HD 41004: A Photometric Sheep in Wolf's Clothing?

Tom Ayres[1,2], Derek Buzasi[3]

Abstract

HD 41004 is an unusual multiple star/planet system. Recent TESS photometry revealed a striking 31 hr period, far too short for the slowly rotating K dwarf primary. Instead, the modulation likely is from the diminutive dM secondary, spun-up to synchronous rotation by its close-in brown dwarf companion, and suffering intense magnetic activity as a result. If so, the red dwarf is perhaps destined to someday return the favor by cannibalizing its substellar partner.

1. INTRODUCTION

HD 41004 is a nearby (d~39 pc) hierarchical multiple system. The primary is an early-K dwarf; the secondary is an early-M dwarf, 3.7 mag fainter and separated by only 0.5" (~20 au); a 2.5 M_J planet circles the primary with a 2.6 yr period (Zucker et al. 2004); and a 19 M_J brown dwarf (BD) tightly orbits the red-dwarf secondary (Santos et al. 2002; Zucker et al. 2003). The dM+BD pair is especially unusual, because substellar objects rarely are found in close orbits around Main sequence stars (so-called "brown-dwarf desert").

HD 41004 is a bright coronal X-ray source, detected in the 1990-91 ROSAT All-Sky Survey and more recently by Chandra (2015, 2020). The K-dwarf primary is known to be moderately active as gauged by chromospheric Ca II emission (Henry et al. 1996). HD 41004 also was an intense far-ultraviolet emission-line source in a 2018–2019 HST/COS survey of high Ecliptic latitude F-G-K dwarf stars (Ayres 2021), in anticipation of the TESS mission. (The TESS camera layout favors the Ecliptic poles with longer duration stares, better for starspot modulation studies.) Periods deduced from the high-precision TESS photometry can help unravel the long-standing "rotation-activity connection" (Skumanich 1972), linked to a magnetic Dynamo lurking deep inside convective stars (Parker 1970).

[1] Corresponding author Thomas.Ayres@Colorado.edu

[2] Center for Astrophysics and Space Astronomy, 389-UCB, University of Colorado, Boulder, CO 80309, USA

[3] College of Arts and Sciences, Florida Gulf Coast University, Fort Myers, FL 33965, USA

2. TESS OBSERVATIONS

In 2018–2019 and 2020–2021, TESS captured HD 41004 in three consecutive 27-d sectors in each epoch, thanks to the deep southern Ecliptic latitude of the star. Figure 1 shows the combined TESS optical light curve. The time series displays a striking, low-amplitude (~0.2% peak-to-peak) quasi-sinusoidal variation on a remarkably short 31 hr cycle. This period was present, albeit weakly, in the first three sectors; but was more prominent in the second set of three. The short period was completely unexpected. The Ca II strength of the primary implies a much longer rotation period (~20 d), consistent with the K dwarf's low $v \sin i$ (only 1.2 km s^{-1}: Santos et al. 2002).

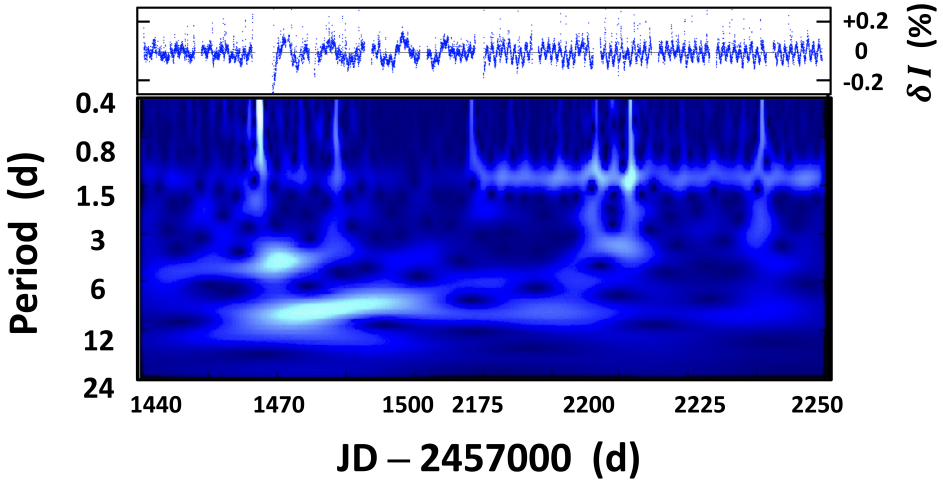

Figure 1. *Upper panel:* TESS light curve, 30 m bins, over two sets of three 27-d sectors separated by 2 years. *Lower panel:* wavelet decomposition showing the prevalence of the 31 hr cycle, but occasional appearance of longer periods.

