Introduction to the main types of astronomical objects observed by ANS Collaboration

Pre-Main Sequence Objetcs

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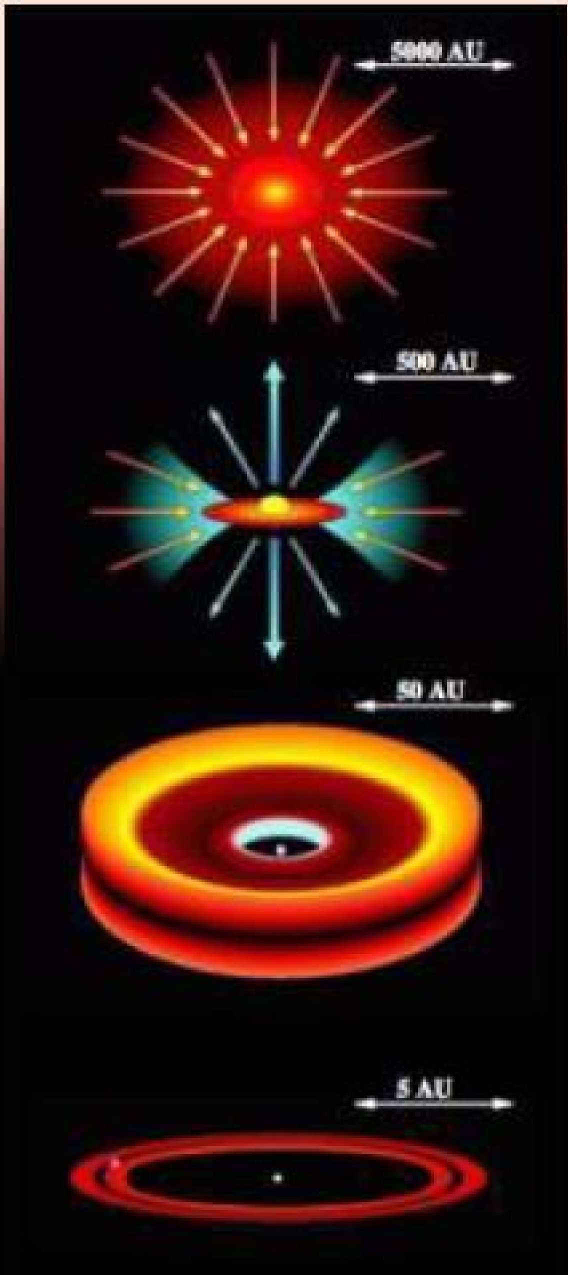

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1 Introduction : the star formation in a nutshell

The first stages of star formation correspond to the fragmentation of a molecular cloud into gravitationally bounded cores (typical masses 10^3 - 10^4 $M_\odot$ and sizes of a few tenths of parsec), which are initially supported against collapse by a combination of thermal, magnetic and turbulent pressure (see panels 1 and 2 of Fig.1).

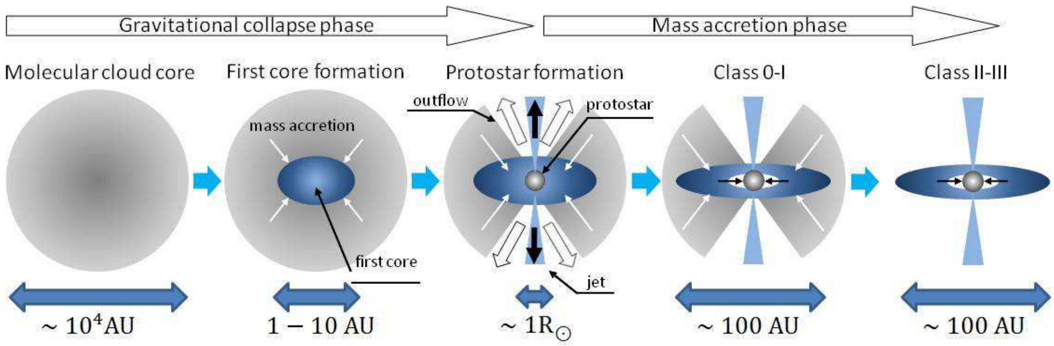

Figure 1: *Schematic view of a star formation process (panels 1 to 5 from left to right).*

Collapse of a cloud leads to the formation of disk-like structures (panel 3 of Fig.1), as the material with high angular momentum cannot fall directly onto the central object, but accumulates in a rotating disk. Observations have shown that this latter process is quite often associated with the powerful ejection of a fraction of the accreted material in form of bipolar jets/outflows aligned with the rotation axis of the protostar. Although the outflow mechanism is so far not completely understood, it is largely accepted that it is a further way to carry away angular momentum and thus to allow mass accretion onto the central object.

These earliest phases of the star formation constitute the so called *main accretion phase* (panel 4 of Fig.1) during which more than 90% of stellar final mass is accumulated. At this stage the young protostar radiates away its accretion luminosity ($L_{acc} \approx GM_\star\dot{M}_\star/R_\star$) and starts burning deuterium (if $M_\star \geq 0.1M_\odot$) or hydrogen (if $M_\star \geq 0.8M_\odot$). In the subsequent pre-main sequence (PMS) phase (panel 5 of Fig.1) nuclear burning will progressively become the main support against self-gravity.

From an observational point of view, star formation evolutionary stages are today empirically divided in four distinct phases (see Figure 2), correspondent to Class 0 objects and to Class I, II, III sources. Roughly speaking, these correspond to: early accretion phase, late accretion phase, PMS stars with protoplanetary disks, PMS stars with debris disks. These classification criteria are based on the shape and the position of the peak of the observed spectral energy distribution (SED), which is derived measuring the flux distribution νF_ν on the broad infrared and sub-millimiter bands.

