

# An Infrared and Optical View of Young Eruptive Stars

THESES OF THE PHD DISSERTATION

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# 1 Introduction

Stars are typically forming in the densest parts of molecular clouds. Following an initial isotherm contraction, a protostar forms in the center which accumulates material from its surroundings. Due to the non-zero angular momentum of the initial cloud core, the material cannot fall directly to the protostar's surface, but forms a disk-like structure. The accretion rate ( $10^{-7}$ – $10^{-8} M_{\odot}/\text{yr}$  in average) from the disk to the protostar is not constant in time, but there are periods of highly enhanced accretion ( $10^{-4}$ – $10^{-3} M_{\odot}/\text{yr}$ ). The enhanced accretion causes the brightening of the system, resulting in what we can observe as an optical outburst of a young star (FUor or EXor phenomenon, named after the prototypes FU Orionis and EX Lupi, respectively). During a FUor eruption, the star brightens by 4-5 mag in a few months or in a few years and stays bright for several years or decades. EXors show outbursts of similar magnitude but on shorter timescale. According to the current picture, the enhanced accretion is due to a thermal instability at the inner edge of the disk, in some cases possibly triggered by perturbation due to the passage of a close companion. Nowadays, we know about 20 FUors, including candidates. Statistics show that probably *all* low-mass ( $M < 2 M_{\odot}$ ) young stars undergo periods of high accretion and collect a significant amount of their final mass, making the FUor and EXor phenomenon an important step in pre-main sequence evolution.

## 2 Scientific goals

A number of issues are still open concerning the circumstellar structure of young eruptive stars. Do all low-mass young stars undergo FUor/EXor-type eruptions? Are FUor-type outbursts recurrent? What can trigger the eruption? Do all young eruptive stars have similar circumstellar structures? How do they evolve?

Current FUor models are usually based on fitting the spectral energy distribution and the optical light curve of the object. However, the geometry usually cannot be determined unambiguously from the modeling, thus, direct observations of the circumstellar environment would be desirable. It is also an open question whether all FUors have companions.

My aim was to contribute to the solution of the above questions and to obtain more information about the FUor phenomenon. For this purpose, I documented and analysed the outburst of two young eruptive stars, *OO Ser* and *V1647 Ori* at optical-infrared wavelengths.

I also analysed high-resolution observations of *Parsamian 21*, a FUor system with an edge-on disk. In my dissertation I present a thorough analysis of these three individual young eruptive stars. Taking into account the small number of known FUors and EXors, these results may contribute to the general understanding of this interesting phase of pre-main sequence evolution.

### 3 Methods

I used optical and infrared data to study the circumstellar properties and evolution of the three aforementioned young eruptive stars. For V1647 Ori, ground-based data were mainly obtained at the Pizskéstető Mountain Station (Hungary) and at the Teide Observatory (Canary Islands) with the involvement of several observers. When higher spatial resolution information was necessary, I analysed VLT/NACO differential polarimetric data for Parsamian 21, obtained within the framework of our ESO observing proposal. For OO Ser and Parsamian 21, I used mid- and far-infrared archival data from the *Infrared Space Observatory* (ISO) and the *Spitzer Space Telescope*. In the case of Parsamian 21, I also utilized archival *Hubble* observations.

For data reduction, usually the standard methods appropriate for the given instrument were followed. For the ISO photometry, VLT/NACO differential polarimetry, and Spitzer/IRS spectroscopy, however, I also developed new algorithms.

Most of these data were taken with international front-line instrumentation. I combined them in order to construct an optical-infrared spectral energy distribution of each object discussed in this work. Then, I compared the results to predictions of the standard outburst model of young eruptive stars (Bell et al. 1995, ApJ 444, 376; Hartmann & Kenyon 1996, ARA&A 34, 207), and estimated the values of different physical parameters.

### 4 Theses

**The outburst of the eruptive young star OO Serpentis between 1995 and 2006 (A&A 470, 211–219, 2007)**

- (1) Based on archival ISO data and new observations, I documented and analysed the brightness evolution of OO Ser during its outburst between 1995 and 2006. I compared

the pre-outburst fluxes with the outburst spectral energy distribution and found that the outburst caused brightening not only at  $2.2\ \mu\text{m}$  (where the outburst was discovered), but at all infrared wavelengths between  $2.2$  and  $100\ \mu\text{m}$ . My analysis revealed that the fading of the source is still ongoing, and OO Ser will probably not return to quiescence before 2011. The flux decay has become slower since the outburst peak and has been practically wavelength-independent.

