A photometric study of the ULLYSES/PENELLOPE T Tauri star sample in Ori OB1 and σ Ori: the accretion process at the highest time resolution

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The ULLYSES/PENELLOPE project on YSO accretion

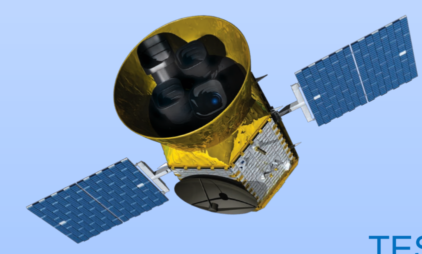
- A legacy spectroscopy survey of accreting pre-main sequence stars, including ~70 T Tauri stars
- Synchronized HST COS/STIS as well as VLT UVES/ ESPRESSO/X-Shooter observing campaigns; for a few sources multiepoch observations
- **ULLYSES** (Roman-Duval et al. 2020): accretion and ejection tracers at ultraviolet/optical wavelengths; **ODYSSEUS** (Espaillat et al. 2022): archive research to model and interpret the HST spectral observations; **PENELLOPE** (Manara et al. 2021): stellar parameters; interstellar extinction, veiling; disk wind and jets;
- Unique and contemporaneous UV, optical, and near-infrared legacy dataset of a large YSO sample, covering all evolutionary stages from full disk to transitional disks and Class III disk-less objects

The Orion sample

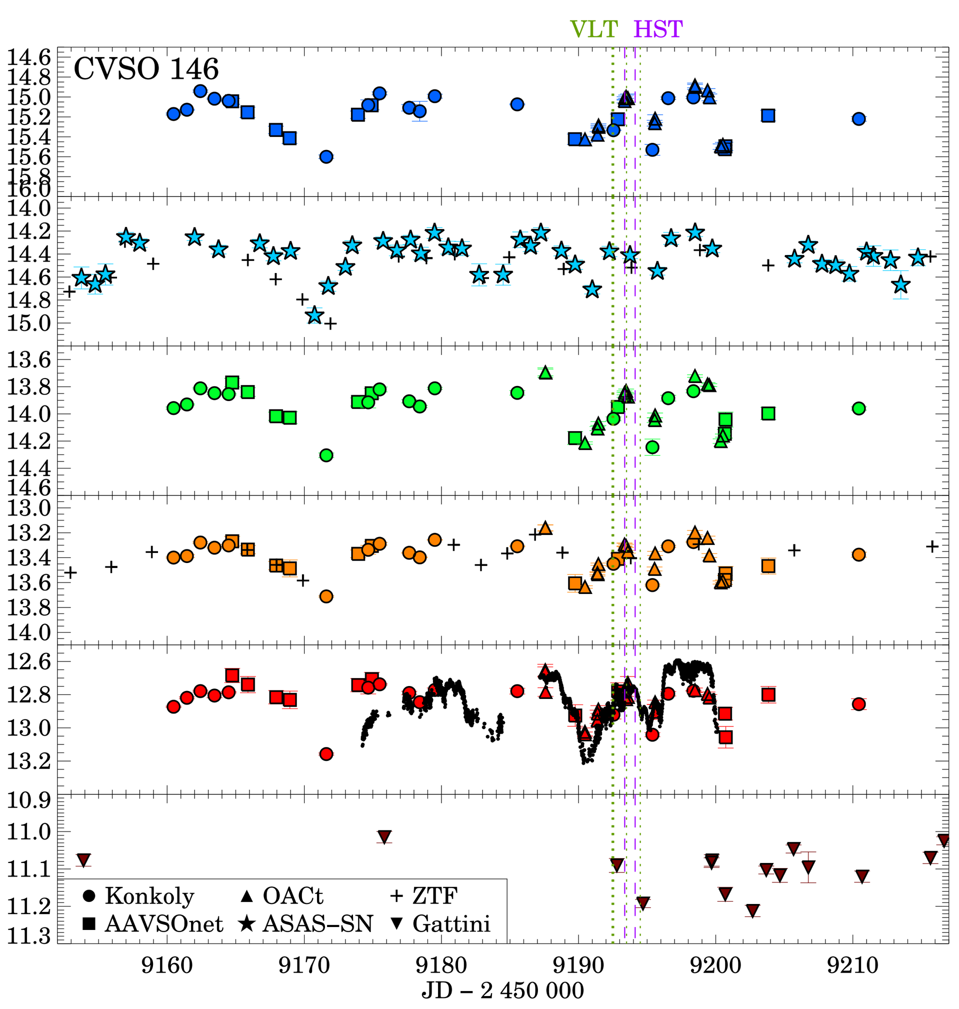
- 10 stars in Ori OB1, 3 stars in σ Ori
- Sp. type: K6-M3.5, Mass: 0.25-1.1 $M_\odot$
- Distance ~400 pc
- CVSO 17, CVSO 36, CVSO 58, CVSO 90, CVSO 104, CVSO 107, CVSO 109, CVSO 146, CVSO 165, CVSO 176, SO 518, SO 583, SO 1153
- ULYSSES/PENELLOPE papers: Manara et al. (2021, survey presentation), Frasca et al. (2021, CVSO104), Espaillat et al. (2022, CVSO109), Froebrich et al. (2022, σ Ori), Pittman et al. (submitted, Ori OB1)
- Our goals: (1) extend the project in the time domain; (2) put the spectroscopic results into variability context; (3) identify the underlying physical processes

