Thesis Booklet

Accretion variability in low-mass young stellar objects

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1 Introduction

Young stellar objects are surrounded by a circumstellar disk made of gas and dust, from which material is being accreted onto the forming star. This accretion mechanism is essential in the star formation process (Hartmann et al., 1998), and the interaction between the star and the disk plays an important role in establishing the physical properties and the evolution of both the newborn star and the circumstellar disk where planets form (Lin et al., 1996). The simplest models describe the accretion process with an azimuthally symmetric disk from which the material is falling onto the star steadily (Hartmann et al., 2016). However, observations show that in reality, the process is more complex: the disk may have substructures and the accretion is non-steady, causing photometric and spectroscopic variations. By studying the time-variable accretion of young stellar objects, we can learn more about fundamental questions: how do stars gain their masses and what are the initial conditions of planet formation in the circumstellar disk?

The rate at which a young stellar object is accreting varies in a wide range. For classical T Tauri stars, the accretion rates are relatively small ($10^{-11} - 10^{-8}\,M_\odot$/yr), however, they are still relevant in terms of disk evolution and planet formation. Short-term accretion related stochastic bursts occur in many T Tauri stars but the accretion variability remains within an order of magnitude for a given system (Fischer et al., 2022). The most extreme accretion related outbursts are exhibited by young eruptive stars, such as the FU Orionis-type objects (FUors, Hartmann & Kenyon, 1996, Audard et al., 2014). According to the current picture of FUors, the outbursts occur due to the rapid disk accretion at rates of $10^{-5} - 10^{-4}\,M_\odot$/yr.

Variable accretion, however, is not the only physical mechanism that causes photometric and spectroscopic changes. Rotational modulation, obscuration by the circumstellar material, stellar activity, or binarity-related phenomena may all contribute to the observed effect to varying degrees (Herbst et al., 1994). The actively researched field of star formation has several questions that are still open. How does mass accretion proceed in realistic and non-axisymmetric disks? How do observations probe the underlying physical mechanisms that models predict? How does the interaction between the star and the disk influence the physical and chemical properties of the planet forming regions of disks?

Studying individual young stellar objects is important and instructive because 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 examination of individual objects allow 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 studied the accretion-driven variability of three young stellar objects with various properties using precise space-based and multifilter ground-based photometric data and high-resolution optical spectroscopic observations.

2 Instruments and methods

Since young stellar objects are highly variable, high-resolution and high-cadence observations are needed to study the fine-structure of the variability on short-timescales. The below described observational techniques and methods helped me to distinguish between the different physical mechanisms causing the observed signatures, and to gain a more complete picture of the studied systems.

High-cadence space photometry. I used high-cadence broad-band optical photometric observations obtained by the TESS space telescope. These highly structured precise light curves allowed me to study the short-timescale variations of young stars, and to distinguish between the effects of spots, accretion, and flares. I carried out frequency analysis, in order to examine the degree of periodicity and symmetry in the light curves, and looked for their physical origin. Furthermore, I identified traces of stellar activity and accretion.

Multifilter photometry. I collected new multifilter ground-based photometric observations at optical and near-infrared wavelengths (Piszkéstető Mountain Station, Telescopio Carlos Sánchez, Liverpool Telescope, SMARTS 1.3 m), and complemented them with data from publicly available surveys (ASAS-3 and ASAS-SN catalogs). Despite being of sparser cadence than the observations of the TESS space telescope, these measurements carry important color information on the variability. Furthermore, I analyzed mid-infrared WISE data available from the NEOWISE-Reactivation catalog. I studied the amplitude of the variations and their wavelength dependence, constructed color-magnitude and color-color diagrams to examine the color changes and identify their physical origin by comparing them with published models. I wrote and used IDL and Python scripts to carry out the data reduction and analysis.

