Testing Unstable Magnetospheric Accretion at Late Disk Ages in TW Hya

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Box 1. Probing the Accretion Structure with High-Resolution Spectroscopy

- We removed the photosphere from VLT/ESPRESSO spectra using STAR-MELT *(Campbell-White et al. 2021)*, and decomposed the calibrated emission lines into broad components (BCs) and narrow components (NCs) with multi-Gaussian fits.

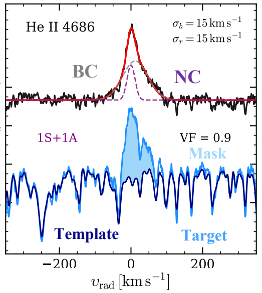


Fig. 1 *Best fit to the He II line in one ESPRESSO epoch, showing the decomposition into NC and BC with a double-Gaussian model. The light blue curve shows the observed spectrum, while the dark blue curve shows the best-fitting stellar template.*

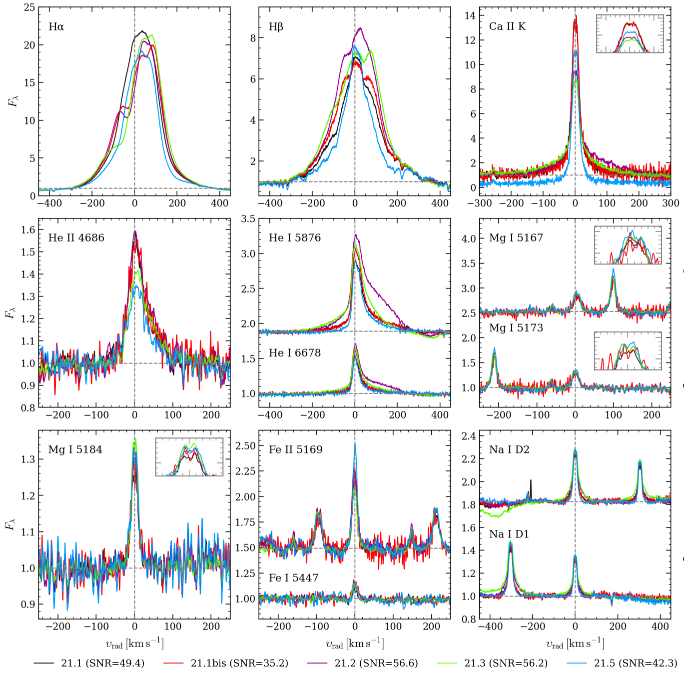


Fig. 2 *Calibrated emission-line profiles of TW Hya from the VLT/ESPRESSO monitoring in five epochs. Lines with double-peaked profiles are shown in the inset panels.*

- He I NCs are red-asymmetric, while He II is more symmetric.
- He NCs are broader than metallic NCs, indicating formation from a vertically stratified shock structure.
- Mg and Ca II K lines are double-peaked, suggesting they are dominated by chromospheric emission.

(JL Linsky. 2017)

Box 2. Stellar rotation period (P_*) from He I λ5876 and He II λ4686 lines

- Assuming that the NC originates from a fixed region centered at latitude (θ_S) and azimuth (ϕ_S) (**Point-like hot-spot model**).
- We measured the centroid radial velocity (v_{NC}) of He I and He II lines from the calibrated VLT/ESPRESSO and CHIRON spectra, and we detected periods of 3.51 d & 3.56 d in their Lomb-Scargle Periodograms (LSPs), **consistent** with $P_* = 3.56$ d from *Setiawan et al. (2008).*

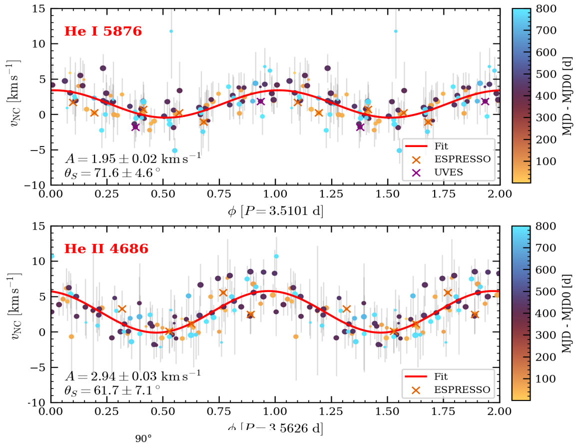
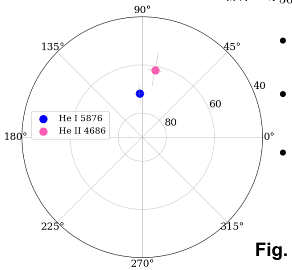


