Highly Structured Inner Planetary System Debris around the Intermediate Age Sun-like Star TYC 8830 410 1

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Abstract

We present a detailed characterization of the extremely dusty main-sequence star TYC 8830 410 1. This system hosts inner planetary system dust (TDust ≈ 300 K) with a fractional infrared luminosity of ~1%. Mid-infrared spectroscopy reveals a strong, mildly crystalline solid-state emission feature. TYC 8830 410 1 (spectral type G9 V) has a 49.5" separation M4-type companion comoving and co-distant with it, and we estimate a system age of ~600 Myr. TYC 8830 410 1 also experiences “dipper”-like dimming events as detected by the All-Sky Automated Survey for Supernovae, Transiting Exoplanet Survey Satellite, and characterized in more detail with the Las Cumbres Observatory Global Telescope. These recurring eclipses suggest at least one roughly star-sized cloud of dust orbits the star in addition to assorted smaller dust structures. The extreme properties of the material orbiting TYC 8830 410 1 point to dramatic dust-production mechanisms that likely included something similar to the giant impact event thought to have formed the Earth–Moon system, although hundreds of millions of years after such processes are thought to have concluded in the solar system. TYC 8830 410 1 holds promise to deliver significant advances in our understanding of the origin, structure, and evolution of extremely dusty inner planetary systems.

Unified Astronomy Thesaurus concepts: Circumstellar disks (235); Exoplanet systems (484); Variable stars (1761)

Supporting material: machine-readable table

1. Introduction

Infrared observations of main-sequence stars have demonstrated the existence of exceptionally dusty inner planetary systems. This is defined here to mean those stars hosting infrared excess emission having fractional infrared luminosity (τ = LIR/Lbol) of ≥1% for dust populations characterized by blackbody emission with an effective temperature of TDust ≥ 300 K. These are the dustiest main-sequence stars known and such systems are exceedingly rare (e.g., Balog et al. 2009; Uzpen et al. 2009; Melis et al. 2010; Kennedy & Wyatt 2013). To date, only a handful are known that have such high levels of mid-infrared excess emission and hence inner planetary system dust (see, e.g., Gorlova et al. 2004, 2007; Song et al. 2005; Rhee et al. 2007, 2008; Melis et al. 2010, 2012, 2013; Zucker et al. 2012; Schneider et al. 2013; Gaidos et al. 2019; Tajiri et al. 2020; Moór et al. 2021). Although it seems reasonably settled that transient collisional events between rocky bodies are necessary to generate the exceptionally dusty disks (Wyatt 2008; Fujiwara et al. 2012a; Olofsson et al. 2012), it is not clear if the dust is generated in a specific star or planet formation event or how it might impact fully formed planets (Melis 2016; Kral et al. 2017; Moór et al. 2021).

Some extremely dusty main-sequence systems have recently been found to exhibit dimming events due to the passage of circumstellar material along our line of sight (e.g., de Wit et al. 2013; Kennedy et al. 2017; Gaidos et al. 2019; Tajiri et al. 2020). These are similar in light-curve behavior to the “dipper” behavior seen for protoplanetary disk systems (e.g., Morales-Calderón et al. 2011; Cody et al. 2014, and references therein), although their circumstellar material is thought to be secondary in nature (generated by the collisional breakdown of mature planetesimals/planets). Such systems are typically young (<100 Myr) and in at least one case are also host to gaseous material (e.g., Punzi et al. 2018).

Main-sequence systems with both strong infrared excess emission from inner planetary system dust and “dipper” behavior can provide unique insight into the structure and evolution of this material (e.g., Kennedy et al. 2017; Gaidos et al. 2019). Infrared excess emission provides the means to localize (to some extent) the dust in the planetary system (avoiding potentially confounding situations like in the cases of J140747.93-394542.6, KIC 8462852, or similar stars; Mamajek et al. 2012; Boyajian et al. 2016, 2018; David et al. 2017; Meng et al. 2017; Mentel et al. 2018; Ansdell et al. 2019; Rappaport et al. 2019; Saito et al. 2019) while occultations in the light curve provide detailed information on its opacity and spatial organization (e.g., van Werkhoven et al. 2014; Kenworthy & Mamajek 2015; Kennedy et al. 2017).

In this paper we present the discovery of the oldest (~600 Myr) extremely dusty main-sequence star to also host dimming events due to orbiting material.

2. Literature Summary

TYC 8830 410 1 was first discovered to be an infrared excess star in the survey of Cotten & Song (2016). They suggest an uncertain spectral type of K3 (stellar Teff of 4900 K), black-body-fit dust temperature of 425 K and associated orbital radius
of 0.2 au for blackbody-emitting grains, and a fractional infrared luminosity of 1.2%. Subsequent works also found TYC 8830 410 1 to be an excess star (e.g., Marton et al. 2016; McDonald et al. 2017), but no further characterization of the excess was presented.

Optical spectroscopy of TYC 8830 410 1 was conducted as part of the Radial Velocity Experiment (RAVE) survey (Kunder et al. 2017). From observations made on 2009 November 10 (MJD of 55145.39994213) they measured a heliocentric radial velocity of 7.0 ± 1.8 km s⁻¹, stellar Teff of 5350 ± 140 K, stellar gravity log g of 4.4 ± 0.3 in cgs, and metallicity [M/H] of −0.1 ± 0.2. Further analysis on the RAVE spectra by Žerjal et al. (2017) suggested the presence of chromospheric Ca II infrared triplet emission from which an age of ≈370 Myr is estimated.

