

A Plasma Torus Around a Young Low-Mass Star

Luke G. Bouma^{1,2}

¹*Observatories of the Carnegie Institution for Science, Pasadena, CA 91101, USA*

²*Carnegie Fellow*

Approximately one percent of red dwarfs younger than 100 million years show structured, periodic optical light curves suggestive of transiting clumps of opaque circumstellar material that corotate with the star^{1–4}. The composition, origin, and even the existence of this material are uncertain. The main alternative hypothesis is that these stars are explained by complex distributions of dark starspots or bright faculae distributed across their surfaces⁵. Here, we present time-series spectroscopy and photometry of a 40 million year old complex periodic variable (CPV), TIC 141146667. The spectra show coherent sinusoidal Balmer emission at up to four times the star’s equatorial velocity, demonstrating the presence of extended clumps of circumstellar plasma — a plasma torus. Given that long-lived condensations of cool (10^4 K) plasma can persist in the hot (10^6 K) coronae of stars with a wide range of masses^{6–11}, these data support the idea that such condensations can become optically thick around the lowest-mass stars, although the exact source of opacity remains unclear.

1 Main

M dwarfs, stars with masses below about half that of the Sun, are the only type of star to offer near-term prospects for detecting the atmospheres of rocky exoplanets with water on their surfaces (CITE). Investment with JWST has proceeded accordingly (CITE CITE). It is therefore important to consider how the evolution of an M dwarf might impact the evolution of its planets. Previous work has established that most M dwarfs host close-in planets (CITE), and that these planets are often subject to long circumstellar disk lifetimes (CITE), to large doses of UV radiation (CITE), and to a high incidence of flares and coronal mass ejections (CITE). However, despite excellent work in these areas, the properties of the circumstellar plasma and magnetospheric environments to which young, close-in exoplanets are subject remain largely unexplored.

One glaring example of our current ignorance is the complex periodic variables (CPVs). Figure 1 highlights the main object of interest in this article, but over one hundred analogous objects have now been discovered by K2 and TESS (CITE, CITE, CITE, CITE). These CPVs are defined by their highly structured and periodic optical light curves, and most are M dwarfs with rotation periods shorter than two days. Within current sensitivity limits, none have primordial disks (CITE). However, $\approx 3\%$ of stars a few million years old show this behavior (CITE), and the observed fraction decreases to $\approx 0.3\%$ by ≈ 150 Myr (CITE).

The two leading hypotheses to explain the CPVs are either that we are in the shadow of transiting clumps of circumstellar material that corotate with the star (CITE, CITE, CITE), or

that these stars represent an extreme in naturally-occurring distributions of starspots or faculae for young M dwarfs ⁵. Currently, the main argument against a starspot-only explanation invokes the timescales and amplitudes of the sharpest photometric features (CITE). However, there has yet to be any direct independent evidence for the presence of circumstellar material in any of these objects. Since transiting circumstellar clumps would geometrically imply an occurrence rate a few to ten times the observed rate (CITE), this phenomenon has the potential to affect 10-30% of M dwarfs during their early lives.

The dearth of evidence for circumstellar material around CPVs is surprising given that separate studies of young BAFGKM stars have, for decades, reported that stellar coronae contain both hot (10^6 K) and cool (10^4 K) plasma. In particular, time-series spectroscopy has shown periodic high-velocity absorption and emission in Balmer lines such as $H\alpha$, implying long-lived, corotating clumps of cool plasma (CITE, CITE, CITE). Such clumps are forced into corotation by the magnetic field, and the geometry of where the plasma can accumulate is thought to be dictated by the magnetic field’s topology. For instance, a tilted dipole field tends to yield an accumulation surface of a warped torus ⁷, whereas in the limit of a single strong discrete field line, accumulation occurs along a fixed point ¹⁰. However, none of these stars have shown any photometric anomalies (CITE), leaving open the issue of whether these two separate areas of study have any direct connection. Nonetheless, CPVs do respond to sudden magnetic field changes: there are many documented cases of otherwise long-lived eclipse features disappearing immediately following stellar flares (CITE, CITE).

In this study, we present the first data showing the existence of corotating clumps of cool plasma around a CPV. We identified TIC 141146667 in previous work as one of fifty high-quality CPVs by searching the TESS two-minute data for stars showing periodic variability with at least three sharp dips. We observed it for five hours with Keck/HIRES on UT 2024-02-17, nearly but not exactly contemporaneously with TESS, which observed the star from UT 2024-02-05 to UT 2024-02-26 with a duty cycle of XX%. Figure 1 shows...