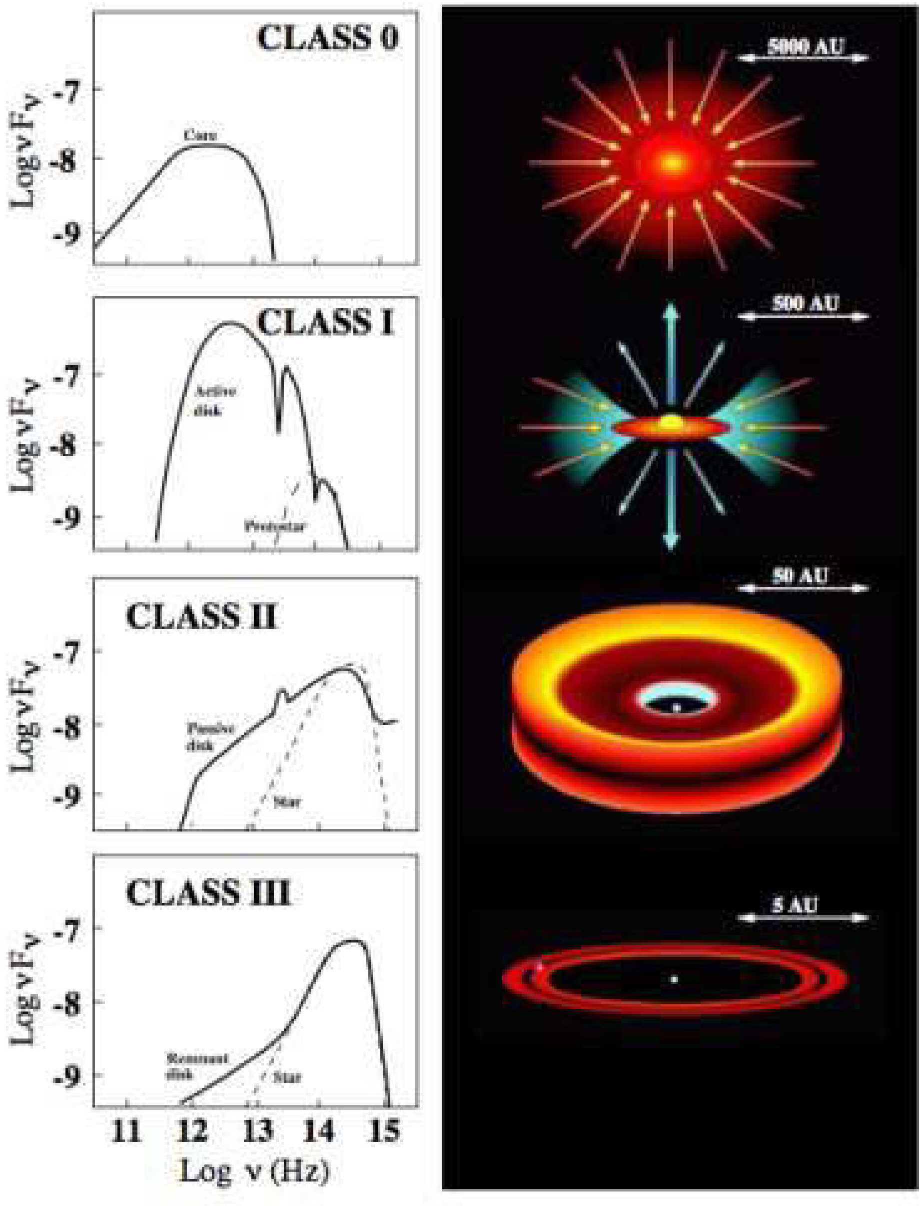

Figure 2: *Evolutionary sequence of the Spectral Energy Distribution (SED) of low-mass Young Stellar Objects (YSOs).*

The earliest stage is the **Class 0** phase. This corresponds to sources with lifetimes typically ∼ 1-3 10^4 years which are believed to be the first condensation within the parental cloud cores heated by the gravitational collapse. Spectral energy distributions of Class 0 sources peak at sub-millimeter wavelengths and can be generally fitted by single blackbody functions with temperatures between 20 and 40 K. The integrated luminosity at wavelengths $\geq$ 350 μm (L_{sub-mm}), coming from the dust emission in the envelope, results greater than 50% of the bolometric luminosity, circumstance which indicates how the envelope and protostellar masses are comparable. Observational signatures of Class 0 sources are: *i*) detection of a centimeter radio source; *ii*) presence of an extended sub-millimeter continuum emission with a definite peak (where the Class 0 should be located); *iii*) discovery of a collimated molecular outflow. So far less than 100 Class 0 sources have been discovered, mainly concetrated in regions like Serpens, Orion and Perseus. The observed bolometric luminosities of Class 0 objects span between 1 and $\sim$ 50 $L_\odot$, while the typical mass accretion rates are of the order of 10^{-4} $M_\odot$ yr^{-1}. From these values masses of few tenths of $M_\odot$ for the accreting protostar are inferred.

The Spectral Energy Distribution (SED) of objects in more evolved phases strongly depend on the immersion degree of the protostar within the envelope. As the dust dissipation goes on in subsequent evolutionary stages, the SED progressively peaks at shorter wavelengths. **Class I** objects are interpreted as relatively evolved protostars with ages $\sim$ 1-2 10^5 years. In this phase the central source is still deeply embedded in the cloud and generally is not visible in the optical, even if, at difference with Class 0 sources, the circumstellar mass is quantitatively lower than that of the protostar. SED's of Class I sources rise towards longer wavelengths and still peak in the sub-millimeter band, but, however, an appreciable emission is observable in the near infrared range. Shapes are broader than a single blackbody and are modelled as due a rotating, isothermal sphere surrounded by an accretion disk mainly composed by optically thick dust. Outflows associated to Class I sources appear less powerful and less collimated than those driven by Class 0 objects, circumstance that reflects a decrease of the infalling rate ($\dot{M} \sim 5\ 10^{-6}$ $M_\odot$ yr^{-1}). Despite that, however, the accretion luminosities of Class I sources result even higher than those measured on Class 0 objects, because these latter have smaller central masses and larger radii.

SED's of **Class II** sources (age $\sim 10^6$ yr) still present a strong infrared excess, but with a decreasing slope at wavelengths longer than 2 μm, and are usually visible also in the optical. Low-mass Class II sources are also named classical T Tauri stars (cTTs). Herbig Ae/Be stars (HAEBE, spectral type A or B) are the high mass counterparts of T Tauri stars ($2 \leq M/M_\odot \leq 10$). Although cTTs are intrinsically much different each other, they all lack dense circumstellar envelopes and are surrounded by luminous accretion disks (optically thick at $\lambda \leq 10$ μm), smaller than those of Class I. According to a widely accepted picture, accretion matter migrates from the outer parts of the circumstellar disk toward the inner edge and then, following the magnetic field lines, onto the central star (See Fig.3). The fall onto the stellar surface produces a shock (star spot) that cools by emitting a hot continuum as well as strong optical emission of hydrogen, calcium and iron. The observed SED's are succesfully modelled as arising from a late-type star which is accreting mass through the circumstellar disk, with typical rates of 10^{-8} $M_\odot$ yr^{-1}.