High-resolution spectroscopy. I collected new high-resolution optical spectroscopic measurements (VLT/ESPRESSO, MPG/ESO 2.2 m/FEROS), and complemented them with archival data (ESO 3.6 m/HARPS, AAT/UCLES). I identified tracers of accretion and outflow in the spectra. The high-resolution spectra reveal the fine-structure of the emission line profiles, which allowed me to infer physical and kinematical properties of the gas emitting these lines. For this reason, I analyzed the amplitude, timescale, and the morphology of the accretion tracers. When contemporaneous multifilter photometry was available, it was utilized for the flux calibration of the spectra in order to determine the accretion rates using empirical relations.

3 Theses

The weakening outburst of the young eruptive star V582 Aur

1. I obtained and analyzed new multifilter photometric observations (partially obtained by myself) of the FU Orionis-type young eruptive star V582 Aur to compare them with previous studies and investigate the evolution of the system. I showed that these new data imply that changing extinction is still the dominant physical mechanism behind the temporary fading of the source, and suggest that the light curve shape may be explained by the viscous spreading of the dust particles along their orbit around the central young star.

2. By comparing the newly obtained data with previously published observations, I found that the distribution of points before and after 2014 outlined similar patterns on the color-magnitude diagrams, however, the system is $\sim$0.3 mag fainter in the later dataset. 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. I determined that if this trend continues, that would mean that the source will reach the quiescent level in approximately 80 years.

Related publication:
Zsidi G.; Ábrahám, P.; Acosta-Pulido, J. A; Kóspál Á. et al., The weakening outburst of the young eruptive star V582 Aur, ApJ, 873, 130 (2019)

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

3. I examined the optical-infrared photometric variability of CR Cha, which reveals moderate brightness changes. I found periodic variations in all of the optical light curves, which is compatible with the 2.3-day stellar rotational period. I demonstrated that CR Cha becomes redder as it brightens in the near-infrared color-magnitude diagram. I interpret this unusual pattern by a disk model, according to which the infrared variability is caused by the changing accretion rate, or by changes in the location of the inner edge of the dust disk.

4. I analyzed the amplitude, timescale, and morphology of the Hα and the Hβ lines in three observing seasons using archival and newly obtained high-resolution spectra. I found significant morphological changes in the line profile of the Hα line on yearly timescales, indicating that the different physical mechanisms responsible for the line profile changes, such as accretion or wind, are present to varying degrees at different times. I computed the accretion rate for each spectroscopic epoch and showed that the accretion variations increase on timescales from hours to days/weeks, after which they saturate, and the overall accretion variability is within a factor of $\sim$3 on decadal timescales.

Related publication:
Zsidi, G.; Manara, C., Kóspál, Á. et al., Accretion variability from minutes to decade timescales in the classical T Tauri star CR Cha, A&A, 660, 108 (2022)

Accretion variability of the multiple T Tauri system VW Cha

5. I studied the photometric variability of VW Cha, and I found that the high-cadence TESS light curves are dominated by stochastic variations related to accretion changes. Furthermore, the color-magnitude diagrams show the unusual trend of the source becoming redder as it brightens. By comparing my results with published models, I found that this trend cannot be explained with stellar spots or variable extinction, however, it can be associated with structural changes in the accretion disk.

6. I studied high-resolution optical spectra taken in both brighter and fainter photometric states of the VW Cha multiple system, which allowed me to examine the origin of a photometric brightening event. I found that this brightening event can be explained by increased accretion, which is supported by both the veiling and

the accretion rate measurements. Furthermore, I demonstrated that the primary component of VW Cha might be a spectroscopic binary with a speculated orbital period of about 10 days.

Related publication:
Zsidi, G; Fiorellino, E.; Kóspál, Á. et al., Accretion variability of the multiple T Tauri system VW Cha, ApJ, in press, eprint arXiv:2205.11435

4 Conclusions

The aim of this work was to examine the variable accretion process of young stars, and to analyze the different physical mechanisms behind the observed photometric and spectroscopic variations by studying a few young stellar objects with diverse accretion and physical properties. While the studies presented in this thesis are focusing on individual stars, they well represent the accretion phenomenon in general, including both moderately accreting T Tauri stars and an outbursting FUor.