Results

Discussion These data rule out “starspot-only” and “dust-only” origin scenarios for CPVs, instead supporting either a purely stellar origin for the phenomenon or extrinsic scenarios involving long-lived disks or outgassing rocky bodies capable of supplying sufficient gas.

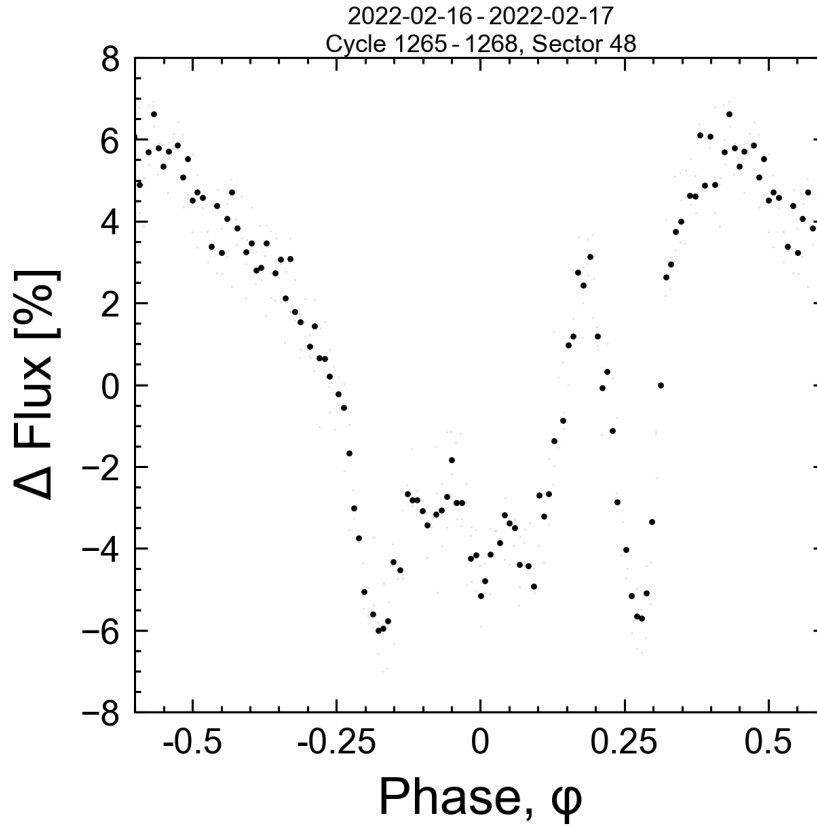


Figure 1: **Figure 1 (Movie): TIC 141146667 is a complex periodic variable (CPV).** For the best experience, please view the online movie available [here](#), which spans a baseline of 5,784 cycles irregularly sampled over three years. The TESS light curve is phased to the 3.930 hour period in groups of a few cycles per frame. This is the period both of stellar rotation, and (we hypothesize) of corotating clumps of circumstellar material. Raw data acquired with two minute sampling are in gray; black is their average. Similar to other members of this class, the sharp photometric features persist for tens to thousands of rotational cycles.

