VARIABILITY OF THE INFRARED EXCESS OF EXTREME DEBRIS DISKS

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ABSTRACT

Debris disks with extremely large infrared excesses (fractional luminosities $>10^{-2}$) are rare. Those with ages between 30 and 130 Myr are of interest because their evolution has progressed well beyond that of protoplanetary disks (which dissipate with a timescale of order 3 Myr), yet they represent a period when dynamical models suggest that terrestrial planet building may still be progressing through large, violent collisions that could yield large amounts of debris and large infrared excesses. For example, our Moon was formed through a violent collision of two large protoplanets during this age range. We report two disks around the solar-like stars ID8 and HD 23514 in this age range where the 24 μm infrared excesses vary on timescales of a few years, even though the stars are not variable in the optical. Variations this rapid are difficult to understand if the debris is produced by collisional cascades, as it is for most debris disks. It is possible that the debris in these two systems arises in part from condensates from silicate-rich vapor produced in a series of violent collisions among relatively large bodies. If their evolution is rapid, the rate of detection of extreme excesses would indicate that major collisions may be relatively common in this age range.

Key words: circumstellar matter – infrared: stars – planets and satellites: formation – stars: individual (2MASS J08090250-4858172, HD 23514)

Online-only material: color figure

1. INTRODUCTION

Circumstellar disks are key signposts for planetary system evolution both because they are associated closely with planets and because they are much more readily observed than the planets themselves. Optically thick protoplanetary disks are born around young stars and dissipate over a time <10 Myr (e.g., Wyatt 2008). Afterward, optically thin planetary debris disks can emerge, sustained by the fragmentation of colliding planetesimals (Wyatt 2008). Debris disks are readily detected through their infrared excess emission (over the stellar photospheric output), which is produced by dust warmed by the star. Such excesses are found over the entire age range of main-sequence stars to ages of ~10 Gyr. Therefore, they can be used to probe the presence and state of planetesimal systems (such as the analogs of asteroid and Kuiper Belts) and, indirectly, the evolution of the accompanying planetary systems. In particular, debris disks can be used to search for phases in the evolution of other planetary systems that played major roles in the evolution of the solar system and in the formation of terrestrial planets.

One such phase extends roughly from 30 to 130 Myr, well separated from the era of protoplanetary disks but when dynamical models (e.g., Chambers 2001; Morishima et al. 2010) predict that giant impacts will still occur (Righter & O’Brien 2011). For example, our Moon formed during this period through a massive collision between the proto-Earth and a Mars-sized protoplanet (Canup 2004). Such events should yield huge amounts of debris; indeed, a few candidates have been found. They take the form of infrared excesses from heated debris that far exceed those expected from the trend for quiescently evolving systems (see summary in Balog et al. 2009). These extreme systems (defined as total emission >four times the stellar photospheric output at 24 μm) occur around only ~1% of solar-like (F5-G9) stars (Balog et al. 2009). If evolutionary timescales similar to those of conventional debris systems are adopted (on the order of 3 Myr; Grogan et al. 2001), then the low level of incidence of such excesses implies that major collisions are rare.

In this paper, we present Spitzer data that show that two of these extreme systems, ID8 in NGC 2547 and HD 23514 in the Pleiades (both with fractional debris disk luminosities $\geq 2 \times 10^{-2}$), vary significantly at 24 μm over a few years. The age of NGC 2547 is ~35 Myr (Jeffries & Oliveria 2005), while that of the Pleiades is ~120 Myr (Stauffer et al. 1998). Despite their large and variable infrared excesses, both ID8 and HD 23514 are well past the age of protoplanetary disks and the variations we report are unlikely to be related to those found to be ubiquitous in the latter disk type at ages < 10 Myr (e.g., Espaillat et al. 2011; Flaherty et al. 2012). Melis et al. (2012) have reported a third example of strong variability in an extreme infrared excess in the same 30–130 Myr age range, so the phenomenon appears to be characteristic of this particular class of circumstellar disk.