Class III objects (age $\sim 10^7$ yr) are optically visible stars. They include post-T Tauri stars as well as young main sequence stars. As a common characteristic, they are surrounded by optically thin circumstellar disks, in which fragmentation is likely occurring with the formation of planetesimals and proto-planets.

2 Pre-main sequence star variability

According with the star formation scenario described in the previous section, star formation appears as a quasi-stationary scenario, with a progressive decrease of the mass accretion rate with time. This theoretical scenario, however, is not confirmed by the observations, since it predicts stellar luminosities (or mass accretion rates) much larger than observed. Possibly, the observed discrepancy can be explained by highly-variable accretion, where much of the mass is accreted in short bursts.

Indeed, variability appears to be a ubiquitous property of Young STellar Objects (YSOs) and it is observed at different wavelengths from the ultra-violet to the far-infrared. In the optical the observed variability timescales range from fractions of days

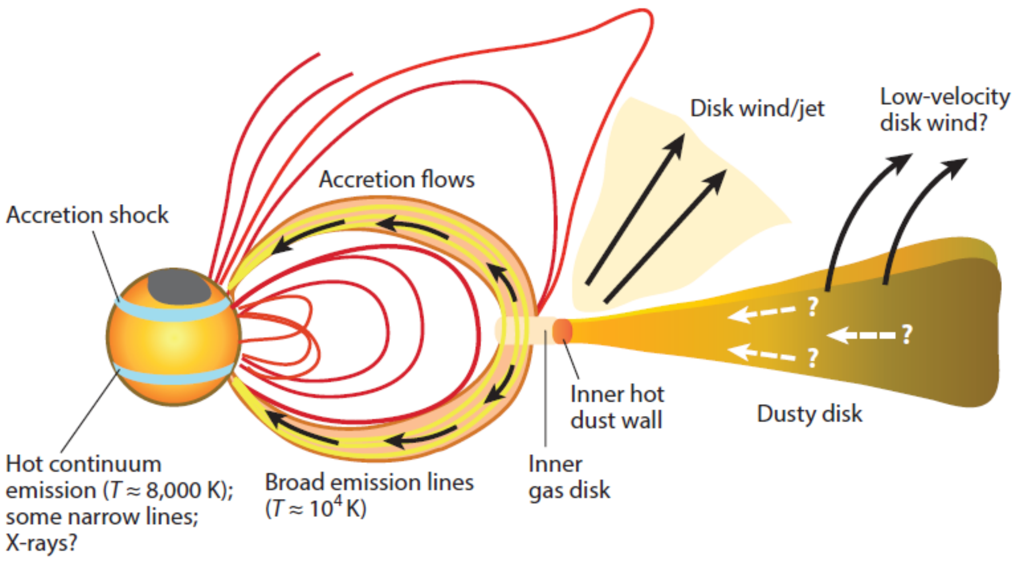

Figure 3: *Schematic view of a young star accreting from a disk through the stellar magnetosphere. The strong magnetic field produces large starspots and truncates the disk at a few stellar radii. The inner disk produces a bipolar outflow/jet driven by accretion energy.*

to weeks, months, and years. These variations reflect a number of causes, such as the geometry of the system, intrinsic physical/dynamical processes, and the evolutionary stage of the source. While light-curves of evolved YSOs (Class III) typically show a regular, periodic profile, with amplitudes ranging from 0.1 to 0.5 mag in the optical, a more complex and diverse picture is observed in cTTS, whose dynamics are dominated by the interaction of the star with an active accretion disk.

In a schematic view, it is possible to distinguish three main types of cTTs variability. The first type is due to spots at the stellar surface during stellar rotation and it produces a modulation of few tens of magnitude. The second type (UXor-type) is observed in sources whose brightness variations are related to dust rotating inside the inner disk that occults part of the photosphere. Typical UXor light-curves present regular fadings on timescales of months-years (see Fig.4). The third kind of variability is displayed by few young sources that undergo powerful accretion outbursts of large intensity (up to 4-5 mag - see e.g. Figs.5 and 6). Observationally, however, only about two dozens of these eruptive protostars are known so far, mostly found serendipitously during observational campaigns dedicated to different scientific aims.

These objects are usually classified into two major classes: (1) **FUors** characterized by bursts of long duration (tens of years) with accretion rates of the order of 10^{-4}-10^{-5} $M_\odot$ yr^{-1} and spectra dominated by absorption lines; (2) **EXors** with shorter outbursts (months–one year) with a recurrence time of years, showing accretion rates of the order of 10^{-6}-10^{-7} $M_\odot$ yr^{-1}, and characterized by emission line spectra. Because of their very small number, FUors/EXors variables have been considered so far as peculiar objects, and episodic accretion very far from being the common way through which young stars accumulate their final mass.

The interest of the star-formation community on eruptive variables has substantially boosted in the last ten years, when multi-wavelength sky surveys (2MASS, VISTA, Spitzer, WISE) have allowed to increase the number of candidate eruptive variables by at least one order of magnitude. This discovery has opened a new and unexplored window for star formation studies, which has a fundamental role both for the comprehension of the star formation mechanism itself, and for the implications