66 **Methods**

67 **Observations TESS:**

68 **Keck/HIRES:**

69 **Data Reduction**

70 **Discussion**

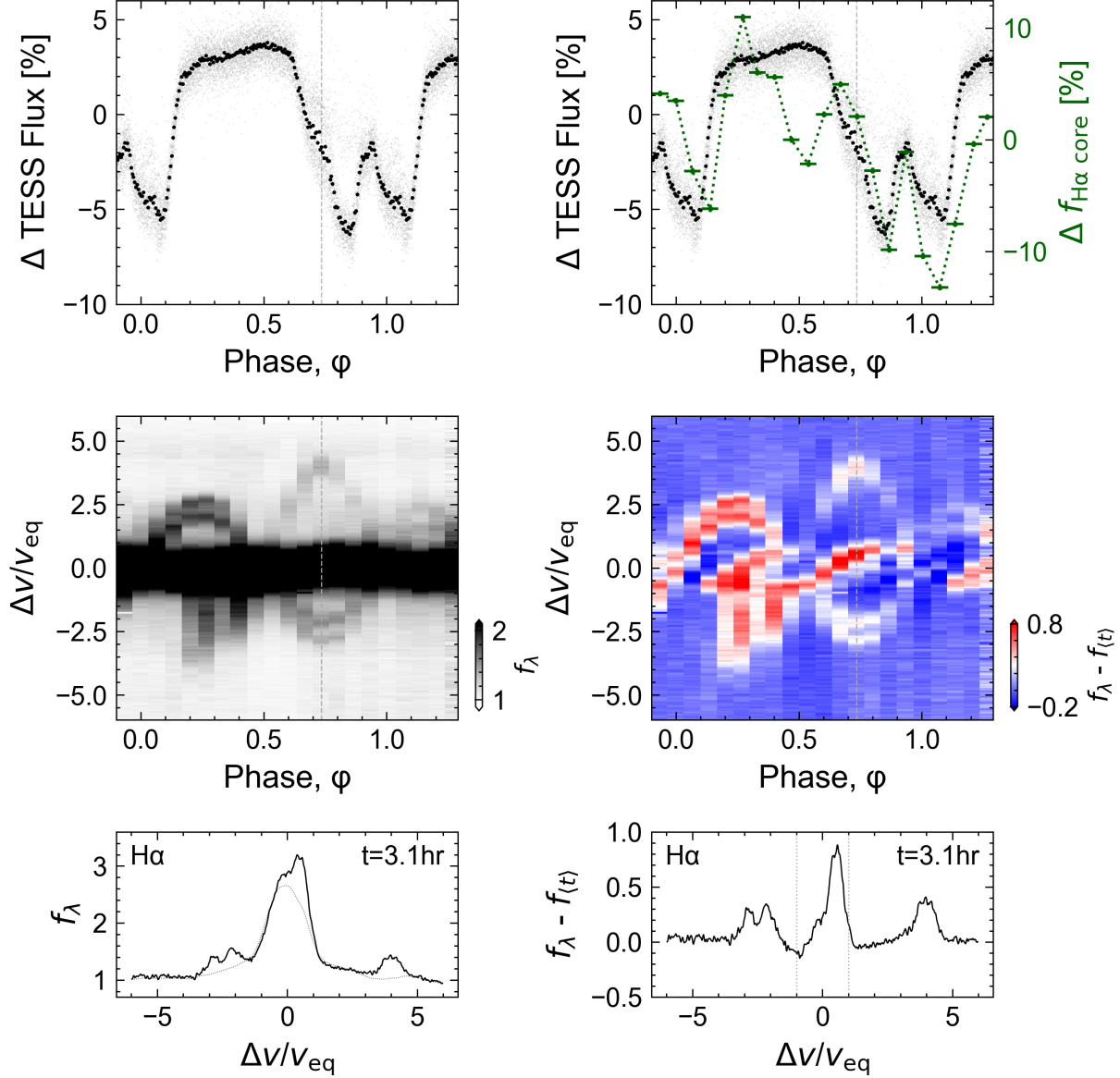
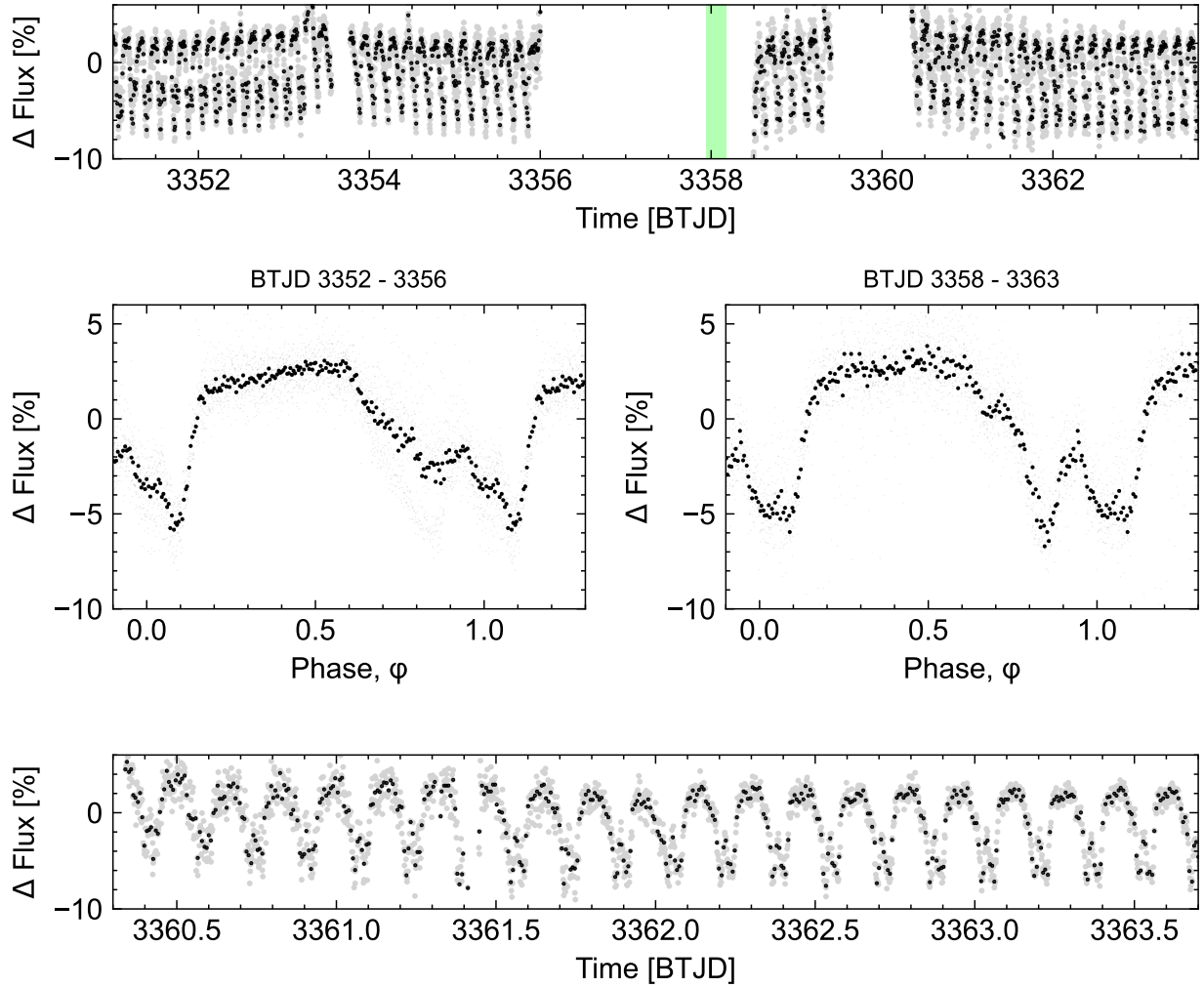


