is the phase of the isothermal collapse.

A protostar, with a mass of $\sim 0.01 M_\odot$, is formed in the center after $10^4$–$10^5$ years of the beginning of the collapse, when the central region reaches a density of around $10^{-13} \text{ g/cm}^3$. At this moment, it becomes optically thick, the radiation cannot escape as efficiently as it did previously, therefore, the temperature rises and the pressure increases in the inner region, which halts the collapse. The central object is still surrounded by the remnants of the parent cloud. Part of this circumstellar material is falling onto the surface of the protostar and part of it forms an accretion disk. Indeed, as the size of the envelope is decreasing, the rotational speed is increasing due to the conservation of angular momentum, and the remnant of the cloud is only able to collapse parallel to the rotational axis, therefore, it forms a disk in the equatorial plane.

The temperature of the central protostar is continuously increasing. First, it reaches a few million K, which is sufficient for deuterium fusion to start. At this evolutionary stage, the accretion rate can vary on a wide range ($10^{-5} - 10^{-7} M_\odot/\text{yr}$) (Bontemps et al., 1996). For this reason, the mass of the central object differ from system to system. The further evolution for the low-mass ($M \leq 2 M_\odot$), intermediate-mass ($2 M_\odot \leq M \leq 8 M_\odot$) and the high-mass ($M \geq 8 M_\odot$) stars deviates at this point; here, I focus on the former. Low-mass stars become fully convective when they reach the deuterium ($^2\text{D}$) burning phase. The strong magnetic field (few kG) of the star generates outflows, for example stellar winds. The mass loss due to the wind decreases the total accretion rate, and it blows away the envelope surrounding the star. Eventually, the system becomes visible at the optical wavelengths, thus the star appears on
1.1. Formation of low-mass stars

The birthline of the Hertzsprung-Russell diagram. The deuterium burning phase does not last long (few million years). When the star runs out of $^2$D, a contraction phase starts again which increases the central temperature. During this stage, the star is still accreting material from the circumstellar disk, however, the mass accretion rate is very low. When the central temperature reaches $10 - 15 \text{ million K}$ required for the hydrogen fusion, the central object becomes a main-sequence star.

1.1.1 The spectral energy distribution of young stellar objects

The examination of the wavelength dependence of the emitted flux of a YSO leads to an interesting result: different regions of the YSO emit at different wavelengths. This property allows studying distinct regions of the central star and its surrounding disk and envelope. By examining the spectral energy distribution (SED) of these objects, we can analyze the structure, the geometry and the different components of the system. Modeling the individual constituents can help in understanding the observations. As an example, Guarcello et al. (2010) presented a model (Fig. 1.1) including emission from the reddened photosphere of the central star ($\sim 0.8 - 30 \mu\text{m}$), radiation scattered by the disk into the line of sight ($\sim 0.4 - 6 \mu\text{m}$), emission from a collapsing outer envelope ($> 9 \mu\text{m}$), and thermal emission from a circumstellar disk ($> 7 \mu\text{m}$).

Lada & Wilking (1984) and Lada (1987) studied the SEDs of forming stars and based on the shape of the SEDs, defined three morphological classes, which correspond to three consecutive evolutionary stages of star formation (Class I–III in Fig. 1.2).

![Figure 1.1: The SED model (solid curves) that reproduces the observed SED (black points) of a young star (6611-27 750). Left: The expected unreddened photospheric flux (dashed curve) is plotted over the data points and the model. Right: The different components of the SED model are indicated with different kind of curves, as explained in the top of the panel. From Guarcello et al. (2010).](image)
Chapter 1. Introduction

Figure 1.2: The classification of young stellar objects based on the Lada & Wilking (1984) classification scheme, which was extended with Class 0 by André et al. (1993). $F_\lambda$ is the total radiated flux at the wavelength $\lambda$. From André (1994).
1.1. Formation of low-mass stars

This classification scheme is based on the so-called spectral index ($\alpha$), which is defined as the slope of the SED in the mid-infrared wavelength range:

$$
\alpha_{\text{IR}} = \frac{d \log(\lambda F_\lambda)}{d \log(\lambda)} = \frac{d \log(\nu F_\nu)}{d \log(\nu)},
$$

where $\lambda$ is the wavelength, $\nu$ is the frequency, $F_\lambda$ and $F_\nu$ are the flux densities. The spectral index is calculated in the near- and mid-infrared region, in the wavelength interval of 2–25 µm. In addition to the three classes defined by Lada & Wilking (1984), Greene et al. (1994) introduced a further intermediate class, the “flat-spectrum sources” (FS), which is an intermediate stage between Class I and Class II YSOs. The earliest evolutionary stage, the Class 0 was later added to the original classification scheme by Andre et al. (1993), when instrumentation became sensitive enough to detect faint far-infrared and millimeter emission, since these objects are undetectable at $\lambda < 20$ µm. Table 1.1 summarizes the main physical properties and observational characteristics of the YSO classes, and they are further described in the following.

In the case of Class 0 objects, the youngest systems in this classification scheme, the peak of the SED appears at the far-infrared or millimeter wavelengths (Fig. 1.2, first row), and its shape closely resembles the SED of a single temperature blackbody with a temperature barely higher than that of the cloud cores (i.e., a few tens of K). The circumstellar disk has already started to form at this stage, almost immediately after the cloud core collapses, however, these sources are still deeply embedded in the parent cloud and are surrounded by significant amount of circumstellar material made of gas and dust ($M_{C*} \geq 0.5 M_\odot$). For this reason, any radiation at shorter wavelength is absorbed and reradiated at longer wavelength. The SED of Class I objects peaks at the far- and mid-infrared wavelengths, and they can be observed at near-infrared wavelength as well (Fig. 1.2, second row). At this evolutionary stage, continued infall is detected from the cloud and the central object is accreting material from the circumstellar environment. The star is still deeply embedded in an envelope made of gas and dust, but the amount of circumstellar matter is decreasing ($M_{C*} \leq 0.1 M_\odot$) and the dust envelope has been cleared enough to reveal the hot gas and dust close to the star. The far-infrared peak is caused by the absorption and reradiation of the near-infrared flux by the remaining dust in the envelope. The system is still invisible at optical wavelengths. On average, this phase lasts for $\sim 0.5$ Myr.

Class II objects are considered to be the classical T Tauri stars (CTTSs), which were named after the prototype: T Tauri in the Taurus star forming region. A large fraction of the envelope has already fallen onto the star by the time they reach this evolutionary stage, and the remnants of the circumstellar matter form a disk around the
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<th>Physical properties</th>
<th>Observational characteristics</th>
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<tr>
<td>0</td>
<td>-</td>
<td>$M_{\text{env}} &gt; M_{\text{star}} &gt; M_{\text{disk}}$</td>
<td>No optical or near-IR emission</td>
</tr>
<tr>
<td>I</td>
<td>$\alpha_{\text{IR}} &gt; 0.3$</td>
<td>$M_{\text{star}} &gt; M_{\text{env}} \sim M_{\text{disk}}$</td>
<td>Generally optically obscured</td>
</tr>
<tr>
<td>FS</td>
<td>$-0.3 &lt; \alpha_{\text{IR}} &lt; 0.3$</td>
<td>$M_{\text{disk}}/M_{\text{star}} \sim 1%$, $M_{\text{env}} \sim 0$</td>
<td>Intermediate between Class I and II</td>
</tr>
<tr>
<td>II</td>
<td>$-1.6 &lt; \alpha_{\text{IR}} &lt; -0.3$</td>
<td>$M_{\text{disk}}/M_{\text{star}} \ll 1%$, $M_{\text{env}} \sim 0$</td>
<td>Accreting disk; strong H\alpha and UV</td>
</tr>
<tr>
<td>III</td>
<td>$\alpha_{\text{IR}} &lt; -1.6$</td>
<td>$M_{\text{disk}}/M_{\text{star}} \ll 1%$, $M_{\text{env}} \sim 0$</td>
<td>Passive disk; no or very weak accretion</td>
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Table 1.1: The extended classification of young stellar objects based on the SED (Lada & Wilking, 1984, Greene et al., 1994, Andre et al., 1993). From Williams & Cieza (2011).

central source. The system has become an optically visible pre-main-sequence (PMS) star, and the observed radiation is dominated by the stellar photosphere, as we can directly see the star from most viewing angles (Fig. 1.2, third row). The emission at infrared wavelengths is dominated by the disk. By the final stage of star formation, i.e. Class III objects, the majority of the disk is dispersed or started forming planetesimals and planets. Therefore, these objects exhibit only little infrared excess due to the remnants of the circumstellar disk (Fig. 1.2, fourth row). The SED is dominated by the stellar radiation at the visible wavelengths but they are still more luminous than main sequence stars of the same effective temperature. The Class III sources are also named weak-line T Tauri stars (WTTSs). It must be noted that the above described classification scheme does not take into account geometrical effects, which can influence the observed SED. For example, edge-on disks can highly extinct the star, which would suggest a more embedded and less evolved system based on the observation.

In this thesis, I am focusing on objects at those later stages of the evolutionary process, in which they are surrounded by a circumstellar disk and the central object is still accreting material from the disk. These objects include, for example, classical T Tauri stars and FU Orionis-type objects, which are described in Sect. 1.4 in more detail.

1.2 Magnetospheric accretion model

The presence of strong magnetic fields, with strengths up to a few kilogauss (kG), have been suspected in YSOs for a long time based on their strong X-ray emissions (Montmerle et al., 1983). The magnetic fields of young stars are complicated to analyze since the rapid rotation typically confuses the Zeeman and the Doppler broadening of spectral lines, however, methods have been developed to allow their detection using high-resolution echelle spectropolatimetric observations. Cross-correlation techniques, such as the Least-Squares Deconvolution, can compute an average line profile from
1.2. Magnetospheric accretion model

Figure 1.3: Schematic view of a young star accreting from a disk through the stellar magnetosphere. The figure is not to scale. From Hartmann et al. (2016).

Thousands of spectral lines and enhance the magnetic field generated Zeeman signature in the shape and the polarization state of the spectral lines. For cool stars, Zeeman-Doppler imaging (ZDI) is the most widely used technique to recover magnetic field signatures and maps (Donati et al., 1997, Johns-Krull et al., 1999). The magnetic field plays a fundamental role in regulating the physical mechanisms that occur in YSOs: it governs the activity, the star-disk interaction, the outflows (including stellar winds, disk winds, jets), it affects the inner disk structure, and it controls the accretion process.

The accretion process of young stars is best described with the so-called magnetospheric accretion model (Camenzind, 1990, Romanova et al., 2003, 2011, Hartmann et al., 2016). This model, in principle, assumes that the stellar magnetosphere truncates the circumstellar disk at a distance of a few stellar radii, and channels the disk material to the star in accretion columns or funnel flows (Fig. 1.3). First, the disk material is transported inwards to the central ∼0.1 au region of the system, within which radius the disk temperatures rise above ∼1000 K and the dust sublimes. The inner wall of the dusty disk is heated by the central star, which then reradiates at longer, near-infrared wavelength. The inner gas disk reaches regions even closer to the star, but is truncated by the stellar magnetosphere, and the disk material is channeled towards the stellar surface along the magnetic field lines. The gas is heated in the accretion columns to temperatures of ∼ 10⁴ K by a presumably magnetic mechanism, which produces the observed broad emission lines.

The material in the accretion funnel is free falling towards the stellar surface with
velocities of about 300 km/s. When it hits the stellar surface, it creates an accretion shock, where the temperature reaches the order of $10^6$ K (Fig. 1.4 left). Emission from the shock is expected to result in excess continuum emission. As it adds to the photospheric fluxes, the absorption lines of the spectra appear shallower than in non-accreting stars – this is the so-called veiling phenomenon. The schematic view of the accretion geometry close to the stellar surface and its surroundings are shown in Fig. 1.4. In this picture, the accretion column can be divided into three main regions: the preshock region, the postshock region, and the heated photosphere. As the infalling material creates a shock close to the photosphere, half of the released energy is radiated towards the postshock region and the photosphere, and the other half is radiated upwards to the preshock region. The preshock region reprocesses it, and reradiates half of it downwards again. In this way, the heated photosphere receives 3/4 of the shock energy, which is then reprocessed and emitted upwards at longer wavelengths (e.g., Calvet & Gullbring, 1998). This process ultimately results in an optically thick emission from the heated photosphere below the shock, contributing to the Paschen and Brackett continua, and an optically thin emission from the preshock region, which dominates at wavelengths shorter than the Balmer threshold.

The magnetospheric accretion model has evolved throughout the years. The initial models described a two-dimensional axisymmetric dipolar magnetic field (Camenzind, 1990) then three-dimensional inclined dipole models were developed (Romanova et al., 2003). Finally, three-dimensional inclined multipoles have been introduced using magne-
1.2. Magnetospheric accretion model

Figure 1.5: The left panel shows a model for accretion flow and the corresponding light curve during funnel accretion. The right panels indicate a model and a corresponding light curve during accretion through instabilities. From Kulkarni & Romanova (2008).

tohydrodynamic (MHD) simulations (Romanova et al., 2011, Long et al., 2011). These 3D MHD simulations show that the disk is expected to be disrupted by the dipole component, which redirects the disk material towards the star in two funnel flows, and they form accretion hot spots below the magnetic poles. Consequently, the dipole field dominates at larger distances from the star. For stars with relatively strong magnetic dipoles, this component remains dominant and it results in a stable, long-lived hot spot that might cause periodic variations in the light curves. Besides the dipolar magnetic field, an octupolar component is typically introduced when multipoles are included in the modeling process. This octupolar component becomes dynamically important very close to the star, as it redirects the matter flow to different latitudes.

At the same time, other theoretical models proposed that accretion variability may be caused by instabilities at the boundary of the accretion disk and the magnetosphere, which results in unstable accretion variability. Kulkarni & Romanova (2008) presented the behavior of Rayleigh-Taylor instability, which resulted in multiple short-lived tongues of matter penetrating between the stellar magnetic field lines. When these accretion tongues reach the star, they create short-lived hot spots at lower latitudes and the observed light curve becomes more stochastic. Romanova et al. (2012), however, suggested that in other cases magneto-rotational instabilities in the inner circumstellar disk may lead to highly variable accretion rates. Fig. 1.5 compares two models and the resulting light curves. One model involves a dipole magnetic field, and results in an approximately periodic light curve. Whereas the other model shows the results of accretion through instabilities, for which the corresponding light curve
exhibits more stochastic variations.

The above described magnetospheric accretion model assumes that the stellar magnetosphere is strong enough to disrupt the disk before it reaches the star. This picture holds for low-mass stars ($\leq 2 \, M_\odot$), however, it may not apply for intermediate- and high-mass stars which possess weak magnetic field. Furthermore, systems with strong accretion outbursts, such as FU Orionis-type objects, also appear not to be consistent with the magnetospheric accretion model.

1.3 Time series photometry and spectroscopy as probes of the star-disk interaction

During the early stages of stellar evolution, the forming star is surrounded by significant amount of gas and dust. Protostars are deeply embedded in their parent cloud and are not visible at optical, only at infrared and millimeter wavelengths. In contrast, pre-main-sequence stars have already left the protostellar phase behind and their envelopes have dispersed, therefore, these systems became visible at optical wavelengths. However, they are still surrounded by a circumstellar disk, from which material is accreted onto the star. Protostars are beyond the scope of this work, therefore, I introduce here a more detailed picture only of pre-main-sequence systems from the observational point of view.

YSOs are greatly extended systems, and observations carried out at different wavelengths provide information on different regions of the system (Dullemond & Monnier, 2010). Disks can be found with a wide range of sizes: in some cases, the outer disk edge may be at a few tens of au but it might extend to more than 100 au in other cases. The inner disk edge do not reach the stellar surface, as it is expected to be truncated by the stellar magnetic field. This occurs where the ram pressure of the accreting disk material is equal to the magnetic pressure, and is often referred to as the truncation radius ($R_{tr}$). This inner disk edge typically occurs at a distance of a few stellar radii. The corotation radius ($R_{co}$), where the Keplerian angular velocity is equal to the stellar angular velocity, typically lies beyond the truncation radius. Due to the diverse properties and physical conditions of the different regions in these systems, different methods and techniques are needed to study them. Observations at longer, far-infrared and millimeter wavelengths reveal the outer parts of the disk, ranging from 10 au to $> 100$ au. Mid- and near-infrared data show the inner few au of the disk, whereas optical and UV measurements carry information on the central star. Fig. 1.6 shows a schematic view of such a star-disk system, and the wavelength ranges
1.3. Probes of the star-disk interaction

Figure 1.6: Schematic view of the structure and the spatial scale of a circumstellar environment (Dullemond & Monnier, 2010).

and the techniques needed to study the different regions are also indicated.

When observing young stars, photometric and spectroscopic measurements reveal that they are highly variable. They show both rapid and slow variations, which appear to be either irregular or, in many cases, periodic or quasi-periodic (Herbst et al., 1994). Different physical mechanisms can contribute to the observed changes, which include variable accretion, rotational modulation, obscuration by a dust cloud between the observer and the source, or rapid structural changes in the inner disk (Cody et al., 2014). In most cases, we observe a combination of these physical processes. Studying such variations in photometric and spectroscopic data of young stars is key to shed light on the variability of the accretion process, and on the temporal evolution of forming stars and their disks.

1.3.1 Photometric variability of young stars

Several studies have been carried out with the aim of revealing the physical origins of the photometric variations of young stars (e.g., Herbst et al., 1994, Bouvier et al., 1993, Rucinski et al., 2008, Robinson et al., 2021), and various processes have been identified that could trigger them. These include, for example, cold and dark spots that occur on the stellar surface, and cause periodic dimming events as the star rotates. An effect opposite to the previously mentioned is caused by hot spots at the base of the accretion columns. For non-periodic variability, flares, forming or decaying active
regions, variable accretion, or dimmings caused by the obscuration of a dust cloud result in stochastic variations.

Hoffmeister (1965) was the first to assume the presence of sunspot-like cold spots on the surface of T Tauri stars. If the spot persists for several rotation periods, it can be observed as periodic changes of the stellar brightness. Further evidence that the observed phenomenon is caused by the presence of one or more starspots is that the periods of the light variations are in agreement with those we would expect from the rotation period of the star based on the $v \cdot \sin i$ measurements and the estimated radius (Bouvier et al., 1993). However, the viewing angle may influence how pronounced this effect is: systems seen at higher inclinations (edge-on) may produce more defined periodic light curve, whereas small inclinations (pole-on systems) might not reveal signature due to rotational modulation. Furthermore, long-term observations have also shown interesting characteristics: as the spot properties (e.g., size, distribution, number of spots) can change in subtle ways, it can lead to variations in the shape and amplitudes of the light curves. The color dependence of the brightness change carries information on the temperature of the spot, and observations showed that their temperatures are typically $500 - 1400$ K lower than the photospheric temperature (Grankin et al., 2008).

In comparison with the sunspots seen on the solar surface, the previously mentioned starspots are significantly larger: they can cover up to 50% of the stellar surface (Bouvier et al., 1995). The examination of light curves of spotted young stars not only carries information on the spot temperature and size, but also on the spot distribution and their temporal evolution. Therefore, since the starspots are currently understood as tracers of the magnetic field of the still-evolving protostar, their study could provide valuable insights of the magnetic field geometry.

Several young stars exhibit irregular photometric variations due to accretion variability (Herbst et al., 1994, Bastien et al., 2011, Cody et al., 2017), which occur on hourly-daily timescales. These accretion bursts arise frequently and irregularly, because a hot spot occurs at the base of the accretion column; and as the amount of the accreted material is not constant, it results in light variations on short timescales. The amplitude of these variations can range from 10% to 700%, and they exhibit various shapes of light curves (Cody et al., 2017). Simulations of light curves caused by accretion variability revealed that several parameters (e.g., stellar mass, inclination, magnetic field geometry, the inner disk radius, and the level of turbulence in the inner disk) contribute to the final result, and they influence the resulting light curve to varying degrees (Robinson et al., 2021). For example, the authors found that typically low inclination ($i < 30^\circ$) systems display stochastic variability, whereas objects with $30^\circ < i < 80^\circ$ show quasiperiodic behavior, and $i > 80^\circ$ systems exhibit
1.3. Probes of the star-disk interaction

Figure 1.7: Amplitude versus timescale for the various types of YSO variability. Blue indicates the accretion-related events, yellow the stellar phenomena, red the extinction-related behavior, and green the variability expected from binary-related phenomena. The disk weather, shown in purple, denotes the routine variability, either brightening or fading, that is detected at longer wavelength. From Fischer et al. (2022).

periodic changes. Additionally, the magnetic field geometry also influences how periodic a light curve appears: pure dipole fields, strong aligned octupole components, or high turbulence in the inner disk tend to result in accretion bursts; whereas objects with anti-aligned octupole components or aligned, weaker octupole components tend to produce light curves with slightly fewer bursts.

There are some observed variations that cannot be explained by stellar activity or accretion. A further mechanism, variable circumstellar obscuration also causes noteworthy light variations of young stars. The obscuring material might be located within the disk, but they could be clumps of matter separated from the disk plane by strong magnetic fields. For example the light curve of UX Ori, the prototype of the UX-ors, is characterized by irregular and deep brightness minima. Initially, their observed color becomes redder in the optical color-magnitude diagram during a dimming phase, however, they display a color reversal after they reach a certain point. This effect has been interpreted as UXors being occasionally obscured to a large part by a dust cloud in the line of sight. When this happens, the observed flux will be dominated by
the inherently blue unobscured scattered component. A similar effect occurs when a system has a warped inner disk, as it can also cause recurrent dimming events. This is thought to originate from the obscuration of the central star by a rotating dusty clump in highly inclined systems. These are the so-called dipper systems, and their prototype is AA Tau (Bouvier et al., 2003).

Fig. 1.7 shows the typical timescales and the amplitudes for several kinds of variability that are anticipated in YSOs. The smallest amplitude variations are expected from star-related phenomena, such as starspots or stellar flares. Accretion related variability appears on wide scale: it might occur as small amplitude fluctuation on short timescales, but larger amplitude accretion bursts are also common. The most extreme variations are expected from the FU Orionis-type objects, which exhibit immense accretion outbursts lasting for decades, or even over a century.

1.3.2 Spectral features of young stars

The spectra of T Tauri stars display some peculiar features (Joy, 1945, Herbig, 1962). The photospheric lines are generally shallow due to the veiling of the spectra caused by excess continuum emission arising from the accretion process (e.g., Calvet, 1997). As the accretion might be variable also on short timescales of a day or less, the veiling of photospheric lines can also vary on similar timescales. The spectra of T Tauri stars are also characterized by the presence of several bright emission lines of low excitation and resemble the upper solar chromosphere (Joy, 1945). Typical emission lines that trace the accretion at optical wavelength range are the hydrogen Balmer lines, He I, He II, Ca II, Na I, or O I (Muzerolle et al., 1998a, Alcalá et al., 2014, 2017, Hartmann et al., 2016). These lines are thought to arise during the accretion process, and show changes to various extents (Joy, 1945, Muzerolle et al., 1998a).

The flux and the shape of the accretion tracers depend on several factors, such as the accretion geometry, the physical properties in line emitting regions, or the mass accretion rate ($\dot{M}_{\text{acc}}$) to the star. Thus, studying lines of different atomic species can be used to constrain the physical parameters of the line-emitting region. The large line widths of some emission lines, whose maximum velocities are roughly consistent with the free-fall velocities, indicate that they must form in the magnetosphere. Indeed, these broad and strong emission lines originate from the heated gas in the funnel flow, however, they show in some cases blueshifted absorption due to absorption by wind, and redshifted absorption by photons emitted in the accretion hot spot and viewed through the accretion column, which causes absorption (e.g. Hartmann et al., 2016). For this reason, the observed redshifted absorption in certain emission lines
1.3. Probes of the star-disk interaction

– such as the Hα, the HeI, or the NaI doublet lines – is interpreted as signature of magnetospheric infall. However, this signature can be less evident in some lines, especially in certain members of the hydrogen Balmer series. Indeed, while in general asymmetries and redshifted absorption components are expected in the hydrogen line profiles, the redshifted absorption component might be completely filled in, and the overall blueward asymmetry is reduced as the damping wing broadening can produce significant high-velocity emission in the Hα line, and to a lesser extent in other Balmer lines (Muzerolle et al., 2001).