- (2) I analysed the physical parameters and evolutionary status of OO Ser. Based on its spectral energy distribution and bolometric temperature, OO Ser seems to be an early Class I object, with an age of  $< 10^5$  yr. The outburst timescale (at least 16 years) and the moderate luminosity ( $4.5 L_{\odot}$  before the outburst and  $\approx 31 L_{\odot}$  at peak brightness) suggest that the object is different from both FUors and EXors, and shows more similarities with V1647 Ori.
- (3) I compared the available observations with a widely accepted model of young eruptive stars (Bell et al. 1995), and concluded that the object is probably surrounded by an accretion disk and a dense envelope. This picture is also supported by the wavelength-independence of the fading. However, due to the shorter timescales, outburst models developed for FUors can only work for OO Ser if the viscosity parameter in the circumstellar disk is set to an order of magnitude larger value than usual for FUors.

**The 2004–2006 Outburst and Environment of V1647 Ori (AJ 133, 2020-2036, 2007)**

- (4) I contributed to the optical monitoring of V1647 Ori, and analysed the brightness evolution and colors of the central source and the nebula around it. My results are:
  - 4/1 The brightness of V1647 Ori stayed more than 4 mag above the pre-outburst level for about two years. Using observations obtained at Pizskéstető, I reported the beginning of its rapid fading in 2005 October (Kóspál et al. 2005, IBVS 5661, 1).
  - 4/2 By calculating the time delay between the brightness variations of the star and a nebular position, I determined an angle of  $61^{\circ}$  between the axis of the nebula and the line of sight.
  - 4/3 From the J–H and H–K<sub>S</sub> color maps of the infrared nebula I derived the presence of a circumstellar envelope whose largest extension is about  $18''$  (0.03 pc).

- (5) Based on our optical and near-infrared spectra obtained at different epochs during the outburst, I analysed the temporal variation of a number of spectral features. The observed decrease of line flux of the hydrogen lines can be interpreted as a decrease in the accretion rate of about an order of magnitude between the peak brightness and the quiescence. An interesting result is that the CO band head emission at  $2.2\ \mu\text{m}$  was observable during the outburst, but is not present in our quiescent spectrum.
- (6) I compared the observed properties of V1647 Ori with the predictions of the thermal instability model of Bell et al. (1995), and concluded that this model reproduces most observational results, but one order of magnitude higher than usual disk viscosity parameter has to be assumed. I argue that V1647 Ori might belong to a new class of young eruptive stars, defined by relatively short timescales, recurrent outbursts, modest increase in bolometric luminosity and accretion rate, and an evolutionary state earlier than that of typical FUors.

**Notes:** Most of the results presented in Acosta-Pulido et al. (2007) are the joint work of the co-authors and it is very difficult to precisely separate the contribution of each co-author. In the theses and in the dissertation I only presented results where I made a significant contribution.

**High-resolution polarimetry of Parsamian 21: revealing the structure of an edge-on FU Ori disc (MNRAS 383, 1015–1028, 2008)**

- (7) I studied the stars in the vicinity of Parsamian 21 in the optical and near-infrared color-color diagrams, and found that Parsamian 21, unlike many other FUors, is rather isolated and is not associated with any known rich cluster of young stars. I found no close companion which could have triggered an eruption.
- (8) From our direct and polarimetric observations I proved the presence of a circumstellar envelope, a polar cavity in the envelope and an edge-on disk. The disk seems to be geometrically flat and extends from at least 48 to 360 AU. The disk is surprisingly flat, its thickness is at most 80 AU, while its inclination is smaller than  $6^\circ$ .
- (9) Within the framework of an evolutionary sequence of FUors proposed by Quanz et al. (2007, ApJ 668, 359) and Green et al. (2006, ApJ 648, 1099), I classified Parsamian 21 as an intermediate-aged young eruptive star. This conclusion is supported by the weak

silicate emission at  $10\ \mu\text{m}$ , the opening angle of  $60^\circ$  of the polar cavity, the shape of the spectral energy distribution, and the bolometric temperature, characteristic of a Class I / Class II transition object.