TYC 8830 410 1 has appeared in every Gaia release. We adopt parameters measured for it from DR2 and EDR3 (Gaia Collaboration et al. 2018, 2021); these are displayed in Table 1. While investigating the Gaia data, we identified a comoving wide-separation companion to TYC 8830 410 1. We describe this object in Section 4.1.

## 3. Observations

In this section we describe observations obtained for this work and archival data analyzed for this system for the first time.

### 3.1. FEROS

Multiple epochs of optical echelle spectroscopy were obtained for TYC 8830 410 1 with the Fiber-fed Extended Range Optical Spectrograph (FEROS) at the MPG/ESO 2.2 m telescope at La Silla Observatory (Kaufer et al. 1999). Observations were conducted in the “Object-Calibration” mode (R ≈ 48,000) with one fiber obtaining a simultaneous ThAr lamp spectrum to produce precise (≤ 20 m s⁻¹) radial velocities to aid in searching for close-separation companions.

Data are reduced with the Collection of Elemental Routines for Echelle Spectra (CERES; Brahms et al. 17), which also produces precision radial velocities for each epoch and associated uncertainties. FEROS observation epochs and measured velocities are listed in Table 2 along with literature velocities. It is noted that several instrumental artifacts are present in the Hα and Li i λ6708 order for each FEROS epoch; we consider results from this spectral order tentative and caution that they should be confirmed.

### 3.2. MagE

Observations with the Magellan Echellette (MagE) at Magellan/Baade were obtained for the wide-separation companion on UT 2019 November 10. The spectrograph was used with a 0.5″ slit resulting in R ≈ 8000 spectra from 4100 Å–10600 Å. Data are reduced with the facility Carnegie Python pipeline (Kelson et al. 2000; Kelson 2003). A total integration time of 2700 s resulted in a signal-to-noise ratio of 40 per pixel near Hα, 50 per pixel near Li i λ6708, and >50 per pixel in the TiO bands at 7000 Å–7600 Å. Two RV and spectral type standard stars were also observed with the same setup: GJ 54.1 in a 60 s integration and GJ 908 in a 10 s integration.

### 3.3. VISIR

Mid-infrared imaging and spectroscopy were obtained with the VLT Imager and Spectrometer for mid-Infrared (VISIR) instrument (Lagage et al. 2004; Käufl et al. 2015) mounted on VLT-Melipal at Paranal Observatory. Observations were conducted in service mode.

Imaging observations were conducted on UT 2016 January 4 in the AutoChopNod mode with default parameters, the chop/nod direction set to perpendicular, and positioning of the source in the left half of the chip. The 1024 × 1024 pixel detector was configured for 0.045′′ pixel⁻¹ yielding a field of view of roughly 46′′ × 46′′. Observations were performed with the PAH1 filter (8.59 μm central wavelength and a half bandwidth of 0.42 μm) and exposed for a total of 2440 s on source. The flux standard HD 220440 (Cohen et al. 1999) was observed immediately after observations of TYC 8830 410 1.

Spectroscopic observations were conducted over four nights: UT 2016 September 23, UT 2016 September 25, UT 2016...
October 1, and UT 2016 October 4. Each visit typically consisted of observations of TYC 8830 410 1 and two calibration stars (one before and one after observation of the science target), spending ≈90 minutes total wall clock time on the science target. The detector was configured for low-resolution spectroscopy and yielded a 0.076″ pixel⁻¹ spatial scale and spectral resolving power of R ≈ 300 from 7.5–14 μm with the N-band prism and 0.75″ slit. Sources were nodded along the slit with a 10″ throw to cancel out background emission and structure.

Data reduction was performed with in-house IDL routines optimized for background-limited observations. In brief, two-dimensional images were chop- and nod-differenced and combined for both the standard stars and the science target. Flux was extracted for each positive and negative beam for all targets with an aperture that yielded approximately 85% encircled energy.

For imaging data, each of the four chop/nod beams were averaged and the uncertainty set to the standard deviation of these four measurements divided by 2 (the square root of the number of measurements). The VISIR calibration webpage-generated flux density for HD 220440 (9.78 Jy) seemed to be too low compared to satellite measurements, so we constructed a broadband spectral energy distribution for the star from available high-fidelity photometry and fit a stellar atmospheric model to it (e.g., Cotten & Song 2016). From the model fit we estimated the flux in the PAH1 filter bandpass to be 10.37 Jy and used that when flux calibrating the extracted counts for TYC 8830 410 1. Photometric measurements for TYC 8830 410 1, including from VISIR, are given in Table 3.

Spectroscopic data reduction followed that done for Subaru mid-infrared data presented in Su et al. (2020). Slight changes were made to the code to account for different spectrum projections onto the VISIR detector and the presence of two negative spectral beams in the VISIR data; only spectral samples with signal-to-noise ratio per pixel of >3 were kept for the final spectrum. From the final combined mid-infrared spectral data set we measure a signal-to-noise ratio of ≈10 near 10.5 μm.