In most cases, the hydrogen Balmer line profiles can be successfully explained by models which assume that the material is free-falling along an axysimmetric, dipolar magnetic field lines (Hartmann et al., 1994). However, the Hα line, which has the highest transition probability in the Balmer series, is thought to originate from multiple regions, including the accretion funnel, the accretion spot, the disk wind, and the stellar wind, therefore, it often exhibits very complex line profile (Reipurth et al., 1996). The metallic lines, such as HeI, CaII or FeI, often consist of multiple components: typically a narrow and a broad component can be distinguished (Muzerolle et al., 1998c, Beristain et al., 1998, 2001). Most studies suggest that the broad emission lines share a common emitting region. Correlation was found between the variations of these broad components and the Balmer lines, which suggest common emitting region, i.e., the funnel flow. However, somewhat different temperatures are needed to form different lines: for instance, the formation of the HeI line requires high-temperature (20 000 K < T < 50 000 K), whereas lower temperature (4000 K < T < 7000 K) is enough to produce the CaII line (Alencar & Basri, 2000). The kinematic properties of the narrow lines suggest that they originate from the postshock region at the base of the magnetospheric accretion column. Their variability typically does not correlate with those of the Balmer lines, which supports the concept that they probe regions that are far away from each other.

The accretion is often accompanied by outflows, including for example stellar winds or disk winds (Hartmann et al., 2016, Bally, 2016). As the material moves towards the star, the process is followed by angular momentum transport as well. This mechanism would cause a spin up in the stellar rotation. However, observations indicate that many of the T Tauri stars are slow rotators with rotational periods between 2 and 10 days. This means that there must be an additional process resulting in angular momentum loss. The angular momentum loss can occur either internally or via a disk wind, furthermore, stellar winds also may play a role in the spindown. Signatures of outflows can be detected in the spectra of T Tauri stars in the form of blueshifted absorption components of emission lines at velocities of a few hundred km/s or by
forbidden lines (e.g., [O I], [N I], and [Fe II]). Broad blueshifted emission is formed in the wind or jet, whereas narrow low-velocity ($v_p < 20$ km/s) component is associated with the disk wind.

MHD simulations are used nowadays to model the accretion process (Romanova et al., 2011, Long et al., 2011), including not only accretion, but also outflows (Kurosawa & Romanova, 2012). All the simulations show different kinds of outflows, such as disk winds, magnetospheric ejections, or stellar winds. The two- and three-dimensional simulations of the star-disk interaction generate still frames of the evolutionary process, and the density, the velocity, and the temperature structure allows us to carry out the radiative transfer calculations to produce observable diagnostics, such as line profiles and light curves, which can be directly compared to the measurements.

Medium to high inclination systems are interesting targets to study, as our line-of-sight goes through all the different structures, and we might be able to trace their signatures, providing a great deal of information on the system and the acting physical mechanisms.

1.4 Accretion variability over several orders of magnitude

When a protostar has formed, matter continues to accrete to it. Several methods have been introduced to determine the mass accretion rate of young stars, which apply both direct and indirect approaches. These techniques include the measurement of the accretion luminosity directly from the excess Balmer continuum emission and the Balmer jump in the blue spectra (e.g., Bertout et al., 1988, Gullbring et al., 1998) and from the veiling of the photospheric spectrum. For heavily extincted objects, the excess continuum in complicated to measure, therefore, indirect methods are applied to determine the mass accretion rate. Studies have found empirical correlations between the line luminosity of certain emission lines and the accretion luminosity (e.g., Muzerolle et al., 1998b, Alcalá et al., 2014, 2017). These empirical correlations, combined with estimated stellar properties, also allow us to estimate the accretion rate.

The rate at which a young stellar object is accreting varies on a wide scale: the typical accretion rate for classical T Tauri stars ranges from $10^{-11}$ M$_\odot$/yr to $10^{-8}$ M$_\odot$/yr (Hartmann et al., 1998, Calvet et al., 2004, Ingleby et al., 2013, Manara et al., 2016) but the mass accretion variability for a given object typically remains within one order of magnitude (Costigan et al., 2012, Venuti et al., 2014). Accretion variability in these objects can be seen as small amplitude sharp bursts that last from hours to a few days,
however, in some cases it might appear on top of more gradual smooth changes. These stochastic variations originate from the instabilities in the star-disk interaction and cause both photometric and spectroscopic changes.

Slightly more powerful outbursts are observed in EXors. These objects show 2 – 4 mag optical brightenings which last from a few months to a few years. The prototype of this class, EX Lupi, shows typical bursts of 1 – 3 mag, however, two larger outbursts of $\sim$5 mag (Herbig, 1977, Ábrahám et al., 2009, 2019, and references therein) have been observed. The outbursts are recurrent though not periodic: sometimes they occur repeatedly over a few years, other times the system stays in quiescence for decades. The EXor outbursts are an indication of increased accretion. EX Lupi itself was studied in both outburst and quiescence, and the observations showed an increase in the accretion rate from $10^{-10} - 10^{-9} \, M_\odot/\text{yr}$ to $2 \times 10^{-7} \, M_\odot/\text{yr}$ (Sicilia-Aguilar et al., 2012, 2015, Juhász et al., 2012).

The most extreme and powerful outbursts are displayed by the so-called FUors, named after the prototype FU Orionis. FU Ori attracted attention when Wachmann (1954) reported its extreme and unexpected brightening by $\sim$6 magnitudes. Similarly rapid brightening has been discovered for a few other sources as well, and these were found to last for decades or even centuries (Hartmann & Kenyon, 1996, Audard et al., 2014, Connelley & Reipurth, 2018). According to the current picture of FUors, the outbursts occur due to the rapid disk accretion at rates of $10^{-5} - 10^{-4} \, M_\odot/\text{yr}$. During an outburst, the disk becomes hot enough to radiate most of its energy at optical wavelengths, therefore, the bolometric luminosity is dominated by that of the disk. Their accretion luminosities can be obtained from the emission of the disk, and they do not show signatures of the previously described magnetospheric accretion.

1.5 Instruments and surveys used in this work

In this Thesis, I analyzed data from several instruments, including ground-based and space telescopes, publicly available surveys, and both photometric and spectroscopic observations. Here, I give a short summary of the technical details of all the instruments and surveys.

Piszkéstető Mountain Station. The Schmidt telescope of the Piszkéstető Mountain Station was put into operation in 1962 by the Konkoly Observatory. It is located at Piszkéstető (Hungary) at the elevation of 944 m. The telescope has a main mirror with 90 cm diameter and a correction lens with 60 cm diameter. It was equipped with a CCD camera which provides a $1.17^\circ \times 1.17^\circ$ field of view with a pixel scale of
This instrument carried out observations at optical wavelengths, in the Bessel $BVRCIC$-filters. The Piszkéstető Mountain Station hosts the 80 cm Ritchey-Chrétien (RC80) telescope as well. This instrument is equipped with an FLI PL230 CCD camera with $18.8' \times 18.8'$ field of view and $0.55''$ pixel scale. The telescope can obtain observations in the Johnson $BV$ and Sloan $ugriz$ filters.

**Telescopio Carlos Sánchez.** The Telescopio Carlos Sánchez (TCS) is located in the Teide Observatory of the Instituto de Astrofísica de Canarias (Tenerife, Spain), and was in operation since 1972. The 1.52 m telescope hosts multiple instruments, including the CAIN-III instrument, which has been decommissioned in 2019. It is equipped with a $256 \times 256$ Nicmos 3 detector, which is sensitive in the 1-2.5 $\mu$m range. It has two optical configurations: “wide” and “narrow”. The “wide” configuration has a $4.2' \times 4.2'$ field of view with $1''$ pixel size, while the field of view for the “narrow” configurations is $1.7' \times 1.7'$ with $0.39''$ pixel size.

**Liverpool Telescope.** The Liverpool Telescope is located at the international Observatorio del Roque de los Muchachos on the summit of the island of La Palma, and is operated by the Astrophysics Research Institute of Liverpool John Moores University. It is a fully robotic telescope with a 2 m primary mirror. The telescope can host nine instruments, which include optical and infrared cameras, optical spectrographs and polarimeter. The IO:I instrument (Barnsley et al., 2016) is the infrared imaging component of the Infrared-Optical suite of the instrument. Its $2048 \times 2048$ pixel Hawaii 2RG $1.7 \mu$m detector has a $6.3' \times 6.3'$ field of view with a pixel scale of $0.18''$. It currently operates with a single $H$-band filter.

**WISE.** The Wide-field Infrared Survey Explorer (WISE) was launched in 2009 with the aim of mapping the entire sky repeatedly at infrared ($3.4$, $4.6$, $12$ and $22 \mu$m) wavelengths (Wright et al., 2010). After completing its primary mission, WISE was placed into hibernation in 2011. However, it was reactivated in 2013 and continued its mission under the name of NEOWISE. As the satellite ran out of the frozen hydrogen, which is needed for cooling the instruments operating at the longer wavelengths, the new mission carries out the survey in the 3.4 and 4.6 $\mu$m infrared bands.

**Gaia.** The Gaia mission was launched in 2013 and is expected to operate until 2025 with the aim of assembling a three-dimensional map of our galaxy (Gaia Collaboration et al., 2016). The satellite consists of three main instruments. The astrometry instrument measures the positions of all stars brighter than 20 mag. These measurements
also allow to the determination of the stars’ parallax, therefore the Gaia catalogs also provide distance and proper motion measurements. The second instrument is the photometric instrument, which measures the brightness of the stars in the $320 – 1000 \text{ nm}$ spectral region with a blue (BP, $330–680 \text{ nm}$) and a red (RP, $640–1050 \text{ nm}$) photometer. The third instruments is the Radial-Velocity Spectrometer (RVS), which determines the line of sight velocity of the stars in the spectral band $847–874 \text{ nm}$ for objects up to 17 mag. In this thesis, I used the distance measurements from Gaia, which are available from the Bailer-Jones et al. (2018) and Bailer-Jones et al. (2021) catalogs for Gaia DR2 and Gaia EDR3, respectively. Furthermore, I also use the mean brightness and the position measurements, which are available from the Gaia archive.

**AAT/UCLES.** The Anglo-Australian Telescope (AAT) was commissioned in 1974 with the aim of increasing the number of telescopes which are able to observe the southern sky, as until the 1970, most of the largest ground-based telescopes were built on the northern hemisphere. The telescope has a 3.9 m diameter mirror, and is equipped multiple instruments, including the University College of London Échelle Spectrograph (UCLES, Donati et al., 1997). This spectrograph covers the wavelength range from 437.6 to 682 nm, and has a spectral resolution of $\sim 70\,000$. For the observations that I present in Chapter 3, the spectrograph was linked to the SemelPol visitor polarimeter, placed at the Cassegrain focus of AAT, which allows to obtain both unpolarized and circularly polarized spectra.

**ESO 3.6 m/HARPS.** The ESO 3.6 m telescope is one of the instruments located at La Silla (Chile), and operated by the European Southern Observatory (ESO). Since 2008, the High Accuracy Radial velocity Planet Searcher (HARPS, Piskunov et al., 2011) is the only instrument available at the 3.6 m telescope. HARPS is a fibre-fed cross dispersed echelle spectrograph, which covers the spectral range of $378–691 \text{ nm}$ with a resolving power $\sim 105\,000$. HARPS is fed by two fibres, one of which observes the star, and the second one records simultaneously either a Th-Ar reference spectrum or the background sky. Both fibres have an aperture of 1”. The detector consists of two CCDs (altogether $4k \times 4k$, 15 microns pixels), where the “upper” CCD covers the $533–691 \text{ nm}$ range (orders 94–114), and the “lower” CCD covers the $378–530 \text{ nm}$ range (orders 116–161).

**ASAS.** The All Sky Automated Survey (ASAS) started in 1997 with the aim of monitoring the whole available sky up to the brightness level of 14 mag, in order to detect and investigate any kind of photometric variability. Initially, it operated only...
with the Las Campanas Observatory in Chile but the Haleakala Observatory (Hawaii) joined the survey in 2006 with a 200/2.8 lens telescope and 8.5° × 8.5° field of view each. Both instruments are equipped with two wide-field cameras, observing in V and I-bands simultaneously. The publicly available ASAS-3 Photometric V-band Catalogue obtained data during years 2000-2009 (Pojmanski, 2003). Later, the ASAS-SN (All-Sky Automated Survey for Supernovae) survey carried on the project and has been monitoring the entire visible sky every night to a depth of V ∼17 mag in V and g-bands (Kochanek et al., 2017, Shappee et al., 2014). The V-band data is available from 2013 December to 2018 August, and the g-band can be retrieved from 2017 December until today. Currently, the ASAS-SN network consists of five stations: Haleakala Observatory (Hawaii), McDonald Observatory (Texas), and the South African Astrophysical Observatory (SAAO, Sutherland, South Africa), and two units at Cerro Tololo International Observatory (CTIO, Chile). All these stations consist of four 14 cm aperture Nikon telephoto lenses, each with 2048×2048 pixel ProLine CCD camera with a field of view of 4.5° × 4.5° with a pixel size of 8"

**TESS.** The Transiting Exoplanet Survey Satellite (TESS) was launched in 2018 and started operating in August 2018 (Ricker et al., 2015). TESS has four identical cameras, and each has a 24° × 24° field of view, which are aligned to cover 24° × 90° strips of the sky called “sectors”. Each camera has four 2k×2k pixel CCDs with a pixel scale of 21″/pixel. TESS provides broad-band optical photometry covering the 600–1000 nm range, but it is centered on the $I_C$-band. The satellite monitors each sector for 27 days. As the sectors overlap at ecliptic poles, it is possible that a light curves longer than 27 days are available. The Prime Mission mapped the southern hemisphere in the first year and mapped the northern hemisphere in the second year, provided full frame images with 30-minute cadence. The satellite continued monitoring the sky during its Extended Mission: during the first year of the Extended Mission, TESS re-observed the southern ecliptic hemisphere; and the second year of the Extended Mission is covering part of the northern ecliptic hemisphere and ∼60% of the ecliptic plane.

**SMARTS 1.3m/ANDICAM.** The Small & Moderate Aperture Research Telescope System (SMARTS) Consortium operates four telescopes at the Cerro Tololo Observatory in Chile. The 1.3m telescope is equipped with A Noval Dual Imaging CAMera (ANDICAM, DePoy et al., 2003), which obtains simultaneous optical and infrared images in the $BVRIJHK$-bands. While the optical images are being obtained, a movable mirror allows dithering for the shorter exposures in the infrared bands. The 1024×1024 CCD has a pixel scale of 0.371″/pixel and a 6′ × 6′ field of view. For the
1.6 Motivation and the structure of this thesis

Infrared images, typically 2×2 binning is applied, which results in a 512×512 image with a pixel scale of 0.276″/pixel and a 2.4′ × 2.4′ field of view.

**VLT/ESPRESSO.** The Very Large Telescope (VLT) is located at Cerro Paranal (Chile) and operated by the European Southern Observatory. This facility consists of four Unit Telescopes (UT) with a 8.2 m primary mirrors each. The telescopes can work together in order to form an interferometer, but they can be used individually as well. The ESPRESSO (Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations) instrument is a fibre-fed échelle spectrograph, which can be connected to either a single or up to four UTs (Pepe et al., 2021). It offers three configurations: high-resolution (140 000, 1-UT), ultra high-resolution (190 000, 1-UT), medium resolution (70 000, 4-UT). In this work, the high-resolution configurations was used, which offers a 1.0″ aperture on the sky. The instrument obtains optical spectra in the 380–788 nm range. The detector consists of two CCDs, where the blue covers the 380–525 nm range, and the red covers the 525–788 nm. ESPRESSO is fed by two fibres, one of which observes the target, and the other one is used for recording a reference spectrum simultaneously.

**MPG/ESO 2.2m/FEROS.** The La Silla Observatory hosts a 2.2 m Ritchey–Chrétien telescope in Chile. The instrument was built by the Max Planck Institute für Astronomie and was initially on indefinite loan to ESO, however, it is operated by the Max-Planck Gesellschaft since 2013. The telescope can be coupled with the Fibre-fed Optical Echelle Spectrograph (FEROS, Kaufer et al., 1999). This instrument can obtain optical spectra (350–920 nm) with a spectral resolution of 48 000. The measurements can be taken in either object-calibration or in object-sky modes. Both modes use the two 2.0″ aperture fibres, one of which always observes the science target. In the object-calibration mode, the second fibre records simultaneously a reference spectrum from a calibration lamp (ThAr+Ne, ThArNe, or HaI+HaI), whereas in the object-sky mode, the reference spectrum is obtained from the nearby sky background simultaneously.

1.6 Motivation and the structure of this thesis

In this thesis, I am examining the variability of young stellar objects with a main focus on the accretion process using data from the above listed instruments and surveys. The accretion of material onto low-mass young stars plays an essential role in the stellar mass assembly, and also has an impact on the physical conditions of the inner
disk, where planets might form. The study of the accretion process is, however, proves to be complicated, since several physical mechanisms – such as extinction, winds, or stellar activity – contribute to the observed phenomena besides accretion. Therefore, multifilter and multi-instrument campaigns are needed to explore the complexities of the variability of young stars, and disentangle the effects of the different physical mechanisms. While statistical studies including large samples of objects provide robust results of a chosen star forming region or of a certain aspect of the variability of young stars, the in-depth study of individual objects is also important because it allows us to take into account the characteristics of the systems (e.g., inclination, physical parameters of the star, characteristics of the circumstellar disk, multiplicity). In this thesis, I present three such detailed studies for three individual, interesting pre-main sequence stars.

In Chapter 2, I introduce an FU Orionis-type object, V582 Aur. I use multifilter ground-based and space-borne photometry with the aim of examining the evolution of this young eruptive star. As currently only a small number of FUors are known, the analysis of the photometric variability of V582 Aur during its eruption can contribute to our better understanding of these particular objects. Moreover, V582 Aur is relatively understudied compared to other well-known FUor since the outburst was detected about a few decades ago.

Furthermore, the recently started mission of TESS provided a unique opportunity to coordinate ground-based photometric and high-resolution spectroscopic observations contemporaneously with the high-cadence measurements of TESS in order to study different parts of a few selected systems, and distinguish physical processes. The high-resolution spectroscopy is a very powerful tool when studying young stellar objects because it reveals the details of the spectral lines, which carries information not only on the presence of accretion but can be also used to infer physical and kinematical properties of the line emitting regions. The VLT/ESPERSSO instrument became available for the astronomer community in 2018, around the time I started my PhD. This provided an exceptional chance for me to be among the first to use this instrument for the purpose of monitoring the optical spectroscopic variability of T Tauri stars combined with high-cadence and multifilter photometry. In Chapter 3, I present a photometric and spectroscopic study of CR Cha, a T Tauri star, for which I was able to study the accretion process on timescales from hours to a decade by including not only the newly obtained data but also earlier measurements. In Chapter 4, I introduce a multiple T Tauri system, VW Cha, for which object this is the first in-depth photometric and high-resolution spectroscopic study where this object is not only part of a large sample but the analyses focuses only on VW Cha itself.
Chapter 2

The weakening outburst of the young eruptive star V582 Aur

2.1 Introduction

V582 Aur is an FU Orionis-type (FUor) young eruptive star, which is considered to be related to the Aur OB1 association (Kun et al., 2017). As described in Sect. 1.4, these FUor type systems show decade long optical–infrared outbursts caused by temporary increase in the mass accretion rate from the inner circumstellar disk onto the star (Hartmann & Kenyon, 1996). While in some cases the initial brightening has been observationally documented, other objects were classified as FUors based on their spectral characteristics (Connelley & Reipurth, 2018). These spectral characteristics in the near-infrared wavelength range include strong CO absorption, prominent water bands, strong blueshifted HeI absorption, and a few emission lines. Typically, the initial photometric brightening of a FUor is followed by a longer fading phase. For example, FU Ori has been in outburst for 80 years, and V1057 Cyg for 50 years (Audard et al., 2014, Szabó et al., 2021). So far only one FUor, V346 Nor seemed to finish its outburst after 30 years (Kraus et al., 2016), however, newly obtained light curves reveal a gradual re-brightening (Kóspál et al., 2020).

V582 Aur has been in outburst since $\sim$1985. The initial brightening was documented by Samus (2009) based on observations by the amateur astronomer Anton Khruslov. V582 Aur was reported as a FUor candidate, and the FUor nature was confirmed spectroscopically by Semkov et al. (2013). Samus (2009) also identified a nebula associated with the star based on images from the Digitized Sky Survey (DSS), which was invisible before 1986. This faint reflection nebulosity was detected in new optical and near-infrared images as well, obtained by Ábrahám et al. (2018). These reveal
an arc-like filamentary structure. Kun et al. (2017) studied the environment and the star forming region associated with the object using slitless spectroscopy, UKIDSS and Spitzer Space Telescope data. They identified 68 candidate low-mass young stars in the region, which appear to be associated with the Aur OB 1 association at a distance of 1.3 kpc. In a previous study (Ábrahám et al., 2018, hereafter A18), of which I also was a co-author, we analyzed the long-term multiwavelength photometric variability of V582 Aur. Using 18 archival photographic plates from Konkoly Observatory, of which five revealed V582 Aur, the initial brightening was confirmed and was settled some time between 1986 January and December. It was also proposed that the most likely progenitor of V582 Aur was a late-type T Tauri star. The more recent multiwavelength light curves of the system, obtained between 2010 and 2018, reveal noteworthy variations even decades after the outburst. We interpreted this as a combined effect of changing accretion and obscuration. In A18, we investigated the nature of these light variations, and also focused on two dimming events, which occurred in 2012 and in 2016. We found that the brightness minima are related to changing line-of-sight extinction, and speculated that it is caused by the obscuration of a dust clump, which is orbiting in the inner disk with the period of \( \sim \) 5 years.

In this Chapter, I present new observations in order to follow the further evolution of V582 Aur and confront the new data with the extinction scenario of A18. This Chapter is based on a collaborative work that I was leading, and the results are published in Zsidi et al. (2019, ApJ, 873, 130). I obtained part of the optical data at the Piszkestető Mountain Station of Konkoly Observatory using the 60/90/180 cm Schmidt telescope, and I carried out the data reduction of these optical photometric data. I was responsible for the analysis of the data presented in Sect. 2.2, the interpretation, and the discussion, where the co-authors contributed with several comments and discussions. The data reduction of the near-infrared observations and the modeling of the accretion disk was the contribution of the co-authors.

### 2.2 Observations

My colleagues and I performed \( B, V, R_C \), and \( I_C \)-band monitoring photometric measurements at the Piszkestető Mountain Station of Konkoly Observatory (Hungary), using the 60/90/180 cm Schmidt telescope. We carried out the observations between 2018 January 14 and 2019 February 5. This project required a monitoring campaign with relatively short observing time on a weekly basis over a long period of time, therefore, only part of the data was obtained by myself when I spent time at the Piszkestető
2.2. Observations

Figure 2.1: Finding chart for V582 Aur and comparison stars. V582 Aur is located in the middle, and the comparison stars, used for obtaining the differential photometry, are indicated with capital letters. Left: Finding chart from Semkov et al. (2013). Right: Excerpt from one of the $R_C$-band images taken with the Schmidt telescope of Konkoly Observatory at the Piszkéstető Mountain Station.

Mountain Station, and the other part of the data was obtained by various support astronomers. When reducing the optical photometric data, first, I carried out the standard bias, dark, and flat-field corrections on the images. Then, I identified stars in the vicinity of V582 Aur, which are included in the URAT$^1$ catalogue and have similar brightness and color to our target. I used these objects as comparison stars when I carried out differential aperture photometry. As the Schmidt telescope has a large field-of-view ($1.17^\circ \times 1.17^\circ$), I was able to use the same comparison stars as the ones used in Semkov et al. (2013) and in A18. I show the finding chart for V582 Aur in Fig. 2.1, where V582 Aur is located in the middle, and the comparison stars are indicated with capital letters. As the last step, I converted the instrumental magnitudes to the standard magnitudes by fitting the difference of the instrumental and the standard magnitudes of the comparison stars as a function of the $V - I_C$ color.