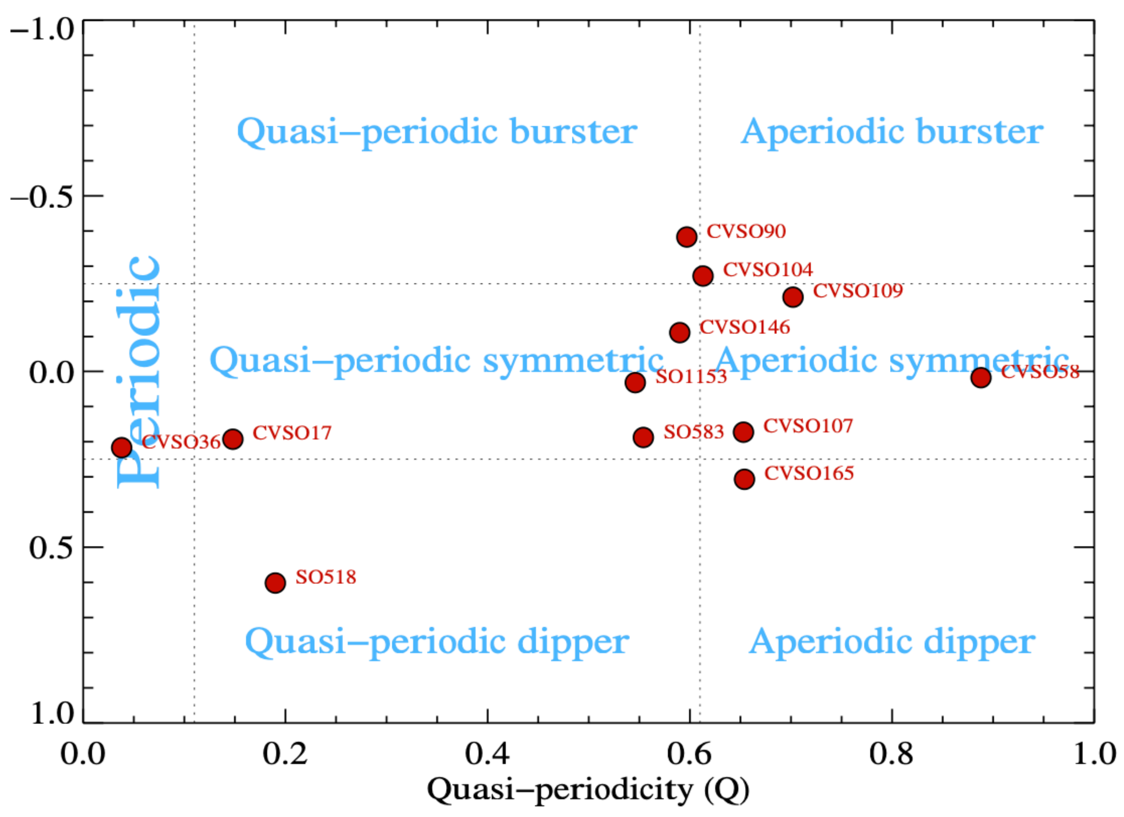
Observations

- BVr'i' images from Konkoly Observatory, Hungary, 2020 Nov 5 – Dec 26
- BVR_CI_Cz' images from OACt, Catania, Italy, 2020 Nov 25 – Dec 16
- BVr'i' images, AAVSOnet, 2020 Nov 8 – Dec 19
- J-band images, GATTINI survey (De et al. 2020), 2020 Oct 29 – Jan 2
- g-band photometry, ASAS-SN survey
- TESS white light (~i-band), 2020 Nov 20 – Dec 16, 10-min cadence



TESS (credit: NASA)





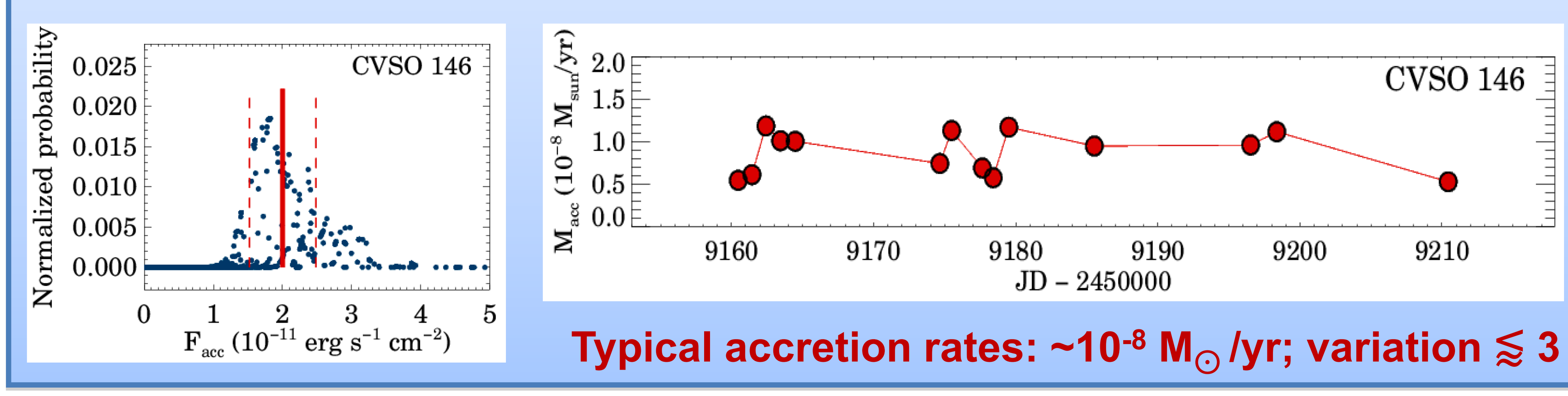
Left: Example multi-wavelength light curves of CVSO 146. Middle: Distribution of the T Tauri stars in the QM parameter space (based on Cody et al. 2014)

Characterization of the light curves

- Variability amplitudes: typically ΔV=0.3-0.7 mag, up to 2 mag. Usually decrease with wavelength
- Two-parameter description (Cody et al. 2014): degree of periodicity (Q) and flux asymmetry (M), computed from the TESS light curves
- QM distribution: three light curves are periodic or quasi-periodic, the remaining ones are close to aperiodic
- Most light curves symmetric, but CVSO 90 and CVSO 104 are bursters; CVSO 165 and SO 518 are dippers
- **Based on light curve parameters, the Ori OB1 and σ Ori sources are rather typical T Tauri stars**