### 3.4. WISE

The Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010; Mainzer et al. 2011, 2014) epoch data products are used to explore variability in the TYC 8830 410 1 system in the thermal- to mid-infrared (W1/3.35, W2/4.60, W3/11.56, and W4/22.09 μm channels). The W3 and W4 channels only collected data over a short time period between MJD 55324 and 55326. Data were accessed via IRSA9 and are taken as reported.

#### 3.5. ASAS-SN

All-Sky Automated Survey for Supernovae (ASAS-SN) photometry data products (e.g., Shappee et al. 2014; Jayasinghe et al. 2019) were utilized in assessing the history of dimming events toward TYC 8830 410 1. We additionally downloaded data products for stars nearby in the plane of the sky to TYC 8830 410 1 with comparable magnitudes for comparison purposes.

#### 3.6. TESS

Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2014) data are available for TYC 8830 410 1 in two sectors. Full-frame image (FFI) 30 minute cadence data were obtained during observations of Sector 1 while 2 minute cadence data were obtained during Sector 28. A light curve from the FFI data products is obtained from the reductions performed by Huang et al. (2020a, 2020b). We additionally reject some data points based on quality flags, unusual character within the time range of BJD 2458347–2458350, and an additional buffer region on either side of the downlink gap (BJD 2458338.8–2458340.4). Shorter cadence data are simple aperture photometry (SAP) flux values as retrieved from MAST.10

#### 3.7. LCOGT

Las Cumbres Observatory Global Telescope (LCOGT; Brown et al. 2013) monitoring of TYC 8830 410 1 has been ongoing since 2020 April. In this paper we present single-band monitoring data obtained through the end of 2020 September; multiband monitoring data has been obtained since then and will be presented in future works.

Images were acquired with the 0.4 m robotic telescope network and were requested to be obtained with a cadence of 2 hr. The 0.4 m network is a system of Meade 16 inch telescopes equipped with SBIG STL6303 cameras. The cameras host detectors with a plate scale of 0.571″ pixel⁻¹ and a field of view of 29′ × 19′. Throughout the 2020 observing period presented herein, only two southern hemisphere sites were operating—Sidong Spring Observatory in Australia and Sutherland Observatory in South Africa. For each visit, telescope guiding was active and three images of 10 s each were obtained of TYC 8830 410 1 with the telescope pointing center within 30″ of the target star. Images were obtained in a Bessel V-band filter.

Data are reduced by LCOGT with the BANZAI data pipeline (McCully et al. 2018). In brief, this pipeline corrects for bad
pixels, subtracts bias and dark current, performs flat-field correction, conducts source extraction with the SEP software suite,11 and then attempts to obtain an astrometric solution with the methods of http://astrometry.net/. Only images where a successful astrometric solution is obtained are used in subsequent analysis. Due to strongly variable seeing and telescope focus between epochs, we adopt Kron-aperture (Kron 1980) magnitudes as produced by SEP for the target and comparison stars; this choice effectively ensures that the target and comparison stars have apertures with similar encircled energy in every epoch.

A selection of stars within the LCOGT imaging field of view with similar brightness as TYC 8830 410 1 are used as comparison stars to derive magnitude measurements for the target star in each epoch. Two comparison stars reproduce well each others’ known V-band magnitudes and show no obvious trends throughout the LCOGT monitoring period. These stars have J2000 positions of 23 00 11.84 −58 54 34.6 and 23 00 27.61 −58 57 32.4 and have V-band magnitudes of 12.25 and 12.37, respectively (these are a combination of ASAS-SN and Gaia results for both stars and have uncertainty of ∼1%). For each visit, we adopt the median value of the three measured magnitudes for TYC 8830 410 1 as the epoch measurement and the standard deviation as the uncertainty. All measurements are reported in the Appendix in Table A1.

4. Results

4.1. Stellar Properties

As the FEROS spectra for TYC 8830 410 1 do not display significant variability (see below), we combine them all into one super-spectrum to characterize the star. From the line ratios of Strassmeier & Felker (1990) and Padgett (1996) we determine that the star has an effective temperature of 5300 ± 400 K and a spectral type of G9 ± 2. These are consistent with the results from the analysis of RAVE spectra as discussed above, although less precise in general; thus, we adopt the RAVE spectroscopic-derived stellar effective temperature and overall spectral type for the star of G9 V (Table 1). In the FEROS super-spectrum we are unable to detect Li i λ6708 absorption and set a 3σ equivalent width limit of <7 mÅ (see Figure 1 and caption for a potential caveat). The bluest orders of the FEROS spectra are then searched for evidence of chromospheric emission in the CaII H and K lines; no obvious core-reversal emission is seen through a varying level of dust and thus could be reddened significantly.

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The methodology of Hempelmann et al. (2016) and references therein, we calculate an S-index of 0.26 ± 0.01 from the FEROS super-spectrum and convert it to log \( R'_{\text{HK}} \) of −4.75 ± 0.10 following the description in Noyes et al. (1984).

