Fireworks while forming Sun-like stars: a new view at bona fide FUors

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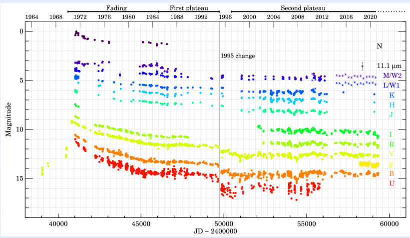
Motivation

FU Orionis-type objects (FUors) are low-mass pre-main sequence stars undergoing powerful accretion outbursts, that significantly impact the planet-forming zone in their circumstellar disks. Our project at Konkoly Observatory aims to re-observe and analyse those classical ‚bona fide' FUors (V1057 Cyg, V1515 Cyg, V1735 Cyg) which were used to define the FUor class several decades ago. We describe the general brightness evolution of their outbursts on decadal timescales, identify temporary variations in the fading rate, and investigate quasi-periodic modulations. We also apply a simple accretion disk modeling on the multi-epoch spectral energy distributions, and outline the simultaneous evolution of mass accretion rate and circumstellar extinction. Our ultimate goal is to provide new constraints for the physical theories of the eruption phenomenon in young stellar objects.

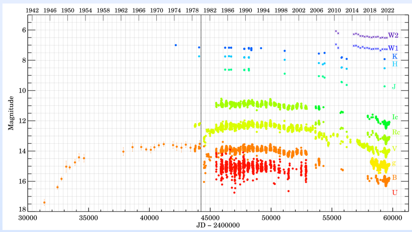
V1057 Cyg



- The second identified FUor (1969, North America Nebula, d=897 pc), which brightened by 6 mag. After its peak in 1970, it faded rapidly, making it the fastest-fading FUor known, with an e-folding time of 12 yr. In 1994-95, it displayed a sudden drop in optical brightness. Since then, the smooth exponential fading has been modulated but significant stochastic variability due to changing circumstellar extinction. The light curves in the past few decades also show longer (1700 d) and shorter (500 d) quasi-periodicities, possibly caused by an orbiting dust structure or disk warp and by a bright spot on the disk, respectively.
- We found a peak accretion rate of 1×10^{-3} M_{sun}^2/yr reached in 1971. Currently still 1×10^{-4} M_{sun}^2/yr, the most heavily accreting FUor ever discovered!
- Optical spectroscopic monitoring revealed high-velocity wind absorption features and lower velocity shell absorption features whose strength and velocity varies with time. Forbidden emission lines are also present and variable. At certain epochs, narrow [OIII], [NII], and [SII] features detected, suggesting time-variable jet-outflow activity. The CO first overtone bandhead has been slowly weakening as the accretion rate is decreasing.
- Despite the significant fading since the peak of the outburst, the spectroscopic properties of V1057 Cyg still resemble those of a classical FUor, it has not yet returned to quiescence.

(Szabó, Zs.M., Kóspál, Á., Ábrahám, P. et al. 2021, ApJ 917, id.80)

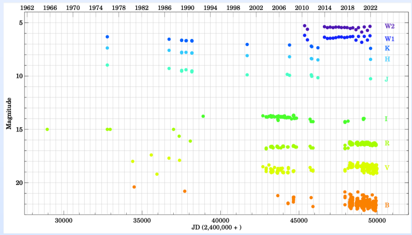
V1515 Cyg



- The third discovered FUor (d = 900 pc), which displayed a slow brightening from the 1940s, with a peak brightness in late 1970s. In 1980, a sharp temporary brightness drop occurred, interpreted as dust condensation in the outflowing wind. After recovering, the source showed a plateau until the late 1990s. The light curves since the 2000s indicate an exponential fading with an e-folding time of 12 yr. Strong variability on weekly and monthly timescales are superimposed, including a 13 d quasi-periodic oscillation. A smaller dust condensation event may have happened in 2021.
- Our results show that the peak accretion rate was 1.3×10^{-5} M_{sun}^2/yr , while currently it is $4.2\text{x}10^{-6}$ M_{sun}^2/yr .
- Optical spectra show P Cygni profiles and broad blueshifted absorption lines, typical high-velocity wind features common in FUors. V1515 Cyg lacks the P Cygni profile in the Ca II 8498 Å line in the Ca IRT, suggesting that the absorbing gas in the wind is optically thin. The CO first overtone bandhead and the FeH molecular band has become stronger, suggesting the cooling of the disk. No forbidden emission lines are present in the spectra of V1515 Cyg, suggesting the lack of jet/outflow activity.
- Overall, the spectroscopic properties of V1515 Cyg are still consistent with those of a bona fide FUor, but the light curves suggest that the object approaches quiescence.