## 5 Conclusions

This work has demonstrated the feasibility and importance of multiepoch, multiwavelength studies as well as of high spatial resolution observations of young stellar objects. Combining data obtained with different instruments at different epochs requires great care and a secure knowledge of instrument effects. Reducing data from non-standard observation modes, such as differential polarimetric imaging at the Very Large Telescope, also requires careful data handling. However, all these work worth to do, since with their help one can obtain information about the target that would be inaccessible with any other, more traditional methods.

The observational results presented here on OO Ser, V1647 Ori and Parsamian 21 are all in general agreement with the standard picture of FUors. I found that the outburst model described in Bell et al. (2005) is consistent with the light curves of OO Ser and V1647 Ori. The model geometry (involving a central star, an accretion disk, and a circumstellar envelope) is also consistent both with the spectral energy distributions of all three sources, and with the circumstellar geometry seen in the polarimetric images of Parsamian 21.

The analysis, however, also revealed some differences between these three objects, supporting the suspicion that the group of FUors is very inhomogeneous. It might well be that there is a connection between the two main classes, FUors and EXors. OO Ser and V1647 Ori might represent such transition objects. We are still far from being able to build a comprehensive picture of the FUor phenomenon. Nevertheless, the concept of an evolutionary sequence to explain the differences between individual FUors seems to be a promising direction.

## 6 Publications on which the theses are based

- (1) Kóspál, Á.; Ábrahám, P.; Apai, D.; Ardila, D. R.; Grady, C. A.; Henning, Th.; Juhász, A.; Miller, D. W.; Moór, A.: *High-resolution polarimetry of Parsamian 21: revealing*

*the structure of an edge-on FU Ori disc*, 2008, Monthly Notices of the Royal Astronomical Society, **383**, 1015–1028.

- (2) Kóspál, Á.; Ábrahám, P.; Prusti, T.; Acosta-Pulido, J.; Hony, S.; Moór, A.; Siebenmorgen, R.: *The outburst of the eruptive young star OO Serpentis between 1995 and 2006*, 2007, Astronomy and Astrophysics, **470**, 211–219
- (3) Acosta-Pulido, J. A.; Kun, M.; Ábrahám, P.; Kóspál, Á.; Csizmadia, Sz.; Kiss, L. L.; Moór, A.; Szabados, L.; Benkő, J. M.; Delgado, R. Barrena; Charcos-Llorens, M.; Eredics, M.; Kiss, Z. T.; Manchado, A.; Rácz, M.; Almeida, C. Ramos; Székely, P.; Vidal-Núñez, M. J.: *The 2004-2006 Outburst and Environment of V1647 Ori*, 2007, The Astronomical Journal, **133**, 2020–2036.
- (4) Kóspál, Á.; Ábrahám, P.; Acosta-Pulido, J.; Csizmadia, Sz.; Eredics, M.; Kun, M.; Rácz, M.: *The rapid fading of V1647 Orionis: the sudden end of a FUor-type eruption?*, 2005, Information Bulletin on Variable Stars, **5661**, 1–4.

## 7 Other publications related to young eruptive stars

- (1) Kóspál, Á.; Németh, P.; Ábrahám, P.; Kun, M.; Henden, A.; Jones, A. F.: *The Extreme Outburst of EX Lup in 2008: Optical Spectra and Light Curve*, 2008, Information Bulletin on Variable Stars, **5819**, 1–4
- (2) Kóspál, Á.; Ábrahám, P.; Ardila, D.: *Long-term Infrared Variability of FU Ori and EX Lup-type Stars*, 2007, 2007 AAS/AAPT Joint Meeting, American Astronomical Society Meeting 209, #133.04; Bulletin of the American Astronomical Society, **38**, 1080
- (3) Kóspál, Á.; Apai, D.; Ábrahám, P.: *Parsamian 21: a FUor surrounded by an edge-on disc*, 2006, Proceedings of the 4th Workshop of Young Researchers in Astronomy & Astrophysics; Budapest, Hungary, 11-13 January, 2006; Publications of the Astronomy Department of the Eötvös University (PADEU), Edited by E. Forgács-Dajka, **17**, 141–147
- (4) van Boekel, R.; Ábrahám, P.; Correia, S.; de Koter, A.; Dominik, C.; Dutrey, A.; Henning, Th.; Kóspál, Á.; Lachaume, R.; Leinert, Ch.; Linz, H.; Min, M.; Mosoni, L.;