Gaia proper motion and parallax measurements for stars in the field around TYC 8830 410 1 reveal a 49.5° separation comoving and co-distant companion. This star, 2MASS J23011901-5858262 (hereafter 2MASS J2301-5858), has an absolute magnitude and \( G_{\text{BP}} - G_{\text{RP}} \) color (Table 1) that strongly suggest it is a mid-M dwarf star. We compare the MagE spectrum of the companion (Figure 2) with spectra of late-type stars with known spectral type and find that stars having a spectral type of M4 V are able to reasonably reproduce the data. The spectrum of 2MASS J2301-5858 is found to have moderately strong Balmer Hα emission (equivalent width of 2.1 ± 0.1 Å, presumably due to magnetic activity), and has no detectable Li i λ6708 absorption (with a 3σ equivalent width limit of <60 mÅ). We additionally measure a radial velocity for the companion consistent with the average of FEROS velocity measurements for the primary star (Tables 1 and 2), thus further confirming them to be truly bound.

Radial velocity data from FEROS (and to a lesser degree other available radial velocity measurements in Table 2) are used to search for and constrain the presence of other companions to TYC 8830 410 1. Taken at their quoted uncertainties, the FEROS velocities suggest variability is present at the level of ∼0.1 km s\(^{-1}\). A periodogram search of the FEROS velocities does not indicate any significant signals are present, but are suggestive of a possible period around ≈4 days. Continued radial velocity monitoring of TYC 8830 410 1 can determine if this signal is real and whether it is due to stellar activity, possibly a hot Jupiter-like companion, or maybe due to transiting dust clouds as described in Dodin & Suslina (2021). With no significant signals present in the FEROS velocity data, we conclude that there are no stellar-mass nor massive substellar companions within an au of TYC 8830 410 1.

4.2. Infrared Excess Emission

We revisit the infrared excess parameters presented in Cotten & Song (2016) based on updated stellar and infrared measurements presented herein. Figure 3 shows that this system hosts warm inner planetary system dust with strong solid-state emission resulting in a fractional infrared luminosity of ∼1%, easily placing it in league with other exceptionally dusty main-sequence star systems (e.g., Melis 2016; Moór et al. 2021). High spatial resolution VLT/VISIR mid-infrared imaging observations find only a single point source, indicating that this object is the source of the WISE-detected excess flux, thus confirming it as a bona fide exceptionally dusty inner planetary disk system.

Stellar parameters retrieved from the spectral energy distribution fit suggest an effective temperature of ∼5000 K which is lower (albeit not especially significantly) than the spectroscopically retrieved value of 5350 K. As discussed below, the star is likely to be seen through a varying level of dust and thus could be reddened leading to the lower spectral energy distribution fit value. We attempted a second stellar spectral energy distribution fit with the model effective temperature fixed at 5300 K and found a reddening of \( A_V = 0.5 \text{ mag} \) with the Cardelli et al. (1989) extinction curve (and \( R_V = 3.1 \)) provides a reasonable fit to the stellar photometry. Additional evidence for reddening appears in the color–magnitude diagram position of TYC 8830 410 1 as discussed in Section 5.1.

The VISIR mid-infrared spectrum (Figures 3 and 4) clearly reveals a strong solid-state emission feature with the characteristic amorphous and crystalline silicate peaks at ∼10 and 11 μm (e.g., Honda et al. 2004; Chen et al. 2006; Lisse et al. 2008). Fitting of this feature proceeds as in Weinberger et al. (2011) and Olofsson et al. (2012), which we briefly summarize here. We used the same optical constants and absorption coefficients as in Olofsson et al. (2012); these are taken from Dorschner et al. (1995) and Jäger et al. (2003) for amorphous silicates with olivine and pyroxene stoichiometry, from Tamanai & Mutschke (2010) for the “Mg-rich” and “Fe-rich” crystalline olivine, from Tamanai (2010) for the silica, from Jäger et al. (1998a) for the crystalline enstatite, and from Jäger et al. (1998b) for the carbonaceous dust grains. For all the dust species, the minimum allowed grain size is 0.1 μm while the maximum grain size is set to 1 μm for the crystalline dust grains and 1 mm for the amorphous dust species. The free parameters of the modeling are the inner radius and radial width of the dust ring, the slope of the density distribution, and

11 https://github.com/kbarbary/sep
the slope of the grain size distribution. The radial distribution is sampled over \( n_r = 80 \) bins, and for each dust species and each grain size the temperature of the particles at a given distance is calculated by equating the energy received and emitted (Equation (3) of Olofsson et al. 2012). For each dust species, we then compute an emission profile at the same wavelengths as the observations, weighted by the grain size distribution. For a given set of free parameters, we then find the linear combination of the emission profiles that best reproduces the observed spectrum, using the \texttt{lmfit} package (Newville et al. 2021). To find the best solution, we used the \texttt{Multinest} nested sampling algorithm (Feroz et al. 2009, 2019), interfaced

Figure 1. FEROS super-spectra of TYC 8830 410 1 showing the Ca II H + K (top) and Li I \( \lambda 6708 \) (bottom) regions. Wavelengths are in air and corrected to the heliocentric reference frame, error spectra are plotted as dotted lines. The vertical dashed line in the bottom panel indicates the expected location of Li I \( \lambda 6708 \); no line is seen. However, several instrumental artifacts are present in the Li I \( \lambda 6708 \) order for each FEROS epoch; we consider results from this spectral order tentative and caution that they should be confirmed.
with Python using the PyMultiNest package (Buchner et al. 2014).

