THE ABSENCE OF COLD DUST AND THE MINERALOGY AND ORIGIN OF THE WARM DUST ENCIRCLING BD +20 307

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Received 2010 May 24; accepted 2010 October 26; published 2010 December 16

Abstract

Spitzer Space Telescope photometry and spectroscopy of BD +20 307 show that all of the dust around this remarkable Gyr-old spectroscopic binary arises within 1 AU. No additional cold dust is needed to fit the infrared excess. Peaks in the 10 and 20 μm spectrum are well fit with small silicates that should be removed on a timescale of years from the system. This is the dustiest star known for its age, which is ≳1 Gyr. The dust cannot arise from a steady-state collisional cascade. A catastrophic collision of two rocky, planetary-scale bodies in the terrestrial zone is the most likely source for this warm dust because it does not require a reservoir of planetesimals in the outer system.

Key words: circumstellar matter – planet–disk interactions – stars: individual (BD+20 307)

Online-only material: color figures

1. INTRODUCTION

A number of extreme collisions may have shaped the final states of the terrestrial planets. Impact by a Mars-sized progenitor on the early Earth, perhaps 30 Myr after the solar system formed, could have created the Moon (e.g., Canup 2004). Other collisions may have stripped Mercury’s mantle (Benz et al. 1988) or caused the hemispheric crustal thickness asymmetry of Mars (Marinova et al. 2008). Subsequent bombardment of the planets may not have generated planetary scale changes, but the “Late Heavy Bombardment,” an era approximately 600 Myr after solar system formation, either culminated a long sequence of bombardments or resulted in a burst of impacts on the terrestrial planets (Gomes et al. 2005; Strom et al. 2005).

Evidence of cataclysmic impacts in other planetary systems is rare. Enhanced collisions should result in the production of copious small particles, i.e., dust, which can be observed by their re-radiation of stellar light (Kenyon & Bromley 2004). Stars older than 100 Myr with substantial amounts of warm dust are rare, and at most a few percent of field stars have any detectable warm dust at all (e.g., Meyer et al. 2008; Trilling et al. 2008; Greaves et al. 2009; Koerner et al. 2010). At any given age, stars that are dustier than average could be interpreted as having had a recent, stochastic, event, but many could also be the result of differing initial masses and configurations of planetesimals. Only the extremely dusty disks at any given age must be from giant collisions.

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observed IRS spectrum over the IRAC filter bandpasses. This yields a correction of 3% at band 3 and 71% for band 4. The band 4 correction is unreasonably large; the difference between the integral under the IRS spectrum and the IRAC band 4 (uncolor corrected) flux density is only 26%. When integrated, the very large spectral slope at 8 μm causes a large change in color correction for any small change in spectral transmission response of the system (telescope + filter, etc.). This transmission does not appear to be well enough known to provide an accurate color correction; therefore, the band 4 flux was not used for further analysis.

2.2. MIPS

At 24 μm, the pipeline produced post-BCD mosaic was used for aperture photometry using a 6 pixel aperture and corrections given in Su et al. (2006). At 70 μm, MOPEX was used to mosaic the pipeline-filtered BCDs. Aperture photometry was performed with the 35” aperture and corrections from Gordon et al. (2007). At 160 μm, the pipeline mosaic was used. Because at this band no source is seen at the nominal location or elsewhere in the field, an upper limit to the source flux was placed by doing a raster of aperture positions on the image around the nominal location and calculating three times the standard deviation of these.

2.3. IRS

For all channels, the pipeline version 14 data were used. The short–low (5.2–14.5 μm) BCD data were cleaned with IRS_CLEAN software to remove bad pixels. Each cleaned BCD was sky subtracted with uncertainties propagated in quadrature. The spectra were extracted with the Spitzer Science Center’s SPICE software using the standard extraction parameters. The short–high (9.9–19.6 μm) BCD data were cleaned with IRS_CLEAN and the unaltered campaign pixel mask. The resulting cleaned BCDs were medianed to make a final spectrum that was extracted with SPICE and the standard extraction parameters. The two nods were averaged together. Orders were trimmed to eliminate as many points with undefined uncertainties as possible.

For the long–high (18.7–37.2 μm) data, separate observations on nearby sky were taken to help in elimination of rogue pixels. A median sky frame was created with the standard deviation of the 20 sky files as its uncertainty. This frame was then subtracted from each of the object spectra, with uncertainties propagated.

The campaign rogue mask was augmented by any pixels that were flagged in 15/20 of the individual spectra. The combined mask was then used to clean the sky subtracted object spectra. The final cleaned BCDs for each nod were median combined and then extracted with SPICE. The spectra from the two nods, which agree to within their statistical uncertainties, were averaged.

