Extreme Variability of the V488 Persei Debris Disk

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Abstract

V488 Persei is the most extreme debris disk known in terms of the fraction of the stellar luminosity it intercepts and reradiates. The infrared output of its disk is extremely variable, similar in this respect to the most variable disk known previously, that around ID8 in NGC 2547. We show that the variations are likely to be due to collisions of large planetesimals (≥100 km in diameter) in a belt being stirred gravitationally by a planetary or low-mass-brown-dwarf member of a planetary system around the star. The dust being produced by the resulting collisions is falling into the star due to drag by the stellar wind. The indicated planetesimal destruction rate is so high that it is unlikely that the current level of activity can persist for much longer than ∼1000–10,000 yr and it may signal a major realignment of the configuration of the planetary system.

Supporting material: machine-readable table

1. Introduction

Planetary debris disks reveal critical stages in planetary system evolution (Wyatt 2008; Gáspár et al. 2013). An important development is finding debris-disk behavior tracing recent major collisions between large planetesimals. These characteristics include either extreme infrared excesses (Gorlova et al. 2007; Balog et al. 2009; Melis et al. 2010) or spectral features indicative of finely divided silica particles possibly associated with condensation out of vapor from very violent collisions (e.g., Rhee et al. 2008; Johnson et al. 2012). Many of these cases are too far in their evolution to be associated with the protoplanetary disk phase (≤10 Myr) but represent the later stages of planetary system formation and evolution when, for example, terrestrial planets are growing (Meng et al. 2017). Understanding these systems can illuminate a critical stage in the building of such planets in the first ∼100–200 Myr of evolution of a planetary system. In addition, some of these systems are beyond this age range (Melis et al. 2021; Moór et al. 2021) and indicate that the phenomenon may also result from major shifts in the structure of exoplanetary systems.

It was expected that the aftermaths of giant planetesimal collisions would evolve slowly on a human scale, e.g., over millions of years (e.g., Grogan et al. 2001; Booth et al. 2009). Surprisingly, some debris disks are variable over a few years or even faster (Melis et al. 2012; Meng et al. 2012, 2015). These systems stretch our understanding but can be explained through specific conditions hypothesized to result from the smashup of bodies at least the size of large asteroids (Meng et al. 2014; Su et al. 2019). Indeed, we now have direct evidence for this process in the case of Fomalhaut (Gaspar & Rieke 2020). An extreme example of this behavior, and thus the most pressing for development of physical models, has been the system ID8 in NGC 2547, where substantial changes in the disk output are seen on monthly timescales (Meng et al. 2014). In this paper, we report on a second system that is nearly as rapidly variable as ID8, demonstrating that the rapid brightness fluctuations of ID8 are not unique. This disk orbits V488 Per, an ∼80 Myr old K2-2.5V star at a distance of 173 pc in the α Persei Cluster.

V488 Per = AP 70 = WEBDA 1570 was originally identified as a member of the α Persei Cluster by Stauffer et al. (1985), who also showed it to be a BY-Draconis variable (i.e., showing periodic variations associated with starspots). Its properties were further explored by Prosser (1992), Randich et al. (1996), Mermilliod et al. (2008), and Cantat-Gaudin et al. (2018). The last of these references utilized Gaia data to establish cluster membership at very high probability. Zucker et al. (2012) reported its huge mid-infrared excess, which they describe as “16% (or more) of the stellar luminosity; this is a larger excess fraction than that of any other known dusty main-sequence star.” The age of the star based on its membership in the α Persei Cluster is ∼80 Myr (Soderblom et al. 2014), far beyond the age for a residual protoplanetary disk (Meng et al. 2017), so this phenomenon must be linked to secondary dust production in a collision between planetesimals in a young planetary system around the star.

In addition to its significance in confirming the extreme form debris-disk variability can take, V488 Per is of unique interest for two reasons: (1) the star is of later spectral type and lower luminosity than previously known examples of highly variable extreme disks, so the processes occurring around it may be driven by additional physics and (2) at 80 Myr, the star is older than many other examples of highly variable disks. In this paper, we explore its behavior in light of these characteristics. We first present the relevant observations (Section 2), then analyze them to derive the behavior of the disk and the possible underlying drivers for the activity (Section 3), and finally summarize our results (Section 4).

2. Observations

2.1. Astrometry

Given the exceptional characteristics of V488 Per interpreted as a debris disk, we have tested whether it could be a chance alignment of the star with a (very peculiar) background source. We show positions of the star (GAIA and 2MASS) and of the excess (WISE and Herschel/PACS (corrected for proper motion)) in Table 1; they coincide virtually perfectly, i.e.,
within ∼0.1 for the three at shorter wavelengths and within ∼0.5 for PACS at 70 μm. In the latter case, the beam is ∼5″ in diameter and the ratio of signal to noise only ∼14:1, so the standard indicator of positional accuracy of beamwidth divided by signal to noise would be ∼0.35, a bit larger than the archive estimates. We show the resulting more conservative errors in Table 1. To put a probability on this circumstance, we searched the WISE catalog for sources within 100″ of V488 Per, as bright or brighter than it is, and with a W1−W2 color > 1 mag (to match its color). There was only one such source, indicating that the probability that the excess of the star results from a chance juxtaposition is ∼10⁻⁶, assuming a matching radius of 1″. We do not consider this possibility further.

2.2. Light Curves

We now discuss observations in the infrared and optical that document the variability of V488 Per and its debris disk. There are two sets of infrared data: one from Spitzer/IRAC and the other from WISE as described in Section 2.2.1 and three sets of optical data as described in Section 2.2.2.

2.2.1. Infrared Light Curve

During the Spitzer warm mission, we monitored V488 Per regularly to search and characterize its infrared viability. V488 Per had two ∼45 days visibility windows every year for Spitzer, separated by ∼120 days. We report in Figure 1 Spitzer/IRAC warm mission observations made under programs 11093, 13014, and 14226 from 2015 April through the end of the mission in early 2020, providing a total time baseline of ∼1800 days. All observations used both the 3.6 and 4.5 μm IRAC wave bands (IRAC1 and IRAC2). Sampling frequencies were typically once per three days. We used a frame time of 30 s with 10 cycling dithering positions for both bands, achieving a typical signal-to-noise ratio of 150–300. The dithering pattern was designed to use a number of random pixel positions to average the intrapixel sensitivity variations of the detector.4 Furthermore, V488 Per was observed once with IRAC (AOR 18853632, PID: 30717) during the Spitzer cold mission as reported by Zuckerman et al. (2012). For consistency, we also conducted our own photometry on these data.

