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Plaskett's Star: a fundamental revision of the architecture of the system

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Background

Plaskett's Star was first discovered by Canadian Astronomer John Stanley Plaskett in 1922 (Plaskett, 1922, MNRAS, 82, 447). It has been historically understood as a very massive ($M \approx 100\,M_\odot$) double-lined, short-period ($P_{orb} \approx 14.4$ d) spectroscopic binary containing two O-type components (see Linder et al., 2008, A&A, 489.2, 713). The broad-lined component was discovered to contain a magnetic field by Grunhut et al. (2013, MNRAS, 428.2, 1686), establishing it as the most rapidly rotating known magnetic O-type star. **Grunhut et al. (2022, MNRAS, 512.2, 1944) have recently presented strong evidence against significant radial velocity variations in the magnetic star, which is supported by spectral disentangling analysis. These results are inconsistent with the near-equal mass binary model for this system and motivate a fundamental revision of our understanding of this system.**

Spectropolarimetry

Narrow-lined Component

O8III/I spectral type[a]
$v \sin i \approx 60 - 75$ km/s[a]
N enh. (16 $\mathrm{N}_\odot$), C dep. (0.03 $\mathrm{C}_\odot$)[a]
$B_d \lesssim 500$ G[b]

Broad-lined Component

O7.5III spectral type[a]
$v \sin i = 360 \pm 40$ km/s[b]
N dep. (0.2 $\mathrm{N}_\odot$), He enh. (1.76 $\mathrm{He}_\odot$)[a]
$P_{rot} = 1.21551^{+0.00028}_{-0.00034}$ d[b]

Magnetic Field

($B_d \approx 850$ G, $B_{\mathrm{avg}} \approx 520$ G)[b]

[a] Linder et al. (2008)
[b] Grunhut et al. (2022)