The near-infrared $J$, $H$, and $K_S$-band images were obtained using the Telescopio Carlos Sánchez (TCS) at the Teide Observatory (Spain) on 2018 November 10. For the data reduction of the TCS measurements, firstly, sky subtraction and flat-fielding was applied, then all frames taken with the same filter were co-added. The instrumental magnitudes were obtained by aperture photometry. The Two Micron All Sky Survey (2MASS) catalogue was used for the photometric calibration, by determining the offset between the instrumental and the calibrated 2MASS magnitudes. In addition, a single

$^1$https://irsa.ipac.caltech.edu/Missions/usno.html
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$H$-band measurement was performed on 2018 April 15 using the 2 m Liverpool telescope at the Observatorio del Roque de Los Muchachos, Canary Islands, Spain (Proposal No. CQ18A01, PI: J. A. Acosta-Pulido). For this observation, we used the IO:I camera built on a 2048×2048 HAWAII 2RG chip (Barnsley et al., 2016). Images were obtained at 9 dither positions, with 5.8 s exposure time each, and aperture photometry was applied. The calibration and error calculus was based on the 2MASS magnitudes of 3 nearby bright stars, and the same procedure was carried out as for the TCS observation. All photometric results are presented in Table 2.1.

Mid-infrared photometry at 3.4 $\mu$m (W1) and 4.6 $\mu$m (W2), obtained by the WISE space telescope (Wright et al., 2010), has already been presented in A18. Here, I complement these sequences with two new data points from 2017. For these epochs, I collected all time-resolved observations from the NEOWISE-R Single Exposure Source Table\textsuperscript{2}, and computed their average and standard deviation. I added in quadrature 2.4% and 2.8% to the formal uncertainty of the average value, in order to account for the uncertainty of the absolute calibration in the W1 and W2 bands, respectively. These WISE measurements are included in Table 2.2. It must be noted that I had access to the photometric data presented in A18 via personal communication, however, those data were reduced by the authors listed in A18. Here, I use those data as a reference in order to understand the long-term evolution of V582 Aur, therefore, I do not include here details on their reduction procedure.

2.3 Results

2.3.1 Optical–near-infrared light curves

The photometric results are plotted in Fig. 2.2. For reference, I also plotted the earlier light curves from A18 until 2018 January 7. Fig. 2.2 demonstrates that following the minimum of 2017 February, the optical light curves show a brightening trend until 2018 February. In A18, we expected that this trend would continue and the source would reach the maximum brightness level (measured in 2013–2014, see horizontal lines on the right-hand side in Fig. 2.2) during 2018. However, the new optical data indicate a break in this trend. After reaching a peak in 2018 February, the source started dimming again. The latest observations from 2018 August–2019 February show similar brightness level to the beginning of the year, interrupted by a local minimum in 2018 October. The latest data in the figure shows that the source is as bright as it

\textsuperscript{2}https://irsa.ipac.caltech.edu/Missions/wise.html
2.3. Results

Figure 2.2: Light curves of V582 Aur. Filled circles represent data from my work, plus signs are from A18, and empty circles are the data from the publicly available ASASSN sky survey (Shappee et al., 2014, Kochanek et al., 2017). The new mid-infrared WISE data points are marked with squares. Tick marks on the top indicate the first day of each month. The measured errors are smaller than or equal to the symbol size. On the right side, I show the maximal brightness levels in each filter from 2014 with horizontal lines.

was in 2018 August–September, but is still about 1 magnitude fainter than it was in 2013–2014.

After 2018 February, the shapes of the $B$, $V$, $R_C$, and $I_C$ light curves are more similar to each other than in 2016/2017 (Fig. 2.2). The new near-infrared $H$-band photometric point on 2018 Apr 15 shows the same brightness level as the last near-infrared data point in 2017 April. On 2018 Nov 10, the source was significantly brighter in the $J$ and $H$-bands than in 2017, while no change in its $K_S$ brightness was detected. These magnitudes are, however, still fainter by 0.5–0.7 mag than the maximum brightness levels before 2016 (see horizontal lines on the right-hand side in Fig. 2.2). The new photometric results imply that the dimming of V582 Aur, which started in 2016, has not finished yet, and its length is at least 3 years, significantly exceeding the length of the 2012 dimming, which lasted for $\sim$1 year.
### Table 2.1: Optical and near-infrared photometry in magnitudes for V582 Aur. Numbers in parentheses give the formal uncertainty.

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<th>R</th>
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2.3. Results

2.3.2 Color changes

In Fig. 2.3, I show the color-magnitude diagrams based on the optical and near-infrared data. I plotted data points measured before 2014 (black circles), photometry from 2014–2017 (blue circles), and the new observations from Table 2.1 (filled red circles). The earlier data points did not populate the brightness range between $V=15.5$ and 16.5 mag. The new data points after 2018 January fill this brightness gap, representing an intermediate brightness level. Fig. 2.3(a)-(c) suggest that the data points obtained before 2014 and the data points measured in 2014–2017 occupy different locations in the color-magnitude space. Comparing the colors of the two samples at any given $V$-band magnitude, the earlier data (black circles) are bluer in Fig. 2.3 (a), have similar $[V-R]$ colors in Fig. 2.3 (b), and are systematically redder in Fig. 2.3 (c) than the 2014–2017 measurements. Moreover, there is an additional discrepancy in the distribution of points before and after 2014. They exhibit similar but parallel patterns in such a way that the data after 2014 seem to be $\sim$0.3 mag dimmer in $V$-band for the same color. In Fig. 2.3 (a)-(c), the new photometry after 2018 January remarkably match the color-magnitude trends outlined by the data points from 2014–2017.

Fig. 2.3 (d), which shows an $I_C$ vs. [$I_C - H$] diagram, indicates that the new data points seem to match the trend outlined by the 2014–2017 measurements. Extrapolating from the 2014–2017 data to brighter $I_C$ magnitudes, there is a hint that the data points before 2014 were systematically redder at a given $I_C$-band magnitude than the later photometry, similarly to Fig. 2.3 (c).

![Figure 2.3: Color–magnitude diagrams of V582 Aur. The filled red circles indicate the new measurements (Table 2.1), which fill the brightness gap between the previous data. The data points from 2014–2017 (published in A18) are overplotted with blue open circles, and the earlier data before 2014 are drawn as black circles. The lines correspond to an extinction change of $A_V = 1$ mag using the Cardelli et al. (1989) extinction law.](image-url)
2.3.3 WISE measurements

I plotted all WISE measurements from Table 2.2 in Fig. 2.4. The first two measurements during 2010 revealed a slight brightening of the source. By the beginning of 2014, V582 Aur was fainter again, and the drop of brightness with respect to 2010 was significantly larger in the W2 than in the W1 band. During 2014, the WISE light curves show a brightening trend, and after reaching a maximum in 2015 March both light curves started a linear fading phase, which is still followed by the source.

In A18, we demonstrated that the optical and near-infrared variability of V582 Aur could be, to a large part explained by changing extinction in the line-of-sight caused by an obscuring dust clump. In order to check if the mid-infrared variability, measured by WISE, was also due to extinction variations, I compared the mid-infrared light curves with the optical ones. I overplotted in Fig. 2.4 a modified version of the $I_C$ light curve scaled down by the relative amplitudes of the interstellar extinction at the respective wavelengths (0.79 $\mu$m and 3.4 $\mu$m). This scaled down light curve would be the expected mid-infrared behavior if the light variations were caused by the same extinction at both the optical and near-infrared wavelengths. Interestingly, the measured WISE light curves do not follow the expected trend, suggesting a different physical mechanism as the origin of the variation. The $[W1-W2]$ color variations during the observed period, plotted in the bottom panel of Fig. 2.4, show that the source was bluer in early 2014 and early 2016, while it was redder in 2017, although not as red as in 2010.

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Table 2.2: Mid-infrared WISE data in magnitudes. Numbers in parentheses give the uncertainty of the last digit.
2.3. Results

Figure 2.4: The upper panel shows the mid-infrared light curves of V582 Aur. The squares show the WISE measurements and the red circles indicate the $I_C$-band data scaled down with the Cardelli et al. (1989) reddening law and shifted along the y-axis (see Sect. 2.3.3). The WISE color change during the observing period is indicated on the lower panel.

2.3.4 New Gaia distance

In A18, following Kun et al. (2017), we assumed a distance of 1.32 kpc for V582 Aur. The Gaia DR2 parallax, however, implies a larger distance of 2.4$^{+0.7}_{-0.4}$ kpc (Bailer-Jones et al., 2018). The results of Kun et al. (2017) suggest that V582 Aur seems to be associated with a complex of bright rim clouds (see Fig. 3 in Kun et al., 2017). The closest OB star, thus the most likely ionization source is HD 281147, whose Gaia DR2 distance is 2.4$^{+0.3}_{-0.2}$ kpc. This result also supports the new distance value for V582 Aur.

We also checked the Gaia DR2 distances for a list of stars used to define the Auriga OB1 and Auriga OB2 associations by Humphreys (1978). This comparison shows that the distances for the two associations overlap, although Aur OB1 ($d = 1.9 \pm 0.7$ kpc) seems to be closer to the Sun than Aur OB2 ($d = 2.8 \pm 0.5$ kpc). Based on these results, it is unclear which association V582 Aur belongs to. Adopting the distance of 2.4 kpc for the FUor, several fundamental parameters would change. The luminosity and accretion rate would increase to 500–1050 $L_\odot$ and $8 \times 10^{-5} M_\odot/yr$ respectively, making the object perhaps the most luminous FUor in the list of Audard et al. (2014). The mass of the circumstellar material derived in A18 would also change to 0.1 $M_\odot$. 

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2.4 Discussion

2.4.1 Nature of the obscuring material

In A18, we demonstrated that the two brightness minima of V582 Aur, observed in several filters, could be explained by variable extinction towards the source. We explored two possibilities depending on whether the eclipses in 2012 and in 2016–2018 were caused by the same orbiting dust clump, or by two independent dust structures. Based on the first scenario and the temporal difference between the two dimming events, we speculated in A18 about an elongated dust clump orbiting at a circular orbit around a 1 M\(_{\odot}\) star with a period of \(\sim 4.75\) yr. Using these parameters, we calculated the characteristics of the orbiting clump, which resulted in an orbital radius of 2.8 au, a length of \(\sim 3.5\) au, and a mass of 0.004 M\(_{\odot}\). The new results, presented here, show that the variability detected after 2018 February also matches the previous color-magnitude trends (Fig. 2.3), implying that changing extinction is still the dominant physical mechanism behind the light variations. However, just this fact does not help to decide between the two possibilities. In the following, I examine how the new observations are consistent with one or the other scenario.

In the light of the new data, the 2016–2018 minimum significantly differs in length and shape from the one in 2012. Therefore, if both fading events were caused by the same dust clump, as we supposed in A18, then the clump covers a more extended part of the orbit in 2016–2018 than in 2012. Since the length of the current minimum is at least 2 years, the clump could be stretched over \(\sim 7\) au if adopting an orbital radius of 2.8 au from A18. It suggests a viscous spreading of the dust particles along the orbit. Since the WISE measurements do not follow the scaled down \(I_C\)-band light curve (Fig. 2.4), either the orbiting dust clump does not cover that part of the inner disk where the mid-infrared radiation is emitted or the clump itself contributes to the mid-infrared radiation.

The other explanation for the observed dimming events includes individual dust clouds entering and leaving the inner part of the system as giant exocomets. In this picture the inward moving dust structure might pass the line-of-sight and may be responsible for the optical dimming events. Approaching the central object, the dust warms up, increasing the mid-infrared thermal emission of the system and making the observed [W1–W2] WISE color bluer. We speculate that this may be the reason of the mid-infrared brightening of V582 Aur in 2014 and early 2015 (Fig. 2.4). When the dust structure is leaving the system, it cools down and emits less at the mid-infrared WISE wavelengths. We may see the beginning of this effect in the latest WISE measurements.
2.4. Discussion

The light curves and the color evolution of V582 Aur show striking similarity to those of another well-known young stellar object, RW Aur A (Dodin et al., 2019, and the references therein). The physical reason for the behavior of RW Aur A is still debated. The possible mechanisms, like dusty disk wind (Petrov et al., 2015, Bozhinova et al., 2016), or a warped inner disk (Facchini et al., 2016) might be invoked to explain the variability of V582 Aur as well.

2.4.2 Prediction for the end of the outburst

The color-magnitude diagram (Figure 2.3) indicates that the distribution of points before and after 2014 outlined similar patterns, however, the later dataset have $\sim$0.3 mag fainter values in the $V$-band. In A18, we identified the origin of the pattern as a combination of the interstellar extinction and the UXor blueing effect. UXors, a subclass of Herbig Ae/Be stars named after the prototype object UX Orionis, are defined by their irregular deep brightness minima in the light curve. As they start fading, their colors become redder in the color-magnitude diagram, however, after reaching a certain faintness, they exhibit a color reversal. This is the so-called blueing effect (The, 1994, Natta & Whitney, 2000, and references therein). The most widely accepted physical explanation for this phenomenon assumes a system seen almost edge-on. As a dust clump begins obscuring the star, the observed light becomes redder according to the dust extinction law. When the star is completely obscured by the dust clump, only the bluer scattered light from the circumstellar environment remains, causing a color reversal in the color-magnitude diagram. In Fig. 2.3, the upper linear part of the pattern is parallel to the extinction path shown by lines in the panels. The lower horizontal part is probably the signature that the central object is significantly obscured and the remaining emission is dominated by scattered light. Here, I speculate that the $\sim$0.3 mag difference arises from the absolute fading of the source, reflecting the long-term evolution of the outburst. In this scenario, the 0.3 mag fading during $\sim$5 years would mean that the source will reach the quiescent level in approximately 80 years. This decades long trend is characteristic for FUor type stars. Future observations will show whether the experienced color change continues. The light curves of the WISE measurements differ significantly from those at the optical wavelengths, suggesting different underlying phenomena.

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3Herbig Ae/Be stars are intermediate mass pre-main sequence stars. They were first recognized by Herbig (1960).
2.4.3 Modeling with an accretion disk

In A18, the near-infrared spectral energy distributions were fitted at each epoch with a simple accretion disk model. We adopted a steady, optically thick, and geometrically thin viscous accretion disk, with a radially constant mass accretion rate. We found that until 2017 April, the mass accretion rate was approximately constant, while the line-of-sight extinction episodically increased during the dimming periods in 2012 and in 2016–2018. Here, the modeling was repeated using the 2.4 kpc distance measured by Gaia, and also including our new $J$, $H$, and $K_S$ measurements from 2018 Nov 10 and the 2MASS measurements from 1998 October 8. The results are plotted in Fig. 2.5. The comparison of this figure and Fig. 11 in A18 shows that the model provided higher accretion rates due to the larger distance of 2.4 kpc. The line-of-sight extinction also increased in the new calculations, since the higher accretion rate corresponds to hotter disk. This requires higher line-of-sight extinction in order to reproduce our measurements. For the new epoch in 2018 an extinction of $A_V \simeq 6.5$ mag was derived, which is significantly lower than what we obtained for the deepest minimum in 2017 February and is only slightly higher than the values measured outside the dimmings, in the maximum brightness state. The corresponding accretion rate value in 2018 November, however, is lower by a factor of 2 than was in the maximum brightness state before 2017. The comparison of these results with earlier ones show that the extinction in 1998 was on the same level as in 2010-2013, apart from the dimming in 2012. The accretion rate, however, was then higher than at any time later. The long term decreasing trend in the accretion rate is consistent with the previous conclusion on the long-term fading of the source (Sect. 2.4.2).

2.4.4 Future prospects with Gaia and TESS

The results of the previous analyses indicate that the light curves of V582 Aur show the combined effect of extinction related dimming events and a general long term decay of the outburst. The latter trend predicts that the source will never return to the pre-2014 state and the 2019 brightness levels may be already close to an unobscured state with a lower central luminosity. Further observations can verify this conclusion and constrain the full length of the eruption. For instance, the ongoing Gaia sky survey will provide improved photometry in two optical passbands starting from 2014. Using the Gaia $G_{RP}$ band observations, which is close to the $I_C$-band (see Fig. 3 in Jordi et al. 2010), it will be possible not only to compare the ground-based measurements with the high precision Gaia photometric results, but we can also examine the long-term variability of V582 Aur. During the nominal 5-year mission, Gaia will provide approximately 50
Figure 2.5: Time evolution of the accretion rate (middle panel) and the extinction (bottom panel) derived from our accretion disk model (Sect. 2.4.3). The top panel shows the $I$-band light curve. Black points are from A18, red symbols are from this work, green symbols indicate results based on data from the 2MASS catalog.

photometric points for V582 Aur, which will cover a large part or the whole ongoing dimming event. Furthermore, the Transiting Exoplanet Survey Satellite (TESS) also carried out observations in the direction of Auriga in 2019 and 2021 autumn, providing 30 minutes cadence photometry in a broad band, which is centered on the effective wavelength of the $I_C$-band (see Fig. 1 in Ricker et al. 2015). In addition, further observations are expected in 2022 December as well.

The most recent measurements, which were obtained since early 2019 and are not included in Zsidi et al. (2019), from the Piszkestető Mountain Station ($Vri$-bands) and the Zwicky Transient Facility (ZTF) survey ($g$ and $r$-bands) in Fig. 2.6 indicates that V582 Aur underwent a new dimming event in 2020/21. The event is well documented only in the $g$ and $r$-band data, however, further $Vri$-band data in 2020 and 2021 cover both the dimmest and the brightest states, which can reveal color information on the event. The presence of this new dimming event supports the interpretation described in the previous Sections, i.e, an orbiting dust clump is responsible for the brightness variation at the optical wavelengths. Furthermore, the high cadence TESS measure-
ments can reveal the short-term or small amplitude variations, which are invisible for ground-based telescopes and may reveal the fine structure of the obscuring dust cloud.

Figure 2.6: Most recent light curves of V582 Aur. The figure is similar to Fig. 2.2 updated with data obtained since 2019 March. I completed the previously analyzed data with the most recent $g$ and $r$-band observations from the ZTF catalogue (light blue and yellow circles), and the most recent observations form the Piszkéstető Mountain Station in Johnson $V$-band and in Sloan $r$ and $i$-bands (colored triangles).
Chapter 3

Accretion variability from minute to decade timescales in the classical T Tauri star CR Cha

3.1 Introduction

Studying the variability of young stellar objects is essential not only with multifilter photometry, but it is important to involve additional observing techniques. This is crucial for understanding the accretion process, the relationship between the inhomogeneous disk structure and the time-variable accretion, and to identify the different physical mechanisms behind the observed variations. The timescale, amplitude, and pattern of the flux changes carry information on the distribution and kinematics of the accreting material, the density structure of the inner disk edge, and the presence of outflows or jets. For a sample of six young stars in the Chamaeleon I star forming region, my supervisors and I arranged ground-based optical and near-infrared photometric, and high-resolution spectroscopic observations contemporaneously with the Transiting Exoplanet Survey Satellite (TESS) observations in 2019, in order to examine the variability of the accretion process, analyze the effects of hot or cold spots, and identify the signs of line-of-sight obscuration by circumstellar matter. For one particular object of this sample, CR Cha, I was able to study the accretion process on timescales from hours to a decade by including earlier data from 2009 and 2018, while I spent one year at the European Southern Observatory (ESO) under the supervision of Gaitee Hussain and Carlo Manara. The results for the analysis of the dataset for CR Cha are described in this Chapter and published in Zsidi et al. (2022a, A&A, 660, A108). I introduce another member of the sample, VW Cha in Chapter 4, which is published in Zsidi
et al. (2022b, ApJ, in press). Furthermore, I give a brief overview of the remaining four members of the sample (WX Cha, CT Cha, WW Cha, VZ Cha) at the end of Chapter 4.

CR Cha is a classical T Tauri star with K spectral type (Hussain et al., 2009, Manara et al., 2016). This star is located in the Chamaeleon I star-forming region at a distance of 184.7±0.4 pc (Bailer-Jones et al., 2021). It has an effective temperature of 4900 K, a stellar luminosity of \( L_\ast = 3.3 - 3.8 \, L_\odot \), and a rotational period of 2.3 days (Bouvier et al., 1986), it shows an average brightness level of \( V = 11.0 \) mag, with photometric variability on the scale of a few tenth of a magnitude. Considering its luminosity and temperature, the stellar mass and age reported in the literature are in the range of \( M_\ast = 1.2 - 2 \, M_\odot \), and an age of 1-3 Myr (D’Antona & Mazzitelli, 1994, Siess et al., 2000, Hussain et al., 2009, Manara et al., 2016). The star displays moderate accretion of \( \dot{M}_{\text{acc}} \sim 2.8 \cdot 10^{-9} \, M_\odot/\text{yr} \) (Manara et al., 2016, 2019) and hosts a protoplanetary disk with \( i = 31^\circ \) inclination (Kim et al., 2020). Recent ALMA observations revealed a dust gap at \( r \sim 90 \) au and a ring at \( r \sim 120 \) au in the disk (Kim et al., 2020).

CR Cha possesses a complex, multipolar magnetic field (Hussain et al., 2009), which might be explained by the star having developed a radiative core. In contrast, fully convective stars have simpler, large-scale almost fully poloidal fields (Donati et al., 2008, Reiners & Basri, 2009). The complex magnetic field with weaker dipole component may allow the inner disk to penetrate closer to the star than the corotation radius.

In this Chapter, I present a multi-epoch photometric and spectroscopic analysis of CR Cha using data covering more than a decade with the goal of understanding the variability of the accretion process on a wide range of timescales. CR Cha is chosen as the target of this study as it is an excellent candidate to study variability: it is a typical classical T Tauri star and its magnetic field has been already mapped (Hussain et al., 2009). In addition, it is known to be a single star and to have a moderate mass accretion rate. Both aspects make it less complicated to interpret the observed variations in the photometry and in the spectra.

This Chapter is based on a collaborative work that I was leading, and the results are published in Zsidi et al. (2022a, A&A, 660, A108). I carried out this work while I was spending time at ESO, and I was collaborating with Gaitee Hussain and Carlo Manara. I reduced the spectroscopic data obtained in 2019 with the VLT/ESPRESSO instrument, and I analyzed the entire dataset presented in Sect. 3.2. I was also responsible for interpreting the results. The co-authors contributed with the reduction of the rest of the dataset and the provision of spectroscopic data from 2009 and 2018. Furthermore, we had invaluable discussions when analysing and interpreting the data. The Chapter is structured as follows. Sect. 3.2 presents the three observing campaigns used
in this work, and describes the data reduction processes. Sect. 3.3 explains how the photometric and spectroscopic data were analyzed, detailing the results of the study of both regular (periodic) and irregular photometric and spectroscopic variations. I then discuss the results in Sect. 3.4 and draw the conclusions in Sect. 3.5.

### 3.2 Observations and data reduction

CR Cha was monitored in three different observing seasons. We carried out spectroscopic observations in 2006, 2018, and 2019, and we complemented the data with ground-based multifilter photometry and high-cadence space photometry. In the following sections, I describe the three observing seasons.

#### 3.2.1 2006 observing season

Spectropolarimetric observations were made with the 3.9 m Anglo-Australian Telescope (AAT) over five consecutive nights from 2006 April 9 to 13 (PI A. Collier Cameron). One to four observations were obtained per night due to varying weather conditions, which resulted in an incomplete phase coverage. A visitor polarimeter (SemelPol) was mounted at the Cassegrain focus of the telescope and was coupled with the UCLES spectrograph covering the wavelength range from 437.6 to 682 nm with spectral resolution of around 70,000. This spectropolarimetric dataset has already been published in Hussain et al. (2009), focusing on the magnetic field properties of CR Cha. Gaiitee Hussain provided the reduced data for me, which I re-analyzed here with the focus on the accretion variability. As described by Hussain et al. (2009), the spectra were reduced using the LIBRE-ESPRIT data reduction package, which includes bias subtraction, flat fielding, wavelength calibration, and optimal extraction of (un)polarized échelle spectra (see Donati et al., 1997, 2011, 2014).

V-band photometric observations are publicly available from the ASAS-3 catalog for the AAT observing period. CR Cha was observed once every 1-3 nights using a $9^\circ \times 9^\circ$ wide-field camera with a pixel size of 15″. The $V$-band magnitudes were calculated by the ASAS-3 team using aperture photometry through five different apertures (2 to 6 pixels) and the results are publicly available from their online catalog\(^1\). For the 2006 data, I used the dataset with the smallest available aperture of 2 pixels. The ASAS-3 $V$-band observations are available for the period 2001–2009.