The data were processed by the Spitzer Science Center (SSC) with IRAC pipeline S18.18.0 for the cold mission and with S19.2.0 for the warm mission. We used the BCD (basic calibrated data) images, which have a native scale of 1/22 pixel⁻¹. We performed aperture photometry using an on-source radius of 3 pixels and a sky annulus between 12 and 20 pixels, with aperture correction factors of 1.112 and 1.113 for 3.6 and 4.5 μm, respectively. The BCD photometry was corrected for the pixel solid angle (i.e., distortion) effects based on the measured target positions using files provided by the SSC. We

| Source  | R.A.      | Decl.      |
|---------|-----------|------------|
| GAIA EDR3 | 03 28 18.683 | 48 39 48.192 |
| 2MASS   | 03 28 18.683 | 48 39 48.222 |
| ALLWISE | 03 28 18.699 | 48 39 47.97  |
| PACS    | 03 28 18.63 ± 0.04 | 48 39 47.8 ± 0.35 |

Note. a Position from PACS Point-Source Catalog at 70 μm (Marton et al. 2017).

Figure 1. Light curves for the entire Spitzer/IRAC monitoring period for V488 Per. Time is given in Julian date along the bottom and in civil date (with double arrows to separate years) along the top. The upper two curves show the evolution of the excess above the stellar photospheric emission at 4.5 μm (red) and 3.6 μm (blue). The middle curve is the optical (V-band) behavior with the zero-point suppressed by 20 mJy, shown in greater detail in Figure 3. The lower curve shows the evolution of the color temperature between these two infrared bands, showing that it peaks when the excess emission is also at a peak.
also discarded any photometry when the target was too close to the edge of the detector array and obtained weighted-average photometry for each of the astronomical observation requests (AORs) by rejecting the highest and lowest photometry points in the same AOR. The same procedures were also conducted on the mosaic post-BCD products for comparison. A few in the same AOR. The same procedures were also conducted on the weighted average of the BCD images, which were not subject to this issue. Table 2 lists all the IRAC band 1 and band 2 photometry. Figure 1 gives a quick overview for the warm mission data, showing large variations in the infrared excess and its temperature while the V-band brightness of the star stays nearly the same.

The nominal ratio of noise to signal for our measurements, including the star and the disk, at individual epochs is typically 0.3%–0.6%. Additional sources of noise typically bring IRAC photometry to the 1% uncertainty level. We have tested our measurements by extracting photometry for six stars within the field for V488 Per, and we find, indeed, that the rms scatter for them is ~1%.

Our fit to the spectral energy distribution (SED) of the star (below) suggests that the disk excess emission varies from 30% to 60% of the total signal at 3.6 μm and from 60% to 75% at 4.5 μm, so the nominal errors in the disk signal (after removing the stellar contribution) range from 1% to 2%. More seriously, any error of the adopted photospheric flux would introduce a systematic error to the disk flux and color, which can hardly be identified in later analysis. As illustrated in Figure 1, the infrared observations show a continuous behavior with no abrupt changes, supporting that the errors are relatively small. Thus, the absolute values of the color temperature of the disk may be biased, but the relative color variations should be more robust. Unlike the case for ID8 (Meng et al. 2014), there is a clear change in the color temperature with output level, with the temperature being higher when the disk is brighter (see lowest panel in Figure 1).

We collected all WISE measurements from the NASA/IPAC Infrared Science Archive where single exposure source catalogs are available through different phases of the WISE mission (WISE All Sky Database, WISE 3-Band Cryo Database, and NEOWISE Reactivation Database). These single-exposure measurements were averaged over a period of three days, i.e., the same cadence as the Spitzer warm mission measurements), rejecting the highest and lowest photometry points. Table 3 and Figure 2 summarize these WISE measurements. They show variations similar in amplitude to those obtained in the Spitzer monitoring campaign, but are much less well-sampled. They start well before our more detailed monitoring and show that the excess has been in place at a similar level and degree of variability for at least 15 yr. The large increase in excess at the end of our intensive IRAC monitoring series is preceded by about 100 days by a similarly large excess in the WISE bands and is only beginning to decay a year after it was first detected with WISE. We compared the first epoch of the WISE data shown in Table 3 with the values from the ALLWISE catalog (same data set, but processed differently) and found that the single-exposure photometry is ≥10% brighter, which is not of concern for this study. The long-term repeatability should be within ~3% (Cutri et al. 2013, 2015).

2.2.2. Optical

V488 Per was identified as a BY-Draconis-type variable by Stauffer et al. (1985), i.e., showing modest periodic variations as large starspots rotate into and out of the direction toward the observer. To study the variability of this star, we have used optical V-band photometry from the AAVSO and ASAS-SN (Shappee et al. 2014) archives, plus measurements specifically obtained for this program with Super-LOTIS (Livermore

### Table 2

| AORKey  | BMJD,11 | F,11 (mJy) | err,11 (mJy) | BMJD,12 | F,12 (mJy) | err,12 (mJy) |
|---------|---------|------------|-------------|---------|------------|-------------|
| 18853632 | 54004.270160 | 62.00 | 0.25 | 54004.267730 | 56.12 | 4.16 |
| 53435922 | 57129.471620 | 41.81 | 0.25 | 57129.469200 | 46.00 | 0.15 |
| 53435136 | 57132.749360 | 41.71 | 0.32 | 57132.746960 | 46.33 | 0.11 |
| 53434880 | 57135.692400 | 41.58 | 0.26 | 57135.690000 | 46.56 | 0.10 |
| 53434368 | 57138.312940 | 42.39 | 0.21 | 57138.310560 | 46.73 | 0.13 |
| 53433856 | 57141.005870 | 41.68 | 0.26 | 57141.003510 | 46.66 | 0.13 |

(This table is available in its entirety in machine-readable form.)

### Table 3

| BMJD | W1 (mJy) | W2 (mJy) |
|------|----------|----------|
| 55243 | 51.7 | 58.7 |
| 55433 | 40.4 | 46.7 |
| 55441 | 40.5 | 47.8 |
| 56707 | 58.7 | 71.1 |
| 56898 | 55.6 | 63.6 |
| 57066 | 34.8 | 38.4 |
| 57260 | 49.0 | 54.0 |
| 57425 | 33.9 | 36.4 |
| 57625 | 36.6 | 37.7 |
| 57792 | 40.9 | 43.8 |
| 57991 | 36.5 | 37.8 |
| 58150 | 37.7 | 41.2 |
| 58355 | 26.0 | 21.0 |
| 58514 | 30.9 | 29.6 |
| 58722 | 80.6 | 87.7 |
| 58878 | 74.6 | 88.6 |
| 59086 | 63.9 | 76.8 |

Note.