Figure 2: **Figure 2 (Movie):** Hydrogen emission from circumstellar plasma orbiting TIC 141146667. **(TODO)**For the best experience, please view the online movie available here. **Panel a:** TESS light curve from UT 2024-02-05 to UT 2024-02-26 folded on the 3.930 hour period. Black points are averaged; gray are the raw data. **Panel b:** Keck/HIRES H α spectra acquired on UT 2024-02-17. The continuum is set to unity, and the darkest color is set at twice the continuum to accentuate emission outside the line core ($|v/v_{\text{eq}}| > 1$, for $v_{\text{eq}}=130 \text{ km s}^{-1}$). While emission in the line core originates in the stellar chromosphere, the sinusoidal emission features are most readily described by a warped plasma torus. **Panel c:** Individual epochs of Panel b, visible in the online movie. The dotted line shows a time-averaged spectrum, $f_{(t)}$. **Panel d:** As in Panel a, but overplotting the median-normalized H α light curve at $|v/v_{\text{eq}}| < 1$. **Panel e:** As in Panel b, after subtracting the time-averaged spectrum. In addition to circumstellar emission, the line core shows absorption during the plasma clump transits. The asymmetric stretch is set to match the dynamic range of the data. **Panel f:** Individual epochs of Panel e, visible in the online movie.