\(^1\)http://www.astrouw.edu.pl/asas/?page=aasc
3.2.2 2018 observing season

Spectropolarimetric measurements were taken with the HARPS instrument on the ESO 3.6 m telescope in La Silla (Pr.Id.0100.C-0708, PI F. Villebrun). The data were acquired using HARPS in polarimetric mode (Piskunov et al., 2011), yielding spectra with a resolving power of about 105,000 and covering wavelengths spanning from 380 to 690 nm. All spectra were recorded as sequences of four individual sub-exposures taken in different configurations of the polarimeter to allow a full circular polarization analysis. The data reduction process was carried out using the LIBRE-ESPRIT package (Donati et al., 1997, Hébrard et al., 2016), and Gaitee Hussain provided the reduced data for me. In total, 24 circularly polarized sequences were acquired over six consecutive nights, from 2018 March 3 to 9, with peak S/N levels ranging from 46 to 140. For a few observations, the blue arm was not extracted due to lower S/N, therefore the whole spectrum is accessible only for 19 observations.

V- and g-band photometric observations are available from the ASAS-SN catalog for the HARPS observing period. The camera has a field of view of 4.5°×4.5° with a pixel size of 8″. Aperture photometry with 2 pixel aperture radius was performed by the ASAS-SN team to obtain the V- and g-band magnitudes and the reduced dataset is publicly available from their online catalog². Multiple measurements are available per night, however, the cadence of the ASAS-SN observations are irregular: at times, these observations were made within 1-2 hours, and at other times, they are separated by a few hours. In total, the V-band observations are available for the 2014–2018 period, and g-band observations are carried out since the end of 2017. This means that observations made in both bands are available for the 2018 HARPS observing period.

3.2.3 2019 observing season

The Chamaeleon I star forming region, including CR Cha, was covered in Sectors 11 and 12 of TESS in 2019. The observations started on 2019 April 22 and finished on June 19, providing almost uninterrupted broad-band optical photometric observations with a 30-min cadence. Details on the TESS data reduction and photometry can be found in Plachy et al. (2021) and Pál et al. (2020), here I only summarize the main steps. The photometry of the source was performed via differential image analysis using the ficonv and fiphot tools of the FITSH package (Pál, 2012). This requires a reference frame, which was constructed as a median of 11 individual 64 × 64 subframes obtained close to the middle of the observing sequence. The convolution-based approach used

²https://asas-sn.osu.edu/
Observations and data reduction

Here exploits all of the information in the images by minimizing the difference and simultaneously correct for the various temporal aberrations (e.g., differential velocity aberration, variations in the PSF, pointing jitter corrections, etc.). This method is therefore equivalent to an ensemble analysis and requires basically no further post-processing of the light curves such as co-trending or similar types of de-correlation methods. The photometry process also requires a reference flux to correct for various instrumental and intrinsic differences between the target and the reference frames. For this, the below described SMARTS $I$-band photometry was used, as it was obtained over the same time period as the TESS data. Aperture photometry in the TESS images was carried out using an aperture radius of 2 pixels, and sky annulus between 5 and 10 pixels (the pixel scale is around 20$''$). The most recent TESS observations, obtained between 2021 April 2 and June 24, are also presented in this Chapter, and those data were reduced with the same procedure.

Optical and near-infrared ground-based photometric observations were carried out on almost every night between 2019 April 30 and June 13, contemporaneously with the 2019 TESS observing period. These observations were obtained with the ANDICAM imager mounted on the 1.3 m telescope at Cerro Tololo (Chile), which is operated by the SMARTS Consortium. Initially, images were taken in the Johnson-Kron-Cousins $VRCIC$ optical and CIT/CTIO $JHK$ infrared filters, but after the first three nights, the $V$ and $RC$ filters were unavailable due to technical complications. Therefore, all the remaining optical images were taken with the $IC$ filter, and I analyze here these data. Typically, 9 images were obtained with 14 s exposure time in the $IC$ filter, and 5–7 images were taken in the near-infrared filters with exposure times between 4 s and 15 s. For the optical images, standard bias and flat-field correction was applied by the SMARTS team. For the infrared images, dithering was performed to enable bad-pixel removal and sky subtraction, which was done using a custom IDL scripts. Photometric calibration in the optical was done using six comparison stars in the $6' \times 6'$ field of view whose magnitudes were taken from the APASS9 catalog (Henden et al., 2015). Since the APASS survey is conducted in eight filters (Johnson $B$ and $V$, Sloan $u'$, $g'$, $r'$, $i'$, $z_s$ and $Z$), the magnitudes of the comparison stars were transformed to the Johnson-Cousins system using the equations of Jordi et al. (2006) for the photometric calibration of CR Cha. For the photometric calibration in the infrared, 2MASS magnitudes (Cutri et al., 2003) of two comparison stars visible in the $2.4' \times 2.4'$ field of view were used.

Four high-resolution $(R=140 000)$ optical spectra were obtained with the VLT/ESPRESSO instrument as part of our DDT proposal Pr.Id.2103.C-5025 (PI Á. Kóspál) between 2019 May 31 and 2019 August 3, partly simultaneously with the TESS observing period. I reduced the spectra using Version 3.13.2 of the EsoReflex/ESPRESSO
pipeline (Freudling et al., 2013). The pipeline carries out the bias, dark, and flat-field corrections, the wavelength calibration and extracts 2D spectra and merged, rebinned 1D spectra, and removes the sky lines from the spectra. We obtained two additional spectra with the FEROS instrument (R=48,000) on the MPG/ESO 2.2 m telescope on 2019 June 6 and 2019 June 11. The observations were carried out in the object-calib mode, where simultaneous spectra of a ThAr lamp were taken using a comparison fiber. The spectra were reduced using a modified version of the FEROSPIPE pipeline (Brahm et al., 2017) written in 

Python. The original pipeline extracts all 33 échelle orders but it calibrates only 25, as it was developed to precisely measure the radial velocity. This modified pipeline\(^3\) allows calibration of all 33 échelle orders by fitting pixel value-wavelength pairs using identified emission lines in the corresponding ThAr spectra. The pipeline was modified by Attila Bódi, and a more detailed description of the modified pipeline can be found in Nagy et al. (2021).

### 3.3 Data analysis

In the following, I present the analysis of the photometric and spectroscopic data obtained in the three observing seasons. In particular, I look for periodicity in the light curves, and for color variations. I then analyze the variability of multiple emission lines, and of the veiling.

#### 3.3.1 Analysis of the light curves

Among the datasets available for CR Cha, the TESS light curve presents the best cadence covering 56 days. The 2019 TESS light curve (Fig. 3.1, middle panel), taken with 30-minute cadence, reveals both periodic and stochastic variations with a peak-to-peak amplitude of \(\sim 0.04\) mag. In order to find periodic signals in these photometric data, I computed the Lomb-Scargle periodogram (Lomb, 1976, Scargle, 1982), which is shown in the bottom panel of Fig. 3.1. The Lomb-Scargle periodogram is an algorithm that is able to analyze time-series datasets by computing a Fourier-like power spectrum in order to detect and characterize periodic signals. The advantage of using this method as opposed to other period-analysis techniques (such as Fourier methods, least square methods, or Bayesian approaches), is that it combines the other methods in such a way that it is motivated by Fourier analysis, it can also be viewed as a least squares method, but it can be derived from the principles of Bayesian probability theory. Furthermore, the Lomb-Scargle algorithm is appropriate for analyzing unevenly-sampled data, which

\(^3\)https://github.com/astrobatty/ceres
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Figure 3.1: The TESS light curve is indicated with a black curve, and the flare-like events are colored in blue. The ground-based $IJHK$-band measurements are shown with colored dots, and were shifted along the $y$-axis by the values indicated in the corresponding labels in the figure. The nightly averaged ASAS-SN $g$-band observations, obtained during the TESS observing period, are plotted with blue points. The orange and purple vertical dashed lines show the epochs when the ESPRESSO (E) and FEROS (F) spectra were taken, respectively. The long tickmarks on the top of the figure indicate the beginning of each month. **Bottom panel:** Lomb-Scargle periodogram obtained using the TESS data.

is important when analyzing ground-based observations. The periodogram obtained from the 2019 TESS light curve resulted in significant peaks at $2.314 \pm 0.033$ days and $1.156 \pm 0.009$ days (Fig. 3.1). I computed the errors for the periods by fitting a Gaussian to the detected peak of the periodogram, and I adopted the errors of the fit parameters as the uncertainties of the periods. An analysis of the more recent TESS light curve taken with 10-minute cadence between 2021 April and June (Fig. 3.2), performed with the same analysis technique as for the 2019 data (see Sect. 3.2.3), confirms the presence of these two peaks. The peak at 2.314 days is consistent with the stellar rotational period found in previous studies ($P = 2.3$ days, Bouvier et al. 1986), suggesting the presence of starspots on the stellar surface. The 1.156-day period is approximately half of the stellar rotational period. The 2019 TESS light curve also hints at long-term oscillation with a timescale of $\sim 25$ days, however, the time coverage of our dataset is not long enough to probe these longer timescales.
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Figure 3.2: The TESS light curve, obtained in 2021, is indicated with a black curve, and the flare-like events are colored in blue. The long tickmarks on the top of the figure indicate the beginning of each month. The bottom panel shows the Lomb-Scargle periodogram obtained from the 2021 TESS data.

Robinson et al. (2021) modeled the effect of inclination on how periodic a light curve appears. They found that larger inclinations lead to more burst dominated light curves. The moderate 31° inclination of CR Cha indicates that the light curve is expected to be not purely periodic. Indeed, I was able to detect a rotational period in the analysis of the light curve but, at the same time, additional effects, such as accretion variation and flares also significantly contribute to the observed light curve.

The TESS light curves indeed reveal a few flare-like events, indicated by the blue points in the middle panel of Fig. 3.1 and the top panel of Fig. 3.2. During the 56-day-long TESS observing period in 2019, I found five flare-like events with durations ranging from 3.8 hours to 7.2 hours, which gives a flare rate of 0.09 days⁻¹. However, these were events showing up to ∼0.02 mag brightening (Fig. 3.3, blue points). Furthermore, the 2021 TESS light curve reveals three flare-like events with durations ranging from ∼1 to 4.5 hours. The 2021 TESS data, depicted with the orange points in Fig 3.3, have higher (10-minutes) cadence than the 2019 observations. This revealed a more detailed flare structure on panels (f) and (g), and allowed to detect a more minor event such as the one in panel (h).

The ASAS-SN data taken between 2014 and 2020 have a sparser time coverage with respect to TESS, but are useful to learn about the long-term behavior of CR Cha. I calculated the Lomb-Scargle periodogram for the available ASAS-SN data taken between 2014 and 2020 (Fig. 3.4). Since the Lomb-Scargle algorithm suited exploration of the Fourier-spectrum also in the case of unevenly sampled data like ours well, this method is able to reveal the existing periods in the ASAS-SN dataset as well. $V$-band
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Figure 3.3: The flare-like events in the TESS light curves of CR Cha. The blue points show the 2019 TESS data, and the orange symbols indicate the 2021 TESS data.
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Figure 3.4: The ASAS-SN $V$- and $g$-band light curves are shown on the top panel along with epochs when the HARPS (gray dashed lines), the ESPRESSO (orange dashed lines) and the FEROS (purple dashed lines) were taken. The black dots indicate the median brightness for each group of data. Bottom left panel: Lomb-Scargle periodogram for the $V$-band data. Bottom right panel: Lomb-Scargle periodogram for the $g$-band data. Observations are available between 2014 and 2018, and $g$-band observations are accessible between 2017 and 2020. The most significant peaks of the periodograms are at $P = 2.327\pm0.0014$ in the $V$-band and $P = 2.326\pm0.0019$ days in the $g$-band. These periods agree with the stellar rotational period found in the TESS light curves. Moreover, I found significant periods around 1 day in both $V$- and $g$-bands, which appear due to the fact that the observations were taken with nightly cadence. An additional 1.754-day period appears to be present in the ASAS-SN data. The TESS data from 2019 do not show signs of a period around 1.7 days, whereas a hint of this periodicity is present in the 2021 observations with TESS. I thus examined if shorter sections of the ASAS-SN data indicate its presence. I found that during the 2019 TESS observing period the ASAS-SN data also do not show any period around 1.7 days. However, randomly selected 56-day long slices of the ASAS-SN light curves show a period around 1.7 days with varying intensity. The origin of this periodic signal is unclear and surely very variable with time.

The long-term behavior of the $V$-band light curve indicates a general, slow brightening of the system by $\sim0.05$ mag over about four years. This effect is not observed
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Figure 3.5: The top panel shows the ASAS-3 light curve with the phases when the AAT spectra were taken (vertical dashed lines), and the black dots show the median brightness for each group of data. The bottom panel shows the Lomb-Scargle periodogram for the whole ASAS-3 dataset.

in the g-band light curve, either because the effect is no longer present after 2018, or because the bluer wavelength coverage of the g-band filter weakens the effect.

Similarly to the ASAS-SN data, the available ASAS-3 V-band photometric data, obtained between 2001 and 2009, are useful to study the long-term trends in CR Cha. These data are shown on the top panel of Fig. 3.5. I computed the Lomb-Scargle periodogram for the ASAS-3 observations, which I show in the bottom panel of Fig. 3.5. A well defined period at $P = 2.327$ days can be observed, which is consistent with the stellar rotation period, and I interpret this signal as rotational modulation due to spots. This period is in agreement with the previous results, and with the other datasets shown here. The 2.3 days period is present in the system for decades, and the most recent high-resolution data also confirm its presence. On the long-term, the data reveal an increasing trend in the brightness by $\sim 0.2$ mag over 8 years, thus in line with the brightening observed in the ASAS-SN data. However, no sudden, extreme brightening or dimming was detected, which indicates the stable behavior of the system.

As the TESS light curves reveal more stochastic variations due to their more frequent timescales sampling, and because the ASAS-SN and ASAS-3 data have longer time coverages, I adopt for this work the $P = 2.327$ days period as stellar rotation period found in the ASAS-SN and ASAS-3 data for our target. I used this period to
construct the phase-folded light curves (Fig. 3.6). Before creating the phase-folded light curve for the ASAS-3 data, I subtracted the linear brightening trend and shifted it back to the median brightness level. In addition, I also removed the long-term oscillating trend from the 2019 TESS light curve, and shifted it back to the median brightness level. I fitted a sine curve to all the different datasets, which are indicated with orange curves in Fig. 3.6. The 2019 TESS light curve (top panel of Fig. 3.6) reveals a trend that can be fitted better with the sum of two sine curves, indicating that multiple spots contribute to the modulation. On the other hand, the 2021 TESS data show a clearer single sinusoidal trend, which suggests that the surface spot distribution has evolved over the course of two years. The peak-to-peak amplitude of the fitted curves show the rotational modulation with different amplitudes in the different bands ranging from \( \sim 0.009 \) mag in the TESS observations to \( \sim 0.09 \) mag in the ASAS-3 measurements.

### 3.3.2 Color variations

The \( I_C, J, H, K \)-band SMARTS observations were obtained simultaneously with the TESS observation (Fig. 3.1) in the 2019 observing period. For most nights, the ground-based \( I_C \)-band magnitudes reproduce the space-based broadband optical TESS photometry well. The near-infrared \( J, H, K \)-band light curves also follow the variability seen in the TESS observations in the first 20 days, although with smaller amplitude. In contrast, in the second half of the TESS observing window, the near-infrared light curves show a brightening trend of 0.1–0.2 mag, whereas the TESS magnitudes remain constant to within 0.03 mag. Because the time coverage and the cadence of the SMARTS data is limited, I did not attempt to perform a periodogram analysis on these ground-based data.

In Fig. 3.7, I show the color-magnitude and the color-color diagrams obtained from our \( I_C, J, H, K \)-band measurements. The color-magnitude diagrams indicate that the source becomes redder as it gets brighter (negative slope). I indicated the more recent data with lighter colors in the color-magnitude diagrams, and they suggest that the system was brightening at near-infrared wavelengths during the last days of the 2019 observing period.

The trajectories on the color-magnitude diagrams can help distinguishing different possible physical mechanisms causing the variability. These physical mechanisms include rotating starspots on the stellar surface, variable accretion, or extinction caused by the circumstellar matter. I indicated the effect of extinction change corresponding to \( A_V = 1 \) mag based on the reddening law by Cardelli et al. (1989) in Fig. 3.7 with an arrow, which highlights that the data distribute orthogonal to the reddening
Figure 3.6: The phase-folded light curves of CR Cha. Vertical dashed lines indicate the epochs of the spectroscopic observations. The top panel shows the TESS measurements with the ESPRESSO (orange lines) and FEROS (purple lines) epochs, the middle panel displays the ASAS-SN observations with the HARPS epochs (gray lines), and the bottom panel presents the ASAS-3 data with the AAT epochs (dark blue lines). The orange curves show the fitted sine curves to each data set.
vector. In addition, the presence of starspots would also result in a positive slope (redder as it gets fainter) in the color-magnitude diagrams (Carpenter et al., 2001). Therefore, starspots and extinction cannot explain all of the variability characteristics we observed, which suggests the presence of an additional mechanism that affects the emission at longer wavelengths more than at shorter wavelengths. These color variations will be discussed in Sect. 3.4.3 in more detail. I explored the \([g - \text{TESS}]\) vs. TESS color-magnitude diagram, the analysis of which resulted in a nearly colorless variation. I also examined if shorter-term color variations associated with rotation period appear in the color-magnitude diagrams. I phase-folded the optical and the near-infrared light curves using the \(P = 2.327\) days period (Fig. 3.8, left). These, however, do not display the rotational modulation as clearly as the other photometric data shown in Fig. 3.6. I color-coded the data points according to the rotational phase, and used the same color on the four right-hand side panels of Fig. 3.8 in order to investigate whether they show any trend associated with the rotational period, but I found no significant trends.
3.3. Data analysis

![Graphs](image)

Figure 3.8: The four panels on the left-hand side show the phase-folded SMARTS light curves, and the four panels on the right-hand side display the color-magnitude and the color-color diagrams with color-coded symbols according to the rotational phase.

### 3.3.3 Spectroscopy

In order to display the phase coverage of the spectroscopic observations, I indicated in Fig. 3.6 with vertical dashed lines the phases at which the spectra used in this work were taken. The middle panel of the figure shows that the HARPS data from 2018 cover the whole phase-space. On the other hand, the AAT observations from 2006 do not cover the dimmest phase (bottom panel), and the ESPRESSO and FEROS measurements from 2019 are more sparse in the phase coverage (top panel). Even though two ESPRESSO observations were taken outside of the TESS observing period, I overplot them in the top panel in order to display the phase coverage of all observations.

The shape of the emission line profiles present in the spectra of CR Cha change throughout the observing seasons on yearly, monthly and daily timescales. The strongest emission line in all spectra is the H\(\alpha\) line. In addition, the H\(\beta\) and the [O I] 630 nm lines were detected in weaker emission. The [O I] 557 nm emission line present in the HARPS and AAT spectra is not astronomical but due to emission in our atmosphere. Indeed, this line was removed from the ESPRESSO and the FEROS spectra during the data reduction process. Besides the emission lines, the Na I doublet and the Li I 670.8 nm absorption lines were also detected in all spectra. The Ca II infrared triplet region (CaIRT) is covered only by the FEROS spectra. Since one line of the triplet is located between two orders, only two CaIRT lines were detected, and they appear in weak absorption. In addition, the Ca II H and K lines appear in emission in the
ESPRESSO and FEROS spectra but they are not covered by the AAT observations. The Ca II K line was detected in the HARPS spectra as well, however, the noise level is too high to identify the Ca II H line.

In the following, I analyze the variability of the two permitted emission lines detected in the spectra and of the veiling of the photospheric lines.

**Analysis of the Hα line**

The Hα line profile shows both short term and long term variability. The mean Hα line profiles for each observing season, indicated with thick black lines in Fig. 3.9, show that the general Hα line profile has changed remarkably on yearly timescales.

All Hα line profiles show a strong central component, however, the intensity of this component varies over time. The largest change in the amplitude, including the weakest peaks, appears during the 2019 observing season. However, it should be noted that this observing season is more sparsely sampled but covers a longer period than the earlier ones: the sampling probes the monthly timescales. Besides the amplitude variations, the Hα line exhibits morphological variations. A red bump appears at about 100 km/s on the night with the strongest emission, moreover, the entire blue wing becomes relatively strong during one of our observations. In contrast, the 2006 data display different line profiles with respect to the more recent datasets. The central peak reaches a maximum among our spectra, but also varies by a factor of 1.5 in peak intensity. A strong blueshifted absorption feature is present around −100 km/s, and this line profile shape is preserved during the entire 2006 observing period with varying amplitudes. The 2018 data show very stable line profiles during the entire HARPS observing period with a small amplitude variation. A small blue absorption appears here as well, however, the profiles are more symmetric than in 2019.

In order to examine and quantify the temporal change of the line profiles, I calculated the so-called variance profile, which measures the amount of temporal variability in each velocity bin in the line profile. I obtained the variance profile as described in Johns & Basri (1995) by the following relation:

\[
\sum_v = \left[ \frac{\sum_{i=1}^{n}(I_{v,i} - \overline{I}_v)^2}{n-1} \right]^{1/2},
\]

where \(n\) is the number of observations, \(I_{v,i}\) is the intensity at a given velocity \((v)\) in each observation, and \(\overline{I}_v\) is the mean intensity of all the observed profiles at a given velocity \(v\). I show the variance profiles of the Hα lines for each observing season in Fig. 3.9 as the blue shaded areas. These indicate the strongest variability of the lines at
Figure 3.9: \( \text{H}\alpha \) line profiles for all three observing seasons. The mean profiles are indicated by a thick black curve and the variance profile is shown with blue shaded area. The numbers indicate the JD of observations with the corresponding color.

The central peak for all three observing periods, with the largest amplitude variations in 2019. The variability of the central peak is likely caused by the varying accretion onto the star on short-term (daily) timescales. The 2018 data show only small amplitude changes with little variations of the amplitude with velocity. In contrast, the 2006 observations indicate variability at the dip around \(-100\, \text{km/s}\), which might indicate a varying wind component, as well as changes in the amplitude of the central peak. Finally, the 2019 data show strong variations both in the central peak, as well as at \(+100\, \text{km/s}\) and \(-100\, \text{km/s}\). While the latter could be again ascribed to a varying wind, the former is possibly the result of varying accretion geometry.

I show the \( \text{H}\alpha \) line profiles ordered by phase for all observations in Fig. 3.10 along with the median profile indicated with black. The 2006 observations on the top panel show that the blueshifted absorption around \(-100\, \text{km/s}\) becomes more pronounced from phase 0 to 0.3, then the strength of component approaches the level of median profile towards the photometric minimum. As the light curve comes out of a minimum, the absorption gets more pronounced again. The redshifted excess emission compared to the median profile around 150 km/s weakens as the phase progresses, and it is weakest right before the minimum. After the photometric minimum, this component strengthens again.

I show the \( \text{H}\alpha \) line profiles ordered by phase for the 2018 observations in the middle panel of Fig. 3.10. In this case, the blueshifted bump at \(-150\, \text{km/s}\) becomes stronger from phase 0 to phase 0.2. Towards the photometric minimum, this component gets weaker than the median value, however, it becomes stronger again closest to the minimum. As the light curve leaves the minimum, this component weakens again. At the same time, the central peak weakens from phase 0 to phase 0.4, however, it also
Figure 3.10: Hα spectra ordered by rotation phase (left), and the Hβ lines ordered by rotation phase (right) for each observing season. Top panels: AAT, middle panels: HARPS, and bottom panels: ESPRESSO and FEROS measurements. The phases with the rotational number are indicated on the left side of each line. The thick black lines indicate the mean line profile for each observing season.
3.3. Data analysis

Figure 3.11: Autocorrelation matrices for the Hα lines. The positive values (more red color) indicate correlation, the negative values (bluer color) show anti-correlation, and the values around zero (yellow color) indicate no correlation. **Left:** 2006 (AAT), **Middle:** 2018 (HARPS), **Right:** 2019 (ESPRESSO and FEROS)

becomes stronger closest to the minimum, and weakens again as the light curve leaves the minimum.

The bottom panel of Fig. 3.10 shows the 2019 ESPRESSO and FEROS observations ordered by phase. Since these observations cover a longer time span with sparser cadence, they are less sensitive to the variability on short timescales, however, they can reveal the variability on monthly timescales. This shows that the amplitude of central component of the Hα line is highly variable during our observing period, which suggests changing accretion onto the central star.