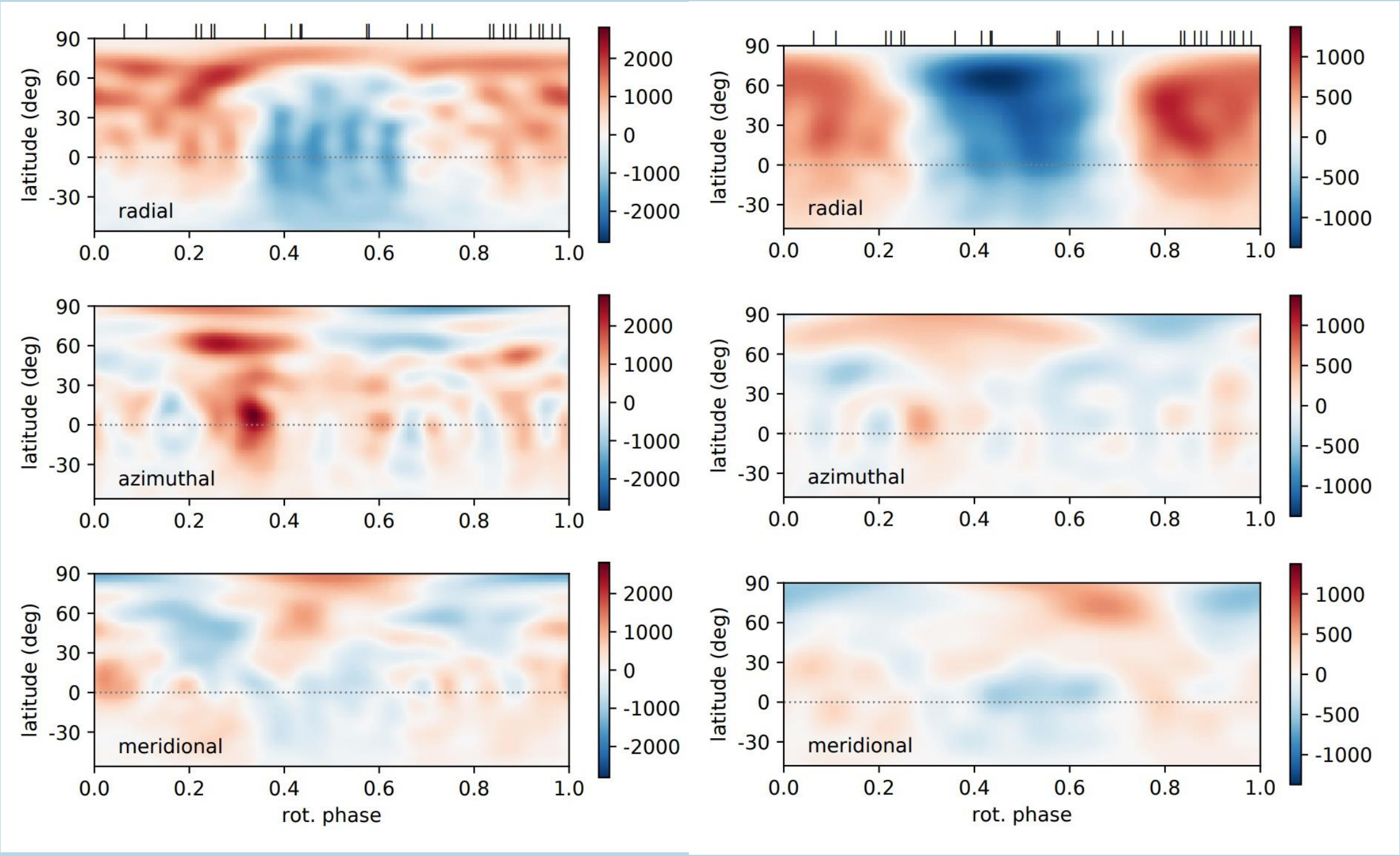


Figure 1: ZDI maps of the magnetic field of the broad line star, assuming a Linder et al. (2008) orbital solution (left) and a constant broad-lined star RV (right) (Grunhut et al., 2022).