Parameter	Host	Source
Identifiers		
TIC	141146667	TESS
Gaia	todo	Gaia DR3
Astrometry		
α	todo	Gaia DR3
δ	todo	Gaia DR3
μ_α (mas yr ⁻¹)	todo	Gaia DR3
μ_δ (mas yr ⁻¹)	todo	Gaia DR3
π (mas)	todo	Gaia DR3
Photometry		
<i>TESS</i> (mag)	todo	TESS
<i>G</i> (mag)	todo	Gaia DR3
<i>G</i> _{BP} (mag)	todo	Gaia DR3
<i>G</i> _{RP} (mag)	todo	Gaia DR3
<i>J</i> (mag)	todo	2MASS
<i>H</i> (mag)	todo	2MASS
<i>K_s</i> (mag)	todo	2MASS
<i>W1</i> (mag)	todo	ALLWISE
<i>W2</i> (mag)	todo	ALLWISE
<i>W3</i> (mag)	todo	ALLWISE
<i>W4</i> (mag)	todo	ALLWISE
Kinematics and Position		
<i>RV_{Bary}</i> (km s ⁻¹)	13.35 ± 3.39	Gaia DR3
<i>U</i> (km s ⁻¹)		
<i>V</i> (km s ⁻¹)		
<i>W</i> (km s ⁻¹)		
<i>X</i> (pc)		
<i>Y</i> (pc)		
<i>Z</i> (pc)		
Physical Properties		
<i>P_{rot}</i> (hours)	3.930 ± 0.XXX	This work
<i>v</i> sin <i>i</i> _★ (km s ⁻¹)	todo	This work
<i>i</i> _★ (°)	todo	This work
<i>F_{bol}</i> (erg cm ⁻² s ⁻¹)	todo	This work
<i>T_{eff}</i> (K)	todo	This work
<i>A_V</i> (mag)	todo	This work
<i>R</i> _★ (<i>R</i> _☉)	todo	This work
<i>L</i> _★ (<i>L</i> _☉)	todo	This work
<i>M</i> _★ (<i>M</i> _☉)	todo	This work
Age (Myr)	todo	This work

Extended Data Table 1: Properties of TIC 141146667.

- 72 1. Rebull, L. M. *et al.* Rotation in the Pleiades with K2. II. Multiperiod Stars. *Astron. J.* **152**,
73 114 (2016).
- 74 2. Stauffer, J. *et al.* Orbiting Clouds of Material at the Keplerian Co-rotation Radius of Rapidly
75 Rotating Low-mass WTTs in Upper Sco. *Astron. J.* **153**, 152 (2017).
- 76 3. Rebull, L. M. *et al.* Rotation of Low-mass Stars in Upper Scorpius and ρ Ophiuchus with K2.
77 *Astron. J.* **155**, 196 (2018).



Extended Data Figure 1: Detailed photometric evolution of TIC 141146667 near the epoch of spectroscopic observation (green). **Panel a:** Subset of TESS SAP_FLUX acquired near time of Keck/HIRES observation. TESS downlinked data to the Deep Space Network from BTJD XXX to YYY, and was affected by scattered light from the Earth from BTJD 3359.4 to 3360.15. **Panels b,c:** Folded light curve before and after spectroscopy. **Panel d:** Zoom-in of Panel a, showing decreasing photometric scatter in the over three days (18 cycles).

4. Bouma, L. G. *et al.* Transient Corotating Clumps around Adolescent Low-mass Stars from Four Years of TESS. *Astron. J.* **167**, 38 (2024).
5. Koen, C. Starspot modelling of the TESS light curve of CVSO 30. *Astron. Astrophys.* **647**, L1 (2021).
6. Collier Cameron, A. & Robinson, R. D. Fast H-alpha variations on a rapidly rotating cool main sequence star- I. Circumstellar clouds. *Mon. Not. R. Astron. Soc.* **236**, 57–87 (1989).
7. Townsend, R. H. D. & Owocki, S. P. A rigidly rotating magnetosphere model for circumstellar emission from magnetic OB stars. *Mon. Not. R. Astron. Soc.* **357**, 251–264 (2005).
8. Dunstone, N. J., Collier Cameron, A., Barnes, J. R. & Jardine, M. The coronal structure of Speedy Mic - II. Prominence masses and off-disc emission. *Mon. Not. R. Astron. Soc.* **373**, 1308–1320 (2006).
9. Petit, V. *et al.* A magnetic confinement versus rotation classification of massive-star magnetospheres. *Mon. Not. R. Astron. Soc.* **429**, 398–422 (2013).
10. Waugh, R. F. P. & Jardine, M. M. Magnetic confinement of dense plasma inside (and outside) stellar coronae. *Mon. Not. R. Astron. Soc.* **514**, 5465–5477 (2022).
11. Daley-Yates, S. & Jardine, M. M. Simulating stellar coronal rain and slingshot prominences. *Mon. Not. R. Astron. Soc.* **534**, 621–633 (2024).

Acknowledgments The author thanks X, Y, Z. L.G.B. was supported by... Acknowledge TESS...

Author Contributions ...

Data Availability ...

Competing Interests The authors declare that they have no competing financial interests.

Correspondence Correspondence and requests for materials should be addressed to ...

Code availability We provide access to a GitHub repository including all code created for the analysis of this project that is not already publicly available.