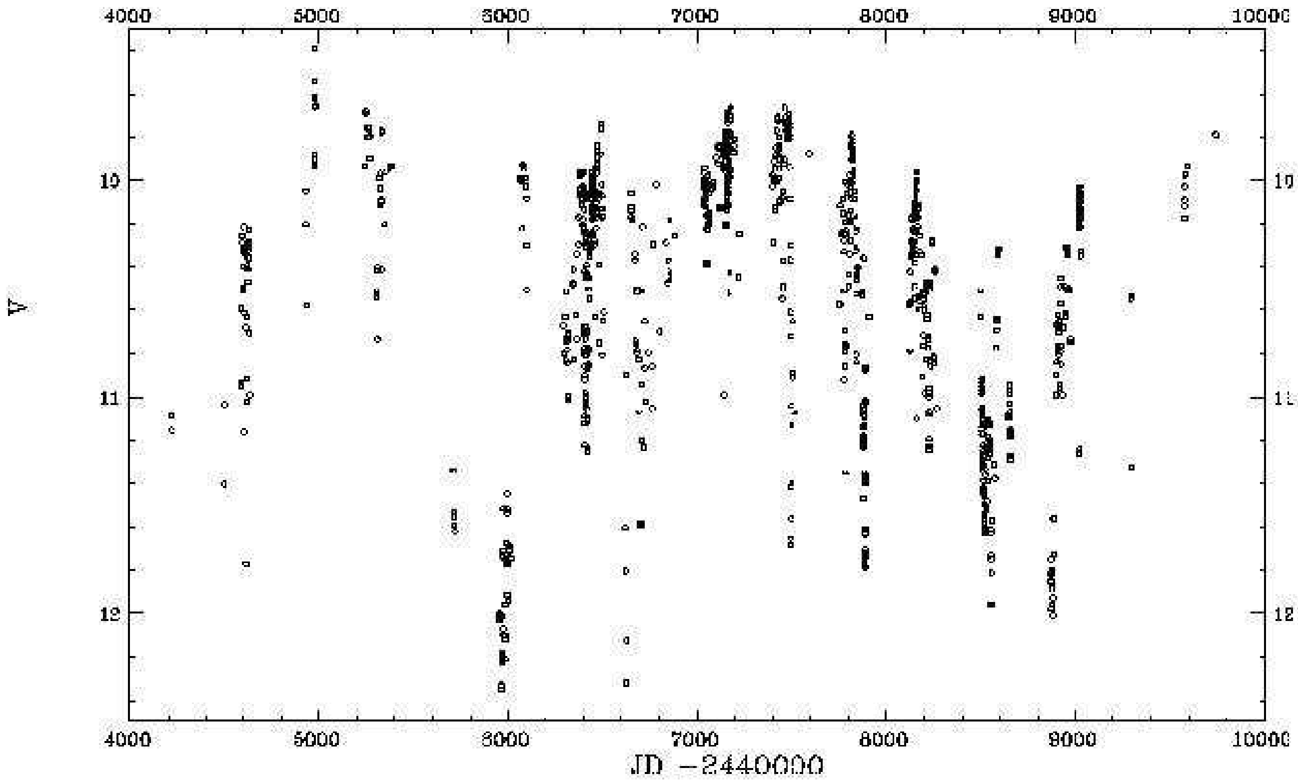

Figure 4: *1979-1995 light-curve of UX Ori in the V band.*

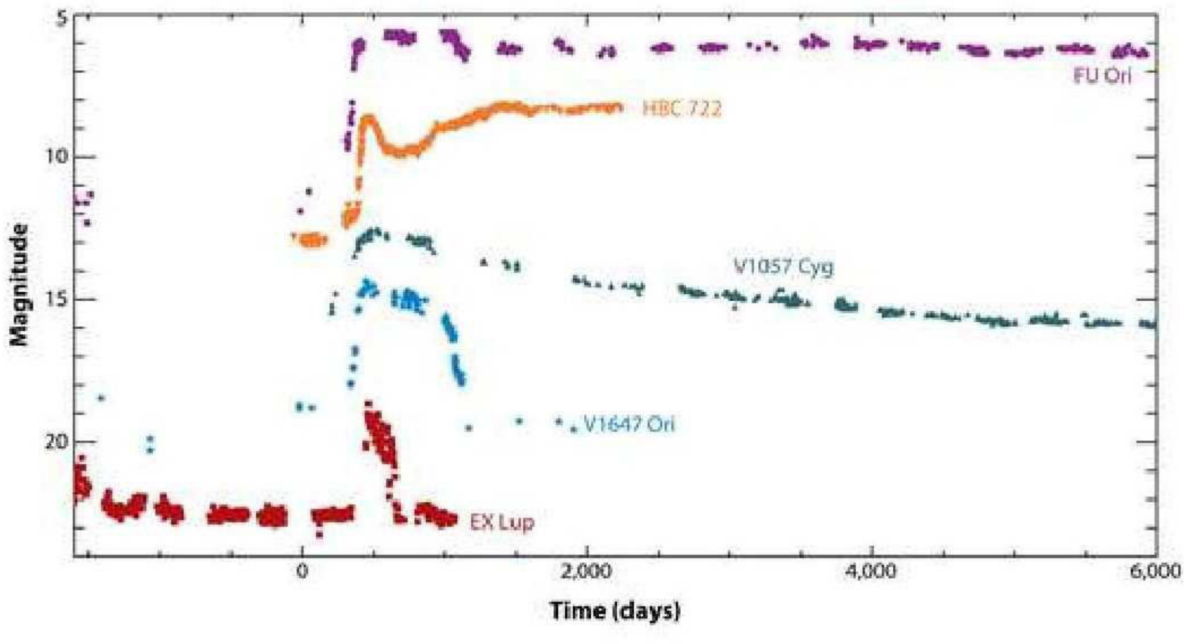

Figure 5: *Light-curves of FUor outburts of FU Ori and HBC722 (V2493 Cyg), EXor outbursts of EX Lup and V1647 Ori, and intermediate outburst of V1057 Cyg.*

that episodic accretion may have on the 'luminosity problem' described above. Therefore, it is fundamental both to search for new eruptive variables and to sistematically monitor the known objects. In this respect, EXor objects are ideally suited, because,