The observed emission lines consist of multiple components and display variability on various timescales. These components might originate from different physical processes. In order to examine the relationship between the variations of these components, I calculated correlation matrices (Johns & Basri, 1995). I divided each emission line into small velocity intervals and calculated the correlation coefficient ($r$) between every pair of velocity bins as follows:

$$r_{ij} = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}},$$

(3.2)

where $x$ and $y$ contains the intensity values of each epoch for a chosen velocity bin. Calculating the correlation coefficient between every pair of velocity bin results in a correlation matrix.

The autocorrelation matrices for the Hα lines are shown in Fig. 3.11. The 2006 observations show correlation in the blue wing of the Hα line, between around $-150$ km/s and $-250$ km/s. There is also anticorrelation between around $-80$ km/s and $-250$ km/s, and $-80$ km/s and $-150$ km/s. The pattern is slightly different for the 2018 observations: anticorrelation appears between the red and the blue parts of the line, at
Figure 3.12: Two dimensional periodogram for the Hα lines. The colorbar represents the periodogram power varying from zero (blue) to the maximum power (red). The inner contours correspond to the 95% confidence level, the outer contours correspond to the 85% confidence level. The stellar rotational period is marked by the horizontal white dashed line.

~50 km/s and −120 km/s. The ESPRESSO and FEROS observations resulted in very different autocorrelation matrix. This probably results from the larger temporal gap between the individual observation.

In order to examine whether the photometry and the spectroscopy are linked in a way that lines vary with the same period as the photometric brightness, I applied a Lomb-Scargle periodogram analysis in each velocity bin for the Hα and the Hβ lines. The resulting 2D periodograms for the 2006 and the 2018 observing seasons are plotted in Figure 3.12. I drew contours around the regions corresponding to the 85% and 95% confidence levels.
During the 2006 observing season, the red wing of the Hα line and the blueshifted absorption component (~100 km/s) showed significant periodic behavior with a period of ~1.1 days, about half of the stellar rotation period. As the data cover 4.24 days, which is less than the twice the rotational period, the analysis might not be sensitive to variability on timescales of the rotation period. However, a 2 – 3-days period was found in the redshifted wing of the Hα line with 85% confidence level. In contrast, the 2018 HARPS observations reveal a somewhat longer periodicity (~3–5 days) in the redshifted side between 0 and 250 km/s and on the blueshifted side between −100 and −200 km/s, and do not seem to be modulated by the rotational period.

Analysis of the Hβ line

The profile of the Hβ line also displays variability throughout the years, however, during a given observing period, it shows variability with small amplitude. I calculated the variance profiles as described above, and indicated them with blue shaded area in Fig. 3.13.

There are several photospheric absorption lines in the Hβ region which are superposed on the Hβ emission. In order to eliminate the effects of the absorption lines, I subtracted the rotationally broadened spectrum of ε Eri, which has the same spectral type as CR Cha, from the observed spectra, and this process resulted in more defined peaks. The results show (Fig. 3.13) that most of the variability come from the amplitude changes of the line during all observing seasons. On the other hand, the strength of the mean line profile, indicated with the thick black line, slightly changes throughout the years. Overall, they do not show as strong variability as the Hα line. I present the Hβ line profiles ordered by phase in Fig. 3.10. The results show similar pattern in the

![Figure 3.13: Hβ line profiles for all three observing seasons. The mean profiles are indicated by a thick black curve and the variance profile is shown with blue shaded area.](image)
amplitude variations as the H\(\alpha\) line, however, no significant morphological variations were found.

The 2D periodograms for the H\(\beta\) line are shown in Fig. 3.14. The 2006 measurements reveal a period around the rotation period in the red wing of the line, but the 2018 data shows only a period around \(\sim 3-4\) days, similarly to H\(\alpha\) but with smaller extent in terms of velocity.

**Veiling measurements**

The photospheric spectrum of classical T Tauri stars is often veiled by additional continuum emission. The veiling continuum is attributed to the shock-heated gas that results in a hot spot on the stellar surface below the accretion stream. The veiling of a star can be determined by measuring the equivalent widths of photospheric lines
3.3. Data analysis

Figure 3.15: The LSD profiles for all three observing periods. The dates of the observations are indicated on the right-hand side of each line. When multiple observations were carried out on the same night, I indicated it with the version number (v#)
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\[ W_{eq}^0 = W_{eq}(V + 1), \]  \hspace{1cm} (3.3)

where \( W_{eq} \) is the measured equivalent width of a photospheric line, \( W_{eq}^0 \) is the equivalent width of the same line in the spectrum of a non-accreting reference object, and \( V \) is the veiling.

Instead of using only a single absorption line, I constructed an average absorption line profile using the Least-Squares Deconvolution (LSD) method (Donati et al., 1997). The Least-Squares Deconvolution is a cross-correlation technique, which computes average line profiles from thousands of spectral lines simultaneously. It assumes additive line profiles, wavelength independent limb-darkening, self-similar local profile shape and weak magnetic fields. This allows the procedure to see the stellar spectra as a line pattern convolved with an average line profile. For this reason, the extraction of the average line profile corresponds to a linear deconvolution problem. I used the unpolarized LSD profiles for calculating the veiling, however, since veiling is wavelength dependent, I recalculated the LSD profiles for a smaller region of the spectrum between 530 nm and 700 nm. I show the LSD profiles for all three observing periods in Fig. 3.15. As \( \epsilon \) Eri is a non-accreting star with the same spectral type as CR Cha, I used the rotationally broadened spectrum of \( \epsilon \) Eri as a reference spectrum in order to calculate the absolute veiling of CR Cha. CR Cha shows moderate veiling of \( \sim 0.2 \) with small variations. As veiling is often considered as a measure of the accretion rate, the small veiling variations hint at a modest change in the accretion rate by a factor of \( \sim 3 \).

I also examined whether the veiling, which was obtained from the absorption lines,
varies in phase with the rotation period. Figure 3.16 shows that the majority of the veiling values are almost constant and they are only slightly modulated by the rotational period. However, I note that the results show three further outlying data points in terms of the veiling at phases 0.33 and 0.76, which are out of the range of Fig. 3.16.

3.4 Discussion

CR Cha shows small-amplitude but significant photometric variability on timescales from hours to years, with a peak-to-peak amplitude ranging from $\sim0.05$ mag in the optical TESS observations to $\sim0.15$ mag in the $K$-band data. Periodic behavior was found in both new TESS observations from 2019 and 2021 and archive ASAS-SN (2014-2020) and ASAS-3 (2000-2010) catalogs. This confirmed that the $\sim2.3$-day periodicity is present in the system for decades. This periodicity can be attributed to stellar rotation caused by spots on the stellar surface. The brightness variations can be modeled with simple spot models, but the available colors and the uncertainty on each value do not allow us to distinguish between cold ($T\sim4350$ K) or hot ($T\sim5300$ K) spots. It is likely that both exist on the surface of this star, which is known to host a complex magnetic field (Hussain et al., 2009). In addition, the ASAS-3 and the ASAS-SN V-band observations hint at a general, slow brightening of the system: the ASAS-3 data show $\sim0.2$ mag brightening during $\sim8$ years of observations, and the ASAS-SN V-band light curve indicates a brightening of $\sim0.05$ mag over $\sim4$ years. The origin of this brightening is unclear, however, change in the average spot coverage as spots slowly evolve over time might contribute to the observed behavior. On the other hand, the TESS data, thanks to their much higher photometric accuracy, reveal a more stochastic behavior with peak-to-peak amplitude of $\sim0.05$ mag, probably due to accretion variability, and a few flares. The multifilter $J$, $H$ and $K$-band light curves have similar shapes to the TESS light curve, however, the amplitude of the variability is different. The $J$-band data have the smallest amplitude of $\sim0.09$ mag and the amplitude increases towards the $K$-band, which have $\sim0.17$ mag peak-to-peak amplitude. While the TESS data probe the variability on the shortest timescales, the ground-based photometry reveals a trend beyond the rotational modulation.

The most striking variable features in the spectra are the highly variable Balmer emission lines. The mean H$\alpha$ line profiles show strong variations in both intensity and line profiles on a yearly timescale. This suggests that different physical mechanisms contribute to the observed variability. In this section I discuss how I interpret these spectroscopic and photometric variations.
3.4.1 Line morphology variations

I discuss here the variability of the emission line profiles during the three observing periods. The observed shifts in the variability period on decadal timescales might originate from the formation of multiple hot spots on the stellar surface at different times: one dominant hot spot would cause modulation at the stellar rotation period, while multiple hot spots at different latitudes would result in different variability periods. Multiple hot spots are expected on CR Cha, as the star hosts a complex magnetic field (Hussain et al., 2009). As the 2019 observations do not have as good phase coverage as the previous epochs, we cannot check if there is any periodicity.

In comparison with studies focused on other T Tauri systems, we see in this target that the period analysis of the Hα lines often do not exhibit a single and highly significant peak. As the Hα line is expected to form not only at the accretion spot but also in the accretion funnel and in the stellar winds, the variability of this line is also influenced by the variations of the circumstellar environment. However, the rotation period might appear in the periodograms with varying strengths. It is instructive to compare these findings with similar analyses of individual targets. In the LkCa 15 system, the strength of the emission at the line center is modulated by the stellar rotation, and this effect is clearly displayed in the periodogram (Alencar et al., 2018). On the other hand, the inverse P Cygni profile of the Hα line of the HQ Tau system displays modulation on the timescale of the stellar rotation not only in the line center but all the way to the red wing (Pouilly et al., 2020). Another interesting system to mention is V2129 Oph. When analyzing this target, Sousa et al. (2021) compared their results with the periodograms for the same system analyzed by Alencar et al. (2012), and they found some differences on ~decadal timescale, similarly to our results. Sousa et al. (2021) discuss a few possible explanations for the observed phenomena, such as variations in the magnetic field strength, which would result in variations in the magnetospheric truncation radius, or latitudinal differential rotation, or a more complex magnetic structure with two major funnel flows originating at different radii in the inner disk. However, in the case of V2129 Oph, a periodicity longer than the stellar rotation period is present at the line center for a time of almost a decade. The likely cause of the periodicity is a structure that is present beyond the corotation radius which is stable for almost a decade. In the case of CR Cha, the rotation period has been stable for decades but the line profiles (and also the photometry) do vary with longer periods as well, likely due to variations of the circumstellar environment.

The overall Hα line profile variations show different characteristics during the three observing seasons indicating the significance of different variable physical mechanisms
3.4. Discussion

on yearly timescale. The 2018 observations show the least amount of variability, mostly showing modulations presumably due to changes in the accretion rate. The 2006 observations reveal slightly different line profile with an additional blueshifted absorption component, which is usually associated with ejection processes, such as wind. In addition, the amplitude variations of the central peak are larger than the ones during the HARPS observations in 2018, which suggests larger change in the accretion rate. The 2019 observations show line profiles similar to those measured in 2018, however, based on their variance profile, these data show the largest amount of variability due to the changing accretion, similarly to the 2018 observing season.

The Hβ line profiles do not show as prominent morphological changes as the Hα lines. However, the amplitude of the Hβ lines vary both over the observing seasons and within one set of observations. The 2018 data show the least amount of variability, similarly to the Hα line, indicating very small changes in the accretion rate. The 2019 and 2006 data exhibit comparable and larger amount of variability across the whole line, which hints at slightly larger changes in the accretion rate. I quantify these variations in the next Section.

3.4.2 Timescales of accretion variability

After describing how the observed emission lines vary in morphology with time, I am investigating here the timescales on which these variations are largest. The presented dataset allows me to explore the timescales from hours to a decade in one particular object. I calculated the equivalent width of the Hα line at each epoch, and since our photometric observations indicate that the brightness of the star barely changes, the equivalent width should be proportional to flux variations. In order to confirm that the variations in equivalent width roughly correspond to variations in accretion rates, I converted the equivalent width values to accretion rates for each observation with the following procedure. First, I calculated the Hα line luminosity using the continuum flux value around the Hα line measured on the flux-calibrated X-Shooter spectra of this target in 2010 (Manara et al., 2016). As the mean brightness of the system did not change significantly between 2010 and 2019 (see Figures 3.4-3.5), I used the same continuum flux value for both the 2018 and the 2019 observations, whereas I accounted for the ∼0.1 mag dimmer state during the 2006 by decreasing the continuum flux by the corresponding flux ratio. The line luminosity was then converted into accretion luminosity using the following empirical relation from Alcalá et al. (2017):

\[ \log_{10} \left( \frac{L_{\text{acc}}}{L_{\odot}} \right) = a \cdot \log_{10} \left( \frac{L_{\text{line}}}{L_{\odot}} \right) + b \] (3.4)
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Figure 3.17: Mass accretion rates calculated at each observing epoch from the estimated luminosity of the H$\alpha$ line for CR Cha.

The value of the $a$ and $b$ coefficients are different for each accretion diagnostic line. For the H$\alpha$ line, $a = 1.13 \pm 0.05$ and $b = 1.74 \pm 0.19$ are the corresponding coefficients.

Finally, I compute $\dot{M}_{\text{acc}}$ with the classical relation (Hartmann et al., 2016). The values of $\dot{M}_{\text{acc}}$ at the time of our observations are shown in Fig. 3.17, and fall between $\sim 2.5 \cdot 10^{-9} \text{M}_\odot/\text{yr}$, in line with previous results (e.g., Manara et al., 2016, 2019).

I then obtained the relative amplitude of the accretion rate variations compared to the mean accretion rate value. In order to cover all the possible timescales from our dataset, every value of the accretion rate was compared with the ones obtained from every other spectrum. These are displayed with small blue dots in Fig. 3.18. I also marked the median amplitude of the variations for the different timescales with larger colored dots, and indicated the 0.25 to the 0.75 percentile of the distribution of the points with black lines. The results show that the amplitude of the variations increases from hours to several days, and it saturates when in the range between a week to a month, which is not well sampled by our data. This result is partially in agreement with the conclusions of Costigan et al. (2014). Indeed, the comparison of this result with the stellar rotation period suggests that the maximum of the variations are on timescales that are longer than the rotation period, whereas Costigan et al. (2014) suggested that the maximum variability is on timescales of the order of the rotation period. In addition, there is an apparent drop at the timescales of a decade. However, this effect might arise from the fact that our sample on decadal timescale is less rich in data than on shorter timescales.

Studies of large samples of low-mass young stars show that the the amplitudes of variability in the accretion rate range from small fractions to $\sim 1$ order of magnitude, with typical value of $\sim 0.4$ dex (Venuti et al., 2014). In this context, the accretion rate of CR Cha is smaller than the typical value for young stars with mass $> 1 \text{M}_\odot$ but
the accretion rate variations of CR Cha reaches the typical value presented in Venuti et al. (2014). The typical timescales of accretion variability of classical T Tauri stars have also been explored in previous works in the framework of large surveys. Nguyen et al. (2009) examined the spectra of several low-mass pre-main-sequence stars and found that the amplitude of the variations increases from hours to several days, after which it saturates. Costigan et al. (2012) analyzed the optical spectra of 25 targets in the Chamaeleon I region and derived an upper limit on the dominant timescale of the accretion variability: they suggest that observations on timescales of a few weeks are sufficient to characterize the majority of the accretion-related variations in typical young stars over a period of ~1 year. Costigan et al. (2014) studied 15 T Tauri and Herbig Ae stars over a wide range of timescales and found that the majority of the variations occur as gradual changes in the Hα emission and the period of days is the dominant timescale of these variations. Our data confirms that accretion variability has a maximum of intensity on weeks to months timescales.

3.4.3 Explanation of the color variations

As discussed in Sect. 3.3.2, the data we have obtained allow studying the variations in the near-infrared colors for CR Cha in 2019. I compare these variations with the models developed by Carpenter et al. (2001).

They examined the near-infrared color variations of young stars and described three
physical models as the possible origin of the observed color changes. In the first of their models, the light variations are caused by starspots, which modulate the brightness of a star as stellar rotation alters the fractional spot coverage. This model resulted in either nearly colorless fluctuations or positive slope on the color-magnitude diagram (i.e., the object becomes bluer as it gets brighter), depending on the fractional spot coverage and spot temperature. This is not observed for CR Cha. The extinction model attributes the observed color changes to extinction, which result from inhomogeneities in either the inner circumstellar environment or the molecular cloud that move across the line of sight. The extinction vectors can be calculated from the interstellar reddening law, and they also result in a positive slope on the color-magnitude diagram. However, the extinction slope is shallower by 25° than those expected from hot spots. Again, this is not what is observed for our target.

The third model that Carpenter et al. (2001) consider is an accretion disk model, which takes into account the emission from a circumstellar disk as a source of near-infrared variability. The near-infrared variability may originate either from changes in the mass accretion rate or changes in the inner disk structure that alter the amount of absorbed and reprocessed stellar radiation. Variations in the accretion rate or in the structure of the inner disk result in a negative slope in the near-infrared color-magnitude diagram. This negative slope (target becomes redder as it gets brighter) on the color-magnitude diagrams observed in CR Cha (Fig. 3.7) is peculiar, and typically observed in a small fraction of targets (∼1%, Carpenter et al., 2001). This behavior suggests that the color variations are not due to changing extinction or to the presence of stellar spots, but more consistent with the accretion disk model described by Carpenter et al. (2001).

Based on the available data, I can attempt to test the hypothesis that the variations in $\dot{M}_{\text{acc}}$ are the cause of the color variability. In order to test this hypothesis, I compared the equivalent widths of the H$\alpha$ lines in the 2019 observing epoch (Table 3.1) with the data points on the color-magnitude diagrams which were taken on the same nights (indicated with green color in Fig. 3.7). Unfortunately, as these data points cover only a small range on the diagram, it is difficult to recognize any pattern. However, a rough comparison is possible. The disk model in Carpenter et al. (2001) indicates that the expected photometric variations can be a few tenth of magnitudes for accretion rates changing from $\dot{M} \sim 3 \cdot 10^{-9} M_\odot/\text{yr}^{-1}$ to $\dot{M} = 10^{-7} M_\odot\text{yr}^{-1}$. The comparison between these models and our photometric data suggests that, if the color variations are only due to accretion rate variations, the variability of the accretion rate during our observations were smaller than a factor of ∼5. This is in line with equivalent width variations, which indicate that the the accretion rate varies by a factor of ∼3.
3.4 Discussion

Table 3.1: Equivalent widths of the Hα lines for the 2019 campaign.

<table>
<thead>
<tr>
<th>JD − 2450000</th>
<th>EW$_{\text{H}\alpha}$[Å]</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>8635.4841</td>
<td>−14.13</td>
<td>ESPRESSO</td>
</tr>
<tr>
<td>8640.4800</td>
<td>−17.89</td>
<td>ESPRESSO</td>
</tr>
<tr>
<td>8640.6016</td>
<td>−15.56</td>
<td>FEROS</td>
</tr>
<tr>
<td>8642.6492</td>
<td>−11.22</td>
<td>ESPRESSO</td>
</tr>
<tr>
<td>8645.5397</td>
<td>−16.38</td>
<td>FEROS</td>
</tr>
<tr>
<td>8697.5039</td>
<td>−29.56</td>
<td>ESPRESSO</td>
</tr>
<tr>
<td>8699.4947</td>
<td>−19.30</td>
<td>ESPRESSO</td>
</tr>
</tbody>
</table>

Thus, the possibility that the color variations are due to an accretion rate variation is compatible with our data.

On the other hand, variations in the size of the disk inner hole, or variations in the thickness of the inner edge of a warped disk may also result in changes in the reprocessed radiation (e.g., Carpenter et al., 2001). Their models suggest a few tenth of magnitude variation in the near-infrared bands when the disk inner hole size changes between $1 \, R_\odot$ and $4 \, R_\odot$. CR Cha shows less than one-tenth of a magnitude variation in Fig. 3.7, indicating a smaller change in the inner hole size. I indicated in Fig. 3.7 the model values of the color and the magnitude changes from Carpenter et al. (2001) with respect to the bluest datapoint of our observations on each panel. Our data line up with two of the open triangles, which correspond to a change in the inner hole sizes from 4 to $2 \, R_\odot$ in the case of mass accretion rate of $\dot{M}_{\text{acc}} \sim 3 \cdot 10^{-9} \, M_\odot/\text{yr}$, which is in line with the measured value for CR Cha. Therefore, variations in the structure of the inner disk are also in line with the observations.

Roquette et al. (2020) carried out an investigation of the near-infrared color variations of a large sample of young stars using $J$, $H$ and $K$-band observations. They calculated the trajectories in the color-space, and measured slopes for stars describing linear trajectories. They found that among the 144 measured $\frac{\Delta K}{\Delta (H-K)}$ slopes 115 systems had negative slopes. On the other hand, among the 196 measured $\frac{\Delta J}{\Delta (J-H)}$ slopes only 3 systems had negative slopes. This might imply that amplitudes of variability due to variable accretion rate and changes in the inner disk are more significant for the $J$ magnitude and $J-H$ color than for the $K$ magnitude and $H-K$ color. However, the flux in the $J$-band is dominated mainly by the stellar flux, whereas the amount of light re-emitted by the disk in the near-IR is larger for longer wavelengths. All in all, Roquette et al. (2020) still found 1.7 times more stars with variability caused by extinction/spot than caused by changes in the inner disk or accretion, which places
Chapter 3. Accretion variability of CR Cha

CR Cha in the class of the rarer systems.

Unfortunately, I cannot measure the size of the inner disk hole with our data because that would need different observational techniques. However, the circularly polarized spectra from our 2006 AAT and 2018 HARPS observations allow me to derive the expected magnetic field truncation radius \( R_{\text{tr}} \). Hussain et al. (2009) showed that CR Cha hosts a complex magnetic field including dipole and octupole magnetic field components as well. As the dipole component is expected to truncate the disk, while the octupole dominates on a smaller scale and at the surface of the star (Gregory et al., 2008), I determined the magnetospheric truncation radius using the dipole component. Assuming a dipole field configuration, the magnetic field truncation radius can be calculated using the following relation (Bouvier et al., 2007):

\[
\frac{R_{\text{tr}}}{R_*} = \frac{B_*^{4/7} R_*^{5/7}}{M^{2/7}(2GM_*)^{1/7}}.
\]  

(3.5)

It must be noted that this relation to derive the truncation radius may not be applicable to stars hosting complex multipolar fields. With this caveat, I can calculate \( R_{\text{tr}} \) for CR Cha. According to Hussain et al. (2009), the dipole component of the large-scale magnetic field is \( \sim 100 \) G; this results in \( R_{\text{tr}} = 2.9 R_* \), which is equivalent to 7.3 R\( _\odot \), assuming \( R_* = 2.5 R_\odot \) (Hussain et al., 2009). Fig. 3.7, depicting the 2019 data, indicates that the change in the inner disk hole size is from 4 R\( _\odot \) to 1 R\( _\odot \). Ignoring variations in \( \dot{M}_{\text{acc}} \), on which \( R_{\text{tr}} \) has a shallow dependence, such variation would imply a variation in \( B_* \) of 24 G. Unfortunately, our data cannot test this variations. Future studies should aim to cover several rotational periods with spectropolarimetric data and near-infrared photometry to test whether variations in the magnetic field strength, and thus in the truncation radius, are compatible with the observed color variations. For now, I can only conclude that the variations in the near-infrared colors are compatible with the observed variations in \( \dot{M}_{\text{acc}} \), but I cannot exclude that variations in the inner disk structure also contribute to these color variations.

3.5 Conclusions

In this Chapter, I presented a spectroscopic and photometric study of the classical T Tauri star CR Cha. I examined several datasets from three different observing seasons in 2006, 2018 and 2019. Based on the analysis of the photometric data, I found that a 2.326 days period is present on the dataset, which is in agreement with the stellar rotation period. This indicates that the photometric variations are modulated by the stellar rotation period due to the presence of stellar spots. In addition, the TESS
light curves revealed a few flare like events thanks to its high temporal resolution. By comparing the color changes of the $I$, $J$, $H$ and $K$-band observations with the models of Carpenter et al. (2001), I found that the color variations are due to changes in the inner disk properties. These can be due to variations in the mass accretion rates compatible with the ones I observe, or with changes in the inner hole size of the circumstellar disk.

The presence of the hydrogen Balmer lines allowed me to examine the accretion process in more detail. The H$\alpha$ line shows the largest variability in shape in 2019, whereas it showed only small amplitude variations in 2018. The comparison between the three observing seasons indicates significant morphological changes, but the variations of the central peak strengths due to changes in the accretion were the most significant differences in all observing seasons.