From the available spectrum we are able to constrain the inner radius of the disk of emitting dust grains to be $\sim 0.25$ au (and certainly $< 0.5$ au) and the crystallinity fraction to being $\sim 30\%$ by mass. We are not able to robustly constrain the type of emitting grains (although some combination of forsterite and enstatite most likely contribute to the $11\,\mu m$ shoulder) and find that the grain size distribution favors small ($< 2\,\mu m$) dust particles. A representative fit illustrating these dust properties is shown in Figure 4.

It is found that the dust continuum temperature is not well constrained as most available excess measurements are part of the solid-state emission complex (we assume there are strong silicate emission features near $\sim 20\,\mu m$ that enhance the WISE W4 measurement). In arriving at the continuum curves plotted in Figure 3, we require the fit to pass through the bottom of the high- and low-wavelength ends of the VISIR $N$-band spectrum. In doing so, we arrive at temperatures $T_{\text{dust}}$ of 300–350 K.

4.3. Occultations

TYC 8830 410 1 was observed with TESS in Sector 1 as a Full-Frame Image target (30 minute cadence). The beginning of the TESS light curve just catches a $\sim 1$ mag deep, $\approx 1.5$ day duration eclipse with irregular shape (Figure 5). Also evident is general variability with a stochastic nature to it (no identifiable period within the $\approx 28$ day time span). Examining precovery ASAS-SN light-curve data for TYC 8830 410 1 shows several dips compatible with the depth of the TESS-observed feature as well as stochastic variability that results in a light-curve rms deviation from the mean of $\approx 0.14$ mag (Figure 6). A periodogram for the ASAS-SN data does not reveal significant signals at any period. Phase folding the light curve across a range of values reveals that some periods between 120 and 200 days can line up most of the dips, but not all of them.

ASAS-SN light-curve data for stars nearby and of comparable brightness to TYC 8830 410 1 do not show any dips nor the stochastic variability (ASAS-SN check stars showed rms fluctuations in their light curves at the 0.01–0.02 mag level). We also examined TESS data for similar magnitude stars around TYC 8830 410 1 and did not find any others with comparable features. This leads us to conclude that the features observed in the optical data are astrophysical and not instrumental in nature. WISE epoch photometry spanning precovery to post-TESS Sector 1 epochs are suggestive of possible deep eclipses even in the thermal infrared. However, after comparison with nearby stars of similar magnitude as TYC 8830 410 1, it is determined that apparent dips are actually instrumental in nature.

Based on the TESS eclipse feature and support for occultations from ASAS-SN, we pursued additional TESS data in the extended mission with a higher cadence and ground-based routine monitoring with LCOGT. LCOGT monitoring shows a wide range of variability, including $\sim 1$ day duration deep eclipses and a host of smaller depth features of various durations (Figure 6). The LCOGT data display an rms deviation from the mean of $\approx 0.17$ mag, reasonably consistent with that seen in the ASAS-SN data (meaning no obvious evolution of the dust screen has occurred in the $\approx 6.5$ yr of observations presented herein). The 2 minute cadence light curve from TESS Sector 28 overlaps with LCOGT monitoring and similarly shows highly structured variability (Figure 5). In general the appearance of TESS and LCOGT/ASAS-SN data where they overlap are similar, although there are some disagreements (especially in the absolute flux level) that could be instrumental or possibly astronomical in nature (TESS has a redder bandpass than the $V$-band monitoring done with LCOGT and ASAS-SN). Ongoing
and future ground-based multiband observations can reveal if the depth of eclipse features are wavelength dependent.

We group the types of dimming events for TYC 8830 410 1 into three categories. In the first category is the stochastic variability when the star is between V-band magnitudes of 11.4 and 12.1. The brightest V-band magnitude measured with ASAS-SN or LCOGT for TYC 8830 410 1 is 11.46 ± 0.1, which we take to be the unocculted V-band magnitude. In the second category are medium dimming events where the star fades to V-band magnitudes of 12.2–12.3. The third category is for the deep dimming events when the star is extinguished to V-band magnitudes of fainter than 12.3. Each of ASAS-SN, TESS (in the two different sectors), and LCOGT see all three categories in their monitoring data.

5. Discussion

5.1. System Age

Estimates for the age of the TYC 8830 410 1 system must be self-consistent for both stars. In addition to measurements described above, we also include an X-ray upper limit from ROSAT (Truemper 1982) and eROSITA (extended ROentgen Survey with an Imaging Telescope Array; Predehl et al. 2021) for TYC 8830 410 1 (and technically its companion, although that is less constraining), 3D Galactic space kinematics (Table 1), and simultaneous isochrone fits for both stars.

Lithium limits for TYC 8830 410 1 rule out ages < 100 Myr and suggest an age ≥ 200 Myr (e.g., Zuckerlman & Song 2004). The non-detection of lithium in the companion spectrum is consistent with these age bounds, although in and of itself is not especially constraining (suggesting ages ≥ 20 Myr).