*Errors will be dominated by WISE repeatability, ~3%.*
Optical Transient Imaging System, a robotic telescope dedicated to the search for optical counterparts of gamma-ray bursts (GRBs) and located at the Steward Observatory Kitt Peak site. There is a single high value, 35.8 mJy, on JD 2457125.57 from the AAVSO data. The fluxes were in the usual range on the previous date and four days later. This could either be a flare, which is common behavior in BY-Dra stars, or a bad measurement. We have omitted it from our further analysis. Figure 3 shows all of the remaining photometry obtained during the same period as the Spitzer data.

2.3. Other Observations

Here, we identify additional measurements that provide additional insights into the V488 Per debris-system behavior, but do not have a cadence that reveals the variations of its output.

2.3.1. Additional Mid-infrared Photometry

Photometry of V488 Per using intermediate-band filters around 10 μm was obtained with COMICS (Kataza et al. 2000; Okamoto et al. 2003) on the Subaru Telescope on 2017 January 14 and 2018 January 28 (BMJD–57120 of 648 and 1027, respectively). The standard chopping by the secondary mirror was used at a frequency of 0.2 Hz; the chopping throw was 15″. Rather than relying on traditional standard stars and air-mass corrections, we observed the nearby star HD 19373, spectral type G0V, and took the WISE measurement of this star to derive the flux calibration. Because the ratio of signal to noise was modest in both runs and the debris disk was of similar brightness (see below), we averaged the measurements for our analysis. These measurements are listed in Table 4 and discussed further in Section 3.5. The flux density for V488 Per observed in the COMICS bands agrees well with the IRAC Band 4 and WISE W3 measurements within the errors, i.e., within the sparse time sampling and limited signal to noise, there is no evidence for variations near 10 μm at amplitudes as large as those seen near 4 μm.

IRAC photometry was reported by Zuckerman et al. (2012) on BMJD–57120 = −3115 (2006 September 26) (AORKEY: 18853632). We have rereduced these measurements with results summarized in Table 5. As shown in Figure 2, these measurements (at the extreme left of the figure) were obtained when the excess was relatively bright.
2.3.2. Herschel

Herschel PACS 70 and 160 μm observations were obtained in 2012 September 11 (PID OT2_cmelis_3, OBSID 1342250847 and 1342250848) using the PACS mini-scan map mode. We retrieved the archival data from the Herschel Science Center and reduced the data following the procedure outlined in Balog et al. (2014) to produce the final mosaics. The source is detected at both bands, but with less signal-to-noise in the 160 μm map due to large-scale cirrus present in the data. We used aperture photometry to estimate the PACS flux by fixing the source center at the centroid of the 70 μm position. Aperture sizes of 6'' and 11'' with aperture correction factors of 1.57 and 1.54 were used for the 70 and 160 μm data, respectively. Including the flux-calibration uncertainty, the final PACS photometry is 63.3 ± 5.9 mJy in the 70 μm band, and 25.7 ± 12.2 mJy in the 160 μm band. Our 70 μm flux agrees well with the Herschel PACS point-source catalog (Marton et al. 2017): 66.45 ± 6.66 mJy. The fluxes are shown in Table 4.

![Figure 3](https://via.placeholder.com/150)

Figure 3. Visible light curve for the entire Spitzer monitoring period for V488 Per. The super-LOTIS measurements contribute to the dense set in the first 500 days and are not shown separately. There is a possible weak trend with time, shown by the fit. We also find evidence for a periodic variation with an amplitude of ~5.9% for the first year, but <2% for the remaining time (see text). Removing this effect, the rms scatter is 2.1%–2.4%.

| Band (μm) | mJy   | Error | References     | Only |
|----------|-------|-------|----------------|------|
| B (0.44) | 12.9  | 0.61  | Mermilliod et al. (1987) | … |
| V (0.55) | 29.17 | 1.31  | This Work      | …   |
| J (1.24) | 63.39 | 1.21  | 2MASS          | 64.2 |
| H (1.66) | 66.55 | 1.75  | 2MASS          | 65.6 |
| Ks (2.16)| 49.06 | 1.12  | 2MASS          | 44.8 |
| W1 (3.55)| 42.8  | …     | This Work      | 23.2 |
| W2 (4.6) | 43.3  | …     | This Work      | 12.4 |
| 8.8 (Δλ = 0.8 μm) | 42 | 4 | This Work | 3.5 |
| 10.5 (Δλ = 1.0 μm) | 52.5 | 9 | This Work | 2.4 |
| W3 (11.56) | 43.68 | 1.4 | ALLWISE | 2.0 |
| 11.7 (Δλ = 1.0 μm) | 40 | 8 | This Work | 1.9 |
| 12.4 (Δλ = 1.2 μm) | 52 | 19 | This Work | 1.7 |
| W4 (22.09) | 74.14 | 2.35 | ALLWISE | … |
| 70       | 63.3  | 5.9  | This Work     | …   |
| 70       | 66.45 | 6.66 | Herschel/PACS | …   |
| 160      | 25.7  | 12.2 | This Work     | …   |

| Band (μm) | mJy   | Error |
|----------|-------|-------|
| 3.54     | 61.4  | 0.9   |
| 4.49     | 57.1  | 0.9   |
| 5.71     | 63.5  | 0.9   |
| 7.84     | 59.8  | 0.9   |

Notes

a The tabulated photometry is for bands either known not to vary over our monitoring period or where the cadence does not document the variations clearly.

b ALLWISE for W1–W4 plus NEOWISE for W1–W2 photometry.

c Average flux density for all WISE measurements in this band, supplied for context.

d 3% error assumed.