3. ANALYSIS

Curiously, evidence for the BD in the system was a 50 m s^{-1} radial velocity cycle *with the same 31 hr period* seen in the TESS photometry (Santos et al. 2002). The simple explanation of the RV curve—a sub-Jovian mass planet in a low-inclination orbit around the primary—was discounted in the discovery paper (the long-period planet, mentioned in the Introduction, was identified later). Instead, a subtle analysis of line bisectors in the blended spectrum suggested that the 31 hr RV signal originated from a larger Doppler reflex of the secondary caused by a close-orbiting substellar object. The M-dwarf velocity shifts were

suppressed in the glare of the brighter primary spectrum, but easily recovered by the high-precision "CORALIE" planet-hunter.

The TESS variations possibly could be caused by reflected light from the BD, although this would require rather extreme dM+BD properties. More likely, the brown dwarf has tidally spun-up the red dwarf to the 31 hr synchronous period (as speculated by Santos et al.), and TESS is simply seeing rotational modulations of surface activity on the dM star. In fact, the dM+BD pair has by far the largest tidal interaction parameter of 29 star-planet systems considered by Scharf (2010: Fig. 6 therein). A hyperactive M dwarf would be a natural source of the frequent TESS white-light flares (upward spikes, top panel of Fig. 1), atypical for a modestly rotating K dwarf like the primary. And, despite its small size, the secondary might be responsible for much of the FUV and X-ray flux of the system, especially if the red dwarf is in a "saturated magnetic state" (see Pineda et al. 2021, particularly their target LP 247-13, a dM3 with P_{ROT}~1.3 d).

4. DISCUSSION

We conclude that the persistent, rapid, photometric fluctuations of HD 41004 revealed by TESS most likely originate on the dimmer red-dwarf secondary, tidally locked to its close-in BD companion. In fact, the TESS light curve might be viewed as additional support for the unusual dM+BD pair. The K-dwarf primary apparently has a much longer rotation period, rather sheepish compared with the wolfish spin of the secondary.

But, there's more to the story. The synchronized dM+BD system must be shedding angular momentum courtesy of rotational braking by the magnetized red-dwarf coronal wind. A steadily shrinking orbit would eventually force the two companions to coalesce, making a new, slightly more massive M dwarf, but spinning very rapidly. The AB Doradus quadruple system is a possible precedent. The primary K dwarf of the A component and the two dMs of the B component all are very fast rotators, and all are believed to be merger products (see Azulay et al. 2015).

In short, HD 41004 appears to be a unique low-mass system, perhaps on the verge of losing a substellar member to activity-driven cannibalism, and in the process further drying the already parched brown-dwarf desert (ironically, by means of a BD dessert, so to speak).

5. Acknowledgments

TA thanks HST and Chandra, and DB thanks TESS, for their support. TESS data were from the MAST archive at STScI. We also acknowledge databases maintained by CDS, Strasbourg, France.

References

Ayres, T.R. 2021, ApJ, 910, 71
Azulay, R., Guirado, J.C., Marcaide, J.M., et al. 2015, A&A, 578, A16
Henry, T.J., Soderblom, D.R., Donahue, R.A., et al. 1996, AJ, 111, 439
Parker, E.N. 1970, ARA&A, 8, 1
Pineda, J.S., Youngblood, A., France, K. 2021, ApJ, 918, 40
Santos, N.C., Mayor, M., Naef, D., et al. 2002, A&A, 392, 215
Scharf, C. 2010, ApJ, 722, 1547
Skumanich, A. 1972, ApJ, 171, 565
Zucker, S., Mazeh, T., Santos, N.C., et al. 2003, A&A, 404, 775
Zucker, S., Mazeh, T., Santos, N.C., et al. 2004, A&A, 426, 695