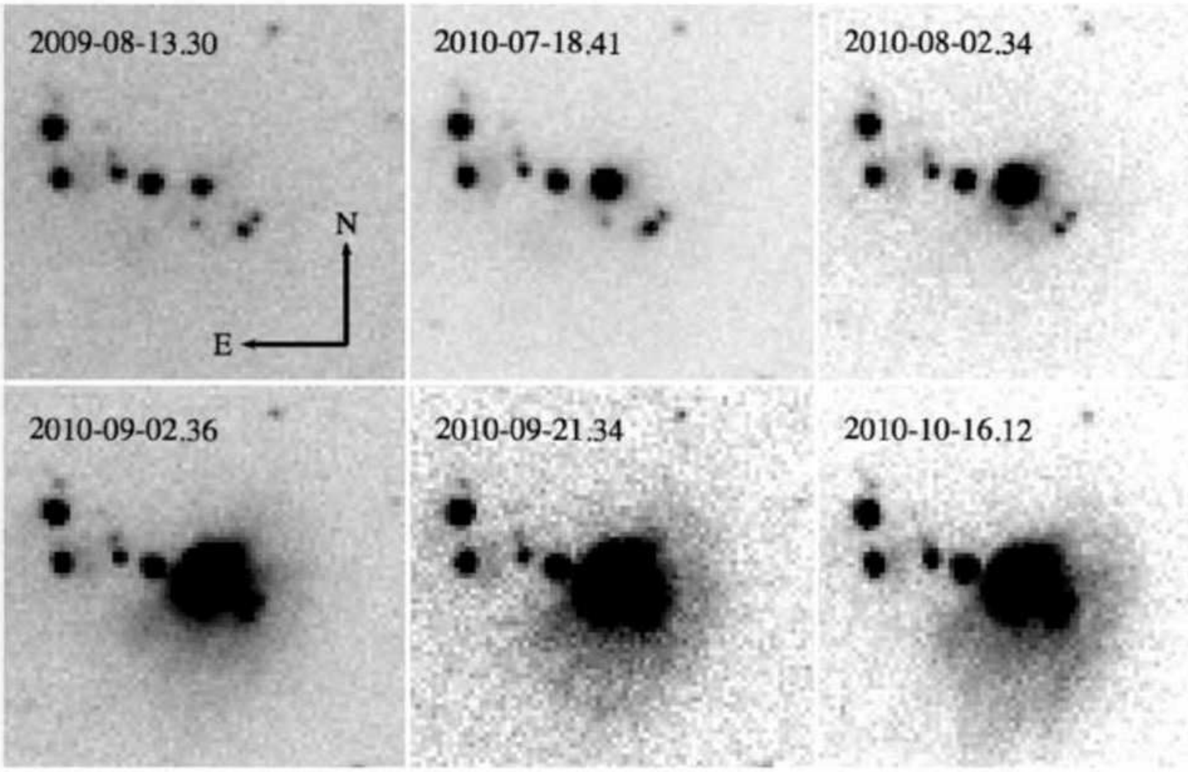

Figure 6: *The outburst of the source HBC 722(=V2493 Cyg) in R-band.*

having a timescale variability of months/years, they can be easily studied in both quiescence and outburst phases on timescales well comparable with the human life. For this reason will concentrate in the following on EXor eruptive variables.

3 Main questions about EXors

The most important questions about EXors are :

1) Which is the physical mechanism that triggers the outburst? Two main scenarios have been proposed to explain the onset of the outburst in EXors. These involve: (1) gravitational, thermal, or magnetospheric instabilities inside the disk, and (2) perturbation of the disk by an external body (a massive planet or close encounters in a binary system).

2) Are EXors very peculiar objects or rather they represent a stage that *all* pre-main sequence stars undergo during their life? In this case EXors could also represent a late evolutionary stage with respect to FUors, being their bursts less intense (see Figure 7).

An answer to these questions can be found only if: 1) the statistics of known objects is dramatically augmented; 2) the known objects are systematically monitored by means of long-term multi-wavelength spectroscopic and photometric observations; 3) quiescence and outburst phases are observed repeatedly, so to properly reconstruct the light-curve (see next section) and to derive the physical parameters (for example the mass accretion rate) in the two phases.

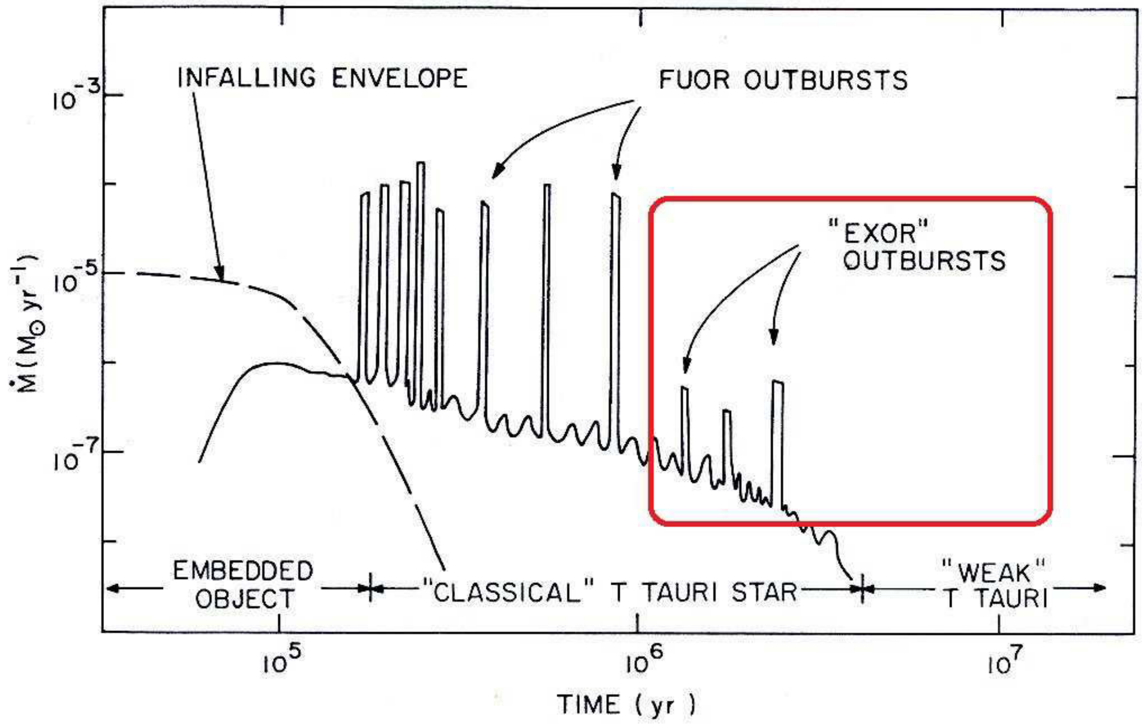

Figure 7: *Schematic illustration of the variation of the mass accretion rate vs. time for a young star. EXor events are framed in red.*

4 EXORCISM: A Monitoring Program

For the reasons described in the previous sections, our group started an observational program dubbed EXORCISM (EXOR optiCal and Infrared Systematic Monitoring) that is intended to perform a photometric and spectroscopic monitoring in the range 0.4-2.5 μm of about 30 objects identified as known eruptive variables or candidates. Recently, **ANS Collaboration** joined our project, providing important contributions dealing with the optical monitoring of a number of EXors. In the following we summarize what information can be derived from photometric and spectroscopic observations.

4.1 Photometry

Optical (UBVRI) and near-IR (JHK) photometric data are widely used to build-up:

- **Light-curves of individual EXors**. Such plots illustrate the different phases of the outburst process: *i*) duration and recurrence of the events, sometime evidencing how the flux increase is typically more rapid then the subsequent fading; *ii*) the appearance of spikes, attributed to hot/cool spots onto the stellar surface; *iii*) the shapes of the flux variations that allow to distinguish between true EXors and UXors; *iv*) clues of some temporal lag shown by two EXors between light-curves in different bands, that, if confirmed by future observations, indicates that a common property (e.g. grains thermal capacitance) regulates the emitting matter response of all EXor sources; *v*) a small scale variability related to some periodicity, such as intermittent obscuration due to geometrical effects.