Table 4
Multiband Photometry of V488 Per

Table 5
IRAC Photometry on 2006 September 26
Table 6
Radial Velocities of V488 Per

| v (km s⁻¹) | Error (km s⁻¹) | JD | References |
|------------|----------------|----|------------|
| −0.1       | 0.6            | ... | Stauffer et al. (1985) |
| −0.31      | 0.15           | ... | Mermilliod et al. (2008) |
| 1.8        | 0.5            | 2450795 | Zuckerman et al. (2012) |
| 0.64       | 0.87           | ... | Gaia DR2 |
| −0.059     | 0.1*           | 2457821.6 | Majewski et al. (2017) |
| 0.337      | 0.1*           | 2458097.8 | Majewski et al. (2017) |
| 0.177      | 0.1*           | 2458148.7 | Majewski et al. (2017) |
| −0.087     | 0.1*           | 2458179.6 | Majewski et al. (2017) |

Note.
* Errors according to the SDSS documentation https://www.sdss.org/.

2.3.3. Radial Velocities

Table 6 reports measurements of the radial velocity of V488 Per. The weighted average of 0.07 ± 0.05 km s⁻¹ is consistent with the average for the α Per Cluster (−1.39 ± 0.17 km s⁻¹ Mermilliod et al. 2008) within the cluster velocity dispersion of ≲1.1 km s⁻¹ (Makarov 2006). The deviation of the individual measurements from the average for the star is insignificant in seven cases (≲2σ) and marginally significant at 1.73 km s⁻¹ for the eighth. The scatter in the APOGEE measurements, which appear to be the most accurate, is ≈0.2 km s⁻¹, only slightly larger than the quoted errors.5

2.3.4. X-Ray

Prosser et al. (1996) report an X-ray detection of V488 Per with the ROSAT Position Sensitive Proportional Counter (PSPC). They find that log(LX (erg s⁻¹)) = 29.68 and log(LX/Lbol) = −3.33. As a K dwarf, the detection is expected; the overall detection rate for K-dwarfs in the cluster is 83%, and the X-ray flux from V488 Per is typical for the cluster members (Prosser et al. 1996).

3. Analysis

In this section, we first show that V488 Per is a main-sequence K2-2.5V star, younger but analogous in many ways to ε Eridani, a similarity we use later in modeling the system (Section 3.1). In Section 3.2, we investigate the stellar variability, showing that the output has been constant within a few percent and that stellar variations do not drive the changes seen in the infrared. Consequently, those changes are driven by motions of the dust grains produced in planetesimal collisions, as we discuss in Section 3.3. In Section 3.4, we identify planets or low-mass brown dwarfs in a V488 Per planetary system as the drivers of those collisions. With the results of these four sections as boundary conditions, we construct a simple, optically thin model of the debris disk in Section 3.5; it consists of an outer, cold disk at ≈25–45 au radius, an inner ring at 0.30–0.35 au, and a population of finely divided dust being dragged from this ring into the star by the stellar wind until it reaches the dust sublimation radius at ≈0.01–0.02 au, where the grains are destroyed. The resulting SED, shown in Figure 4, provides a pictorial summary of the section. In Section 3.6, we show that the level of activity we are witnessing must involve collisions of large asteroid-sized bodies and that it is unlikely to be sustained for much longer than ∼1000–10,000 yr. Section 3.7 briefly summarizes the status of the system.

3.1. Stellar Properties of V488 Per

V488 Per is often described as being a K0-type star (e.g., Zuckerman et al. 2012), but this designation appears to arise from photometric, not spectroscopic, arguments (Allain et al. 1996). Its Teff of ∼4930 K (Balachandran et al. 1988; Randich et al. 1998), ~4906 K (LAMOST), or 4977 K (Bai et al. 2019) suggests a spectral type of K2—K2.5V (Pecaut & Mamajek 2013).6 At the age of the α Per cluster, a K2V star will have settled onto the main sequence. We compare the photometry of the star with a Kurucz model for a main-sequence 5000 K dwarf in Figure 4. The agreement is excellent, indicating that the type designation is appropriate and that the star is very little reddened. Integrating the Kurucz model fitted to the photometric points (see Figure 4), we derive a luminosity of 0.28 ± 0.03 L⊙, again midway between K2V and K2.5V (Pecaut & Mamajek 2013).

The basic properties of V488 Per are very similar to those of ε Eridani, as shown in Table 7. The latter star provides the closest example of a substantial debris disk and is very thoroughly studied. Given the similarity of the two stars, it will be beneficial to argue by analogy in interpreting some of the behavior of V488 Per and its debris system.

3.2. Optical Variability

Stauffer et al. (1985) reported periodic variations for V488 Per with a peak-to-peak amplitude in V-band of ∼5% and a period of ∼5.15 days. Eleven years later, Allain et al. (1996) found the star to have a peak-to-peak variability amplitude in the V-band of ∼10% with a period of ∼6.4 days. In both cases the observations extend only over two periods, but Allain et al. (1996) suggest that the period difference is real and might reflect differential rotation. Heinze et al. (2018) did a Fourier analysis of photometry of the star from the ATLAS survey (ATLAS uses a robotic telescope with a CCD covering 5° and scans half of the accessible sky each night), finding a period of 5.975 days.

We used a phase-curve analysis to look for periodic variations in our much longer optical data string, searching for periods between 5 and 6.5 days to bracket the previous reports. There is an indicated periodicity at 5.967 days, in agreement with the value from the ATLAS survey. With this approach, the results are degenerate with a number of indications of different periods, but none is any larger in amplitude than the 5.967 day one. There are also TESS data from 2019 November, for three weeks (i.e., only a few periods). They show a possible period at about 5.24 days, supporting the evidence for differential rotation. The peak-to-peak amplitude of the variations is ≲2%.

BY-Dra-type variations typically only change significantly in amplitude over long timescales—of order a year or more (Alekseev & Kozhevnikova 2018). Therefore, to investigate further, we analyzed just the first year, 2015–2016, which as shown in Figure 5, shows periodic variations with a peak-to-peak amplitude of 5.9%. We then analyzed the second year, then the third, and finally the rest, into early 2020, i.e.,

5 https://www.sdss.org/
6 Also see http://www.pas.rochester.edu.
including the period when the TESS data were obtained. None of these latter intervals showed evidence for variability with this period greater than 2% peak-to-peak, in agreement with the short sequence obtained with TESS. Figure 6 shows the period plot for all the data past the first year. The difference in behavior between the first year and the remaining time is supported by the rms scatter without removing the variability: 3.1% for the first year; 2.4% for the rest. If we compensate for the variability in the first year, the rms scatter is reduced to 2.1%, indicating that the decrease in rms scatter after the first year is associated with a reduction in the amplitude of the BY-Dra-type behavior. In addition, the star is about 2% brighter after the first year (see Figure 3), consistent with lower surface coverage by spots (Alekseev & Kozhevnikova 2018).