Analysis of RAVE CaII infrared triplet data suggested an age of ≥ 370 Myr (Zerjal et al. 2017). Our analysis of CaII H+K activity levels from the FEROS data suggest an age range of 1.5–4.0 Gyr if one applies directly Equation (3) of Mamajek & Hillenbrand (2008). However, if one instead considers Figures 4 and 5 and Tables 7 and 9 of Mamajek & Hillenbrand (2008) it is possible—given the range of log $R'_{\text{HK}}$ values observed for various open cluster members of known age—that TYC 8830 410 1 could be between 100 Myr and 4 Gyr. The extremes of the latter age range would require TYC 8830 410 1 to be an activity outlier while ages between 600 Myr and 2 Gyr are more likely to produce the observed activity level. As such, we consider chromospheric activity to rule out ages < 100 Myr and to be suggestive of an age ≥ 500 Myr. Chromospheric activity for the companion star in the form of Hα emission is consistent with chromospheric ages suggested for the primary star, and specifically suggests an age ≤ 2 Gyr (e.g., Shkolnik et al. 2009; Kiman et al. 2021, and references therein).

The ROSAT all-sky survey and first eROSITA all-sky survey did not detect TYC 8830 410 1 nor its companion in the X-rays (An. Merloni 2021, private communication). eROSITA provides better sensitivity than does ROSAT, so we focus discussion on its X-ray limits. We obtain X-ray limits by assessing the flux and associated uncertainties for detected sources in the region of TYC 8830 410 1. A conservative limit of the ≈ 95% source completeness level is adopted, resulting in a flux limit in the 0.6–2.3 keV band of < $2 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$. The eROSITA limit suggests a ratio of X-ray to bolometric luminosity for TYC 8830 410 1 of log($L_X$/$L_{\text{bol}}$) < −3.6 and a limit for its companion of log($L_X$/$L_{\text{bol}}$) < −2.0. Comparison to Figure 4 of Zuckerman & Song (2004) suggests the primary is ≥ 100 Myr old. Limits for the companion are not especially restrictive (e.g., Zuckerman & Song 2004; Stelzer et al. 2013).

Three-dimensional Galactic space motions (UWV in Table 1) are compatible with young stars (< 100 Myr) within 200 pc of the Sun (e.g., Zuckerman & Song 2004; Torres et al. 2008). Interestingly, the best matches between the UWV space motions for the TYC 8830 410 1 system and known nearby moving groups are e Cha and the Local Association or Pleiades moving group. The former is far too young to be home to TYC 8830 410 1 (with an age of ∼ 6 Myr), in addition to inconsistencies between their respective distances and locations on the plane of the sky (Torres et al. 2008). The legitimacy of the latter association is questionable (e.g., Zuckerman & Song 2004) and in any case is suggested to mostly have ages between 20 and 150 Myr (Montes et al. 2001 and references therein), again incompatible with age constraints for TYC 8830 410 1 discussed above. Other possible matches also suffer distance, age, or positional issues (e.g., Gagné et al. 2018b; Balu et al. 2020). TYC 8830 410 1 appears to have a young-star-like UWV space motion by coincidence, but otherwise is not particularly young (as suggested by other age
indicators). In such a case, kinematics are not capable of placing any reasonable constraints on the age of the system.

Attempts to age-date the TYC 8830-410-1 system via simultaneous isochrone fitting are confounded by what appears to be reddening of the primary star. In most color-absolute magnitude diagrams TYC 8830-410-1 appears either too bright or too red (e.g., Figure 7). Based on the evidence for significant (and variable) quantities of dust lying along our line of sight to the primary star, we consider it to be reddened. We do, however, mention briefly and dismiss the possibility that TYC 8830-410-1 itself could be an unresolved binary system composed of nearly equal-mass stars. This setup is highly contrived as it would require the binary orbit to not exhibit obvious radial velocity variability (a nearly face-on orbital inclination or wide orbit; see restrictions in Section 4.1) and to have orbital parameters that allow the inner disk component to exist over decade timescales (see Section 4.3).

Given the issues with the primary discussed above, we rely on the position of the companion alone to inform isochrone age estimates. In all colors explored (Figure 7), 2MASS J2301-5858 lies above the locus of field stars of similar spectral type and tends to agree well with colors and absolute magnitudes of mid-M-type Hyades stars. As such, we adopt isochrone age bounds of >500 Myr and <5 Gyr.

Taking in aggregate all of the above age bounds, we can confidently rule out ages <200 Myr for the TYC 8830-410-1 system. The best age estimate is roughly Hyades-aged (≈600 Myr), but the system could very well be between 500 Myr and 2 Gyr in age. X-ray detections of both stars could help improve the age estimate for this system, as well as high signal-to-noise ratio optical spectroscopy monitoring the Ca II H + K chromospheric activity (especially if a stellar rotation period could be measured).

Based on the best age estimate above, TYC 8830-410-1 is intermediate in age relative to other known extremely dusty main-sequence stars, which span from several megayears to >1 Gyr (e.g., Melis 2016; Moór et al. 2021, and references therein). Notably, most extreme debris disk systems have ages \( \lesssim 200\) Myr with the exceptions of BD+20 307 (age > 1 Gyr, Zuckerman et al. 2008; Moór et al. 2021) and TYC 4479 3 1 (age 5 ± 2 Gyr, Moór et al. 2021). The latter system we consider to be contaminated by Galactic dust emission (see Figure 1 of Moór et al. 2021 where extended nebular emission overlapping with the star is clearly evident in the WISE channels where excess is claimed); it needs to be confirmed with higher resolution mid-infrared imaging before being included in any extremely dusty main-sequence star analyses.