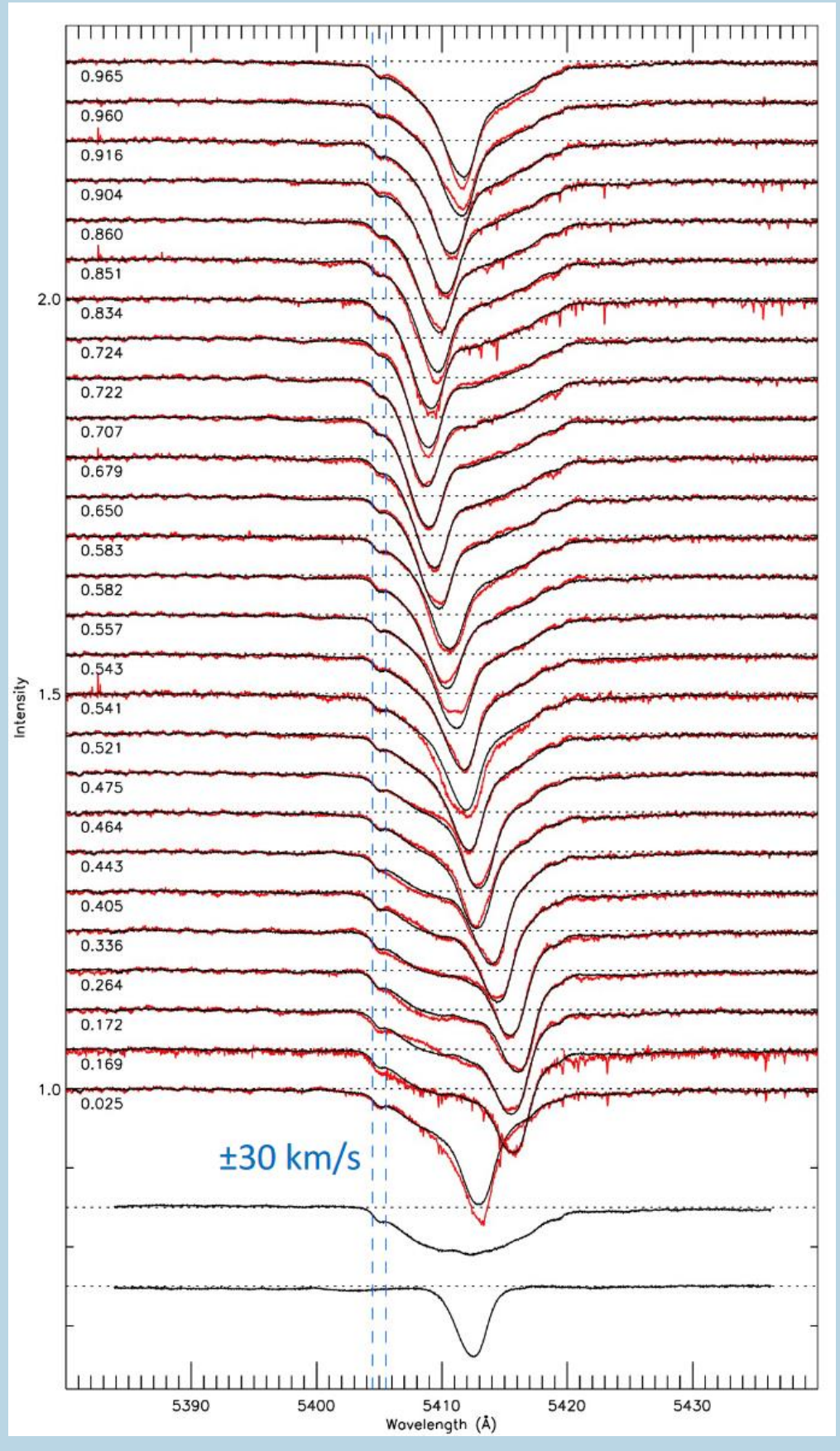


Figure 2: Several stacked Stokes I spectra of the He II $\lambda 5411$ line phased according to the 14.4 d orbital period. The disentangled profiles are illustrated below. Additionally, the dashed blue lines bound an unexplained static feature in the blue wing of the broad-lined profile.

Spectroscopy of HD 47129 reveals a narrow-lined O8 component and a broad-lined O7.5 component (Linder et al., 2008) associated with a clear magnetic signature in Stokes V (Grunhut et al., 2013). Plaskett's Star was recently observed extensively with the high resolution ESPaDOnS and Narval spectropolarimeters as reported by Grunhut et al. (2022). Analyzing these spectra, they found that substantially better fits to the Stokes V profiles were achieved assuming a constant RV for the magnetic star instead of the Linder et al. (2008) model. This is also reflected in the magnetic maps in each case, with the latter yielding an unrealistically complex magnetic geometry (see Fig. 2). This is supported by direct measurement of radial velocities from disentangled Stokes I spectra (see Figs. 2, 3). **These results provide strong evidence against significant RV variability of the magnetic star that is required for the historical orbital model. This has motivated a fundamental revision of our model for the composition and structure of Plaskett's Star.**

