Radial velocity variations in EX Lup: hints for a low-mass close companion

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Abstract

EXors are low-mass pre-main sequence objects producing repetitive optical outbursts attributed to highly enhanced accretion from the circumstellar disk onto the star. One type of outburst theories requires a close stellar or sub-stellar companion that perturbs the inner part of the disk and triggers the onset of the enhanced accretion. Here, we look for a possible companion to EX Lup, the prototype of the EXor class, using radial velocity (RV) observations. The RVs show large periodic variations that can be explained by the presence of a close companion in the brown dwarf mass range. Chromospheric activity or starspots are less likely to explain the observed RV curve.

EXors

- Low-mass pre-main sequence objects, characterized by repetitive optical outbursts of 1–5 mag, lasting for a few months–few years.
- The outburst is due to enhanced accretion from the inner circumstellar disk (within ≈0.1 AU) to the star (Herbig 1977, 2008).
- The episodes of highly increased accretion may contribute to the build-up of the final stellar mass.
- The origin of outbursts is still highly debated. Certain outburst theories involve a close stellar or sub-stellar companion that perturbs the disk and triggers the onset of the enhanced accretion.
- The actual physical process could be thermal instability induced by density perturbations due to, e.g. a massive planet in the disk (Lodato & Clarke 2004), or tidal effects from close companions (Bonnell & Bastien 1992).

Motivation

- Do all EXors have companions?
- There are known examples:
  - UZ Tau E (spectroscopic binary, Jensen et al. 2007)
  - VY Tau (separation: 0.66″, Leinert et al. 1993).
- The triggering mechanism requires a companion that perturbs the inner part of the disk, typically at a few tenths of an AU ⇒ radial velocity (RV) methods are best suited to find such companions.
- Most EXors have never been searched for RV companions, mostly due to the difficulty of measuring RV in young, chromospherically active and/or actively accreting stars.
- Here, we will study EX Lup, the prototype of the EXor class, using RV and photometric data.

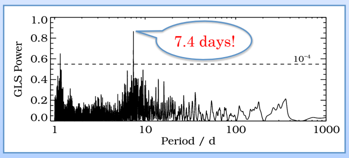
Observations

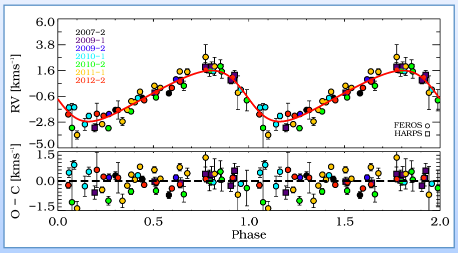
- **FEROS**
  - 57 spectra between 2007–2012
  - Échelle spectra with R = 48,000
- **HARPS**
  - 10 spectra between 2008–2009
  - Échelle spectra with R = 115,000
- **RV determination**
  - Cross-correlation method using an M0.5-type template
  - EX Lup is a highly active star with many emission lines; photospheric absorption lines contaminated with emission were discarded
  - RV determined for each échelle order by fitting a Gaussian to the cross-correlation function; weighted average of the RV from all orders
- **Optical and infrared light curves**

  2-week-long monitoring with daily cadence:
  - V, J, H, and K (0.55 – 2.2 μm) with the Rapid Eye Mount Telescope at La Silla, Chile
  - 3.6 and 4.5 μm with the Spitzer Space Telescope

Companion candidate

- Significant, periodic RV variations (see figure)
- RV phase and amplitude stable for at least 5 years
- RV curve can be explained by a companion on an eccentric orbit
- See table for parameters of Keplerian orbital solution





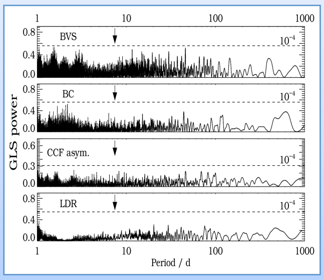
Parameter	Unit	Fitted value
Period	day	7.417 ± 0.001
RV semi-amplitude	km s^{-1}	2.18 ± 0.10
Eccentricity		0.23 ± 0.05
Longitude of periastron	°	96.8 ± 11.4
Epoch of periastron passage	JD	2455405.1 ± 0.2
RV offset	km s^{-1}	–0.52 ± 0.07
False alarm probability		6.7×10^{-27}
m sin i	$M_{Jupiter}$	14.7 ± 0.7
Semi-major axis	AU	0.063 ± 0.005

Active chromosphere or starspots?

None of the following activity indicators show periodicity:

- Bisector velocity span (BVS), bisector curvature (BC)
- Asymmetry of the CCF
- Temperature-sensitive spectral features: line depth ratio of 6269 Å V I and 6270 Å Fe I lines (LDR), TiO bands, CaH bands, CaOH bands, H_α
- Chromospheric activity: S_{FEROS} index for 3933 Å Ca II line, EW of the 8662 Å Ca II line, asymmetry analysis for the Ca II K line

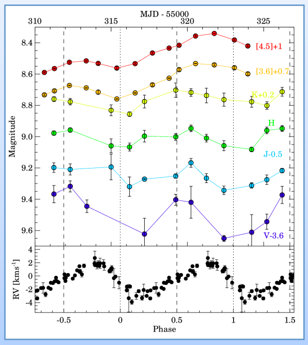
Conclusion: there are no signs of large spots on the star that would cause rotational modulation, and there is no periodic chromospheric activity present.



Our attempt to simultaneously reproduce the RV variations and the light curves with a spot model was not successful:

- EX Lup is a slow rotator: v sin i < 3 km s^{-1}
- Large spots (covering a whole hemisphere) are needed to reproduce the observed RV semi-amplitude of 2.2 km s^{-1}, but these would over-estimate photometric variations.
- Spots that would reproduce the observed photometric light curves would significantly under-estimate the RV amplitude.

Conclusion: it is unlikely that the RV variations of EX Lup are caused by hot or cold stellar spots.



The companion of EX Lup

- Most probable mass: 0.02 $M_\odot$ (using i=50°) ⇒ brown dwarf T_{eff} ≈ 2500 K, ΔJ ≈ 7 mag
- Periastron and apastron distances: 0.049 AU (6.5 R_*) and 0.078 AU (10.4 R_*)
- Orbits within a dust-free inner hole in the disk ($R_{in,disk}$=0.2 AU), possibly caused the opening of the dust-free hole
- Unusual object:
  - Its separation is very small: the distribution of separations peaks at 30–50 AU for companions around Sun-like stars, or at 2–16 AU for M dwarfs (Raghavan et al. 2010, Gizis et al. 2003)
  - Its mass falls into the "drown dwarf desert": less than 0.6% of Sun-like stars have brown dwarf companions (Sahlmann et al. 2011)
- Did it form as a (sub-)stellar companion or as a (deuterium-burning) planet in the disk of EX Lup?
- How does it affect the accretion in the EX Lup system?
  - Can it stabilize the accretion columns?
  - Can it initiate pulsed accretion?
  - Can it have a role in the big outbursts?

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