The extensive dataset presented here allowed me to examine the variability on timescales from minutes to decades. The photometric data can be interpreted as variations on timescales of $\sim 2.3$ days due to stellar rotation. On a decadal timescale, I found a slight brightening trend, and on the shortest timescales of minutes-hours, flare-like ($\sim 0.02$ mag) events also cause short brightenings.

The H$\alpha$ line amplitude, thus accretion rate changes, show fluctuations on wide range of timescales. The amplitude of the variability increases from minutes to several days, and it saturates when it reaches the weeks-month timescale. The results suggest that a week or so is the dominant timescales of accretion variability for this target. This is in line with previous works, and suggest that, apart from secular variability, any measurement of accretion is likely to vary by $\sim 0.4$ dex on a timescale of weeks to months.

### 3.6 Future prospects

Future works covering various timescales of variability with spectroscopy should aim at covering the phase of the periodicity of the target at all observing seasons, which would provide a possibility of checking whether variations in accretion are due to variations in the magnetic field topology. The dataset presented here would allow to study the changes in the magnetic field topology on decadal timescales. Hussain et al. (2009) already analyzed the spectropolarimetric data from 2006, and presented the magnetic field maps for CR Cha. However, the 2018 HARPS data can be also used to study the magnetic field of the system. Here, I only presented its analysis from the spectroscopic point of view in order to study the accretion variability of CR Cha, but the investigation of the polarimetric data would reveal information on the decadal change of the magnetic
field when comparing the results with the 2006 AAT observations.

Furthermore, CR Cha belongs to the rare class of targets that gets bluer when fainter at infrared wavelengths. This phenomenon should be investigated with surveys, in order to verify whether the size of the inner disk varies with time, as suggested by the models. In the brightest of these systems it would be important to assess if this behavior is predominantly associated with a particular type of stellar magnetic field (e.g., complex, variable multipolar fields or more stable simple axisymmetric fields).
Chapter 4

Accretion variability of the multiple T Tauri system VW Cha

4.1 Introduction

The project that my colleagues and I designed in order to study the accretion variability in a sample of young stellar objects in the Chamaeleon I star forming region includes six objects. CR Cha, which I presented in Chapter 3, is a single star with fairly rich observation history. In contrast, VW Cha, another member of our sample, is a multiple system which has been mainly included previously in spectroscopic and imaging surveys targeting several young stars in Chamaeleon I, and no detailed, in-depth study is available for it. These former studies give snapshots of this object, however, it is interesting to study the temporal evolution of such a multiple system using a high-quality monitoring dataset like ours.

The majority of stars form in a binary or multiple system. Their configuration ranges from close binaries with circumbinary disks to systems with wide companions and individual circumstellar disks. Their evolution is affected by the companion; close, eccentric binaries tend to produce pulsed accretion (Kóspál et al., 2018), but wide companions might have only a minor effects. Examining binary and multiple systems with high-resolution multitechnique campaigns combining spectroscopy and photometry would help in understanding their evolution, and the impact of the companion on the circumstellar disk, which might host planets, via studying the details of the star-disk interaction, the accretion, outflows, or winds.

This Chapter focuses on VW Cha, a young low-mass classical T Tauri multiple system (Brandner et al., 1996, Brandeker et al., 2001, Nguyen et al., 2012) in the Chamaeleon I star forming region at a distance of $d = 194.5^{+10.6}_{-9.1}$ pc (Bailer-Jones...
et al., 2021). This source has already been studied in previous works, mainly as part of larger samples. Daemgen et al. (2013) carried out a survey of multiple systems in the Chamaeleon I region. They resolved the primary and the secondary components of VW Cha, and their study resulted in the physical parameters for the A and B components as reported in Table 4.1. The study provides a lower limit for the accretion luminosity and accretion rate of the primary with $\log L^A_{\text{acc}} = -1.51 \, L_\odot$ and $M^A_{\text{acc}} = 4.20 \cdot 10^{-9} \, M_\odot/\text{yr}$, whereas Manara et al. (2016) did not resolve the components and reported $\log L_{\text{acc}} = -0.78 \, L_\odot$, $M_{\text{acc}} = 2.51 \cdot 10^{-8} \, M_\odot/\text{yr}$ and $A_V = 1.9 \, \text{mag}$ for the system, both assuming a distance to Chamaeleon I of 160 pc. Banzatti & Pontoppidan (2015) reported a disk inclination of 44° based on the rovibrational band of CO near 4.7 μm, using an empirical line width–inclination relation. It must be noted that for their survey the slit of the spectrograph was oriented to observe both components (Brown et al., 2013), however, in case of VW Cha, the companion was too faint for further analysis, therefore the reported disk inclination presumably corresponds to the circumstellar disk around the A component.

In this Chapter, I aim to study the accretion variability of VW Cha using ground-based and space photometry and high-resolution spectroscopy. I describe the observations in Sect. 4.2, show the results in Sect. 4.3, and discuss them in Sect. 4.4. This Chapter is based on a collaborative work that I was leading, and is published in Zsidi et al. (2022b, ApJ, in press). I was responsible for the reduction of the high-resolution spectra, the analysis of the entire presented dataset, except for the flux-calibration of the spectra and the determination of the mass accretion rates based on the emission line fluxes. I, however, include in this thesis a brief description of these latter analyses points as well in Sect. 4.3.4, as they carry important information for understanding the system’s behavior. Furthermore, I was also responsible for drawing conclusions from the results, where the co-authors helped with several invaluable discussions and comments. The co-authors also contributed to the reduction of the photometric data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Primary (A)</th>
<th>Secondary (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{eff}}$</td>
<td>4060 K</td>
<td>3850 K</td>
</tr>
<tr>
<td>$L_*$</td>
<td>1.6 $L_\odot$</td>
<td>0.76 $L_\odot$</td>
</tr>
<tr>
<td>$M_*$</td>
<td>0.75 $M_\odot$</td>
<td>0.57 $M_\odot$</td>
</tr>
<tr>
<td>$R_*$</td>
<td>2.55 $R_\odot$</td>
<td>1.97 $R_\odot$</td>
</tr>
<tr>
<td>Spectral type</td>
<td>K7</td>
<td>M0</td>
</tr>
<tr>
<td>Age</td>
<td>1.0 Myr</td>
<td>1.5 Myr</td>
</tr>
</tbody>
</table>

Table 4.1: Physical parameters of the primary and secondary components of VW Cha (Daemgen et al., 2013)
4.2 Observations

TESS covered parts of the Chamaeleon I star forming region in Sectors 11 and 12 in 2019. My colleagues and I designed a contemporaneous observing program including multifilter ground-based photometric monitoring and high-resolution spectroscopic measurements in order to study the variability, the star-disk interaction, and the accretion process in T Tauri systems.

TESS provided a 56-day-long light curve of VW Cha with a 30-min cadence between 2019 April 22 and 2019 June 19. The data reduction was carried out via differential photometry, using the *ficonv* and *fiphot* tools of the FITSH package (Pál, 2012). As a reference flux is needed for the process, the median of the below described SMARTS $I_C$-band photometry was used, taken contemporaneously with the TESS observations. A more detailed description of the TESS data reduction and photometry process can be found in Sect. 3.2.3, in Plachy et al. (2021), and in Pál et al. (2020). I also inspected the most recent TESS light curves of VW Cha because it was also covered in Sectors 38 and 39 in 2021. This resulted in an additional 58-day-long light curve with a more frequent, 10-min cadence between 2021 April 28 and 2021 June 24.

The ground-based photometric observations were obtained contemporaneously with the 2019 TESS light curve using the 1.3 m telescope (Cerro Tololo, Chile) operated by the SMARTS Consortium. The observations were performed with approximately nightly cadence in the $I_CJHK$-bands, covering the time interval between 2019 April 29 and June 10. In addition, in the first three nights $V$ and $R_C$-band measurements were also taken but they could not be continued due to issues. Typically seven images were obtained in the $I_C$-band with an exposure time of 14 s, and five to seven frames in the near-infrared bands with exposure times of 12 s (4 s at the first two epochs) in the $J$-band and 4 s in the $H$ and $K$-bands. The optical images were delivered to us by the SMARTS team after standard bias and flat-field corrections. For the $JHK$ images, dithering was performed in order to enable bad-pixel removal and sky subtraction. These steps were completed by using our custom IDL scripts. In the optical bands, the photometric calibration was based on two comparison stars in the 6′ × 6′ field of view (2MASS J11072405–7741258 and 2MASS J11081648–7744371) whose magnitudes were extracted from the APASS9 catalog (Henden et al., 2015) and transformed to the Johnson-Cousins system using the equations of Jordi et al. (2006). The near-infrared photometric calibration was based on the 2MASS magnitudes (Cutri et al., 2003) of a carefully selected comparison star, 2MASS J11075699–7741558. Due to this procedure, although the $JHK$ observations were carried out in the CIT/CTIO $JHK$ filters, the final calibrated magnitudes quoted in Table 4.6 are in the 2MASS photometric system.
Chapter 4. Accretion variability of VW Cha

<table>
<thead>
<tr>
<th>Date (Epoch)</th>
<th>JD−2450000</th>
<th>Instrument</th>
<th>Seeing [arcsec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019 May 31 (Ep 1)</td>
<td>8635.49998</td>
<td>ESPRESSO</td>
<td>0.96</td>
</tr>
<tr>
<td>2019 June 08 (Ep 2)</td>
<td>8642.52353</td>
<td>FEROS</td>
<td>1.26</td>
</tr>
<tr>
<td>2019 June 08 (Ep 3)</td>
<td>8642.66358</td>
<td>ESPRESSO</td>
<td>0.47</td>
</tr>
<tr>
<td>2019 June 11 (Ep 4)</td>
<td>8645.57175</td>
<td>FEROS</td>
<td>1.70</td>
</tr>
</tbody>
</table>

Table 4.2: Log of the spectroscopic observations.

Furthermore, I also included the publicly available ASAS-SN data\(^1\) in the analysis. These data are available for the last \(~8\) years (as described in Sect. 1.5 and 3.2.2). I, however, inspected only those \(g\)-band data, which were taken contemporaneously with the 2019 and the 2021 TESS observing periods.

High-resolution (\(R=140\,000\)) optical (380−788 nm) spectroscopic observations were carried out with the ESPRESSO instrument mounted on the Very Large Telescope as part of our DDT proposal (Pr.Id.2103.C-5025, PI: Á. Kóspál) on 2019 May 31 and June 8. I performed the bias, dark, and flat-field corrections and the wavelength calibration using Version 3.13.2 of the EsoReflex/ESPRESSO pipeline (Freudling et al., 2013). The resulting 2D spectra were merged producing rebinned 1D spectra. Two additional high-resolution (\(R=48\,000\)) optical (350−920 nm) spectra were obtained on June 8 and June 11 with the FEROS instrument on the MPG/ESO 2.2 m telescope in object-calib mode, where contemporaneous spectra of a ThAr lamp were recorded throughout the whole object exposure. These spectra were reduced similarly to the CR Cha spectra, as described in Sect. 3.2.3. For a summary of all spectroscopic observations of VW Cha, see Table 4.2.

In order to flux calibrate the spectra, they were first normalized by fitting the continuum. Then, the ASAS-SN (\(g\)-band, \(\lambda_{\text{eff}} = 470\) nm) and TESS (\(I_{\text{C}}\)-band, \(\lambda_{\text{eff}} = 784\) nm) magnitudes, which were obtained contemporaneously with the ESPRESSO and the FEROS spectra, were converted to fluxes by using the zero fluxes\(^2\) at 470 nm and 784 nm for the \(g\) and \(I_{\text{C}}\)-bands, respectively, and were used to calculate the calibration coefficients. The calibration function was obtained by linearly interpolating the calibration coefficients from the \(g\) and \(I_{\text{C}}\)-bands. Finally, the calibrated spectra were obtained by multiplying the normalized spectra by the calibration function. The flux-calibrated spectra are shown in Fig. 4.1.

\(^1\)https://asas-sn.osu.edu/
\(^2\)http://svo2.cab.inta-csic.es/theory/fps/
4.2. Observations

Figure 4.1: Flux-calibrated and smoothed ESPRESSO and FEROS spectra.

4.2.1 The observations in the context of the multiplicity of VW Cha

VW Cha is known to be a multiple T Tauri system. It was identified as a binary by Brandner et al. (1996) with 0.72″ separation and a $\Delta Z = 0.25$ mag brightness difference between the companion and the primary at 1 μm. Brandeker et al. (2001) reported an additional close companion to the secondary star with a separation of 0.10″ and suggested that VW Cha is a physical triple system. They found that the primary increasingly dominates the emission at increasingly longer wavelengths and reported a brightness difference of $\Delta J = 0.73$ mag and $\Delta K = 1.32$ mag between the primary (A) and the secondary (Ba+Bb) components. Daemgen et al. (2013) also detected this close companion of the secondary. Correia et al. (2006) found a wide companion (C) at 16.8″. Melo (2003) suggested that the primary component (A) is a double-lined spectroscopic binary (SB2), i.e., some spectral lines of the primary appear to be double-peaked implying that the primary component consists of two stars which are too close to be resolved separately, however, their trace can be observed via the difference in their Doppler shifts. Nguyen et al. (2012) also arrived to a similar conclusion on the SB2 nature of the A component. I will examine this possibility further in Sect. 4.4.4.

In order to investigate which component contributes to the observed flux and the variability of our photometric and spectroscopic data, I examined the astrometric measurements and the $G$ magnitudes ($\lambda_{\text{eff}} = 582$ nm) from the Gaia EDR3 catalog\(^3\). According to these data, the separation between the A and the B components is 0.664″ and the position angle is 185.778°. The primary component is slightly brighter with

\(^3\text{https://gea.esac.esa.int/archive/}\)
Figure 4.2: Left: A simulated TESS image of the Chamaeleon I star forming region. VW Cha can be found at the bottom. The primary and the companions are not resolved in this image due to the large pixel size. Right: This $K_s$-band image is taken from Daemgen et al. (2013), where the authors resolved the secondary at 0.72" separation.

Gaia magnitude $G = 12.40$ mag for A and $G = 12.77$ mag for B; i.e., 58.3% of the total flux comes from the primary component and 41.7% from the companion. In our photometric observations from SMARTS, we did not resolve the primary (A) and the secondary (B) components, furthermore, the TESS observations might even be contaminated by the C component due to the large pixel size (see e.g. left panel of Fig. 4.2).

Our spectroscopic observations were made with fibre fed spectrographs. ESPRESSO has a 1.0" aperture, which means that when the fibre is centered on the primary, the secondary at 0.72" separation is excluded from the aperture, however, due to varying seeing conditions (see Table 4.2), we might observe some contamination from the companion. The FEROS instrument has larger aperture (2.0"), which means that the secondary contaminates our observations. Furthermore, if the primary (A) is an SB2, as suggested by Melo (2003) and Nguyen et al. (2012), both components of the primary would have been observed by the ESPRESSO and the FEROS spectrographs. It must also be noted that according to Daemgen et al. (2013), the probability of the A component hosting a disk is 1.00, whereas the same probability of the B component is only 0.01, based on measurements of the Br\textgamma equivalent width and the continuum noise measurements in each target spectrum and using Bayesian approach to derive the probability density function of the disk frequency. For this reason, any accretion-related variability is attributed here to the primary component.
4.3 Results

4.3.1 Light curves

The light curves of VW Cha carry important information on the nature of the variability and its origin. The TESS light curve, displayed with black dots in Fig. 4.3, reveals variations on various timescales with a peak-to-peak amplitude of \(~0.8\) mag. Small-amplitude fluctuations appear on timescales of hours, and a brightening event occurs towards the end of our observing period (JD\(~2458642\), i.e., around 2019 June 7), which lasts for a few days. In order to look for any periodic signals in the TESS light curve, I carried out a period analysis. I computed a Lomb-Scargle periodogram (Lomb, 1976, Scargle, 1982), which reveals a period at \(P = 9.69\) days (bottom panel of Fig. 4.3). I also found a peak around 26 days \((f = 0.037\) day\(^{-1}\)), which suggests a longer-term oscillation in the light curve. No further peaks were found with higher frequencies outside of the indicated frequency range of Fig. 4.3. The 2021 TESS light curve (Fig. 4.4) shows similar peak-to-peak amplitude \(\sim0.9\) mag, however, the mean brightness of the system slightly increased. I calculated a Lomb-Scargle periodogram from the 2021 TESS light curve as well (Fig. 4.4, bottom panel), which does not confirm the presence of the 9.69 days period but shows a small peak at 9.03 days instead. As the TESS photometry is not resolving the system (see Fig. 4.2), the results of the period analysis might be the superposition of the signals produced by all members of the system.

Although the ground-based SMARTS observations have a sparser cadence than the TESS measurements, they carry crucial information on the color variations during our observing period. The \(I_C\)-band measurements perfectly follow the variations seen in the TESS light curve with a similar peak-to-peak amplitude. This is expected, as TESS offers broadband photometry that is centered at the \(I_C\)-band (see Fig. 1 in Ricker et al., 2015). The shapes of the NIR \(J\), \(H\) and \(K\)-band light curves also follow the shapes of the optical light curves with slightly increasing amplitudes toward the longer wavelengths, i.e., \(~0.6\) mag peak-to-peak variations in the \(J\)-band and \(~0.8\) mag variations in the \(K\)-band. The ground-based photometry can be compared with the TESS data by plotting the data points as a function of the TESS measurements (Fig. 4.5, four panels on the left). These plots could be well fitted with a line whose slope gives the variability amplitude relative to the TESS band. The measured amplitudes can be compared with the interstellar extinction law (Cardelli et al., 1989). The results show that the variability amplitudes do not follow the extinction law (Fig. 4.5, right panel), which suggests that another mechanism is responsible for the optical-NIR variability.
Figure 4.3: Light curves and periodogram of VW Cha in 2019. **Top:** The near-infrared SMARTS $JHK$-band light curves are shown with colored circles. I show the optical $I_C$-band SMARTS photometry with red circles, the TESS light curve with black dots, and the nightly averaged ASAS-SN $g$-band data with green circles. The $JHK$ and $g$-band light curves are shifted along the $y$-axis with the values indicated in the figure. I marked the epochs of the spectroscopic observations with vertical orange (ESPRESSO) and purple (FEROS) lines. **Bottom:** The Lomb-Scargle periodogram obtained from the TESS data.

The ground-based SMARTS data allow the examination of the color variations during the observing period. I show the color-magnitude and near-infrared color-color diagrams in Fig. 4.6 along with the extinction path by Cardelli et al. (1989) indicated with black arrows assuming $R_V = 3.1$. The near-infrared color-magnitude diagrams show that the pattern does not follow the extinction path in the near-infrared wavelength range, but VW Cha becomes redder as it brightens. This trend is further discussed in Sect. 4.4.1.

I also show the publicly available ASAS-SN $g$-band measurements in Figs. 4.3 and 4.4. The $g$-band light curve also resembles the TESS observations. However, two brightening events at JD$\sim$2458605 and JD$\sim$2458642 stand out from the daily variations. Among the available optical light curves, the $g$-band observations display the largest peak-to-peak amplitude with $\sim$1.4 mag variations in the 2019 observing season and $\sim$1.2 mag in 2021.
4.3. Results

Figure 4.4: Light curves and periodogram from 2021. Top: The black dots show the TESS observations from 2021 and the green circles indicate the nightly averaged ASAS-SN $g$-band data. Bottom: Lomb-Scargle periodogram obtained from the 2021 TESS data.

Figure 4.5: Variability amplitudes of VW Cha. Left: The multifilter ground-based SMARTS photometry as a function of the TESS measurements. Right: The variability amplitudes.
Chapter 4. Accretion variability of VW Cha

Figure 4.6: Color-magnitude and color-color diagrams obtained from the SMARTS data. I drew the extinction corresponding to $A_V=1$ mag with black arrow using Cardelli et al. (1989) reddening law. I indicated the values from the disk model of Fig. 25 from Carpenter et al. (2001) with triangles. The open triangles represent a mass accretion rate of $10^{-8.5} M_\odot/yr$ and filled triangles indicate $10^{-7} M_\odot/yr$. The three triangles correspond to inner disk hole sizes of 1, 2, and 4 $R_\odot$.

4.3.2 Absorption lines

The spectra of classical T Tauri stars encompass numerous absorption lines, however, these absorption lines are typically weaker than those of the non-accreting stars (e.g., WTTS) due to the veiling. This effect is detected in the absorption lines of VW Cha and it is further discussed in Sect. 4.3.5.

The absorption lines of VW Cha also show some morphological variations. In order to investigate the origin of these changes, I calculated the average absorption profile using the LSD method (as described in Sect. 3.3.3). In order to achieve better signal-to-noise ratio (S/N), I obtained the LSD profile from the red half of the spectra ($\lambda = 584 - 788$ nm) using a mask based on a line list from the Vienna Atomic Line Database (VALD$^4$, Ryabchikova et al., 1997) with absorption lines whose normalized flux is less than 0.985 in the line list, i.e., using the strongest absorption lines. This resulted in the line profiles presented in Fig. 4.7.

The primary component of VW Cha is a suspected SB2, and the observed variations might originate from this close binary nature. In order to examine this possibility, I determined the radial velocity of the system by fitting Gaussians to the LSD profiles.

$^4$http://vald.astro.uu.se/
4.3. Results

The first ESPRESSO observation (JD=2458635.5, 2019 May 10) showed a single Gaussian profile, whereas the second ESPRESSO measurement (JD=2458642.6, 2019 June 8) hints at a split profile with two Gaussian components. The FEROS observations are noisier, but as the first FEROS spectrum was taken on the same night as the second of the ESPRESSO spectra, I applied two Gaussians for this measurement, whereas we used one component for the last epoch. I show the fitted Gaussians in Fig. 4.7 as well.

The results show that the average radial velocity of the system is 16.8 km/s. For the JD=2458642 night (2019 June 8), I found two radial velocity components with a separation of ∼19 km/s in both the ESPRESSO and the FEROS spectra. The radial velocity results are given in Table 4.3.

### 4.3.3 Emission lines and their variability

The spectra of VW Cha exhibit several emission lines (Fig. 4.1). The Balmer lines, in particular the Hα and Hβ, are the most striking features of all of the spectra, and show strong and variable line profiles. In addition, I identified several permitted lines, such as He I, Fe I, Fe II, and the Na I doublet in emission; however, not all of them were clearly detected in all epochs. The wavelength region of the Ca II infrared triplet was covered only by FEROS, detecting two of the three lines on both epochs. The 854.2 nm
The most conspicuous feature of the spectra of VW Cha is the Hα emission line, which shows significant variability over the observing period (Fig. 4.8, top left panel). The central peak exhibits amplitude variations that appear to be correlated with the photometric variations. When a brighter photometric state was observed, the Hα line presented a stronger peak, which implies that the Hα line became stronger by a larger factor than the continuum. Apart from the amplitude variations, I also found morphological changes in the Hα line. The first epoch shows a strong blueshifted absorption component around $-150\,\text{km/s}$ that was mostly filled by the second epoch. This effect is also shown by the blue shaded area in Fig. 4.8, which indicates the variance profile. The variance profile measures the variability in each velocity bin in the line profile, and was obtained as described in Johns & Basri (1995) and in Sect. 3.3.3. The variance profile of the Hα line suggests that besides the feature at $-150\,\text{km/s}$, the red wing is also highly variable at velocities lower than $250\,\text{km/s}$.

The Hβ line exhibits similar amplitude variations as the Hα line, i.e., when the system becomes brighter the emission gets stronger (see middle top panel of Fig. 4.8). The line has a peculiar double-peaked shape, and the relative amplitudes and positions of the two peaks vary over time. The first observation indicates one peak at the systemic velocity and one redshifted peak. By the second observation, the peak at the center had moved to the blueshifted side, whereas the redshifted peak remained around $130\,\text{km/s}$. The last observation reveals similar peak positions as the first one; however, the redshifted peak shows a more pronounced amplitude decrease than the other.