Given that the measurements include contributions from a large number of observers using a similarly large number of instruments, it is likely that a significant contribution to this remaining scatter is systematic errors from one photometric system to another, as well as statistical errors. That is, the variation of the star other than the periodic modulation and possible long-term trend, is likely to be <2%. Although only for a short interval, the TESS data support this conclusion.

Table 7

Comparison of V488 Per with ε Eri

| Property                     | V488 Per | References            | ε Eri    | References            |
|------------------------------|----------|-----------------------|----------|-----------------------|
| Spectral type                | K2-2.5 V | This work             | K2V      | Gray et al. (2006)    |
| Temperature (K)              | 4977     | Bai et al. (2019)     | 5084     | Kovtyukh et al. (2003)|
| Luminosity (L_☉)             | 0.28 ± 0.03 | This work          | 0.335    | Bonfanti et al. (2015)|
| Rotation period (days)       | 5–6      | This work             | 11.2     | Fröhlich (2007)       |
| Variability type             | BY Dra   | Stauffer et al. (1985)| BY Dra   | Fröhlich (2007)       |
| X-ray luminosity (erg s⁻¹)   | 5 × 10²⁹ | Prosser et al. (1996) | 2 × 10²⁸ | Coffaro et al. (2020) |
| Outer debris ring radius (au) | ~35     | This work             | 64       | Chavez-Dagnosto et al. (2016) |
| Age (Myr)                    | ~80      | Soderblom et al. (2014)| ~440    | Barnes (2007)         |
| Distance (pc)                | 173.5    | Gaia EDR3             | 3.22     | Gaia EDR3             |

Figure 4. Model SED for V488 Per. Photometry in the stellar-dominated regime is shown as black points, which are fitted well by the 5000 K Kurucz dwarf star model, as shown. The model is extended to longer wavelengths with the points showing the stellar flux at some of the mid-IR bands. The mid-IR disk measurements have been determined for two output levels (see text), one shown in red and the other in blue with the disk SED model shown for each on the assumption that the amplitude does not affect the silicate emission strength. The disk point at 2.16 μm is shown in orange because the output level when it was obtained is not known. The variability is not expected to extend into the far-infrared, hence only one set of values is shown here (based on a disk extending from 25 to 45 au). The dashed line is the sum of the two disk component fluxes in the range where they are comparable for the red model. These models have 3.6% of the stellar luminosity being reradiated by the outer disk component and 10.1% (blue model) or 16% (red model) by the inner one, for a total fractional excess (L_disk/L_☉) of ~14–20%, reproducing the high fractional luminosity of ~16% reported by Zuckerman et al. (2012).
There is no other evidence for variations in the V band over the entire set of data; in particular, although flares are sometimes seen in BY-Dra variables, there is no convincing evidence of any for this star (other than the single measurement early in our monitoring period). The average magnitude over the 1760 measurements, $V = 12.84$, agrees with values of 12.83 reported over the past 15 yr (e.g., Stauffer et al. 1985; Allain et al. 1996). That is, the star is non-variable to the few % level in V over our entire measurement period, from 2015 to 2020. Even in the first year of our monitoring, where there was a significant amplitude of periodic optical variations, there was no infrared variability at that period. That is, there is no stellar variability that could power the variations seen in the infrared debris-disk emission.

### 3.3. Grain Dynamics

We now move toward modeling the behavior of the debris disk as revealed by the infrared variations. Given a mechanism to stir the planetesimals around V488 Per and cause them to collide, the observational signatures of this process depend on the production of dust in the collisions and their aftermath, and then the motion of dust grains subsequent to these collisions. The production of copious amounts of dust on a short timescale is common to other extreme and variable debris disks (e.g., Su et al. 2019). However, because of the low stellar luminosity of V488 Per, it is plausible that the subsequent motions of those dust grains differ from the previously studied systems. Here we discuss the grain dynamics as constrained by the variability characteristics.

#### 3.3.1. Loss by Radiation-Pressure Force

The infrared light curve (Figures 1 and 2) shows decays after emission peaks with timescales as short as a few months, requiring a rapid grain removal mechanism. Similar behavior is seen in some other variable debris disks such as ID8 (e.g., Su et al. 2019), where the behavior is sampled much better because of the longer visibility window for Spitzer. However, in all the other cases, the rapidly variable disks are around more massive and luminous stars. In those situations, once grains are broken down to micron sizes, radiation-pressure force blows them outward from the star relative to their birth places. The affected grains will quickly flow to radii where they are at reduced temperatures and hence do not contribute substantially to the infrared signals at 3–5 μm where the variability is observed. Issues remain because a normal collisional cascade will continue to replace the very small grains, but if the grains are produced in ways that avoid this process (e.g., condensed from vapor), then the short timescales are readily explained. However, at the luminosity of V488 Per, first-order estimates, generally assuming solid spherical grains, indicate that radiation-pressure force will be too weak to eject grains.

A more complete picture is provided by calculations assuming more realistic grain properties, i.e., irregular shapes, differing compositions. Arnold et al. (2019) report calculations for these more complex cases, which include ε Eri so we can apply their results directly to V488 Per. They show that carbon grains smaller than ~1 μm in size are subject to radiation-pressure blowout, but silicate and ice grains of any size are not (this would be particularly the case at the modestly lower luminosity of V488 Per). Grains of mixed composition with a dominant fraction of carbon were also subject to blowout, but those of predominantly silicates were not. That is, blowout cannot be ignored but at least a large subset of grains are not likely to be removed by this process.