- **Spectral Energy Distributions (SEDs)**. Given the intrinsic nature of an EXor system (typically composed of a visible star and its circumstellar accretion disk), optical and near-IR photometry form an important part of their SEDs. Very often, quiescence and outburst SED are jointly presented to evaluate the differences between both states: L_{bol} typically increases from 1-2 (or even fractional values) to tens of $L_{\odot}$ (e.g. the case of V2493 Cyg in Figure 8). Also the shape of the SED changes, becoming bluer while the source brightens. The differential SED between the outburst and the quiescence can be well fitted with a single blackbody component with temperatures varying from 1000 K to 4500 K and emitting radii of 0.01 to 0.1 AU, as if an additional thermal component appears during the outburst phase.

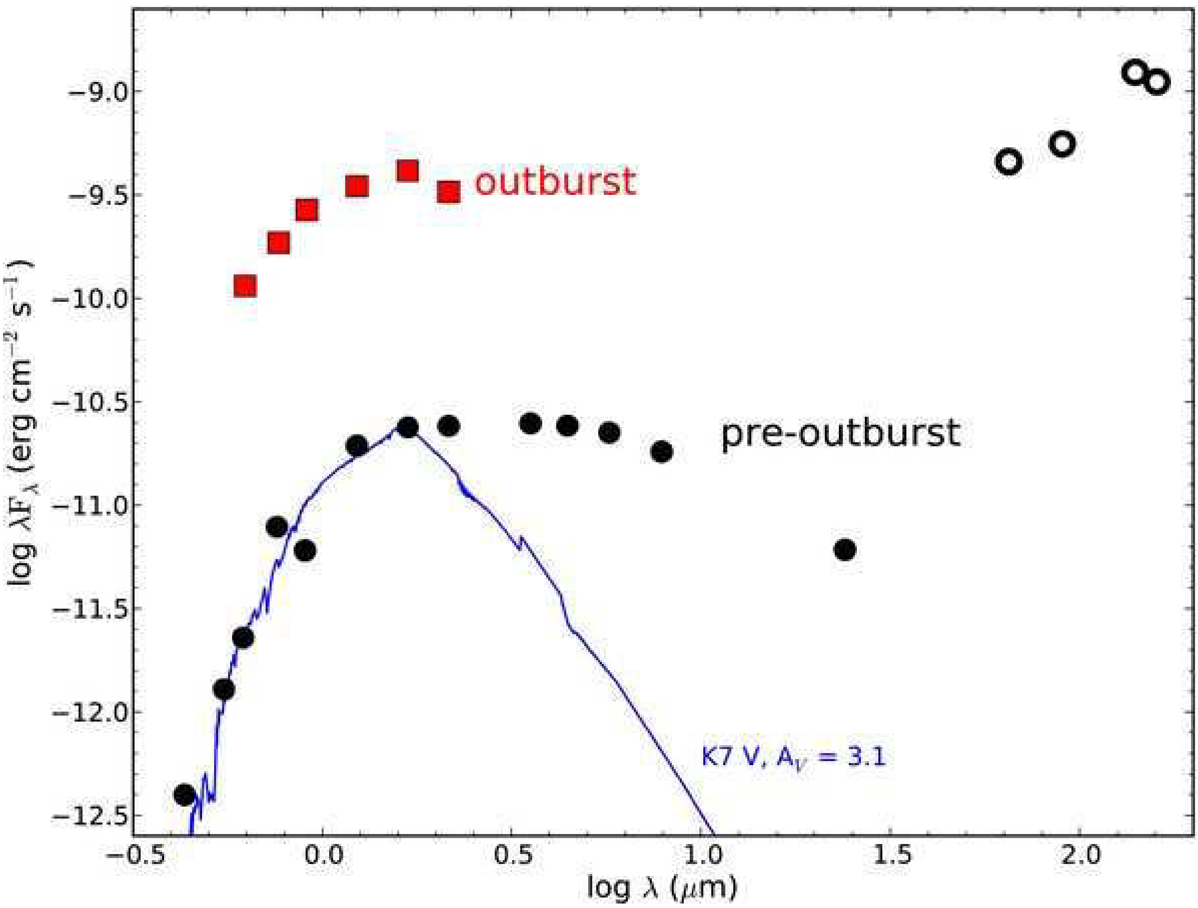

Figure 8: *SED of HBC 722(=V2493 Cyg) before and during outburst.*

- **Color-color and color-magnitude diagrams** are reliable and widely used tools to evaluate the main mechanism(s) responsible for the SED evolution. Optical and near-IR plots both show that all the EXors (classical and candidates) are bluer when brighter, likely indicating that a hotter stellar component prevails during bursts while a colder disk dominates the quiescent phases (Figure 9).

4.2 Spectroscopy

During our monitoring program we have collected a large database of low ($\mathcal{R} \lesssim 2000$) and high ($\mathcal{R} \gtrsim 10000$) resolution spectra (both optical and near-IR) that has allowed a meaningful comparison between pre-outburst, outburst, and post-outburst phases. Here a more detailed description of the information that can be derived of the optical and near-infrared spectra:

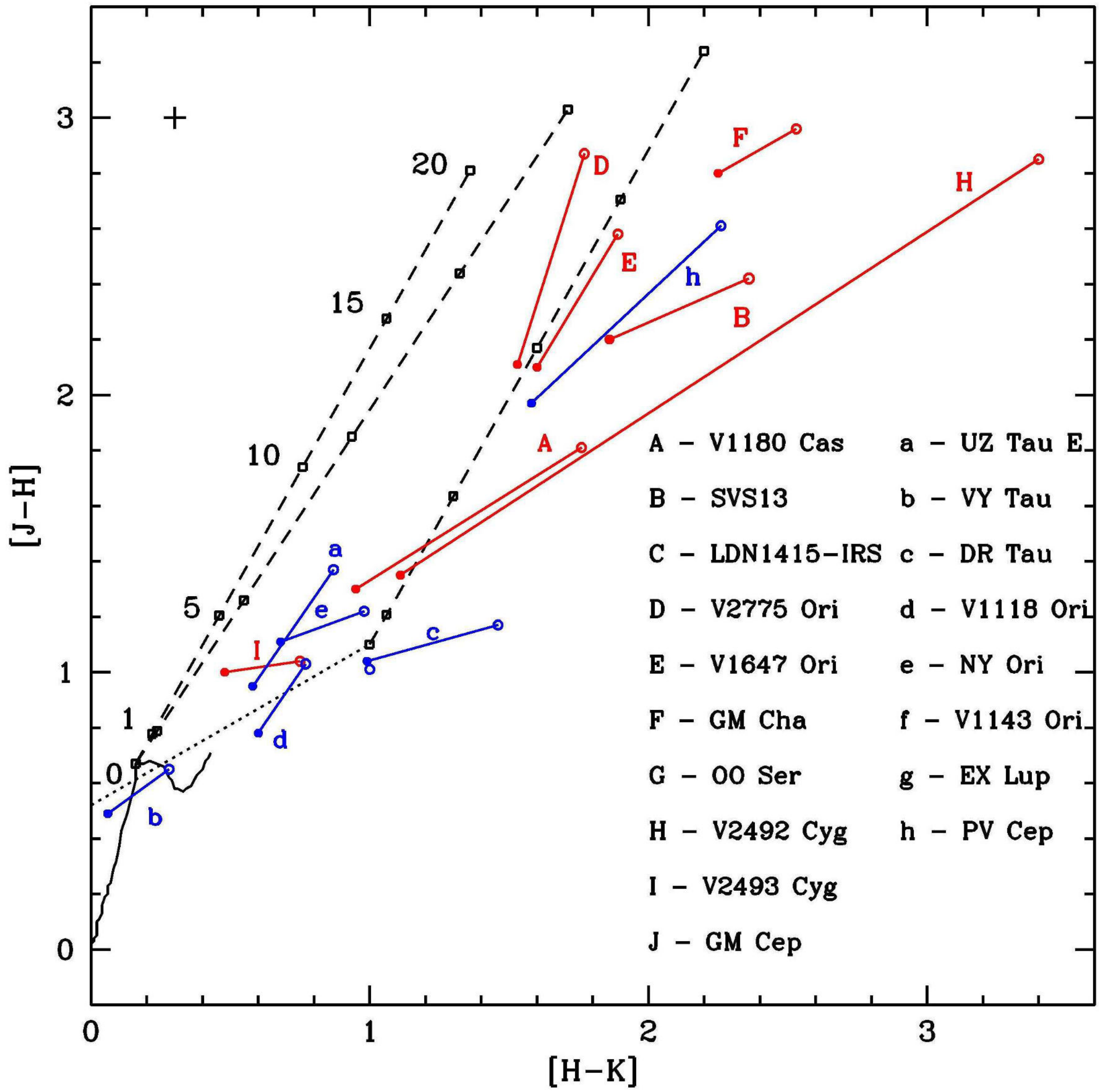

Figure 9: *Near-IR two-colors plot of classical (blue) and new candidates (red) EXor in two different epochs. The solid black line (low left corner) marks the unreddened main sequence, whereas the dotted one is the locus of the T Tauri stars. The dashed lines represent two reddening laws. Solid (open) circles identify the outburst (quiescence) colors.*

- **Optical spectroscopy**. EXor spectra are rich of lines of atoms and ions of gaseous material infalling onto the central star along the magnetic field lines. During the outburst, the number of emission lines increases dramatically (mostly FeI, FeII, CaI, HI lines of the Balmer series) as well as temperature and density. As a consequence, the intensity of the lines increases with the respect to quiescence, and can be used as a proxy of the mass accretion rate (see Figure 10). This latter parameter span from 10^{-10}-10^{-8} $M_\odot$ yr^{-1} in quiescence to 10^{-8}-10^{-6} $M_\odot$ yr^{-1} in outburst. While during outburst these lines present broad profiles, suggestive of gas traveling at velocities of the order of 100 km/s, during quiescence they have narrow profiles suggestive of an origin in the stellar chromosphere. Line profiles indicate the presence of ejection and accretion flows (P-Cyg profiles) at velocities up to hundreds km/s. Accurate correlations between accretion and ejection signatures investigated at high spectral resolution are fundamental to