The spectra from all channels were combined by using their overlap regions—short–low to short–low spectrum in the region 11.5–14 μm and long–high to short–high at 19.02–19.47 μm. The complete spectrum was then normalized to the MIPS channel 1 photometry by integrating the spectrum under its transmission curve. A check that this process works well is that integrating the final normalized spectrum under the IRAC channel 3 filter yields 155 mJy compared with the measured 165 ± 12 mJy from the photometry reported in Table 1.

### Table 1

Summary of Observations and Photometry

| Instrument | Band | Date       | Integ. Time (s) | Photometry (mJy) |
|------------|------|------------|-----------------|------------------|
| IRAC       | 1 (3.5 μm) | 2005 Aug 20 | 0.64            | 285.0 ± 7.3      |
| IRAC       | 2 (4.5 μm) | 2005 Aug 20 | 0.64            | 210.4 ± 4.8      |
| IRAC       | 3 (5.7 μm) | 2005 Aug 20 | 0.64            | 165.3 ± 12.0     |
| IRAC       | 4 (7.9 μm) | 2005 Aug 20 | 0.64            | 410.2 ± 22.5     |
| MIPS       | 1 (24 μm)  | 2007 Jan 21 | 2.62            | 441.0 ± 0.8      |
| MIPS       | 2 (70 μm)  | 2007 Jan 21 | 167.8           | 28.6 ± 1.9       |
| MIPS       | 3 (160 μm) | 2007 Jan 21 | 209.8           | <22              |
| IRS        | 0 (5.2–14.5 μm) | 2006 Jan 15 | 12.6           | ...             |
| IRS        | 1 (9.9–19.6 μm) | 2006 Jan 15 | 188.7          | ...             |
| IRS        | 3 (18.7–37.2 μm) | 2006 Jan 15 | 1219           | ...             |

*Note.* a Not color corrected.

3. RESULTS

Results of the new *Spitzer* photometry are given in Table 1. As first reported in Song et al. (2005), the SED of BD +20 307 at wavelengths longer than 5 μm is dominated by emission by small silicate particles. We show the overall SED including the new *Spitzer* spectrum and photometry along with previous ground-based photometry in Figure 1.

3.1. Photosphere Modeling

We model the combined flux density of the nearly identical central stars with a single Kurucz model atmosphere fit to the *Tycho-2* and Two Micron All Sky Survey (2MASS) photometry at 0.4–2.2 μm. The best-fit model has a gravity of log(g) = 4.5, $T_{\text{eff}} = 6000$, and, at the parallactic distance of 96 pc, a luminosity of 1.94 $L_\odot$. Zuckerman et al. (2008) find the luminosity ratio of the two stars as 0.78, which would imply individual luminosities of 1.10 and 0.84 $L_\odot$. Table 2 gives the amount of photosphere in each *Spitzer* band and the remaining disk flux. The model photosphere was also subtracted from the IRS spectrum.

3.2. Spectral Fitting

We proceed by assuming a simple model for the composition and location of the circumstellar dust and asking whether it is a plausible match to the data. The presence of both broad and sharp spectral features indicates emission by both amorphous and crystalline materials (e.g., Campins & Ryan 1989).

The shortest observed peak, at 9.7 μm, is matched well by the wavelength of the peaks in measurements of glassy silicates, although its width is narrower than that produced by even very small (<0.1 μm) grains. The breadth of the 16–20 μm peak is better fit by larger, 1 μm grains. We chose to set the minimum grain size to 0.5 μm, which is approximately the blow-out size...
for radiation pressure from the stars. We then use a power-law distribution of sizes rising from 0.5 μm with slope −3.5, but the fit does not materially change whether the power-law distribution or just the minimum-sized grains are used. Smaller grains result in narrower peaks that improve the fit at 10 μm but make it worse at 20 μm.

We take the simple model to be dust at a single distance from the star and composed of four types of particulates: small amorphous dust of olivine composition (MgFeSiO₄; hereafter called amorphous olivine), small crystalline olivine (forsterite; Mg₂SiO₄), small amorphous pyroxenes (Mg₀.₅Fe₀.₅SiO₃), and large grains (i.e., those that behave as blackbodies). These are common constituents used to model solar system comets and circumstellar disks (e.g., Li et al. 2004).

All small particles (size ≪ wavelength of observation) have absorption efficiencies that fall faster than Rayleigh–Jeans (i.e., ∝λ⁻²) at wavelengths much larger than the particle size. Therefore, some bigger grains are necessary to match the measured flux densities at 20–70 μm. Again, as a matter of taste, we have chosen to keep the grain size distributions for the olivines and pyroxenes the same, as that seems the most likely physical outcome of a collisional cascade and introduce a blackbody component to the fit. The minimum size of the pyroxenes is not well constrained by the shape of the spectrum, because pyroxenes have relatively broad features. A larger minimum size for the amorphous pyroxenes could be traded off against the blackbody grain component.