#### 3.3.2. Loss by Stellar Wind Drag

For grains where radiation-pressure force does not overcome gravity, grain dynamics are determined by Poynting–Robertson ($P - R$) drag and the effects of the stellar wind. $P - R$ drag is much too slow to account for the variability. However, stellar wind drag has already been shown to be of potential interest for
places an upper limit of \( \sim \) radius for plausible grain properties is \( r \)

\[ \beta \text{ where} \]

\[ \text{where} \]

\[ \text{of the} \]

\[ \text{the} \]

\[ \text{output. Thus, although the wind does not appear to dominate} \]

\[ \text{indicates that it should be indicative of the current} \]

\[ \text{dynamics around} \]

\[ \text{likely that the stellar wind plays a central role in the} \]

\[ \text{stars can be estimated to be} \]

\[ \text{we get} \]

\[ \text{proportional to} \]

\[ \text{X-ray surface} \]

\[ \text{impact dust grains and they recoil anisotropically. The process is} \]

\[ \text{analogous to} \]

\[ \text{timescales:} \]

\[ \frac{\tau_{P-R}}{\tau_{SW}} = \frac{Q_{SW}}{Q_{P-R}} \frac{M_{SW}}{M_*} \frac{c^2}{L_*}, \]

where \( Q_{SW} \) and \( Q_{P-R} \) are the coupling coefficients and \( M_{SW} \) is the mass loss in the wind. For \( Q_{SW}/Q_{P-R} = 1 \) and \( M_{SW} = 2 \times 10^{-14}M_\odot \text{yr}^{-1} \) (values appropriate for the Sun), the ratio is 0.37. \( M \) for \( \epsilon \) Eri is about 30 times that for the Sun (Wood et al. 2002) and taking \( M_{SW} \) for V488 Per to be 25 times higher still, we get \( \tau_{P-R}/\tau_{SW} \sim 300 \) for V488 Per. From Gustafson (1994), the time required for a particle under \( P-R \) drag to fall into a star can be estimated to be

\[ \tau_{P-R} \approx \frac{400}{\beta} \left( \frac{M_*}{M_{\odot}} \right) \left( \frac{r_0}{\text{au}} \right)^2 \text{yr}, \]

where \( \beta \) is the ratio of radiation force to gravitational force and \( r_0 \) is the starting distance from the star. Since the sublimation radius for plausible grain properties is \( \sim 0.01-0.02 \text{au} \), this equation is also appropriate for a grain to reach this radius. For grains between 0.1 and 1 \( \mu \)m in size, we can take \( \beta = 0.2-0.4 \) from Arnold et al. (2019). Equation (2) gives a time of \( \sim 300-150 \text{yr} \) for such a grain to be destroyed by falling from the inner debris ring at \( \sim 0.3 \text{au} \) (see next section) to the sublimation radius through \( P-R \) drag, confirming that this process is much too slow to account for the variability. However, these estimates convert to only 6–12 months for stellar wind drag to bring a grain inwards from 0.3 \( \text{au} \). This is a sufficiently good match to the observed behavior to identify stellar wind as the driving effect causing the grains to spiral inward and be lost by sublimation, leading to a drop in the debris-disk flux after a peak.

This loss mechanism can also account for the increase in color temperature between 3.6 and 4.5 \( \mu \text{m} \) when the flux in these bands increases (see Figure 1). If an increase marks a major collision, grains of size \( \leq 2 \mu \)m will migrate rapidly inward where they are heated toward their sublimation temperatures. Grains larger than 2 \( \mu \)m have smaller values of \( \beta \) (Arnold et al. 2019) and will remain closer to their creation positions, where they can participate in collisional cascades to restore small grains to maintain their equilibrium value in the disk. That is, a qualitative description of the variations is that there is a belt of planetesimals with a highly elevated rate of collisions. When a particularly large collision occurs, we see an elevation of the debris-disk-reradiated energy, which we have been able to monitor between 3 and 5 \( \mu \text{m} \) but presumably also affects the longer wavelengths, e.g., 10 \( \mu \text{m} \). This behavior decays and the dust grains are heated and destroyed as they spiral into the star under the influence of stellar wind drag.

### 3.4. What Drives the Variability?

At the age of \( \alpha \) Per (80 Myr), the most durable protoplanetary disks will have dissipated (Meng et al. 2017), requiring that the V488 Per disk originate as a massive debris...
disk, i.e., replenished by planetesimal collisions rather than being primordial. The vast majority of debris disks at this age have settled into a regime with fractional excesses $<1\%$ and are geometrically thin. The high fractional excess of the inner ring in the V488 Per disk requires not just that it be very dense, but that it have sufficient thickness out of the disk plane to capture a large fraction (i.e., $\sim 10\%–15\%$) of the stellar luminosity, requiring a thickness of order 0.1 au. Along with the variability, these attributes require that the disk must undergo substantial disturbances that stir it to enhance the collisional rates. We consider three possibilities: (1) coronal activity, (2) stirring by nearby stars, or (3) stirring by members of a V488 Per planetary system.

3.4.1. Coronal Activity

It has been suggested that rapid debris-disk variability is triggered by coronal ejections and similar activity from the star (Osten et al. 2013). The overall X-ray luminosity that indicates a typical level of coronal activity rather than an extraordinary one, plus the behavior of the BY-Dra variability, with a low amplitude during most of the period when we observe substantial infrared variations, would seem to contradict this hypothesis. Other than an initial possible flare, there is no indication in the optical for flare-like events. In addition to the lack of evidence for extraordinary coronal activity, it is hard to understand how this mechanism can produce major increases in the amount of dust, particularly as seen at the end of our Spitzer monitoring. We therefore discard the possibility of the infrared variations being related directly to coronal activity.

3.4.2. Possible Stellar Companions

Zuckerman (2015) has suggested that the extreme debris-disk phenomenon may be linked to close stellar companions and the resulting possible perturbations. Specifically for V488 Per, he identified two X-ray-emitting stars with proper motions consistent with membership in the $\alpha$ Per cluster as possibly being linked with the huge infrared excess. One of these stars, APX 43A, has a parallax from Gaia EDR3 of 5.914 $\pm$ 0.013 mas, consistent with cluster membership but is indicated to be 4.4 $\pm$ 0.6 pc in front of V488 Per. The second star, APX 43B, has a Gaia EDR3 parallax of 7.081 $\pm$ 0.27 mas compared with 5.764 $\pm$ 0.012 mas for V488 Per and thus appears to be roughly 40 pc in the foreground of the cluster. However, as already indicated by the relatively large quoted error, the fit to this star is poor and its parallax may be consistent with cluster membership.\(^7\) The projected distance of this star from V488 Per is $\sim 70$ au, but the debris system model discussed below indicates that the physical separation is larger. The presence of a cold debris-disk component at a nominal radius of 25–45 au (as discussed in the next section) is probably incompatible with a stellar mass companion closer than $\sim 100–135$ au (Yelverton et al. 2019). Given the low mass of APX 43B (as a M4.5 dwarf Zuckerman 2015), its influence from this distance on the 0.3 au ring responsible for the huge warm excess therefore should be very small.