(Szabó, Zs.M., Kóspál, Á., Ábrahám, P. et al. 2022, ApJ 936, id.64)

V1735 Cyg



- The fourth discovered FUor (IC 5146, d=663 pc), which brightened by at least 5 mag in the R band some time between 1957 and 1965, and has been slowly fading since then. It is a heavily obscured object and is very faint at optical wavelenths, therefore much less photometric and spectroscopic information is available for it compared to V1057 Cyg and V1515 Cyg. If bears spectroscopic similarities to the other classical FUors and also drives a molecular outflow. Our light curve analysis revealed a 278 d periodicity in the r band light curve, potentially interpreted as variable extinction caused for example by an asymmetric outflow.
- Our results show that its decreasing accretion rate has been steadily decreasing from $7\text{x}10^{-5}$ to $2\text{x}10^{-5}$ M_{sun}^2/yr .
- The optical spectra show clear emission components for the Hα and Ca II IRT lines but only weak hints for the blueshifted absorption component typically formed by and outflowing wind in FUors. We did not detect any forbidden emission lines in the optical spectrum of V1735 Cyg. The near-infrared spectra show strong CO first overtone bandhead feature in absorption.
- In conclusion, V1735 Cyg shows clear FUor characteristics, is still highly accreting, but suffers much higher extinction than either V1057 Cyg or V1515 Cyg.

(Szabó, Zs.M., Kóspál, Á., Ábrahám, P. et al., in prep.)

A simple accretion disk model to outline accretion rate and extinction evolution

Analytical model

We assume that optical and near-infrared flux in FUors is emitted by a steady, optically thick, geometrically thin viscous accretion disk, in which the mass accretion rate is radially constant (Hartmann & Kenyon 1996).

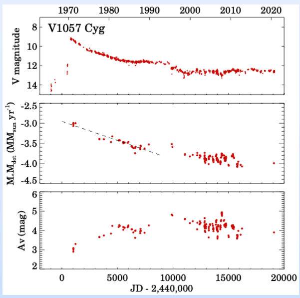
Radial temperature profile of the disk: $T_d^4(R) = \frac{3GM\dot{M}}{8\pi R^3 \sigma}\left[1-\left(\frac{R_*}{R}\right)^{1/2}\right]$

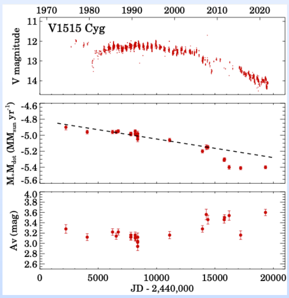
The disk's SED is computed by integrating blackbody fluxes of concentric annuli between R_{in} (=R_*) and R_{out}. The SED is reddened by an extinction A_V.

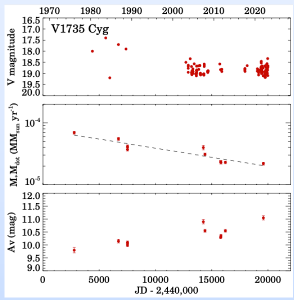
Simultaneously fitted parameters: $M\dot{M}$ ($M_\odot$/yr) and A_V

A new application of the model

Instead of fitting an average SED, we fit many individual SEDs constructed at single epochs, and derive the long-term time evolution of $M_*\dot{M}$ ($M_\odot$/yr) and Av.







Results

- Accretion rate drops exponentially
- τ_{exp}= 12 – 40 yr
- When the source is fading, A_V is increasing
- Anti-correlation between $\dot{M}$ and A_V?
- Degeneracy between R_{in} and A_V : a larger A_V is equivalent with a larger R_{in}.
- Increasing Av trend in FUors may mark that the inner disk becomes optically thin as accretion depletes disk matter

Other FUors whose SEDs were modeled with this accretion disk: HBC 722 (Kóspál et al. 2016, A&A 596, A52), V582 Aur (Zsidi et al. 2019, ApJ 873, id.130), Gaia18dvy Szegedi-Elek et al. (2020, ApJ 899, id.130)

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