Accretion variability occurs on a wide range of timescales, and even a single object, such as CR Cha, can show accretion-related changes on timescales from hours to years. Furthermore, multiple systems, like VW Cha, also deserve special attention, as they represent a large fraction of the young stellar objects. A further interesting result is that both stars from the Chamaeleon I region exhibit a rare patter in the near-infrared color-magnitude diagram, i.e, the object becomes redder as it brigtens. This rises the question whether this phenomenon occurs more frequently in this star forming region than in others.

As only a small number of FUors have been identified to this day, the examination of less known objects contribute to the understanding of this class of young eruptive stars. The work has demonstrated that there are still relatively understudied FUors among the known ones, which show interesting brightness variations during the outburst due to changes in the circumstellar environment.

This work also showed the importance of multifilter and multi-instrument campaigns when identifying and distinguishing the mechanisms causing the variability of young star. It was also demonstrated that time domain astronomy is becoming a very efficient tool to study these phenomena.

5 Publications

Publications related to the thesis

Refereed publications

- **Zsidi, G.**; Ábrahám, P.; Acosta-Pulido, J. A; Kóspál Á., Kun M.; Szabó Zs. M.; Bódi A.; Cseh B.; Castro Segura, N.; Hanyecz O.; Ignácz B.; Kalup Cs.; Kriskovics L.; Mészáros L.; Ordasi A.; Pál A.; Sárneczky K.; Seli B.; Sódor Á.; Szakáts R., "The weakening outburst of the young eruptive star V582 Aur", The Astrophysical Journal, Volume 873, Issue 2, article id. 130, 6 pp. (2019)
- **Zsidi, G.**; Manara, C., Kóspál, Á.; Hussain, G.; Ábrahám, P.; Alecian, E.; Bódi, A.; Pál, A.; Sarkis, P., "Accretion variability from minutes to decade timescales in the classical T Tauri star CR Cha", Astronomy & Astrophysics, Volume 660, id.A108, 15 pp. (2022)
- **Zsidi, G**; Fiorellino, E.; Kóspál, Á.; Ábrahám, P.; Bódi, A.; Hussain, G.; Manara, C.; Pál, A., "Accretion variability of the multiple T Tauri system VW Cha", (The Astrophysical Journal, in press, arXiv:2205.11435)

Further publications in the topic of the thesis

Refereed publications

- Juhász, T.; Ábrahám, P.; Moór, A.; Chen, L.; Kóspál, Á.; Varga, J.; Ragály, Zs.; **Zsidi, G.**; Pál, A., "A Gap at 1 au in the Disk of DI Cha A Revealed by Infrared Interferometry", The Astrophysical Journal, Volume 932, Issue 2, id.79, 15 pp. (2022)
- Nagy, Zs.; ...; **Zsidi, G.**; ..."Dipper-like variability of the Gaia alerted young star V555 Ori"; MNRAS, Volume 504, Issue 1, pp.185-198 (2021)
- Manara, C. F.; ... **Zsidi, G.**; ... "PENELLOPE: the ESO data legacy program to complement the Hubble UV Legacy Library of Young Stars (ULLYSES) I. Survey presentation and accretion properties of Orion OB1 and σ-Orionis", A&A, Volume 650, id.A196, 46 pp. (2021)
- Kóspál, Á.; Ábrahám, P.; **Zsidi, G.**; Vida, K.; Szabó, R.; Moór, A.; Pál, A., "Spots, Flares, Accretion and Obscuration in the Pre-main Sequence Binary DQ Tau", The Astrophysical Journal, Volume 862, Issue 1, id. 44, 16 pp. (2018)

- Ábrahám, P.; Kóspál, Á.; Kun, M.; Fehér, O.; **Zsidi, G.**; Acosta-Pulido, J. A.; Carnerero, M. I.; García-Álvarez, D.; Moór, A.; Cseh, B.; Hajdu, G.; Hanyecz, O.; Kelemen, J.; Kriskovics, L.; Marton, G.; Mező, Gy.; Molnár, L.; Ordasi, A.; Rodríguez-Coira, G.; Sárneczky, K.; Sódor, Á.; Szakáts, R.; Szegedi-Elek, E.; Szing, A.; Farkas-Takács, A.; Vida, K.; Vinkó, J., "An UXor among FUors: Extinction-related Brightness Variations of the Young Eruptive Star V582 Aur", The Astrophysical Journal, Volume 853, Issue 1, article id. 28, 16 pp. (2018).