The HeI line at 587.6 nm exhibits a peak at the rest velocity and wide wings on both sides. Besides the amplitude variations of the central peak, the wings are also changing; when brighter photometric state was observed, the line wings were more

<table>
<thead>
<tr>
<th>Date</th>
<th>JD−2450000</th>
<th>RV₁</th>
<th>RV₂</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006 Feb 22</td>
<td>3789.26999</td>
<td>23.72 ± 0.29</td>
<td>5.79 ± 0.41</td>
<td>N12</td>
</tr>
<tr>
<td>2006 Apr 10</td>
<td>3836.16847</td>
<td>27.16 ± 0.21</td>
<td>6.02 ± 0.37</td>
<td>N12</td>
</tr>
<tr>
<td>2006 Dec 12</td>
<td>4072.37156</td>
<td>26.31 ± 0.26</td>
<td>2.51 ± 0.35</td>
<td>N12</td>
</tr>
<tr>
<td>2019 May 31</td>
<td>8635.49998</td>
<td>16.00 ± 0.10</td>
<td></td>
<td>This work</td>
</tr>
<tr>
<td>2019 Jun 8</td>
<td>8642.52353</td>
<td>28.66 ± 0.43</td>
<td>8.26 ± 0.20</td>
<td>This work</td>
</tr>
<tr>
<td>2019 Jun 8</td>
<td>8642.66358</td>
<td>26.82 ± 0.42</td>
<td>6.83 ± 3.26</td>
<td>This work</td>
</tr>
<tr>
<td>2019 Jun 11</td>
<td>8645.57175</td>
<td>14.49 ± 0.14</td>
<td></td>
<td>This work</td>
</tr>
</tbody>
</table>

Table 4.3: Radial velocity measurements for VW Cha. N12 indicates the results from Nguyen et al. (2012). For the epochs I report only one value, I was not able to resolve the two components.
Figure 4.8: Normalized line profiles of the Hα, Hβ, He I, Li I, [O I], and Na I lines. The lines with different colors indicate the different epochs (as listed in the upper right panel), the thick black line shows the average line profile, and the blue shaded area illustrates the variance profile in each panel.

pronounced. The wings extend to ±200 km/s during the brightest epochs, whereas it recedes to around ±120 km/s when fainter state was observed. The variance profile of the He I line reveals larger variability in the red wing than in the blue wing.

I also identified three [O I] lines in all of our spectra at 557.8 nm, 630.0 nm, and 636.3 nm. In Fig. 4.8, I show the 630.0 nm line from the normalized spectra, as this was the strongest among the observed forbidden lines. The region of the [O I] line is contaminated by telluric lines; nonetheless, I observed some amplitude variations in the normalized line profiles. It must be noted that these variations appear only in the continuum-normalized spectra, the line flux is almost constant during our observations. I discuss this further in Sect. 4.4.3. The Na I doublet shows high variability, with two observations in emission and two measurements below the continuum (Fig. 4.8).

It must be noted that two measurements, the first FEROS spectrum and the second ESPRESSO spectrum, were taken on the same night only a few hours apart. The two spectra look very similar, as expected, but some strong accretion tracer lines, such as the Hα and Hβ lines, show noticeable differences (Fig. 4.8). In order to examine whether this discrepancy is an instrumental or a physical effect, I compared several
emission and absorption lines in the two spectra. I found that most lines are in agreement within 10%. Only the strongest lines differ by \(\sim 20\%\), but as these are typically accretion tracers, the change might have a physical origin.

### 4.3.4 Line flux, accretion luminosity and accretion rate

Typical accretion tracers in T Tauri systems include e.g. the hydrogen Balmer, the He I, the Ca II, and the Na I emission lines (Hartmann et al., 1998, 2016). By measuring their line fluxes using the flux-calibrated spectra, it is possible to determine the accretion rate once the line flux is converted to line luminosity. The relation between the line luminosity \(L_{\text{line}}\) and the accretion luminosity \(L_{\text{acc}}\) has been examined in several works (Herczeg & Hillenbrand, 2008, Rigliaco et al., 2012, and references therein), however, Alcalá et al. (2014) and Alcalá et al. (2017) studied multiple UV, optical and near-infrared lines in a larger sample of young stellar objects, in order to determine an accurate empirical relation between these quantities:

\[
\log_{10} \left( \frac{L_{\text{acc}}}{L_\odot} \right) = a \log_{10} \left( \frac{L_{\text{line}}}{L_\odot} \right) + b \tag{4.1}
\]

where \(a\) and \(b\) are coefficients that vary from line to line. They have some natural uncertainty originating from the measurement of the line flux, and the linear fit between the line luminosity and the accretion luminosity. The overall uncertainties for the relations differ from line to line, and the standard deviation of the linear fit ranges from \(\sigma = 0.26\) to \(\sigma = 0.45\) among those relations which are suggested for deriving the accretion luminosity.

As the first step to determine the accretion rate, the line fluxes of the accretion tracers in the spectra of VW Cha were determined by integrating the flux of the pixels contained between the local continuum, which is estimated with a linear fit, and the line. The noise level was calculated by multiplying the standard deviation of the local continuum \((RMS)\) by the width of the line \(\Delta \lambda_{\text{line}}\) and by the square root of the number of pixels included in the line \((N_{\text{pix}})\). A line is considered to be detected when its \(S/N \geq 3\). For the non-detected lines, we computed the upper limit of the line flux \((F_{\text{line}}^{\text{upp}})\) by multiplying the noise by three:

\[
F_{\text{line}}^{\text{upp}} = 3 \times \left( RMS \times \frac{\Delta \lambda_{\text{line}}}{R} \times \sqrt{N_{\text{pix}}} \right) \tag{4.2}
\]

The results are presented in Table 4.4.
<table>
<thead>
<tr>
<th>Species</th>
<th>$\lambda_{line}^{\text{obs}}$ [nm]</th>
<th>$F_{\text{obs}}^{\text{pl}}(E)$ [$10^{-14}$ erg s$^{-1}$ cm$^{-2}$]</th>
<th>$F_{\text{obs}}^{\text{pl}}(F)$ [$10^{-14}$ erg s$^{-1}$ cm$^{-2}$]</th>
<th>$F_{\text{obs}}^{\text{pl}}(E)$ [$10^{-14}$ erg s$^{-1}$ cm$^{-2}$]</th>
<th>$F_{\text{obs}}^{\text{pl}}(F)$ [$10^{-14}$ erg s$^{-1}$ cm$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H3</td>
<td>656.32</td>
<td>382.788 ± 0.196</td>
<td>919.390 ± 0.525</td>
<td>726.983 ± 0.236</td>
<td>285.018 ± 0.517</td>
</tr>
<tr>
<td>H4</td>
<td>486.16</td>
<td>54.788 ± 0.088</td>
<td>122.292 ± 0.290</td>
<td>105.076 ± 0.080</td>
<td>24.481 ± 0.449</td>
</tr>
<tr>
<td>H5</td>
<td>434.07</td>
<td>25.390 ± 0.289</td>
<td>36.937 ± 0.540</td>
<td>41.370 ± 0.221</td>
<td>7.050 ± 0.583</td>
</tr>
<tr>
<td>H6</td>
<td>410.17</td>
<td>18.400 ± 0.344</td>
<td>25.994 ± 0.946</td>
<td>25.940 ± 0.280</td>
<td>94.672 ± 5.548</td>
</tr>
<tr>
<td>H7</td>
<td>397.03</td>
<td>21.356 ± 0.263</td>
<td>41.300 ± 1.145</td>
<td>40.656 ± 0.205</td>
<td>29.485 ± 2.256</td>
</tr>
<tr>
<td>H8</td>
<td>388.93</td>
<td>8.756 ± 0.348</td>
<td>&lt; 4.643</td>
<td>13.416 ± 0.286</td>
<td>7.110 ± 1.930</td>
</tr>
<tr>
<td>H9</td>
<td>383.56</td>
<td>10.940 ± 0.610</td>
<td>–</td>
<td>11.367 ± 0.465</td>
<td>–</td>
</tr>
<tr>
<td>H10</td>
<td>379.81</td>
<td>6.789 ± 1.057</td>
<td>–</td>
<td>13.272 ± 0.748</td>
<td>–</td>
</tr>
<tr>
<td>He I/Fe I</td>
<td>492.22</td>
<td>2.404 ± 0.130</td>
<td>14.947 ± 0.276</td>
<td>10.454 ± 0.096</td>
<td>2.681 ± 0.476</td>
</tr>
<tr>
<td>He I</td>
<td>402.64</td>
<td>&lt; 0.272</td>
<td>&lt; 1.687</td>
<td>&lt; 0.209</td>
<td>1.057 ± 0.315</td>
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<tr>
<td>He I</td>
<td>447.17</td>
<td>2.377 ± 0.059</td>
<td>3.225 ± 0.220</td>
<td>3.370 ± 0.050</td>
<td>3.524 ± 0.440</td>
</tr>
<tr>
<td>He I</td>
<td>471.34</td>
<td>0.776 ± 0.099</td>
<td>0.953 ± 0.195</td>
<td>0.957 ± 0.080</td>
<td>1.581 ± 0.296</td>
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<tr>
<td>He I</td>
<td>501.6</td>
<td>&lt; 0.342</td>
<td>19.588 ± 0.245</td>
<td>&lt; 0.800</td>
<td>4.593 ± 0.396</td>
</tr>
<tr>
<td>He I</td>
<td>587.6</td>
<td>9.293 ± 0.098</td>
<td>25.047 ± 0.206</td>
<td>19.603 ± 0.088</td>
<td>7.345 ± 0.275</td>
</tr>
<tr>
<td>He I</td>
<td>667.85</td>
<td>2.888 ± 0.044</td>
<td>8.839 ± 0.144</td>
<td>6.075 ± 0.049</td>
<td>2.546 ± 0.126</td>
</tr>
<tr>
<td>He I</td>
<td>706.56</td>
<td>2.729 ± 0.056</td>
<td>12.545 ± 0.150</td>
<td>6.786 ± 0.049</td>
<td>7.996 ± 0.190</td>
</tr>
<tr>
<td>He I</td>
<td>468.81</td>
<td>1.101 ± 0.092</td>
<td>&lt; 0.998</td>
<td>1.127 ± 0.075</td>
<td>&lt; 2.063</td>
</tr>
<tr>
<td>Ca II (K)</td>
<td>393.39</td>
<td>19.906 ± 0.324</td>
<td>40.339 ± 1.563</td>
<td>46.111 ± 0.258</td>
<td>21.368 ± 2.280</td>
</tr>
<tr>
<td>Ca II (H)</td>
<td>396.87</td>
<td>20.968 ± 0.548</td>
<td>40.279 ± 1.172</td>
<td>40.079 ± 0.451</td>
<td>30.425 ± 2.240</td>
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<tr>
<td>Ca II</td>
<td>849.85</td>
<td>–</td>
<td>252.089 ± 0.380</td>
<td>–</td>
<td>25.077 ± 0.456</td>
</tr>
<tr>
<td>Ca II</td>
<td>866.26</td>
<td>–</td>
<td>232.491 ± 0.824</td>
<td>–</td>
<td>26.310 ± 0.642</td>
</tr>
<tr>
<td>Na I</td>
<td>589.03</td>
<td>&lt; 0.289</td>
<td>8.470 ± 0.445</td>
<td>4.650 ± 0.160</td>
<td>2.190 ± 0.284</td>
</tr>
<tr>
<td>Na I</td>
<td>589.63</td>
<td>&lt; 0.291</td>
<td>4.467 ± 0.398</td>
<td>2.105 ± 0.182</td>
<td>1.266 ± 0.213</td>
</tr>
<tr>
<td>O I</td>
<td>777.35</td>
<td>7.205 ± 0.143</td>
<td>29.358 ± 0.503</td>
<td>18.012 ± 0.150</td>
<td>5.970 ± 0.340</td>
</tr>
<tr>
<td>O I</td>
<td>844.68</td>
<td>–</td>
<td>54.033 ± 1.145</td>
<td>–</td>
<td>10.570 ± 0.543</td>
</tr>
</tbody>
</table>

Table 4.4: Line fluxes for the emission lines of VW Cha
Chapter 4. Accretion variability of VW Cha

Figure 4.9: Color-color diagram of VW Cha. Red circles are data from SMARTS observations at different epochs. Blue dashed line represents the CTTS locus. The orange solid line and the green dot-dashed line correspond to the ZAMS and the giant branch, respectively. The black arrow shows the vectorial shift from the CTTS locus for a source with 1 mag of extinction.

The line luminosities were then obtained from the line fluxes via the following relation, using only the detected accretion tracer lines from Table 4.4:

\[ L_{\text{line}} = 4\pi d^2 F_{\text{line}}, \]  
(4.3)

where \( F_{\text{line}} \) is the extinction corrected line flux and \( d = 194.5 \) pc is the distance (Bailer-Jones et al., 2021). For performing the extinction correction, the extinction was estimated from the color-color diagram, by determining the distance between the location of the star on the \([J - H]\) vs. \([H - K]\) diagram and the CTTS locus (see Fig. 4.9), the location of CCTSs if they were unextincted (\(A_V = 0\)). Applying the extinction vector by Cardelli et al. (1989) and assuming \(R_V = 3.1\), the mean extinction is \(A_V = 1.70 \pm 0.1\) mag using all the NIR photometry.

The line luminosities were then converted to accretion luminosity \(L_{\text{acc}}\) of the VW Cha system using the empirical relations of Equation 4.1 and the coefficients from Alcalá et al. (2017). As several accretion tracers were detected, this procedure resulted in multiple \(L_{\text{acc}}\) estimates for each observation, therefore, the mean value was used for calculating the accretion rate for each epoch. The mass accretion rate was calculated
4.3. Results

Figure 4.10: Accretion luminosity and mass accretion rate as a function of the time.

<table>
<thead>
<tr>
<th>Date</th>
<th>$\log L_{\text{acc}}$ [L$_\odot$]</th>
<th>$\log M_{\text{acc}}$ [M$_\odot$/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019 May 31 (E)</td>
<td>0.022 ± 0.083</td>
<td>−6.785 ± 0.075</td>
</tr>
<tr>
<td>2019 June 08 (F)</td>
<td>0.360 ± 0.086</td>
<td>−6.447 ± 0.082</td>
</tr>
<tr>
<td>2019 June 08 (E)</td>
<td>0.225 ± 0.079</td>
<td>−6.582 ± 0.075</td>
</tr>
<tr>
<td>2019 June 11 (F)</td>
<td>−0.103 ± 0.082</td>
<td>−6.910 ± 0.082</td>
</tr>
</tbody>
</table>

Table 4.5: Accretion parameters for VW Cha

using the following relation:

$$M_{\text{acc}} \sim \left(1 - \frac{R_*}{R_{\text{in}}} \right)^{-1} \frac{L_{\text{acc}} R_*}{GM_*},$$  \hspace{1cm} (4.4)

where $R_{\text{in}}$ is the inner-disk radius which is assumed to be $R_{\text{in}} \sim 5R_*$ (Hartmann et al., 1998), $M_* = 0.75^{+0.5}_{-0.35}$ M$_\odot$, and $R_* = 2.55 \pm 0.29$ R$_\odot$ from Daemgen et al. (2013). The results are shown in Table 4.5. Fig. 4.10 displays the accretion luminosity and the mass accretion rate as a function of the time, which show increased accretion luminosity and accretion rate in the second and third epoch, and a decrease by the last epoch.

4.3.5 Veiling

The absorption spectra of classical T Tauri stars are often veiled by an additional continuum emission due to accretion. The Li I line in Fig. 4.8 displays this effect: some observations show deeper absorption, whereas other measurements reveal shallower line. As the veiling is also indicative of the accretion rate, it is expected that when the accretion rate changes, the veiling and the stellar brightness changes accordingly. I calculated the veiling for our four spectroscopic observations using the same relation, as described in Sect. 3.3.3.

Instead of using one absorption line, I used the LSD profiles obtained from the
Chapter 4. Accretion variability of VW Cha

spectra previously (see Sect. 4.3.2). For reference, I obtained the LSD profile based on the same criteria for a non-accreting K7-type weak-line T Tauri star, TWA 6, whose spectrum is available from the Polarbase database. I used this reference in order to calculate the absolute veiling. I show the results in Fig. 4.11.

Figure 4.11: Absolute veiling measurements.

4.4 Discussion

4.4.1 Near-infrared color variations

Our ground-based near-infrared observations of VW Cha reveal an unusual trend: the source becomes redder as it brightens (Fig. 4.6). In order to examine the physical origin of this behavior, I compared our results with three models described by Carpenter et al. (2001) that use the models by Meyer et al. (1997).

The first model involves starspots, which often appear on the surface of T Tauri stars and can be responsible for the variability observed in these systems. Carpenter et al. (2001) inspected the impact of starspots at near-infrared wavelengths and found that cool spots with small fractional coverage result in nearly grey fluctuations. In the case of larger spot coverages and hot spots, the color-magnitude diagram shows that the system becomes bluer as it gets brighter which is the opposite of the effect seen in our observations.

The second is the extinction model. Inhomogeneities in the inner circumstellar environment can cause changing extinction, which also results in photometric variability.

5http://polarbase.irap.omp.eu/
This model introduces a positive slope in the near-infrared color-magnitude diagrams; i.e., the object gets redder as it becomes fainter. In order to compare our observations with this model, we indicated the extinction arrow in Fig. 4.6 corresponding to $A_V = 1$ mag, which shows that our data are not consistent with changing extinction.

The disk model discussed by Carpenter et al. (2001) and Meyer et al. (1997) attributes the near-infrared variation to changes in the accretion disk, such as variable inner disk structure or accretion rate. This model results in a negative slope in the near-infrared color-magnitude diagrams (i.e., the source gets redder as it brightens) and predicts a shallower slope in the $[J - H]$ vs. $[H - K_S]$ diagram than the above-mentioned spot and extinction models. In order to compare the disk model with our observations, I indicated the color changes predicted by this model compared to our bluest data point with triangles in Fig. 4.6. The open triangles represent mass accretion rate of $10^{-8.5} M_\odot yr^{-1}$, and the filled triangles show $10^{-7.0} M_\odot yr^{-1}$ (Carpenter et al., 2001). The three triangles correspond to disk inner hole sizes of 1, 2, and $4 R_\odot$, respectively. These models of Meyer et al. (1997) include a fiducial M0 type star with fixed $M_\star = 0.5 M_\odot$, $R_\star = 1.8 R_\odot$, and $T_{eff} = 4000$ K. These stellar parameters describe a typical T Tauri star, but do not agree entirely with the parameters of VW Cha; therefore, this analysis gives a qualitative explanation for the observed trajectory. The comparison suggests that the near-infrared color variations seen in our dataset are orthogonal to the trajectory of the spot and the extinction models, and they are consistent with those predicted by the disk model. This means that the observed color variations originate from the changes in the accretion disk.

I also considered another set of models by D’Alessio et al. (1998, 1999, 2001) that provides the spectral energy distributions (SED) for accretion disks with various disk parameters\(^6\) ($R_{\text{disk}}$, $R_{\text{hole}}$, $\dot{M}_{\text{acc}}$, $\alpha$, $i$) for systems with different central stars. First, I selected a central star with stellar parameters closest to our target ($T_{eff}=4000$ K, 1 Myr, $R_\star = 2.64 R_\odot$, $M_\star = 0.7 M_\odot$, $L_\star = 1.6 L_\odot$), and I studied the corresponding disk models. From the available models, I chose the ones with $R_{\text{disk}} = 100$ au, $i = 30^\circ$, and $\alpha = 0.01$, which parameters are expected for VW Cha. This left two parameters free: $R_{\text{hole}}$ and $\dot{M}_{\text{acc}}$. Unfortunately, the $R_{\text{hole}}$ and $\dot{M}_{\text{acc}}$ grid of these models are sparser than the ones presented by Meyer et al. (1997), therefore, these models are less representative of VW Cha. Nonetheless, I attempted to compare our data and the models by placing our observations on the SEDs of the models with the following pairs of parameters: $R_{\text{hole}} = 9 R_\star$ and $\dot{M}_{\text{acc}} = 10^{-9} M_\odot/yr$, $R_{\text{hole}} = 9 R_\star$ and $\dot{M}_{\text{acc}} = 10^{-8} M_\odot/yr$, $R_{\text{hole}} = 11 R_\star$ and $\dot{M}_{\text{acc}} = 10^{-7} M_\odot/yr$, $R_{\text{hole}} = 22 R_\star$ and $\dot{M}_{\text{acc}} = 10^{-6} M_\odot/yr$. This comparison

\(^6\)https://lweb.cfa.harvard.edu/youngstars/dalessio/
Figure 4.12: The D’Alessio et al. (1998) models. *Top left:* The SEDs of the four models that were considered for the comparison. The $\dot{M}_{\text{acc}}$ and $R_{\text{hole}}$ are indicated in the panel for each model with the corresponding color. *Top right and bottom left:* The color-magnitude diagrams constructed from the D’Alessio et al. (1998) models. *Bottom right:* The color-color diagram constructed from the D’Alessio et al. (1998) models.

did not lead to any strong conclusions, which might arise from the fact that both the inner disk hole size and the accretion rate vary from model to model, and there is no option to change only one of these parameters. Additionally, I converted the fluxes close to the $JHK$-bands from the SED models to magnitudes and we constructed the NIR color-magnitude and color-color diagrams (Fig. 4.12). In general, I found that these models also reproduce the observed trend (i.e., the source becomes redder when it brightens). However, the trend appears in the opposite way compared to the Carpenter et al. (2001) models: in Carpenter et al. (2001), larger hole sizes correspond to smaller infrared excess, whereas the D’Alessio et al. (1998) models resulted in an opposite trend; i.e., larger hole sizes correspond to larger infrared excess. Again, this might arise from the fact that for the D’Alessio et al. (1998) models, both the inner
disk hole size and the accretion rate change from model to model (larger inner hole size is paired with larger accretion rate). This does not contradict the Carpenter et al. (2001) models: their models with larger accretion rates (filled triangles) also predict redder colors.

Apart from changes in the inner disk hole size, other changes in the inner disk structure may contribute to the observed trend in the NIR color-magnitude and color-color diagrams. These involve e.g. variations in the thickness of the inner disk edge of a warped disk (Mahdavi & Kenyon, 1998, Lai, 1999, Terquem & Papaloizou, 2000), or the spectroscopic binary nature (see Sect. 4.4.4) might also disturb the inner disk edge and cause structural changes.

### 4.4.2 Changes between the brighter and fainter states

The light curves of VW Cha display significant photometric changes: 0.6–0.9 mag peak-to-peak variability was observed in the different photometric bands in 2019. This dynamical range is dominated by the brightening event at JD~2458642. We measured a spectrum before, during, and after this event, which allows studying its nature and origin.

The spectra taken at the bright and the faint states show noteworthy differences. The Balmer lines undergo the most striking evolution, however, other accretion tracers also vary in time. The significant amplitude variations of these lines in the normalized spectra suggest that accretion rate change might be the major contributor of the observed effect. The computed line fluxes also support this concept, since we measured higher line fluxes in the brighter state. The veiling measurements (Fig. 4.11) are also consistent with the described picture; i.e., the veiling was higher during the brighter state, indicating a higher accretion rate. Indeed, we calculated the accretion rates for each epoch, which show an increase by a factor of 2.17 during the brighter state (Tab. 4.5).

The emission lines also exhibit morphological evolution during the previously discussed brightening event. The HeI lines show only mild changes; however, the wings become more pronounced in the brighter epoch. In addition, the variance profile highlights a slight asymmetry: the red wing varies more during our observations than the blue wing. This broad component extends to ~250 km/s, and is thought to form in the magnetospheric flow (Hartmann et al., 2016). The more pronounced broad component in the brighter state might arise due to the increased accretion. The Hβ line exhibits an interesting double-peaked profile where both the strength and the position of the two components are changing.
The Hα line has the most striking morphological differences between the different measurements. The first epoch shows an emission peak with a strong blueshifted absorption component. This suggests that the accretion is accompanied by an outflow, which is discussed in Sect. 4.4.3. As the accretion rate increases by the second observation, this blueshifted absorption component becomes filled.

Stauffer et al. (2014) examined the light curves and spectra for a sample of young stellar objects in NGC 2264, including several CTTSs. They studied light curves dominated by accretion bursts, similarly to the that of VW Cha, and found that these brief – several hours to a day-long – brightenings have amplitudes in the range of 5%–50% of the quiescent level. The longer duration (several days) of the brightening event at JD~2458642 in the light curve of VW Cha and the fine-structure, revealed by the high-cadence TESS data, suggest that this event might be a superposition of multiple smaller accretion bursts. The spectral features that were found here, are also consistent with the results of Stauffer et al. (2014); i.e., accretion burst stars have a modestly structured and centrally peaked Hα line during the accretion burst and the 667.8 nm He I line in emission.