Accretion rates estimated from optical photometry

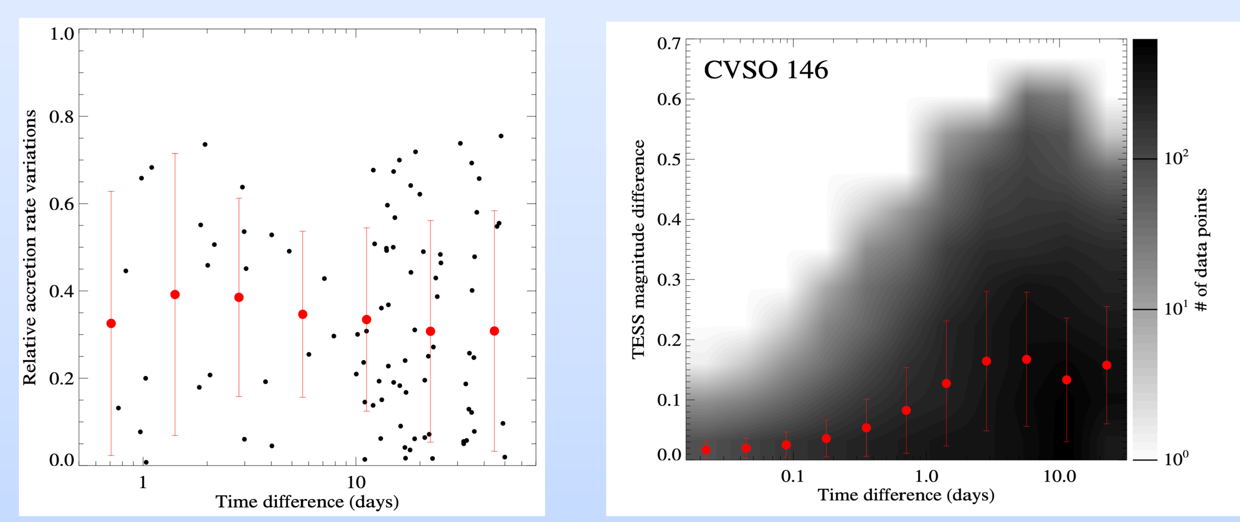
- The X-Shooter UV-optical-infrared spectra were fitted with a model composed of a stellar photospheric template and a slab of gas to simulate the accretion hot spot (Manara et al. 2021)
- Adopting stellar and extinction parameters from the X-Shooter model, slab models were fitted to optical broad-band photometry from Konkoly Observatory. We assigned chi2-based probability to each fit, and determined the most likely accretion rate value and its uncertainty at each epoch (left figure)



Typical accretion rates: ~10^{-8} $M_\odot$/yr; variation ≲ 3

Variability timescales

- The observed timescales of variability are related to the physical processes causing the flux changes
- Accretion rate (left) and TESS magnitude (right) differences vs. Δt between any two measurements:



- Variability amplitudes steadily increase up to ~2 days, and level off afterward

➡ **Probably related to rotational timescales**

➡ **Hot accretion spots, funnel flows**

➡ **Does this pattern changes on yearly timescales?**

Summary and outlook

- With the aim to support the synchronized HST and VLT spectroscopy surveys of accreting low-mass pre-main sequence stars (ULLYSES and PENELLOPE, respectively), we carried out extensive multi-band photometric monitoring of 13 objects in Ori OB1 and σ Ori at different ground-based observatories. The data were supplemented by simultaneous TESS observations.
- Our ongoing analysis aims at characterizing the accretion process based on multi-filter photometry. We observed BVr'i' light curves with an approximately daily cadence, and derived the brightness and color evolution of the stars. We developed a new method to estimate the accretion rate from broad-band optical photometry, utilizing a grid of slab modeling. We then produced accretion rate curves with nightly cadence, that will help to define the exact variability state of the stars at the precise epochs of the HST and VLT spectroscopy.
- **The analysis of the amplitudes and timescales of the accretion rate curves will be used to identify the underlying physical mechanisms. The results, together with similar T Tauri samples from other star forming regions, will make ULLYSES/PENELLOPE one of the highest impact study of the stellar accretion process of today.**

References

Cody et al., AJ 147, id.82 (2014); De et al., PASP 132, id.025001 (2020); Espaillat et al., AJ 163, id.114 (2022); Frasca et al., A&A 656, id.A138 (2021); Froebrich et al., MNRAS 510, 2883 (2022); Manara et al., A&A 650, id.A196 (2021); Roman-Duval et al., RNAAS 4, id.205 (2020)

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