As such, TYC 8830-410-1 and BD+20 307 are the oldest (confirmed) extremely dusty main-sequence stars known and TYC 8830-410-1 the oldest such system where the dusty debris eclipses the host star (robust ages are not yet known for systems presented by Tajiri et al. 2020).

TYC 8830-410-1 joins the growing number of extremely dusty main-sequence stars with wide-separation binary companions. This association was first noted by Zuckerman (2015) and expanded upon in Moór et al. (2021). The assertion by Moór et al. (2021) that such dusty systems are more likely to host wide-separation companions as a function of age is supported by the age estimate for TYC 8830-410-1 derived here. Moór et al. (2021) develop a cometary delivery model to
explain the origin of extremely dusty main-sequence stars—especially the older population—and suggest perhaps such delivery is amplified by instabilities due to wide-separation companions. The cometary model proposed by Moór et al. (2021) suffers from a major weakness in that any instability which sends a significant quantity of mass to a star’s inner planetary system should also produce a substantial population of small dust grains in the star’s outer planetary system (e.g., Fujiwara et al. 2012b; Bonsor et al. 2013, 2014; Raymond & Bonsor 2014, and references therein). Indeed, Moór et al. (2021) acknowledge this shortcoming of their proposed cometary model and note results by Vican et al. (2016) which

Figure 5. TESS light curves for TYC 8830 410 1. A deep dip and stochastic variability at the ~20% level are apparent. Each light curve is normalized to unity at its respective maximum value. Top: TESS Sector 1 FFI light curve. Bottom: TESS Sector 28 two-minute cadence light curve.
show very few extremely dusty main-sequence stars host outer planetary system dust populations consistent with a cometary model. In Section 6, we suggest an alternative model that will be explored further in later works.

5.2. Dust Properties

With a fractional infrared luminosity of $\sim 1\%$, TYC 8830 410 1 is not especially remarkable among the currently known sample of extremely dusty main-sequence stars. The dust composition is at first glance reasonably compatible with what is seen for other such stars (e.g., Olofsson et al. 2012 and references therein), although the available data leaves ambiguous many of the dust properties. One potentially interesting difference that remains to be conclusively measured is an apparent enstatite dominance over forsterite. In some of our models there can be as much as a factor of 2 more enstatite than forsterite which is not typically seen in extremely dusty star disks (e.g., Fujiwara et al. 2010; Olofsson et al. 2012). Enstatite-rich bodies are known in the solar system, including the surface of Mercury and E-type asteroids which make up a significant fraction of the inner asteroid belt (e.g., Zellner et al. 1977; Keil et al. 1989; Sprague & Roush 1998). Future comprehensive mid-infrared spectroscopy (e.g., with James Webb Space Telescope) can help establish if this result is robust for TYC 8830 410 1.

With the photometric monitoring conducted to date it is not possible to demonstrate if the deeper dips seen are (quasi-) periodic or aperiodic. Routine monitoring at a cadence of $\lesssim 1$ day without gaps in temporal coverage is essential to catch these events or conclusively say they did not occur. For example, the sporadic cadence of the ASAS-SN monitoring could easily have missed any number of $\sim 1.5$ day duration events like those seen in the TESS and LCOGT data. Two such events are found in the LCOGT monitoring from 2020 April to September separated by about 82 days, although the April event was captured with a single epoch only and sufficient gaps in coverage are present that other events could have been missed. Even allowing for missed events, it is not possible to find a periodic spacing that matches the four lowest measured magnitudes in the ASAS-SN data, the deep dip in the TESS data, and the two deep dips in the LCOGT data. A period near 180 days can get close to lining up most of the ASAS-SN and first LCOGT deep dips, but not the TESS and second LCOGT deep dips which appear to themselves be separated by a factor of roughly 180 days. A speculative idea is that we might be seeing multiple orbiting sites of major collisions that shear out and disperse with time.

Stochastic variability similarly has no discernible period associated with it. This combined with a lack of strong magnetic activity on TYC 8830 410 1 indicates that this variability must also be due to dust transiting across the face of the star. The medium dimming events are a few times more frequent than deep dimming events and tend to be longer in duration ($\sim 3$ days...
in the TESS Sector 28 light curve), but again show no clear periodicity in the available data.

We conclude that all variability seen in optical light curves for TYC 8830 410 1 is due to transiting dust. It is not possible to robustly identify the configuration of such dust with the available data, but we comment on two possibilities. In one configuration, the dust disk is vertically thin (scale height $\lesssim$ the stellar diameter), radially narrow ($\Delta R_{\text{dust}} < 0.1 R_{\text{dust}}$), and the dust is fairly homogeneous in density in the vertical and radial axes. In this case all the light curve changes are due to changes in the azimuthal density in the dust and indicate substantial clumpiness in the dust ring. Such a configuration would be reminiscent of the distribution of material presented in Watt et al. (2021) for post-giant impact-type events. Adapting the models of Watt et al. (2021) to predict stellar brightness changes if post-collision dusty ejecta transits the host star would be valuable in further assessing the nature of TYC 8830 410 1 and possibly the systems presented by Gaidos et al. (2019) and Tajiri et al. (2020).