In Fig. 4.13, VW Cha is compared with other sources from the Chamaeleon I star forming region using the results of the accretion rates and the stellar parameters of Manara et al. (2019), and the fit from Fiorellino et al. (2021). The accretion luminosity is depicted against the stellar luminosity in the top panel and the accretion rate against the stellar mass in the bottom panel. The results show that, as it is expected based on previous studies, VW Cha has a high accretion luminosity and accretion rate compared to the other members of this sample and places VW Cha at the high end of the distribution. While our new results match perfectly with the fitted relation for Cha I in the $L_{\text{acc}}$ vs. $L_*$ diagram, it must be noted that the $\dot{M}_{\text{acc}}$ is larger than the trend fitted for the overall region.

### 4.4.3 Outflow

A natural by-product of accretion is the ejection of mass and energy back into the circumstellar environment. Depending on their velocities, these can be jets (for velocities above 100 km/s) and winds (for velocities below 50 km/s). They lead to forbidden line emission and often to blueshifted absorption components superimposed on background emission, which is also known as the P Cygni profile (Calvet, 1997, Bally, 2016).

VW Cha shows signs of outflow in the form of forbidden [O I] emission lines and a blueshifted absorption component of the Hα line. This absorption component, however, is not always present in our observations. The reason for this is the fact that
4.4. Discussion

![Figure 4.13: Top: Accretion luminosity as a function of stellar luminosity. Bottom: Mass accretion rate as a function of the stellar mass. Black stars are results of the Chamaeleon I survey of CTTSs from Manara et al. (2019). For this work, we plot with black dashed lines the error bars only for VW Cha. Black filled circle corresponds to the mass accretion rate computed by using the accretion luminosity from Manara et al. (2019) and stellar parameters from Daemgen et al. (2013), errors bars are shown with dotted black lines. The linear fit is taken from Fiorellino et al. (2021). Colored filled circles show the results of this work, different colors correspond to different epochs as in Fig. 4.10.](image)

it is superimposed on background emission arising due to the magnetospheric accretion. When the accretion rate increases, the accretion-powered emission component strengthens and fills the absorption component.

The [O I] emission lines are also detected in the spectra at 557.7 nm, at 630.0 nm and 636.3 nm. They appear to be variable based on the normalized line profile (Fig. 4.8 bottom middle panel); however, this line is expected to be intrinsically stable on a time scale of days (Petrov et al., 2011), and the observed effect might be due to the fact that during the brighter state, the continuum level rose. Indeed, the line fluxes were
calculated for the detected forbidden oxygen lines, which differ by only a few percent suggesting that the normalized line profiles change due to continuum variations.

The observed line profile carries information on the kinematics of the emitting gas. In the case of VW Cha, the \([\text{O I}]\) exhibits one, low-velocity component (FWHM \(\sim 30 - 60\) km/s) that is slightly blue shifted compared to the systemic velocity \((\sim 4\) km/s). The low-velocity component with peak velocity \(v_p \leq 30\) km s\(^{-1}\) is thought to be associated with extended disk winds (Kwan & Tademaru, 1995, Pascucci et al., 2020). For a sample of T Tauri stars, Gangi et al. (2020) examined the component at the lowest peak velocity of the \([\text{O I}]\) line, and our results for VW Cha are consistent with the typical line kinematic parameters that Gangi et al. (2020) found, suggesting that it originates from the innermost few au of the system.

### 4.4.4 Spectroscopic binary

The primary component of the VW Cha system is a suspected spectroscopic binary (SB2). Melo (2003) observed line doubling based on their cross-correlation function and report 15.31 km/s as a mean radial velocity for the system. Nguyen et al. (2012) found evidence for two components of the primary separated by 20 km/s.

I determined the radial velocities by fitting the LSD profiles and reported the results in Table 4.3 along with the radial velocities from Nguyen et al. (2012). In the cases where I was able to resolve the two components, our results are in agreement with Nguyen et al. (2012), where they found that their spectra of the primary show evidence for two components (Aa, Ab) separated by 20 km/s (see their Fig. 10.10). As in our observations, I found one component in the first epoch, two components in the second and third epochs, and again one component in the fourth epoch ten days later; an orbital period for the SB2 of \(\sim 10\) days can be speculated. In case the primary is indeed an SB2, and it is needed to account for the possibility that both components contribute to the observed spectroscopic variations in our new measurements. Frasca et al. (2021) examined a similar multiple system, CVSO 104, where they confirmed that the target is a double-lined spectroscopic binary. They determined the mass accretion rates of the two components from the fluxes of the lines where the profiles of the two components could be deblended. In our case, the individual components of the accretion tracers, such as the H\(\alpha\) or the He I lines appear to be blended (see Fig. 4.8), similarly to the H\(\alpha\) line presented in Frasca et al. (2021); therefore we were not able to determine the accretion rates for the individual components. The H\(\beta\) is the only line that shows a double peaked line profile; however, the peak velocities do not correspond to the radial velocities that were determined for each epoch.
4.5 Summary

We designed a complex observing campaign for the multiple T Tauri system VW Cha with multifilter photometry and high-resolution optical spectroscopy contemporaneously with the TESS space telescope observations. The high-cadence TESS photometry reveals variations on hourly-daily timescales with a peak-to-peak amplitude of $\sim 0.8$ mag. The near-infrared data show that the amplitude of the variability is slightly increasing towards the longer wavelengths. The NIR color-magnitude diagrams show the unusual trend of the source becoming redder as it brightens. This trend cannot be explained with stellar spots or variations in the extinction; however, it can be associated with changes in the accretion disk.

The light curves show a distinct brightening event in the second half of our observing period at all wavelengths. High-resolution spectra were taken before, during, and after this event, allowing us to examine its nature. The results suggest that it originates from increased accretion. The accretion tracers, the measured mass accretion rate, and the veiling are also consistent with this scenario.

Apart from the accretion, the spectra indicate the presence of an outflow as well. I found [O I] lines with one, low-velocity component, which is considered to be associated with disk winds.

Moreover, VW Cha is known to be a multiple system; however, some studies suggest that the primary itself is a spectroscopic binary. Our observations also hint at the spectroscopic binary nature with a speculated orbital period around 10 days.

4.6 Future prospects for the Chamaeleon I sample

The above presented project, of which VW Cha and CR Cha are a part, include six young stellar objects in total from the Chamaelon I star forming region (CR Cha, CT Cha, VW Cha, WX Cha, VZ Cha, and WW Cha). Besides CR Cha and VW Cha, WX Cha has also been studied in detail. We found that the system shows quasi-periodic photometric variations, and the amplitude of the photometric changes is decreasing with increasing wavelength. We obtained the accretion luminosity and the mass accretion rate using empirical relations and found values between $L_{\text{acc}} \sim 1.6 L_\odot - 3.2 L_\odot$ and $\dot{M}_{\text{acc}} \sim 3.3 \times 10^{-7} M_\odot/\text{yr} - 7.9 \times 10^{-7} M_\odot/\text{yr}$. This suggests that the accretion rate for WX Cha is larger than the typical values for the T Tauri stars in the same star-forming region with the similar stellar parameters. I show the H$\alpha$ lines of WX Cha in the top left panel of Fig. 4.14. The work on WX Cha was led by my colleague, Eleonora Fiorellino, and the publication is currently under review. I also
took a significant part in this investigation as a second author.

Similar analysis can be also carried out for the other targets as well, which will allow to make comparison between them. The objects in our sample were selected based on some similarities: they exhibit high variability at infrared wavelengths, furthermore, the targets are located in the same star forming region, i.e. they are coeval, thus the observed differences are not related to evolutionary or environmental differences but should be connected to other physical processes, such as accretion, winds or jets. The preliminary results show that despite the similarities in the sample, the significance of the abovementioned physical mechanisms might be different for the individual systems.
The Hα lines are good tracers of this, as they are expected to form throughout the circumstellar environment. They indeed reveal differences for the systems (Fig. 4.14): CT Cha shows mainly amplitude changes (top right panel), WW Cha exhibits variations in the blue wing (bottom left panel), and the most significant morphological changes are detected for VZ Cha (bottom right panel).
Table 4.6: Optical and near-infrared photometry of VW Cha.

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Chapter 5

Summary

Young stellar objects are still in that early stage of stellar evolution, when they are surrounded by a rich circumstellar environment made of gas and dust, from which they accrete material. The accretion mechanism is essential in the star formation process, and the star-disk interaction plays an important role in establishing the physical properties of the circumstellar disk where planets might form. The simplest models describe the accretion process with an azimuthally symmetric disk from which the material is falling onto the star steadily. However, the process in reality is more complex: the disk may have substructures and the accretion is non-steady, causing photometric and spectroscopic variations. The aim of this work is examining the variable accretion process of young stars, understanding the relationship between the inhomogeneous disk structure and the time-variable accretion, and to identify the different physical mechanisms behind the variations by studying a few young stellar objects with diverse accretion and circumstellar properties.

V582 Aur is an FU Orionis-type object (FUor), which is currently in an outbursting state but shows photometric variations due to an orbiting dust clump. I studied the optical–infrared photometric variability of the system in order to examine its evolution. The new data presented in this thesis imply that changing extinction is still the dominant physical mechanism behind the light variations, and suggest the viscous spreading of the dust particles along the orbit. Since the WISE measurements do not follow the scaled down $I_C$-band light curve, either the orbiting dust clump does not cover that part of the inner disk where the mid-infrared radiation is emitted or the clump itself contributes to the mid-infrared radiation. The color-magnitude diagrams indicate that the distribution of points before and after 2014 outlined similar patterns, however, the later dataset have $\sim0.3$ mag fainter values in the $V$-band. Here, I speculate that the $\sim0.3$ mag difference arises from the absolute fading of the source, reflecting
the long-term evolution of the outburst. In this scenario, the 0.3 mag fading during \( \sim 5 \) years would mean that the source will reach the quiescent level in approximately 80 years, which decade long trend is a characteristic of FUor type stars. The long term decreasing trend in the accretion rate is consistent with the previous conclusion on the long-term fading of the source.

With the aim of studying the accretion variability, my supervisor and I, with the involvement of other researchers (Gaitee Hussain, Carlo Manara, Péter Ábrahám), constructed an observing program for a sample of six objects in the Chamaeleon I star forming region. We arranged ground-based optical and near-infrared photometric, and high-resolution spectroscopic (VLT/ESPERRESSO, 2.2/FEROS) observations contemporaneously with the TESS space telescope observations in order to examine the accretion process, analyze the effects of hot/cold spots, and identify the signs of line-of-sight obscuration by circumstellar matter.

For one particular object, the CR Cha single T Tauri star, I was able to study the accretion process on timescales from hours to a decade by including earlier data from the AAT/UCLES and the HARPS instruments. These show that the accretion variations increase on timescales from hours to days/weeks, after which it saturates, and the overall accretion variability is within the factor of \( \sim 3 \) on timescales of a decade. The regime of short-timescale variations is covered by the TESS space telescope, with which I was able to examine the periodic brightness changes related to the stellar rotation, and also the more stochastic accretion-related variations. The near-infrared \( JHK \)-band light curves reveal an interesting pattern in the color-magnitude diagrams: they show that CR Cha becomes redder as it brightens. This unusual pattern may be explained by a disk model, which states that this behaviour may be caused by the changing accretion rate, or by changes in the inner disk structure.

For another object, the VW Cha multiple system, four high-resolution spectra were taken besides the TESS and the ground-based photometry. Similarly to CR Cha, the near-infrared color-magnitude diagrams show the unusual trend of the source becoming redder as it brightens. This trend cannot be explained with stellar spots or variations in the extinction, however, it can be associated with changes in the accretion disk. Spectra were obtained in both fainter and brighter photometric states of the system, allowing me to examine the origin of a photometric brightening event. The results show that this brightening event can be explained by increased accretion. VW Cha is a multiple system, and the primary component is known to host a circumstellar disk, while the secondary is probably not surrounded by a disk according to previous statistical studies. On this basis, I attributed the accretion-related variability to the primary component. In addition, our spectroscopic data also suggest that the primary
component of VW Cha is a spectroscopic binary with a speculated orbital period around 10 days. Furthermore, I found indicators of outflow in the form of [OI] line with one low velocity component, which is considered to be associated with disk winds.

While the studies presented in this thesis are examining individual stars, they well represent the accretion phenomenon in general, including both moderately accreting T Tauri stars and an outbursting FUor. This work also showed the importance of multifilter and multi-instrument campaigns when identifying and distinguishing the mechanisms causing the variability. It was also demonstrated that time domain astronomy is becoming a very efficient tool to study these phenomena.
Chapter 6

Összefoglalás

A fiatal csillagokat fejlődésük korai szakaszában még körülveszi egy gázból és porból álló korong, amelyből anyag hullik a csillagra, így építve fel azt. Ez a tömegbefogási, azaz akkréciós folyamat alapvető fontosságú a csillagkeletkezés során. A csillag és a korong kölcsönhatása fontos szerepet játszik a korong fizikai tulajdonságainak meghatározásában is, éppen azon belül végi régióban, ahol bolygók keletkezhetnek. A legegyszerűbb modell az akkréciós folyamat leírásakor egy szimmetrikus korongot feltételeznek, amelyből az anyag egyenletesen hullik a csillagra. Ezzel a megfigyelések azt mutatják, hogy a folyamat a valóságban jóval összetettebb: a korong szerkezete különféle finomszerkezetet mutat, valamint az anyagbefogás mértéke sem állandó, ami fotometriai és spektroszkópiai változásokhoz vezet. Jelen munkának a célja a változó tömegbefogás folyamatának vizsgálata fiatal csillagokban, illetve a megfigyelt fotometriai és spektroszkópiai változások fizikai hátterének tanulmányozása néhány olyan rendszerben, amely különböző akkréciós és egyéb fizikai paraméterekkel rendelkezik.

A legnagyobb akkréciós ráttakkal rendelkező objektumok az FU Orionis (FUor) típusú fiatal eruptív csillagok, amelyek évtizedekig tartó kitöréseket mutatnak. A V582 Aur jelű rendszer ebbe a csoportba tartozik, és jelenleg magas akkréciójú állapotban, azaz kitörésben van. Ennek az objektumnak tanulmányoztam az optikai-infravörös fotometriai változásait azzal a céljával, hogy a rendszer fejlődését vizsgáljam korábbi mérésekkel is összehasonlítsa. A disszertációmban analizált újonnan – részben általam felvett többszín-fotometriai mérések azt mutatják, hogy a rövid távú időszakos elhalványodások mögött rejlő domináns fizikai folyamat a változó extinkció. Amennyiben az itt bemutatott legújabb mérések alapján megfigyelt elhalványodást ugyanaz a porfelhő okozza, mint egy korábbi kutatás által említett ~ 5 éves periódussal keringő felhő, akkor az a porfelhő viszkozus széterülsére utal. A WISE mérések nem követik a $I_C$-szűrőben végzett méréseket, ami arra utal, hogy a rendszerben keringő
porfelhő vagy nem fedi el a belső korog közép-infravörös sugárzó régióját, vagy maga a porfelhő is hozzájárul a közép-infravörös sugárzásához. A korábbi méréseket is figyelembe véve a hosszútávú adatok alapján elkészített szín-fényesség diagramok azt mutatják, hogy a 2014 előtt és után felvett adatok hasonló mintát mutatnak, azonban az újabb mérések ~0.3 magnitúdóval halványabb állapotot fednek fel. Ez a ~0.3 magnitúdós halványodás eredhet a forrás abszolút halványodásából, ami a FUor kitörés hosszú távú fejlődését mutatja. Ebben az esetben az 5 év alatt történt ~0.3 magnitúdós halványodás azt jelenti, hogy a V582 Aur nagyjából 80 év alatt vissza fog térni a kitörés előtti nyugalmi állapotba. Az akkréciós ráta csökkenése is összhangban áll ezzel a forgatókönyvvel.

Az akkréciós változékonyság vizsgálata céljából a témavezetőmmel és más kutatók bevonásával (Gaitee Hussain, Carlo Manara, Ábrahám Péter) kidolgoztunk egy megfigyelési programot, amelynek a keretében a Chamaeleon I csillagkeletkezési terület hat csillagáról gyűjtöttünk földi optikai és közeli-infravörös fotometria méréseket, valamint nagyfelfontású spektroszkópiai adatokat (VLT/ESPRESSO, 2.2m/HEROS), amelyek a TESS űrtávcső mérési időszakával közel egyidejűleg készültek. Ezeket felhasználva vizsgáltam az akkréciós folyamatot, a hideg és forró foltok hatását, és azonosítani tudtam a csillagkörülü anyag által okozott fedésből eredő változásokat.

A Chamaeleon I minta egyikére, a CR Cha jelű T Tauri típusú csillagra korábbi spektroszkópiai adásorokat is bevontam a vizsgálatba (AAT/UCLES, HARPS), így az akkréciós változékonyságot hosszú távon is tudtam vizsgálni. Az eredmények azt mutatják, hogy az akkréciós ráta relatív változása növekszik órás időskalálától napos/hetes időskáláig, majd ennél hosszabb időskálnán változatlan marad, valamint a teljes akkréciós változékonyság háromszoros faktorom belül marad. A rövid időskálájú változást a TESS méréseinek segítségével tudtam vizsgálni, ami a csillag tengely körüli forgásához köthető periodikus változást fed fel, továbbá az akkrécióval kapcsolatos véletlenszerű változások is mutatkoznak. A közeli-infravörös mérések érdekes mintát rajzolnak ki a szín-fényesség diagramon: azt mutatják, hogy a CR Cha fényesedésével a forrás vörösebbé válik. Ez a szokatlan jelenség egy korong modellel magyarázható, amely a változásokat a korongban történő szerkezetbeli változásoknak vagy az akkréció változásának tulajdonítja.

A Chamaeleon I minta egy másik tagjára, a VW Cha többes rendszerre a TESS és a földi optikai-infravörös többszín-fotometria mellett négy időpontban készült nagyfelbontású spektrum. A közeli-infravörös szín-fényesség diagram ebben az esetben is a CR Cha-hoz hasonló különös mintát mutat: az objektum fényesedés során vörösebbé válik. Ezt a mintát csillagolékknek vagy változó extinkció nem magyarázza, azonban az akkréciós korong szerkezetbeli változásával értelmezhető a detektált jelenség. Mivel a VW Cha
esetén sikerült spektrumot felvenni a rendszer fényesebb és halványabb fotometriai állapotában is, ezek kombinálásával meg tudtam vizsgálni a fényesedés fizikai eredetét. Az eredményem azt mutatják, hogy a fényesedés magyarázható megnövekedett akkrécióval. A VW Cha egy többes rendszer, és korábbi tanulmányok megmutatták, hogy a főkomponens körül van véve egy csillag körüli koronggal, míg a kísérő feltételezhetően nincs. Ez alapján a detektált akkréciós változékonyságot a főkomponensnek tulajdonítom. A spektroszkópiai adatok arra utalnak, hogy a VW Cha többes rendszer elsődleges komponense egy spektroszkópiai kettős, melynek a feltételezett keringési periódusa 10 nap körüli. A szíNKépben találtam továbbá [O I] vonalat, amely a valamilyen formájú kifújásra utal. Az egy, alacsony sebességű komponessel rendelkező színképvonal korong szél jelenlétét jelzi.

Ugyan az itt ismertetett munkák egy-egy csillag részletes analízisét mutatják be, ezek az objektumok jól reprezentálják általánosságban az akkréciós folyamatot mérsékelten akkretáló T Tauri csillagokat és épp kitörésben lévő FUort is bevonva. Továbbá a dolgozat jól mutatja annak fontosságát is, hogy többszín-fotometriát és különféle észlelési technikákat ötvöző megfigyelési kampányokat alakítsunk ki a fiatal csillagokban és környezetükben lezajló fizikai folyamatok beazonosítására és vizsgálatára.
# Appendix

List of acronyms and abbreviations

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<th>Description</th>
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<td>ANDICAM</td>
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<tr>
<td>ASAS</td>
<td>All Sky Automated Survey</td>
</tr>
<tr>
<td>ASAS-SN</td>
<td>All-Sky Automated Survey for Supernovae</td>
</tr>
<tr>
<td>au</td>
<td>Astronomical unit</td>
</tr>
<tr>
<td>CaIRT</td>
<td>Ca II infrared triplet</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
</tr>
<tr>
<td>CTTS</td>
<td>Classical T Tauri star</td>
</tr>
<tr>
<td>DDT</td>
<td>Director’s Discretionary Time</td>
</tr>
<tr>
<td>DSS</td>
<td>Digital Sky Survey</td>
</tr>
<tr>
<td>ESO</td>
<td>European Southern Observatory</td>
</tr>
<tr>
<td>ESPRESSO</td>
<td>Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations</td>
</tr>
<tr>
<td>EW</td>
<td>Equivalent width</td>
</tr>
<tr>
<td>EXor</td>
<td>EX Lupi-type object</td>
</tr>
<tr>
<td>FEROS</td>
<td>Fiber-fed Extended Range Optical Spectrograph</td>
</tr>
<tr>
<td>FUor</td>
<td>FU Orionis-type object</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full width at half maximum</td>
</tr>
<tr>
<td>HARPS</td>
<td>High Accuracy Radial velocity Planet Searcher</td>
</tr>
<tr>
<td>IDL</td>
<td>Interactive Data Language</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>LSD</td>
<td>Least-Squares Deconvolution</td>
</tr>
<tr>
<td>$L_{\odot}$</td>
<td>Solar luminosity</td>
</tr>
<tr>
<td>$L_*$</td>
<td>Stellar luminosity</td>
</tr>
<tr>
<td>$M_{\text{acc}}$</td>
<td>Accretion rate</td>
</tr>
<tr>
<td>$M_{\odot}$</td>
<td>Solar mass</td>
</tr>
<tr>
<td>$M_*$</td>
<td>Stellar mass</td>
</tr>
<tr>
<td>$M_{\oplus}$</td>
<td>Earth mass</td>
</tr>
<tr>
<td>$M_{C*}$</td>
<td>Mass of circumstellar material</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>MHD</td>
<td>Magnetohydrodynamic</td>
</tr>
<tr>
<td>MPG</td>
<td>Max-Planck Gesellshaft</td>
</tr>
<tr>
<td>NIR</td>
<td>Near-infrared</td>
</tr>
<tr>
<td>pc</td>
<td>Parsec</td>
</tr>
<tr>
<td>PMS</td>
<td>Pre-main-sequence</td>
</tr>
<tr>
<td>PSF</td>
<td>Point Spread Function</td>
</tr>
<tr>
<td>$R_{\odot}$</td>
<td>Solar radius</td>
</tr>
<tr>
<td>$R_*$</td>
<td>Stellar radius</td>
</tr>
<tr>
<td>RV</td>
<td>Radial velocity</td>
</tr>
<tr>
<td>SB2</td>
<td>Double-lined spectroscopic binary</td>
</tr>
<tr>
<td>SED</td>
<td>Spectral Energy Distribution</td>
</tr>
<tr>
<td>SMARTS</td>
<td>Small &amp; Moderate Aperture Research Telescope System</td>
</tr>
<tr>
<td>S/N</td>
<td>Signal-to-noise ratio</td>
</tr>
<tr>
<td>SpT</td>
<td>Spectral Type</td>
</tr>
<tr>
<td>$T_{\text{eff}}$</td>
<td>Effective temperature</td>
</tr>
<tr>
<td>TCS</td>
<td>Telescopio Carlos Sánchez</td>
</tr>
<tr>
<td>TESS</td>
<td>Transiting Exoplanet Survey Satellite</td>
</tr>
<tr>
<td>UCLES</td>
<td>University College of London Échelle Spectrograph</td>
</tr>
<tr>
<td>UKIDSS</td>
<td>UKIRT Infrared Deep Sky Survey</td>
</tr>
<tr>
<td>UXor</td>
<td>UX Ori-type object</td>
</tr>
<tr>
<td>VALD</td>
<td>Vienna Atomic Line Database</td>
</tr>
<tr>
<td>VLT</td>
<td>Very Large Telescope</td>
</tr>
<tr>
<td>WISE</td>
<td>Wide-field Infrared Survey Explorer</td>
</tr>
<tr>
<td>WTTS</td>
<td>Weak-line T Tauri star</td>
</tr>
<tr>
<td>YSO</td>
<td>Young Stellar Object</td>
</tr>
<tr>
<td>ZAMS</td>
<td>Zero-age main sequence</td>
</tr>
<tr>
<td>ZDI</td>
<td>Zeeman-Doppler Imaging</td>
</tr>
<tr>
<td>ZTF</td>
<td>Zwicky Transient Facility</td>
</tr>
</tbody>
</table>
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