- Preibisch, Th.; Quanz, S.; Ratzka, Th.; Schegerer, A.; Waters, R.; Wolf, S.; Zinnecker, H.: *Disks around young stars with VLTI/MIDI*, 2006, *Advances in Stellar Interferometry*. Edited by John D. Monnier; Markus Schller; William C. Danchi. Proceedings of the SPIE, **6268**, 62680D
- (5) Kóspál, Á.; Ábrahám, P.; Prusti, T.; Siebenmorgen, R.; Acosta-Pulido, J.; Moór, A.: *Infrared Monitoring of the Outburst of OO Serpentis*, 2006, *Astrophysics of Variable Stars*, Pécs, Hungary, 5-10 September 2005, C. Sterken and C. Aerts (eds). ASP Conference Series, **349**, 269–272. San Francisco: Astronomical Society of the Pacific.
- (6) Ábrahám, P.; Mosoni, L.; Henning, Th.; Kóspál, Á.; Leinert, Ch.; Quanz, S. P.; Ratzka, Th.: *First AU-scale observations of V1647 Orionis with VLTI/MIDI*, 2006, *Astronomy and Astrophysics*, **449**, L13–L16
- (7) Kóspál, Á.; Apai, D.; Ábrahám, P.: *Parsamian 21: High-Contrast Infrared Mapping of an Edge-on FUor Disc*, 2006, *Visions for Infrared Astronomy, Instrumentation, Measure, Métrologie*, **6/1-4**, 181–186, Proc. of the Conference held in Paris, March 20-22, 2006. Publisher: Lavoisier
- (8) Kóspál, Á.; Ábrahám, P.; Prusti, T.; Acosta-Pulido, J.: *OO Serpentis, an Intermediate Object between FUors and EXors?*, 2006, *Visions for Infrared Astronomy, Instrumentation, Measure, Métrologie*, **6/1-4**, 87–90, Proc. of the Conference held in Paris, March 20-22, 2006. Publisher: Lavoisier
- (9) Ábrahám, P.; Csengeri, T.; Juhász, A.; Kóspál, Á.: *Infrared Variability as a New Possibility to Explore Circumstellar Disk Structure*, 2006, *Visions for Infrared Astronomy, Instrumentation, Measure, Métrologie*, **6/1-4**, 79–82, Proc. of the Conference held in Paris, March 20-22, 2006. Publisher: Lavoisier
- (10) Kóspál, Á.; Csizmadia, S.; Eredics, M.; Kun, M.; Rácz, M.: *V1647 Orionis*, 2005, *Central Bureau Electronic Telegrams*, **308**, 1. Edited by D. W. E. Green
- (11) Mosoni, L.; Ratzka, T.; Ábrahám, P.; Kóspál, Á.; Henning, Th.: *First AU-scale observations of V1647 Ori: The outbursting young star in the McNeil’s Nebula*, 2005, *Astron. Nachr.*, **326**, 565–565

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- (14) Kóspál, Á.; Ábrahám, P.; Csizmadia, Sz.; Kun, M.; Moór, A.; Prusti, T.: *The long-term evolution of 7 FU Orionis-type stars at infrared wavelengths*, 2004, *Proceedings of the 3rd Workshop of Young Researchers in Astronomy & Astrophysics; Hungary, 3-7 February 2004; Publications of the Astronomy Department of the Eötvös University (PADEU)*, Edited by E. Forgács-Dajka, K. Petrovay and R. Erdélyi, **14**, 119–125
- (15) Ábrahám, P.; Kóspál, Á.; Csizmadia, Sz.; Moór, A.; Kun, M.; Stringfellow, G.: *The infrared properties of the new outburst star IRAS 05436-0007 in quiescent phase*, 2004, *Astronomy and Astrophysics*, **419**, L39–L42
- (16) Kóspál, Á.; Ábrahám, P.; Csizmadia, Sz.: *Long-Term Evolution of FU Ori Type Stars at Infrared wavelengths*, 2004, *Baltic Astronomy*, **13**, 518–521