In another—perhaps more contrived—configuration, the dust disk is again radially narrow and the density is homogeneous in the radial and azimuthal axes. The disk has a structured vertical density distribution and is additionally warped and precessing. Such a configuration has been suggested for pre-main-sequence “dipper” stars where gas and/or interactions with stellar magnetic fields help shape the disk inner edge (e.g., Bouvier et al. 2003 and references therein). However, there is currently no evidence for gas in the disk around TYC 8830 410 1, and it appears to lie at orbital separations well beyond the reaches of the stellar magnetic field (Section 4.2). As such, any vertical structuring in its disk (if present) would have to come from other sources, perhaps from Kozai–Lidov-type interactions with the wide M-type companion. In this case the changes in the light curve are due to the different heights in the disk being probed by the line of sight to the star. They would not be strictly periodic due to the precession of the warp and possibly due to warp evolution.
6. Conclusions

We present detailed characterization of the TYC 8830-410-1 system. Infrared excess emission from circumstellar dust is seen and occultations from this dust are caught in stellar photometric monitoring. TYC 8830-410-1 appears to have an age of $\sim$600 Myr, and is definitely older than typical extremely dusty main-sequence stars which have ages of $\lesssim$200 Myr.

The unusual deep dimming event shapes, lack of a companion detection in radial velocity measurements, the general stochastic variability seen in light curves, and the strong mid-infrared excess emission with clear solid-state emission from small dust grains point to a possible origin of the transit events as due to dust released in the aftermath of a giant impact between rocky planets. Giant impact-type collisions would produce significant quantities of dusty ejecta that would go into orbit around the host star (e.g., Melis et al. 2010; Genda et al. 2012; Jackson & Wyatt 2012; Watt et al. 2021, and references therein). Ejecta would collisionally grind itself down generating small dust grains that would produce the observed mid-infrared excess emission and the stochastic variability (similar to what is seen in Gaidos et al. 2019). Clumps of dust, or dust around the post-impact rocky planet (possibly in a proto-lunar disk configuration; e.g., Kokubo et al. 2000) could be responsible for the deep dips seen if they subtend a large angular size relative to the host star they orbit (e.g., Mamajek et al. 2012; Kenworthy & Mamajek 2015).

The implied giant impact-type event is unlikely to be associated with rocky planet formation given the intermediate age of TYC 8830-410-1 (such events should occur for stellar ages $\lesssim$100 Myr; e.g., Hartmann & Davis 1975; Genda et al. 2015; Levison et al. 2015) and instead could be due to a late-stage instability (e.g., Izidoro et al. 2021; Moór et al. 2021 and references therein). Izidoro et al. (2021) specifically follow the long-term dynamical evolution of planetary systems that form as chains of first order mean motion resonances (resonant chains), finding that up to $\approx$95% of resonant chains become dynamically unstable after dispersal of the gas disk. They find timescales for these instabilities that extend up to the limit of their simulations ($\approx$300 Myr), and it could be the case that such instabilities could occur for even older ages. Eccentricities and orbital inclinations of planets in a resonant chain grow in the absence of the damping effects of the gas disk due to mutual interactions and their orbits can eventually cross leading to collisions and scattering events. Eccentricities and relative velocities could be further enhanced by the effects of a widely separated companion (like 2MASS J2301-5858 in the case of the TYC 8830-410-1 system) through the Kozai–Lidov mechanism (e.g., Nesvold et al. 2016 and references therein) increasing the likelihood of instability and destructive collisions. This instability-driven phase of late giant impacts would be where the dust seen in extremely dusty stars like TYC 8830-410-1 originates from.

If the proposed interpretation for TYC 8830-410-1 is correct, then it would serve as a Rosetta stone for understanding exceptionally dusty stars. It would be capable of providing the first-ever detailed look at the structure of post-giant impact ejecta and its evolution, thus allowing direct tests and constraints on models of this important pathway for rocky planet evolution. Multiband monitoring of this system is essential in conducting such work, and with a reasonable brightness of $V_{\text{mag}} \sim 12$ amateurs could easily contribute.

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Facilities: VLT(VISIR), MPG(FEROS), Magellan(MagE), TESS, LCOGT.

Appendix

LCOGT V-band Photometry for TYC 8830 410 1

Table A1 presents epoch V-band magnitudes for TYC 8830 410 1 as measured with the LCOGT and described in Section 3.7. There are 484 measurements presented.

Table A1

| Modified Julian Date | $V_{\text{mag}}$ | $V_{\text{mag}}$ Error |
|----------------------|-----------------|------------------------|
| 58953.79529          | 12.44           | 0.03                   |
| 58960.78542          | 11.59           | 0.01                   |
| 58962.78541          | 11.67           | 0.03                   |
| 58963.78535          | 11.88           | 0.01                   |
| 58972.74410          | 11.80           | 0.02                   |
| 58972.78802          | 11.77           | 0.01                   |
| 58973.74359          | 11.63           | 0.02                   |
| 58973.78536          | 11.64           | 0.02                   |
| 58975.74365          | 11.70           | 0.07                   |
| 58975.78527          | 11.77           | 0.04                   |

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