Conference proceedings

- **Zsidi, G.**; Kóspál, Á.; Ábrahám, P.; Szabó, R.; Cseh, B.; Sárneczky, K.; Sódor, Á.; Szakáts, R.; Vida, K.; Vinkó, J., "Brightness variations of young Sun-like stars from ground-based and space telescopes", Origins: From the Protosun to the First Steps of Life. Proceedings of the International Astronomical Union, Volume 345, pp. 380-382 (2020)

- Kóspál, Á.; Ábrahám, P.; **Zsidi, G.**; Vida, K.; Szabó, R.; Moór, A.; Pál, A, "Spots, flares, accretion, and obscuration in the pre-main sequence binary DQ Tau", Origins: From the Protosun to the First Steps of Life. Proceedings of the International Astronomical Union, Volume 345, pp. 314-315 (2020)

- Ábrahám, P.; Kóspál, Á.; Kun, M.; Fehér, O.; **Zsidi, G.**; Acosta-Pulido, J. A., "An UXor among FUors: extinction-related brightness variations of the young eruptive star V582 Aur", Origins: From the Protosun to the First Steps of Life. Proceedings of the International Astronomical Union, Volume 345, pp. 390-392 (2020)

Further refereed publications

- Wang, Q.; . . . ; **Zsidi, G.**; . . . , "SN 2018agk: A Prototypical Type Ia Supernova with a Smooth Power-law Rise in Kepler (K2)", The Astrophysical Journal, Volume 923, Issue 2, id.167, 22 pp. (2021)

- Armstrong, P.; . . . ; **Zsidi, G.**; . . . , "SN2017jgh: a high-cadence complete shock cooling light curve of a SN IIb with the Kepler telescope", MNRAS, Volume 507, Issue 3, pp.3125-3138 (2021)

- Zhang, J.; . . . ; **Zsidi, G.**; . . . , "SN 2018zd: an unusual stellar explosion as part of the diverse Type II Supernova landscape", MNRAS, Volume 498, Issue 1, pp.84-100 (2020)
- Könyves-Tóth, R.; . . . ; **Zsidi, G.**; . . . , "Constraints on the Physical Properties of SNe Ia from photometry", The Astrophysical Journal, Volume 892, Issue 2, id. 121 (2020)
- Szalai, T.; . . . ; **Zsidi, G.**; . . . , "The Type II-P Supernova 2017eaw: From Explosion to the Nebular Phase", The Astrophysical Journal, Volume 876, Issue 1, article id. 19, 24 pp. (2019)
- Li, W. ; . . . ; **Zsidi G.**; . . . , "Photometric and Spectroscopic Properties of Type Ia Supernova 2018oh with Early Excess Emission from the Kepler 2 Observations", The Astrophysical Journal, Volume 870, Issue 1, (2019) article id. 12, 33 pp.
- Dimitriadis, G.; . . . ; **Zsidi G.**; . . . , "K2 Observations of SN 2018oh Reveal a Two-component Rising Light Curve for a Type Ia Supernova", The Astrophysical Journal Letters, Volume 870, Issue 1, article id. L1, 16 pp. (2019)
- Boyajian, T.; . . . ; **Zsidi, G.**; . . . , "The First Post-Kepler Brightness Dips of KIC 8462852", The Astrophysical Journal Letters, Volume 853, Issue 1, article id. L8, 14 pp. (2018)

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