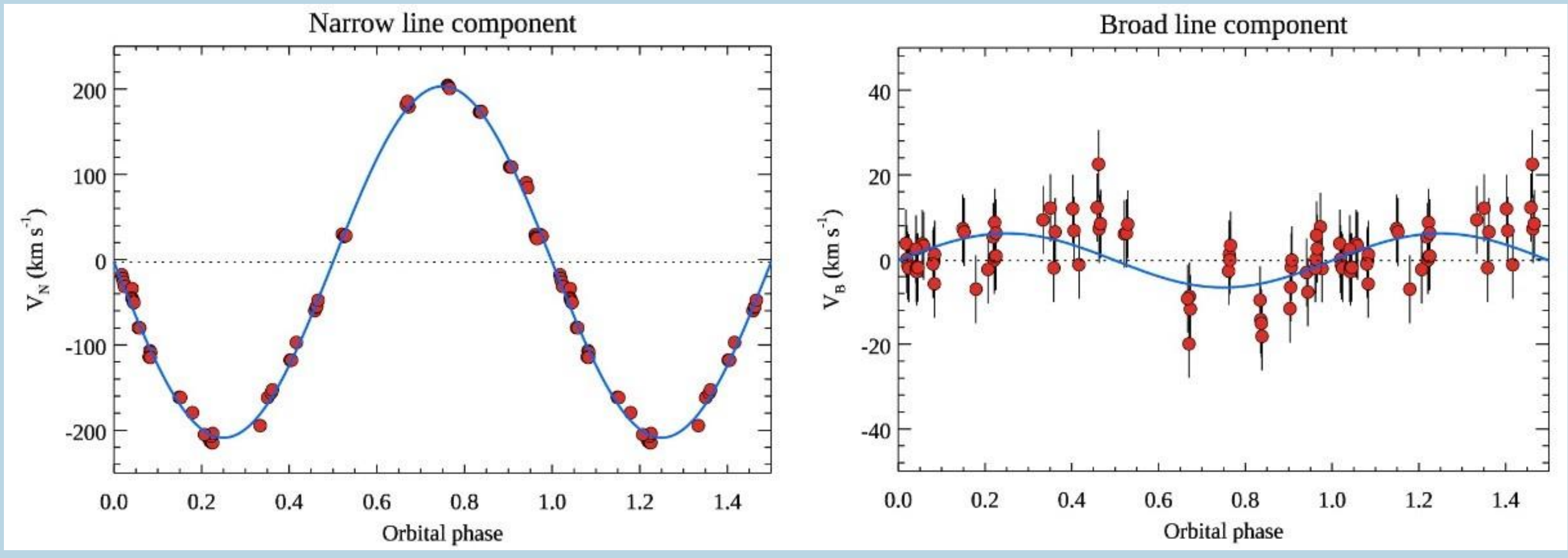
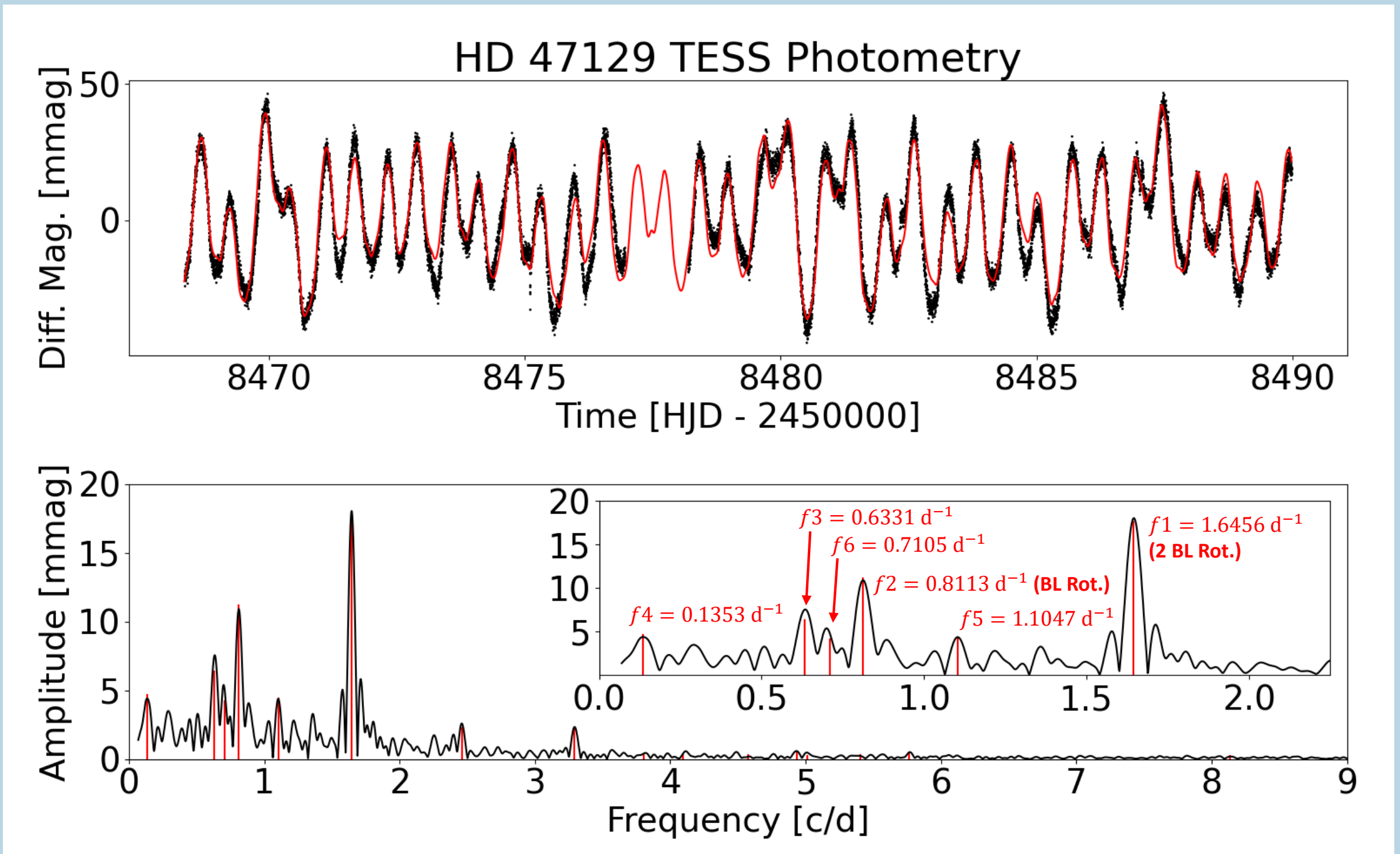


