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

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HD 41004 is a nearby (39 pc) hierarchical quadruple system. The primary is an early-K dwarf; the secondary is an early-M dwarf, 3.8 mag fainter and separated by only 0.5" (∼20 au); a few-M_{Jup} planet circles the primary with a several-year period (Zucker et al. 2004); and a 19 M_{Jup} brown dwarf (BD) tightly orbits the red-dwarf secondary (Santos et al. 2002; Zucker et al. 2003). HD 41004 was the brightest FUV 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 (which accumulates deeper exposures near the Ecliptic poles). Starspot modulation periods deduced from the high-precision TESS photometry can play an important role in helping unravel the long-standing "rotation-activity connection" (Skumanich 1972), linked to a magnetic Dynamo lurking inside convective stars (Parker 1970). Previous and contemporary Chandra pointings showed that HD 41004 was a strong coronal X-ray source as well. This was not surprising because the K-dwarf primary is moderately active in chromospheric Ca II emission (Henry et al. 1996), falling between Alpha Cen B (K1 V: P_{ROT}∼40 d) and Epsilon Eridani (K2 V: P_{ROT}∼12 d).

Meanwhile, TESS collected two pairs of three consecutive 27-d sectors on HD 41004, two years apart. The multiple-sector coverage was thanks to the deep southern Ecliptic latitude of the star. The TESS light curve displays a striking, though low amplitude (∼0.2% peak-to-peak), modulation on a remarkably short 1.3-d period. This period was present, albeit weakly, in the first three sectors; but was more prominent in the second set of sectors. Such fast spin was unexpected, given the much longer rotation period of the K star implied by its Ca II strength (perhaps 20 d), and the fact that the primary has a low $v \sin i$ (only 1.2 km s^{-1} : Santos et al. 2002).

Curiously, evidence for the BD in the system was a 50 m s^{-1} radial velocity cycle *with the same 1.3 d period* as 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. Instead, a subtle analysis, involving line bisectors in the blended spectrum, suggested that the 1.3-d RV signal originates from a larger Doppler reflex of the secondary caused by a substellar object orbiting it. The M-dwarf velocity shifts were suppressed in the glare of the brighter primary, but recovered by the high-precision "CORALIE" set-up.

The TESS photometric amplitude possibly could be caused by variations in reflected light from the BD, although requiring extreme assumptions concerning the M-BD properties. More likely, the brown dwarf has tidally spun-up the red dwarf to the 1.3-d synchronous period (as speculated by Santos et al.), and the TESS signal arises from rotational modulations of surface activity. In fact, the M-BD component has by far the largest tidal interaction factor of the 29 star-planet systems considered by Scharf (2010: Fig. 6 of that paper). A hyperactive M dwarf would be a

natural source of the frequent white-light flares seen in the TESS light curve (upward spikes in top light curve panel of Fig. 1), atypical for a more modestly rotating K dwarf like the primary.

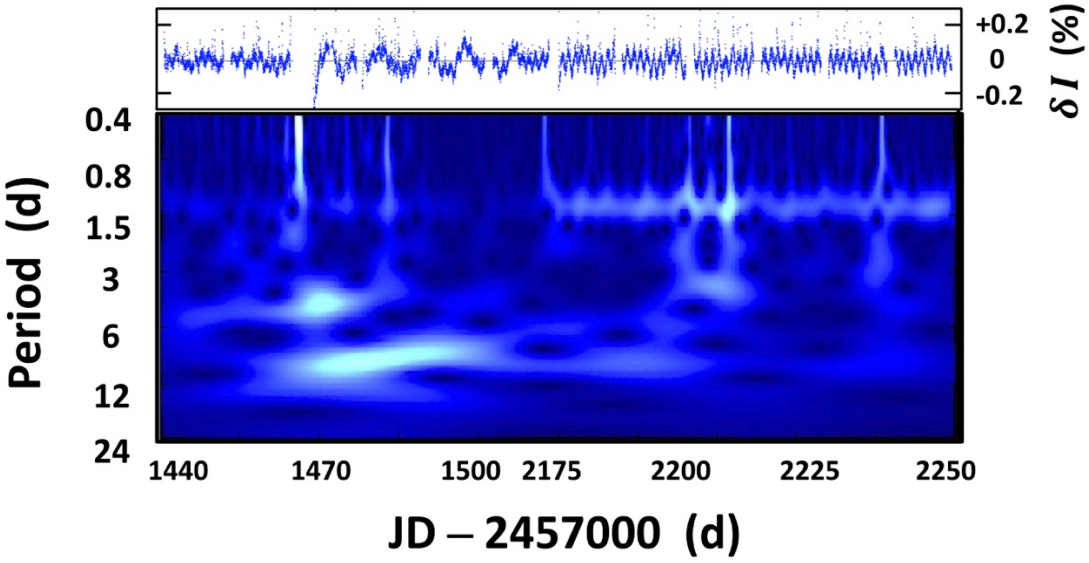

Figure 1. *Upper panel:* TESS light curve, 30 m bins, over two sets of three 27-d sectors separated by 2 years. *Lower panel:* wavelet decomposition showing prevalence of 1.3-d modulation, but occasional appearance of longer periods.

In fact, an ultra-fast rotating early-M dwarf, despite its small size, might be responsible for the majority of the FUV and X-ray flux of the system, especially if the red dwarf is in a "saturated state" (see Pineda et al. 2021, particularly their target LP 247-13, a dM3 with P_{ROT}~1.3 d).

We conclude that the persistent, rapid, photometric variations of HD 41004 captured 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 indirect confirmation of the unusual red-dwarf/BD pair. The K-dwarf primary apparently has a much longer period, rather sheepish compared with the wolfish spin of the secondary.

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

In short, HD 41004 appears to be a unique low-mass system, perhaps about to lose a substellar member to activity-driven cannibalism, and in the process further drying the already parched brown-dwarf desert.

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