ID8 is a type G6-G7 dwarf (N. Gorlova et al. 2012, in preparation) at a distance of ~450 pc and with optical colors indicating negligible extinction. HD 23514 is of F5V spectral type (Gray et al. 2001) at a distance of ~130 pc, with normal colors for this type (Mendoza 1967) when corrected for the foreground reddening (Cernis 1987). ID8 is possibly a binary star based on a radial velocity measurement 8 km s$^{-1}$ different from the cluster mean (N. Gorlova et al. 2012, in preparation); a late-M companion to HD 23514 has recently been discovered at a projected distance of 360 AU from the star (Rodriguez et al. 2012). Neither star is variable in the optical, to within the ~1% measurement errors.
2. DATA

Spitzer/MIPS observations of ID8 at 24 μm were obtained in programs for G. Rieke (PID 58) and C. Lada (PID 20124). The data for HD 23514 are from programs led by M. Meyer (PID 148) and G. Rieke (PIDs 30503, 30566). We also show in Figure 1 Infrared Spectograph (IRS) spectra; that for ID8 is from PID 40227, PI G. Rieke, while that for HD 23514 is from PID 50228, PI I. Song. In summary, we have three epochs of MIPS 24 μm observations for both targets, supplemented with a fourth epoch observation using IRS spectra. In addition, one epoch of IRAC observation is available for each target, from PID 58 for ID8 (PI G. Rieke) and PID 50228 for HD 23514 (PI I. Song).

The 24 μm data were reduced with the MIPS instrument team Data Analysis Tool (Gordon et al. 2005). In addition, a second flat field constructed from the 24 μm data itself was applied to remove scattered-light gradients and dark latency (Engelbracht et al. 2007). We extracted the photometry using PSF (point spread function) fitting. The input PSFs were constructed using observed calibration stars and smoothed STinyTim model PSFs, and have been tested to insure the photometry results are consistent with the MIPS calibration (Engelbracht et al. 2007). The final photometry errors also include the errors from the detector repeatability (≤1% at 24 μm; Engelbracht et al. 2007). These errors should apply directly to HD 23514, which is similar in brightness to the standard stars described in Engelbracht et al. (2007). We measured an isolated, similar brightness star ~4′ south of ID8 to test the 24 μm photometry stability among the three epochs of data. The measured 24 μm flux (5.46 mJy) is constant within 1.5% (rms), consistent with the repeatability of MIPS photometry on brighter stars. The measured flux densities and 24 μm magnitudes ([24]) assume 7.17 Jy as the zero magnitude flux density.

The IRAC photometry of ID8 has been published by Gorlova et al. (2007). For HD 23514, the IRAC BCD images were retrieved from the Spitzer archive, and mosaicked with the MOPEX software with a scale of 0.6 pixel−1. The final mosaic images were checked against the archival PBCD images for consistency. Aperture photometry was then performed on the verified mosaic images with an aperture radius of 15″ and sky annulus between 24″ and 36″ from the opto-center. The flux conversion issue in the S18.18 IRAC processing is corrected.

IRAS spectra were reduced and extracted using the SMART software (Higdon et al. 2004; Lebouteiller et al. 2010). We also computed synthesized 8.0 and 24 μm photometry by integrating the IRS spectra and comparing with similar integrals over an A-star spectrum. We adopt 5% uncertainty for the synthesized photometry which is consistent with the cross calibration among IRAC, MIPS, and IRS (Cushing et al. 2006; Carey 2010). The 24 μm photometry is summarized in Table 1 and shown in Figure 1. Both stars are found to vary at 24 μm at a high degree of significance.

Visible photometry was collected from the literature (Table 2). Neither star has been noted to vary; in fact, HD 23514 has been used as a local photometric standard to study variations in neighboring stars (Alphenaar & van Leeuwen 1981). Because there were only four relevant measurements for ID8, we obtained two more; eight measurements were already available for HD 23514. The data for both stars show a scatter of only ±1%, consistent with measurement errors and corroborating the lack of variability at visible wavelengths.

WISE observations of ID8 were performed in mid 2010 May, nearly 6.5 years after the IRAC observation. Here we consider only the W1 and W2 bands because of their spectral proximity to the two short wavelength bands in IRAC. We randomly select three other NGC 2547 member stars whose JHK colors are all similar to that of ID8. The (Ks - W2) colors of the three comparison stars are in a narrow interval between 0.00 and 0.03, while that of ID8 is approximately 0.67, confirming the 4.5 μm excess. On the other hand, the (I - W2) colors of the comparison stars range from 0.01 to 0.05, while that of ID8 is 0.28. Given the similarity of the IRAC 4.5 μm and WISE W2 bands, the significant difference between the fluxes in these bands at different epochs is most easily explained as the result of variability. The same trend may also be observed at 3.6 μm (or W1) at a low degree of significance. However, variations in the 3–4 μm region are not seen for HD 23514 over the ~1.5 year time span between the IRAC and WISE observations.