Figure 3: The measured radial velocities for each component from disentangled spectra. At a fixed $P_{orb} \approx 14.4$ d orbital period, the blue fit yields a RV semi-amplitude for the broad-lined star of 6.9 ± 1.2 km/s.

Photometry

Plaskett's Star was observed in 2008 with the Convection, Rotation, and Planetary Transits (CoRoT) satellite and again in 2018 by the Transiting Exoplanet Survey Satellite (TESS). In both cases, **the majority of the observed photometric variability can be attributed to rotational modulation of the magnetic star** which appears to be stable on the order of 10 years (Stacey et al., in prep.). The CoRoT data also demonstrates strong (~6.5 mmag) variability at the Linder et al. (2008) 14.4 d orbital period, which is not detected in the TESS data. The photometric data also reveal the presence of stochastic low-frequency variability (SLF) as described by Blomme et al. (2011, A&A, 533, A4) which is approximately consistent with the *O bright giant and supergiant star* sample of Bowman et al. (2020, A&A, 640, 17).

Figure 4: The TESS photometry for HD 47129 (top), and its associated periodogram (bottom). The red line imposed on the light curve corresponds to the Stacey et al. (in prep.) model fit from prewhitening analysis. The red vertical lines on the periodogram correspond to detected frequencies. The inset in the periodogram illustrates a region containing the five frequencies of highest amplitude from frequency analysis.