3.4.3. System Members

The radial velocity measurements (Table 6) let us put constraints on closer-in companions that might be triggering the debris-generating activity. The mass of any companion is

\[
M_{\text{comp}} = \sqrt{\frac{M_\star v_\star}{G \sin(i)}}
\]

where $M_\star$ is the mass of the host star, $v_\star$ is its Doppler velocity, $i$ is the inclination of the companion orbit to the plane of the sky, and $r$ is the radius of the orbit of the companion, all in SI units. From the APOGEE measurements (Majewski et al. 2017), we adopt an upper limit to any radial velocity due to a companion of 0.5 km s$^{-1}$. The BY-Dra variability of the star arises through rotation of starspots in and out of our view. It therefore implies that the rotation axis lies roughly on the plane of the sky and that we see the star roughly equator-on. Assuming an orbit at the same inclination, we set $i = 60^\circ$ and also set $M_\star = 0.75 M_\odot$. We then find that any companion orbiting within 25 au of the star, i.e., inside the outer debris ring, must have a mass $<0.08 M_\odot$, i.e., must be a substellar member of the V488 Per system. However, a massive brown dwarf close to this limit is unlikely to be compatible with the existence of the outer ring (Trilling et al. 2007; Rodriguez & Zuckerman 2012; Rodriguez et al. 2015; Yelverton et al. 2019). Only an object close to planetary mass would be consistent with the existence of the outer debris component (Yelverton et al. 2020), so it is probable that a planetary or low-mass brown-dwarf system member (or members) is responsible for the inner disk activity.

3.5. Simple Model

To obtain a rough idea of the layout of the circumstellar material around V488 Per, we have computed an optically thin debris-disk model.\(^8\) This fit suggests the need for three disk components: (1) an outer ring at 25–45 au that dominates the far-infrared, (2) a ring at 0.30–0.35 au, and (3) a distribution of micron-sized grains extending from 0.3 au inward to the sublimation radius and representing the grains being dragged inward by the stellar wind. A flat distribution with radius is appropriate for grains migrating under stellar wind drag (e.g., van Liefhout et al. 2014). The $n_0$ dependence of the inflow timescale in Equation (2) already implies this behavior.

The modeling begins by assembling two SEDs, corresponding to the two times where we can assemble the appropriate measurements across the 3–15 $\mu$m range and representing two disk emission levels. Figure 2 illustrates the assembly of the data for the models. The first period, which uses the cryogenic WISE data from BMJD 55243 (2010 February 15, the first WISE measurements in Figure 2), is shown in red dots in Figure 4. We combine the WISE data with the full IRAC set in Table 5; at least for the two bands at almost the same wavelength (IRAC2 and W2), the flux levels are similar. The shorter wavelength IRAC band indicates a higher temperature than is typical, resulting in a point that lies somewhat above our fitted continuum. We include the W4 and Herschel data in both SEDs since we will show that it is unlikely that the variability extends to these wavelengths. The second model will apply for the times when we obtained the COMICS observations. To construct a full SED requires that we relate these measurements to the level of activity in the shorter bands. Fortunately, Figure 1 shows that the variability over any 45 day interval is

\(^7\) The indicated error is $\sim 2.2$ mas from the quality of the fit.

\(^8\) Using Debris Disk Simulator (Wolf & Hillenbrand 2005).
modest compared with the full amplitude. The second set of COMICS measurements (2018 January 28, BMJD 58147) was followed in three days by a set of WISE W1 and W2 photometry, with a value of 41.2 mJy for W2. The first set of COMICS measurements (2017 January 14, BMJD 57768) was preceded by 11 days with IRAC2 data and followed by 24 days with a W2 measurement; the flux density dropped by only 9% between them. We estimated a value at the time of the COMICS data of 43.8 mJy in W2 by linear interpolation. Since the two sets of COMICS measurements were obtained when the shorter wavelength activity was at closely the same level, we averaged the results from the two runs. Figure 4 also shows the excess in the $K_s$ band from the 2MASS photometry; since this cannot be associated with any particular level of activity, it is plotted as an orange triangle.

The model of the outer disk is appropriate for both activity levels. We fitted it with a dust mass of 0.05 $M_\odot$ in grains between 0.1 $\mu$m and 1 mm in size with a power-law grain size index of 3.65, distributed with grain density falling as $r^{-1.3}$ where $r$ is the distance from the star, and placed at 25–45 au. The total mass including bodies $>1$ mm in size would be much larger. We assumed grains with the optical constants derived as providing the best fit to the outer disk of $\beta$ Pic by Ballering et al. (2016).

For the inner material, we start by modeling the blue points. We first explored possible grain compositions; the modeling of Ballering et al. (2016) of the outer $\beta$ Pic disk need not apply to dust close to a star. In fact, we found that overall fits to the spectrum at wavelengths $<8$ $\mu$m could be obtained with dust of that composition or with astronomical silicate, placed at 0.13–0.15 au from the star with a radius-independent distribution inward to the sublimation radius. However, these fits (and ones using crystalline silicates in general) produced a very strong silicate emission feature radiated by the small grains and this meant the fit to the data at 8–13 $\mu$m was poor. We therefore took the inner ring to be 50% astronomical silicate and 50% carbon. We found a good fit with a mass of $6 \times 10^{-6} M_\odot$ with lower and upper grain size limits of 0.1 $\mu$m and 1 mm; this component was placed at 0.3–0.35 au from the star with the same grain size slope and density behavior relative to the star as for the first component.

For the third component, we assumed the same grain composition but included grains from 0.03 to 2 $\mu$m in size and distributed them with constant density from the inner radius of this ring, 0.3 au, to the sublimation radius at $\sim$0.01 au (we took the sublimation temperature of the carbon to be 2000 K, given the short duration of the exposure of the grains to the highest temperatures). The required grain mass is $\sim2.5 \times 10^{-8} M_\odot$. The overall fit, illustrated in Figure 4, is reasonable with this model. In it, 80% of the luminosity from the inner zone ($r < 20$ au) is radiated by the ring and 20% from the inner component representing the small grains being dragged into the star.

The red points were modeled by assuming an increase in the inner, dragged-in component with no other changes. A good fit was obtained (see Figure 4) by increasing the dragged-in dust output by a factor of $\sim 4.5$, so they contribute about half of the luminosity of this inner dust component in this case. These values are compatible with the change in fractional luminosity derived below.