In summary, we found 10%–30% peak-to-peak variation at 24 μm on yearly timescales while no changes were found at optical wavelengths for these two systems. The change between IRAC and WISE, as well as the IRS synthetic photometry, suggests that variations are also possibly seen at 4.5 and 8.0 μm.

3. DISCUSSION

HD 23514 and a few other of extreme-excess stars (e.g., HD 15407; Fujitava et al. 2009; Melis et al. 2010) show spectra in the 10 μm region (see Figure 1) indicative of the presence...
Table 1
Infrared Photometry by Spitzer and WISE

| Date              | 3.6 μm (mJy) | 4.5 μm (mJy) | 5.8 μm (mJy) | 8.0 μm (mJy) | 24 μm (mJy) | Source            |
|-------------------|--------------|--------------|--------------|--------------|------------|------------------|
| 2003 Dec 4        | 9.74 ± 0.1   | 7.35 ± 0.1   | 6.56 ± 0.1   | 7.64 ± 0.1   | ...        | Gorlova et al. (2007) |
| 2004 Jan 29       | ...          | ...          | ...          | ...          | 6.23 ± 0.10 | AOR 4318976       |
| 2006 May 9        | ...          | ...          | ...          | 8.34 ± 0.12  | ...        | AOR 16798464      |
| 2006 Dec 4        | ...          | ...          | ...          | 7.32 ± 0.11  | ...        | AOR 16800512      |
| 2007 Jun 16       | ...          | ...          | 6.38a        | 6.74a        | ...        | AOR 21755136      |
| 2010 May 13–21    | 12.05 ± 0.26b| 9.11 ± 0.17b | ...          | ...          | ...        | WISE All-Sky Catalog |

HD 23514

| Date       | 4.5 μm (mJy) | 5.8 μm (mJy) | 8.0 μm (mJy) | 24 μm (mJy) | Source            |
|------------|--------------|--------------|--------------|------------|------------------|
| 2004 Sep 22| ...          | ...          | ...          | ...        | 67.7 ± 0.7        | AOR 5320192       |
| 2007 Feb 25| ...          | ...          | ...          | ...        | 68.0 ± 0.7        | AOR 18303232      |
| 2007 Sep 17| ...          | ...          | ...          | ...        | 61.6 ± 0.7        | AOR 17656576      |
| 2008 Sep 18| 206.3 ± 1.1  | 180.7 ± 1.2  | 154.6 ± 0.7  | 203.9 ± 1.0 | ...        | AOR 25790208      |
| 2008 Oct 1  | ...          | ...          | 169.3a       | 64.8a       | ...        | AOR 25789952      |
| 2010 Feb 12–13| 225.3 ± 4.5b| 180.6 ± 3.1b | ...          | ...        | ...        | WISE All-Sky Catalog |

Notes.

a Synthetic photometry based on IRS spectrum and the response curves of IRAC and MIPS. The cross-calibration uncertainties of the Spitzer instruments are expected to be ~5% (Carey 2010).

b Flux densities at WISE W1 and W2. The effective wavelengths are 3.35 and 4.60 μm, slightly different from those of IRAC.

Table 2
Visible Photometry

| V    | I^a | References |
|------|-----|------------|
|      |     | ID8        |
| 13.14|     | 12.34      | 1          |
| ...  |     | 12.34      | 2          |
| 13.12|     | 12.34      | 3          |
| ...  |     | 12.32      | 4          |
| 13.12|     | ...        | 5          |
| 13.14|     | ...        | 5          |
|      |     | HD 23514   |
| 9.42 |     | ...        | 6          |
| 9.42 |     | 8.67       | 7          |
| 9.44 |     | ...        | 8          |
| 9.43 |     | ...        | 9          |
| 9.42 |     | ...        | 10         |
| 9.44 |     | ...        | 11         |
| 9.43 |     | ...        | 12         |
| 9.44 |     | ...        | 13         |

Notes.

a Cousins filter for ID8 and Johnson filter for HD 23514.