Approaching a revised model

This system demonstrates several characteristics that are well explained by the historical model of the system and are challenging to reconcile otherwise. There are three primary questions underpinning the development of a revised model:

1. **What is responsible for the RV variations of the narrow-lined star?** If it's the magnetic star, a mass ratio of $32.3^{+8.3}_{-5.5}$ is implied from the RV amplitudes depicted in Fig. 3. If it's *not* the magnetic star, we require a third object that is not apparent in the optical spectra line profiles.
2. **Why does the magnetic star demonstrate such rapid rotation?** O-type stars have high luminosities and thus strong winds. Magnetic fields in these stars interact with the wind to quickly shed angular momentum. Plaskett's Star was interpreted as a post Roche Lobe overflow (RLOF) system by Linder et al. (2008) (in the context of the SB2 model), which implies the magnetic star's angular momentum was supplemented by past mass transfer.
3. **What is responsible for the peculiar chemistry of the system?** The observed chemical peculiarities suggest the system is evolved and has experienced past mass transfer. This was consistent with the historical model of this system as a post RLOF system.

Hypothesis 1: An unseen object

We consider a case where the narrow-lined star is in a close $P \approx 14.4$ d orbit with a third object, and the broad-lined star is either dynamically unrelated or weakly dynamically bound (e.g. hierarchical trinary). The minimum mass of a companion based on the RV variations of the narrow-lined star is approximately 14 $\mathrm{M}_\odot$, which is consistent with a potential black hole (BH) companion. Cyg X-1 is a O/BH binary system with an orbital period of approximately 6 days (Brocksopp et al., 1999, A&A, 343, 861) and an estimated BH mass of $10 - 23$ $\mathrm{M}_\odot$ (Ziolkowski, 2014, ApJ, 742.2, 10), which is nominally similar to what we expect of an O/BH binary model for Plaskett's Star. However, this system exceeds the X-ray luminosity of Plaskett's Star ($L_X = 8.34 \times 10^{32}$ ergs/s; Linder et al., 2006, MNRAS, 370.4, 1623) by approximately 5 dex (Orosz et al., 2011, ApJ, 742.2, 10). Casares et al. (2014, Nat, 505.7483, 378) describes a Be/BH binary with relatively low X-ray luminosity ($L_X < 1.0 \times 10^{32}$ ergs/s) owing to inefficient accretion. Therefore, **it does appear that examples in literature could support a potential O/BH binary model to explain the RV variability, but nevertheless it may be challenging to reconcile the strong winds expected from the O star with the low X-ray luminosity.**

Turner et al. (2008, AJ, 136.2, 554) and Sana et al. (2014, ApJS, 215.1, 35) report a total of three companions detected with infrared interferometry from 1 to 8000 mas (subtending ≈ 1 to 8000 AU), none of which are consistent in luminosity with the broad-line component. Therefore, this solution restricts the broad-lined component to narrow ranges of orbital phase in a hierarchical configuration. Additionally, **this solution does not provide a clear explanation for the high rotation rate of the magnetic star nor the chemical peculiarity of either component.**

Hypothesis 2: A stripped star

A second revised model under consideration for HD 47129 instead enforces the mass ratio as implied by the radial velocity models depicted in Fig. 3. Assuming the broad-lined star is a "normal" magnetic O star with a mass of (47.3 ± 0.3) $\mathrm{M}_\odot$ (Linder et al., 2008), this requires a mass of approximately $1 - 2$ $\mathrm{M}_\odot$ for the narrow-lined star star. This component still demonstrates an O spectral type in the spectroscopic observations and comparable luminosity to the broad-lined star. Therefore, we postulate the narrow-lined component may be a stripped sdO star – a star that has lost its envelope through binary interaction leaving a hot, compact object (Götberg et al., 2018, A&A, 615, A78). **This prescription addresses the radial velocity measurements of both components simultaneously with the anomalously high rotation rate of the magnetic star (through angular momentum transfer in the stripped material).** Götberg et al. (2018) remarks that the layers exposed at the surface of stripped stars will have been regions of CN and CNO hydrogen burning, yielding enhancements in He and N and depletions in H, C, and O. This is particularly consistent with the strong N enhancement and C depletion measured by Linder et al. (2008), and the absence of oxygen lines in the spectra. **Interpreting the narrow-lined component as a stripped sdO star currently appears to best address the outstanding issues with modelling Plaskett's Star while remaining consistent with existing observational results.**