Fig. 3 Phase-folded radial velocity curves of the He I and He II NC, using periods identified from the LSPs. The red curves represent the best-fitting sinusoidal models (see below). With known $v \sin i \sim 6.3 \pm 1.3$ km/s, we estimated the modulation amplitude ($A = v \sin i \cdot \cos\theta_S$), and the surface position (θ_S, ϕ_S) of the emitting region.



- Fitted the phase-folded radial velocities with: $v_{NC}(\phi) = v_0 + v \sin i \cdot \cos\theta_S \cdot \sin[2\pi(\phi - \phi_S)]$
- He I λ5876 result implies a nearly pole-on magnetic obliquity of $\Theta \sim 18.2 \pm 4.4°$.
- He II λ4686 has a larger amplitude *(A)* than He I λ5876, but from a lower-latitude origin.

(e.g., Sicilia-Aguilar et al. 2023)

Fig. 4 *Polar plot for the distribution of He I 5876 and He II 4686.*

Box 3. Constraining the hot-spot size with an Extended Spot Model

- We developed an **extended** hot-spot model as a finite spherical cap centered at (θ_S, ϕ_S), with spot temperature (T_s) and filling factor (f_s).
- The model line profiles $F_l(v, t)$ and their centroid radial velocities v_{NC} were computed by summing all visible surface elements ΔS_i over rotational phase.
- Adopting the (θ_S, ϕ_S) from the point-like model for He I (See Box 2), we found that the amplitude *(A)* decreases nearly linearly with increasing f_s.

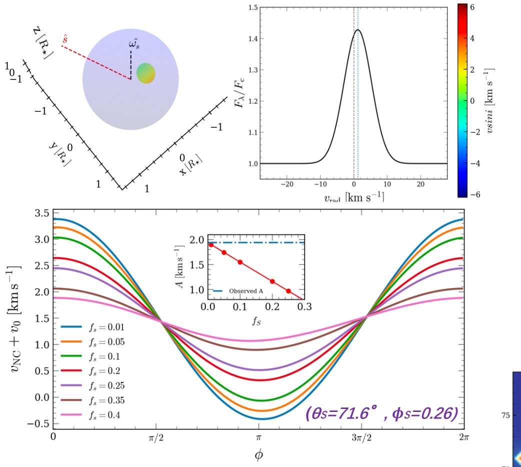


Fig. 5 *Extended hot-spot models. (Top Left) 3D snapshot of a spot with filling factor f_s = 0.01, color-coded following the sinusoidal equation from Box 2. $\vec{\omega}_S$ and $\hat{s}$ are the stellar rotation axis and the observer's line of sight, respectively. (Top Right) He I 5876 emission line produced by this spot. (Bottom) RV curves as a function of phase for different f_s. The inset shows the amplitude A versus f_s, where the horizontal dashed line marks the amplitude of the point-like hot spot.*

- The linear relation of A vs. f_s suggests a small hot spot with $f_s \simeq$ ***0.178%***. The $1/\chi^2$ map supports this result and helps break the degeneracy between θ_S and f_S.

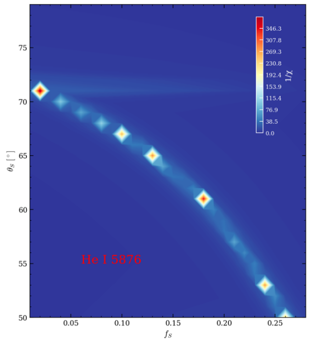


Fig. 6 *Model amplitude (A) on a two-dimensional grid in (θ_S, f_S). The best-fitting model is identified from the peak of the $1/\chi^2$, which corresponds to the minimum-χ^2 solution for the observed He I λ5876 amplitude from Box 2.*

CONCLUSIONS

- Vertically stratified accretion column
- The NC radial velocities recover the P_*
- The hot spot has a low magnetic obliquity
- The extended spot model suggests a small spot

OUTLOOK

- Coordinated simultaneous multi-epoch photometry and spectroscopy can link photometric bursts with accretion-rate changes and constrain unstable accretion.

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