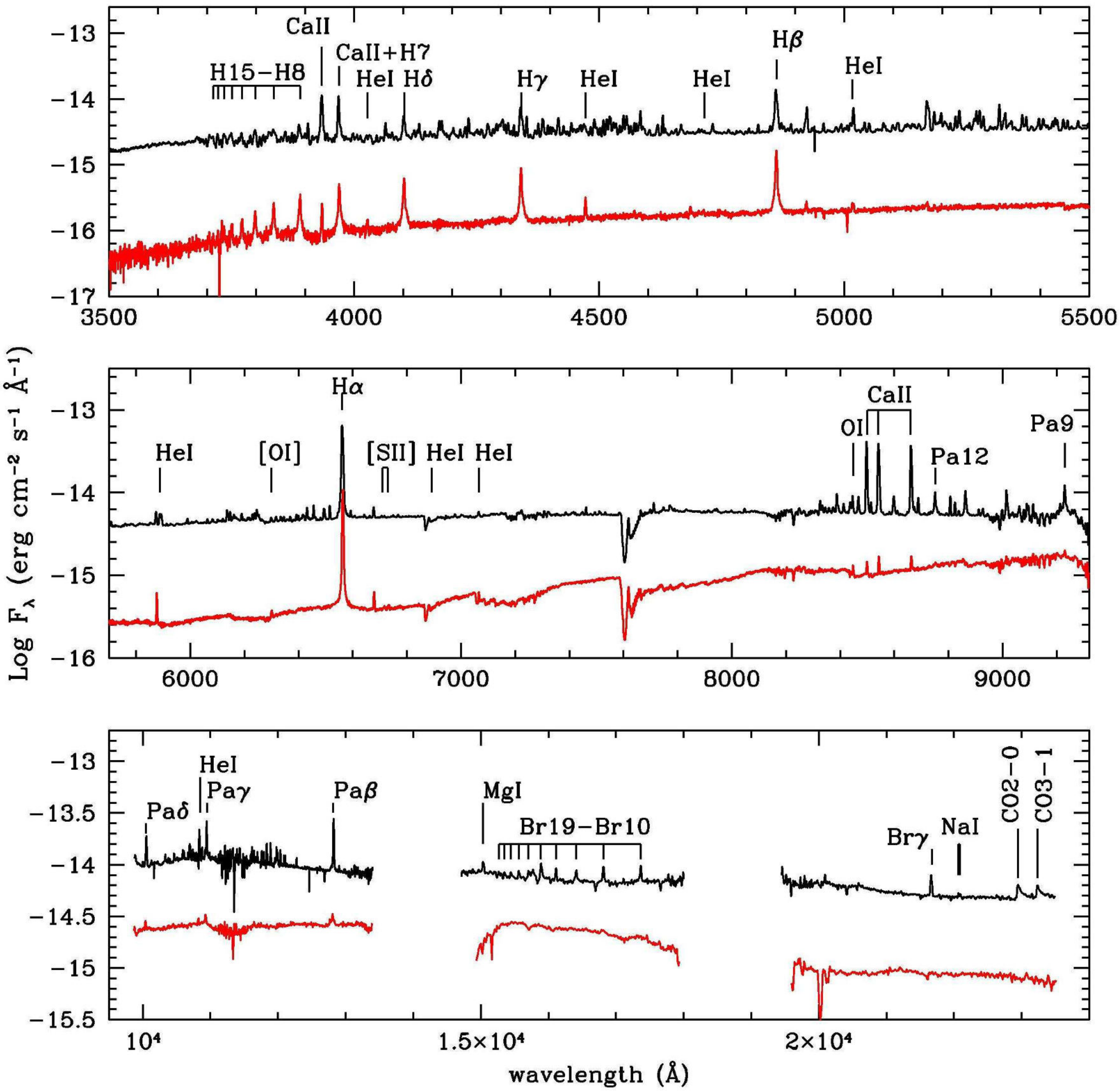

Figure 10: *Optical (LBT/MODS) and near-IR spectrum (LBT/LUCIFER) of V1118 Ori in outburst (black) shown in comparison with the quiescence spectrum (red).*

ascertain quantitative relationships between both phenomena. Forbidden line emission (such as [OI], [SII], [FeII]) is often detected on the continuum source position and in some cases also offset from that. These lines exhibit blueshifted profiles and trace the shocked gas accelerated by protostellar winds and jets which are usual by-products of the accretion process.

- **Near-IR spectroscopy**. In this spectral range one finds the Paschen and Brackett HI recombination lines that represent a complementary probe to the Balmer ones to investigate the mass accretion rate variability, especially for highly obscured EXors. HeI 1.08 μm provides evidence for a wind associated with the outburst, showing strong blueshifted absorption out to about 300 km. Concerning the molecular lines, H_2 transition at 2.12 μm and CO at 2.29 and 2.32 μm, respectively, are often recurring features. The first line (in emission) traces shocked regions close to the star and emitted as a consequence of an accretion event. CO is present in EXor spectra both in absorption and in emission: it is believed to originate in the gaseous inner disk where it traces zones relatively warm (being CO completely dissociated at $\sim$4000 K) at high densities ($>10^7$

cm^{-3}). As the outburst proceeds toward the quiescence, the spectrum displays strong CO emission, absence, and finally CO absorption.

5 Future perspectives

Open questions and observational perspectives have been mentioned through all the sections above, here some further points that could be addressed in the next future are listed.

- Large-field monitoring of substantial portions of already known star forming regions are fundamental to enlarge the EXor sample. In this respect, the forthcoming LSST facility thanks to its specific capabilities (monitoring cadence, sensitivity, wide field, spatial resolution), will offer a new conceptual paradigm to investigate on a statistical basis the episodic accretion phenomenon and its implication on the overall star formation process.

- Models of magnetized accretion disks have been recently proposed: ALMA will provide direct measurements of magnetic fields and their morphology at disk scales.

- EXor are too faint for the current sensitivity of interferometric facilities, but an improved instrumentation (e.g. *LINC-NIRVANA* at LBT) combined with deconvolution algorithms of high contrast images, already developed, will be used to recover information on both disk morphology and presence of close companions.

- Several processes, such as crystallization, extinction by dust, mass loss, are not merely concomitant with matter accretion, but intimately related to it, hence advanced studies on these subjects are essential to reach a consistent view of the EXor key parameters.

6 ANS publications on pre-Main Sequence objects up to the end of 2017

(**2017**) T. Giannini, U. Munari, S. Antoniucci, D. Lorenzetti, A.A. Arkharov, S. Dallaporta, A. Rossi, G. Traven
The 2016-2017 peak luminosity of the pre-main sequence variable V2492 Cyg
A&A, in press (arXiv:171008151)

(**2017**) T. Giannini, S. Antoniucci, D. Lorenzetti, U. Munari, G. Li Causi, C. F. Manara, B. Nisini, A. A. Arkharov, S. Dallaporta, A. Di Paola, A. Giunta, A. Harutyunyan, S.A. Klimanov, A. Marchetti, G.L. Righetti, A. Rossi, F. Strafella, V. Testa
The 2015-2016 outburst of the classical EXor V1118 Ori
ApJ 839, 112

(**2017**) Munari U., G. Traven, S. Dallaporta, D. Lorenzetti, T. Giannini, S. Antoniucci
High resolution spectroscopy of the young eruptive star V2492 Cyg currently peaking at record brightness
ATel 10183

(**2017**) Jurdana-epi, R.; Munari, U.; Antoniucci, S.; Giannini, T.; Li Causi, G.; Lorenzetti, D.
Investigating the past history of EXors: the cases of V1118 Orionis, V1143 Orionis, and NY Orionis
A&A 602, A99

(**2016**) Jurdana-epi, Rajka; Munari, Ulisse
The past photometric history of the FU Ori-type young eruptive star 2MASS J06593158-0405277 = V960 Mon
NewA 43, 87

(**2012**) Semkov, E. H.; Peneva, S. P.; Munari, U.; Tsvetkov, M. K.; Jurdana-epi, R.; de Miguel, E.; Schwartz, R. D.; Dimitrov, D. P.; Kjurkchieva, D. P.; Radeva, V. S.
Optical photometric and spectral study of the new FU Orionis object V2493 Cygni=HBC 722
A&A 542, A43

(**2010**) Semkov, E.H., Peneva, S.P., Munari, U., Milani, A., Valisa, P.
The large amplitude outburst of the young star HBC 722 in NGC 7000/IC 5070, a new FU Orionis candidate
A&A 523, L3

(**2010**) Munari, U., Valisa, P., Dallaporta, S., Itagaki, K.
A New Variable Star in Cygnus
CBET 2428

(**2010**) Munari, U., Milani, A., Valisa, P., Semkov, E.
Spectroscopic confirmation of HBC 722 as a new FU Orionis star in NGC 7000
ATel 2808

(**2009**) Munari, U., Siviero, A., Ochner, P., Fiorucci, M., Dallaporta, S.
V582 Aurigae
CBET 1898