References.
(1) Naylor et al. 2002; (2) Jeffries et al. 2004; (3) Lyra et al. 2006; (4) DENIS catalog; (5) this work, observed on 2011 November 18; (6) Johnson & Mitchell 1958; (7) Mendoza 1967; (8) Rufener 1978; (9) Alphenaar & van Leeuwen 1981; (10) Cernis 1987; (11) van Leeuwen et al. 1986; (12) Tycho catalog, transformed from Bessell (2000); (13) Droege et al. 2006.

of finely divided silica dust (Lisse et al. 2009) or analogs of silica "smoke" (Kimura & Nuth 2007). The spectrum of ID8 is also complex, with features indicating significant amounts of finely divided crystalline silicates (N. Gorlova et al. 2012, in preparation). The large equivalent widths of the features in these spectra require grain sizes of order 0.1 μm (Bouwman et al. 2008), well below the blowout size for these stars. The dust properties suggest that the infrared excesses of these stars are associated with violent, recent events (Lisse et al. 2009) and hence may differ significantly from typical planetary debris systems whose mid-infrared spectra tend to be featureless (Wyatt 2008) and whose evolution is dominated by an overall slow monotonic decay with time (Rieke et al. 2005; Wyatt 2008). BD +20 307 (several Gyr old; Song et al. 2005), which also has a very strong emission band around 10 μm, may also vary by ~7% in the WISE W3 and W4 bands (12 and 22 μm) between two scans ~188 days apart, although it is probably stable at W1, suggesting that the mid-infrared variability might be correlated with the presence very fine dust particles.

Traditional planetary debris disks are sustained by collisional cascades in which populations of planetesimals collide until they are ground down to micron-sized dust, when they are ejected by radiation pressure or spiral into the star due to Poynting–Robertson drag. The timescale for the overall changes in the infrared excesses in these systems is expected to be millions of years (Wyatt 2008). However, around stars of solar mass or less, theoretical models by Kenyon & Bromley (2005) indicate that short-term spikes in the 24 μm output can occur due to large collisions (of ~100 km bodies). Thus, the variations support the arguments that we are seeing the consequences of individual collisional events and the resulting rapid generation of large swarms of particles.

We can estimate the timescales for such events from the scaling relations given by Wyatt (2008). To apply these relations, we need to estimate the location of the planetesimal belts around the two stars. Because small grains associated with recent transient events dominate the mid-infrared properties, it is not possible to derive the properties of the parent body planetesimal system from the mid-IR measurements. Instead, we assume that the parent body populations are similar to those around stars of similar spectral type and age. The infrared excesses at 5.8 and 8.0 μm trace dust within ~1 AU of a solar-type star. We have complemented studies of these excesses by Gorlova et al. (2007); Carpenter et al. (2009) by analyzing the data for the Pleiades from Stauffer et al. (2007). In the latter case, we found that none of the stars with [3.6] ≤ 10 (corresponding to solar-like absolute magnitudes) have excesses. The net result is that, in the age range (30–130 Myr), there are only two cases other than ID8 and HD 23514 with reliably detected excesses at 5.8 μm and 8.0 μm out of a total of 352 solar-like
stars observed. This result shows that planetesimal belts in debris systems in this age range are nearly always located outside 1 AU. If we substitute solar masses and luminosities into Equations (14)–(16) of Wyatt (2008), a fractional luminosity of $2 \times 10^{-2}$, a radius of 1 AU, $dr/r$ of 0.5, and eccentricity of 0.2 (values to yield as rapid evolution as possible), we find that the time to remove a 100 km diameter body by collisional cascade is $t_c \gtrsim 100$ years. On the other hand, the time to remove 1 mm particles is $t_c \sim 0.1$ year, an order of magnitude shorter than the time span of the observations. This suggests that small particles are replenished by secondary collisions. Given that the variations are $\sim 10\%$ of the fractional luminosity, the mass associated with them is $\sim 10^{-2} M_\odot$, integrating the particle size distribution from 0.1 $\mu$m to 100 km. Significantly lower mass estimates are only possible if the planetesimal belt is well inside 1 AU.

Grogan et al. (2001; Figure 19) present detailed models that find a characteristic timescale of $3 \times 10^6$ years for the decay of dust from collisions in the asteroid belt. The behavior is supported by the role of recent collisions in the production of zodiacal dust bands (Nesvorný et al. 2003). This result provides an independent test of the timescale for decay of excess due to collisional cascades around ID8 and HD 23514. For the population of disks around stars of similar mass and age to these two, a typical fractional luminosity in a quiescent state is $5 \times 10^{-7}$ (Carpenter et al. 2009). Most of this emission is from cool dust that must be well outside a few AU from the star. The fractional luminosity for warm dust is an order of magnitude lower (Carpenter et al. 2009), i.e., $5 \times 10^{-5}$. These values, the scaling relations in Wyatt (2008), a solar fractional luminosity of $10^{-7}$ (Backman & Paresce 1993), and orbital radius of 2.5 AU for the zodiacal cloud and asteroid belt indicate $\sim 100$ years as the characteristic time for decay of a transient event via collisional cascade at 1 AU around ID8 and HD 23514. This value agrees well with that obtained directly from the scaling relations.