The model indicates that 3.6% of the stellar luminosity is reradiated by the outer disk component and 10.1% (blue model) or 16% (red model) by the inner one, for a total fractional excess ($L_{\text{disk}}/L_{\text{star}}$) of $\sim 14\%–20\%$. In addition, the color temperature based on synthetic photometry to reproduce the IRAC1 and IRAC2 bands for the red points is about 80 K higher than with the blue-point model, in agreement with the observations in Figure 1. In addition to the extreme level of activity in the inner component, the 3% fractional luminosity of the outer disk component is also very high, indicating that the entire disk system is in a heightened state of activity. However, in the model, the outer disk component does not partake in the variability.

In general, models of this nature for debris disks are notoriously degenerate and the limited constraints and unique properties for this one make this even more the case. Our goal, therefore, is not to generate a unique model, but to show that the behavior can be explained within the constraints. However, the general properties appear to be robust. For example, fitting the far-infrared points with a blackbody model and applying a correction as in Equation (8) of Pawellek & Krivov (2015) indicates that the outer ring should have a radius of $\sim 35$ au, i.e., similar to the result above. The rapid variations of the 3–5 $\mu$m flux indicate the need for the inner component since it is required to produce the necessary high grain temperatures. It is not possible to match the flux density at 70 $\mu$m with this component and any plausible grain properties, thus requiring the outer component. That is, although more sophisticated models, e.g., including optically thick ring components, will modify the parameters, they are unlikely to avoid the necessity for two dust rings with the variations originating in one around 0.3 au from the star. The possibility of a lower density of grains between these components is not excluded—and in fact should exist due to stellar wind drag on grains in the outer component.

### 3.6. Required Masses

We can estimate the mass of the colliding objects that produce the dust as follows. We consider the major event in 2019 and the increase in dust of size between 0.3 and 2.0 $\mu$m that it requires over the more quiescent level of activity (from Figure 2, we take this to be twice the increase of the model for the red points over that for the blue ones). The resulting mass applies to grains between 0.3 and 2 $\mu$m in size; integrating up to a meter in size, and assuming a density of 3 g cm$^{-3}$, we estimate that the amount of material in the collisional cascade to produce the observed dust is equivalent to a single object of radius 85 km or if divided between two equal-sized bodies, each would be 60 km in radius. That is, this event alone represents the collision and breakup of two bodies similar in size to large asteroids in the solar system.

Another consequence of the model is that the dust mass flow into the star is high, of order $10^{17} - 10^{18}$ kg yr$^{-1}$ depending on whether the infall time is 1 or 0.1 yr. This is equivalent to the mass of Ceres every 10,000–1000 yr. That is, the extreme level of debris-disk activity around V488 Per must be very short-lived. Given that it is by a considerable margin the most extreme debris disk known, this conclusion is perhaps expected. At the age of 80 Myr, models suggested that the system should be past the era of the largest planetesimal impacts (e.g., Genda et al. 2015). Therefore, the extremely large amount of debris suggests that the planetary system around the star (as discussed in Section 3.4.3) is undergoing a major readjustment, perhaps roughly analogous to that resulting in the late heavy bombardment in the solar system.
3.7. Summary

The infrared excess of V488 Per is not only extremely large but is also variable on timescales of a few months. This behavior has persisted for at least 15 yr, but the mass required to sustain it suggests that it can have persisted for no more than 1000–10,000 yr. We interpret our results in terms of a massive planetesimal belt or low-mass brown dwarf perturbing the members of an asteroid-like belt about 0.3 au from the star, resulting in a high level of planetesimal collisions. The dust that results (largely from secondary collisions) migrates inward toward the star due to drag with the stellar wind. V488 Per is ∼80 Myr old, past the primary period for high rates of planetesimal collisions as terrestrial planets form in classical simulations of terrestrial planet formation (Genda et al. 2015). However, the collisional activity in its planetesimal system is perhaps the most extreme known. As a result, although an extreme collision rate associated with classical terrestrial planet formation scenarios is still possible (Chambers 2013), we may be witnessing a delayed instability as suggested in some recent simulations (e.g., Clement et al. 2020), i.e., with the high rate of dust production arising from migration or other forms of orbital instability within its (unseen) system of massive planets.

4. Conclusion

We report on a detailed study of the variations in the infrared emission by the most extreme known debris disk, that around the 80 Myr old K2-2.5V star, V488 Persei. Our observations and analysis of them show that:

1. The debris-disk emission varies with a very high level, comparable to the most variable systems known (e.g., ID8 in NGC 2547).
2. The star itself shows only small variations of the BY-Dra variety, and does not drive the infrared variations.
3. The debris system consists of an inner and an outer component, both of which have very high fractional luminosity (∼3.6% for the outer component, 10%–16% or even higher for the inner one).
4. The variations in the output of the inner component are most likely initiated by gravitational stirring of a belt of planetesimals at ∼0.3 au by a low-mass brown dwarf or a planet in the V488 Per system. This stirring is resulting in a high rate of collisions among massive planetesimals, resulting in episodic outbursts of dust production.
5. The dust grains generated as a consequence of this stirring migrate inward toward the star due to stellar wind drag, and eventually sublime at about 0.01 au from the star. As a result, they heat as they leave their place of formation.
6. Evidence for this type of migration is the increase in color temperature when the excess is bright.
7. This behavior contrasts with that of ID8, where the dust color temperature remains constant, consistent with the grains in that system being blown away from the star by radiation-pressure force, so they cool as they leave their place of formation.
8. The mass-loss rate from the V488 Per inner debris ring is extremely high and it is being produced by collisions of large planetesimals, indicating that the extreme excess and fractional luminosity will be short-lived. There is truly an exceptional level of collisional activity in the planetesimals around this star.
9. This extreme level of collisional activity is occurring relatively late in the system evolution. Although it might be a late event in the process of terrestrial planet formation, it may also signal a readjustment in the star’s planetary system roughly analogous to the Late Heavy Bombardment in the solar system.

The behavior of V488 Per along with that of ID8 in NGC 2547 and other related variable debris disks establishes that short-lived extreme episodes of planetesimal collisions are fairly common during the first 100 Myr of planetary system evolution. However, the details of this behavior for this star are unique in showing evidence that the mechanism for the loss of finely divided dust is stellar wind drag, rather than radiation-pressure force as is typical of more massive and luminous stars. The system also supports the possibility that some of the extreme systems around relatively old (≥50 Myr) stars are experiencing major readjustments of their planetary systems, rather than representing a continuation of the early phase of terrestrial planet building represented in classical simulations.

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Facilities: AAVSO, Spitzer, Herschel, TESS, Gaia, WISE, 2MASS, Subaru.