Although this estimate is rough, it indicates that generating the variable excesses through collisional cascades may not be impossible, but would require extreme assumptions. We therefore will explore alternatives. The possibility that the $24 \mu$m changes reflect varying rates of heating by the star is made unlikely by the complete lack of variations in the visible for both stars. Phenomena that avoid any kind of collisional cascade will inherently have faster timescales. One such process might be a collision that caused a large body to lose its regolith, injecting pre-processed small dust into the interplanetary space around the star. However, very small grains tend to be absent in planetesimal regoliths because radiation pressure slowly drives the small particles away (Masiero et al. 2009); the regolith hypothesis is possibly contradicted by the evidence for small grains in the mid-IR spectra. In addition, regoliths have a full size spectrum of objects (Housen & Wilkening 1982), so such a regolith ejection event would be analogous to launching a fully developed collisional cascade and it would have a similar evolutionary timescale to the cascades already considered. An alternative might be the disintegration of one or several extremely large comets. The most finely divided dust released would have a short dwell time near the star, since it would be ejected by radiation pressure or lost through Poynting–Robertson drag; the larger bodies would remain for some time because the comet orbit would not coincide with a dense planetesimal belt and would have inadequate density of objects for vigorous collisional activity. The timescale for the first process is probably too short, making the resulting excesses too rare to agree with the simultaneous detection of a number of them, and that for the second too long to explain the variability of ID8 and HD 23514.

None of these possibilities can convincingly be shown to produce the huge amounts of dust around these stars while having the necessary short timescales for variability. Therefore, we consider another possibility—that the dust condenses from silicarich vapor associated with violent collisions among large bodies. For example, in massive collisions such as the one that formed our Moon, of order 20% of the mass emerges as vapor rich in silica (Canup 2004). The production of silica-rich vapor can occur at collisional velocities above about 2 km s$^{-1}$ based on simple energetic arguments. However, a threshold of about 10 km s$^{-1}$ is generally adopted because a substantial portion of the energy is deposited in collisionally produced fragments (Hornung et al. 2000). Laboratory experiments suggest that the vapor will condense quickly into silica “smoke” (Kimura & Nuth 2007), and forsterite-like crystals are the most common crystalline form to grow from the condensation products (Kobatake et al. 2008). The spectrum of silica smoke (Kimura & Nuth 2007) resembles that of the infrared excess of HD 23514 (Rhee et al. 2008), while the small grains that dominate the spectrum of ID8 are rich in forsterite-like materials (N. Gorlova et al. 2012, in preparation). The resulting small particles will be cleared quickly by radiation pressure and the Poynting–Robertson effect. The cooling and disk spreading timescale for the silica-rich protolunar disk that later formed the Moon is $\sim 1$ year (Thompson & Stevenson 1988; Canup 2004). However, most of the ejected mass in the moon-forming impact remained gravitationally bound to the Earth; the small solid angle viewed from the Sun indicates that such a single event could not raise the infrared luminosity high enough to explain the excesses in these systems. However, the significant amount of escaping material from a major impact might initiate a violent collisional cascade and elevate the infrared excess of the star for a longer period. Thus, the extreme excesses around ID8 and HD 23514 are unlikely to be due to an individual violent collision, but to reflect extended episodes of such collisions possibly triggered by a single event.

4. CONCLUSION

Dynamical models indicate that giant impacts continue to build terrestrial planets into the 30–130 Myr age range. A small number of stars have extreme infrared excesses and mid-infrared spectra that suggest that such impacts have occurred recently around them. However, the duration of these indicators, and hence the frequency of events required to account for the numbers we detect, is not clear. We report that the excess is variable on year timescales around two of these stars, ID8 in NGC 2547 and HD 23514 in the Pleiades; a third variable example has been reported by Melis et al. (2012). The variability is too rapid to be explained readily if the excesses are generated in collisional cascades, as is the case for most planetary debris disks. Instead, it is possible that the dust producing the excess condenses from vapor generated in violent collisions. The timescale for variations of years, rather than millions of years, suggests that the evolution of the infrared excesses might be rapid. In that case, major collisions would need to occur frequently to account for the number of stars in this age range that are observed to have extreme excesses.

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Facilities: Spitzer (IRAC, IRS, MIPS), WISE

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