We assume that the disk dust is optically thin, so that each dust grain is in thermal equilibrium based on its own absorption efficiency and that the various emission components simply add. The Spitzer 3.5, 4.5, 5.7, and 70 μm photometry and the combined 5.6–25 μm spectrum are fit simultaneously.

We write the emission due to the disk dust in the optically thin case as

\[ F_v = \sum A_i \kappa_i B_v \sigma T^4(d), \]

where the sum is over i independent dust species each with their own mass absorption coefficients, \( \kappa_i = 3Q_{\text{abs}}/4\rho \) where \( Q_{\text{abs}} \) is the absorption efficiency, \( \sigma \) is the grain radius and \( \rho \) is the grain density. The dust grains are not assumed to be in thermal contact; thus each species has its own temperature determined by its \( Q_{\text{abs}} \), distance from the star and the luminosity of the star by assuming it is in thermal equilibrium. These temperatures are calculated self-consistently by making distance from the star the free parameter. The other free parameters are the number or surface density of dust grains of each type, i.e., the \( A_i \).

A major choice is what absorption efficiencies to use. Various authors have taken different approaches to this problem. Because we do not leave temperature as the free parameter, we need genuine ultraviolet and visible absorption efficiencies, as this is where the star emits and the grains absorb most efficiently, in order to calculate temperatures. For this reason, we opt for Mie calculations.

Mass absorption efficiencies from the group at Kyoto Pharmaceutical University (e.g., Koike et al. 2000; Sogawa et al. 2006) are available only in the infrared. Optical constants from the Jena group are provided into the UV–visible, but are only accurate in the near-infrared and longer (e.g., Dorschner et al. 1995). For the amorphous olivine, we adopted the optical constants of Li et al. (2004) which combine the Jena measurements with ultraviolet data. We then used a Mie code⁴ to calculate the mass absorption opacities.

For crystalline olivine, shape is a major determinant of spectrum. The Jena group has measured the triaxial indices of refraction, but how one uses these to calculate the absorption is a matter of taste. Assumption of spherical particles results in sharp peaks that are not observed (Fabian et al. 2001). The Jena group provides two computations of continuous distributions of ellipsoids (CDE) in the Rayleigh limit. We combined these with the ultraviolet efficiencies calculated in the Mie limit from the constants of Li et al. (2004). We tested both the CDE1 (weighted toward spherical grains) and CDE2 (all shapes weighted equally) calculations against our spectra and found that CDE1 was a better match. It is also CDE1 that fairly closely matches a real grain measured in the Jena laboratory (Fabian et al. 2001).

It is because of the flexibility in spectral shape granted by choosing the exact distribution of grain shapes, that we have not attempted a multi-component fit that would reduce our chi-square to a level approximately equal to one. We believe that the large number of free parameters to choose from makes this exercise of limited value.

To find the best fit, we compare the model excess as described above to the photometric (2.16–70 μm) points and IRS spectrum in the classic \( \chi^2 \) formalism. We first perform a search over a

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**Table 2**

| Band   | Photosphere | Disk Flux | Model (mJy) |
|--------|-------------|-----------|-------------|
| IRAC1  | 261.0       | 24.0      | 9.3         |
| IRAC2  | 167.0       | 43.4      | 28.8        |
| IRAC3  | 107.1       | 58.2      | 70.8        |
| IRAC4  | 60.7        | 349.5     | 293.2       |
| MIPS1  | 6.8         | 434.2     | 424.4       |
| MIPS2  | 0.8         | 27.8      | 40.2        |
| MIPS3  | 0.3         | <22       | 8.7         |

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⁴ http://www-atm.physics.ox.ac.uk/code/mie/index.html
The Astrophysical Journal, 726:72 (6pp), 2011 January 10

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large range of parameter space for the free parameters using the Amoeba routine from Numerical Recipes (Press et al. 1992) as implemented in IDL. Once the best fit has been found, we then loop over a small range of values for the free parameters to determine the shape of the \( \chi^2 \) and determine a better minimum.

The best fit is shown in Figure 2. The best distance to the dust is 0.85 AU from the star. The calculated temperatures of the grains are 461 K for the pyroxene, and 460 and 507 K for the amorphous and crystalline olivine silicates, respectively. The blackbody temperature is 358 K. The reduced chi-square value of this fit is 19.7. Obviously, the reduced chi-square is not near one, but nonetheless, the fit is capable of explaining all of the main features of the spectrum including the excess emission at \( 3–5 \mu m \) the whole of the \( 70 \mu m \) emission, and the locations of peaks (10, 12, 17, 19, and 24 \( \mu m \)) in the 7–35 \( \mu m \) spectrum. The overall match between spectrum and the model is good except in the heights of the peaks at 10 and 17 \( \mu m \) and the continuum at 25–30 \( \mu m \). For the issues of most relevance, namely the temperature of the dust, the presence of small grains, and the crystallinity fraction, this model adequately represents the spectrum. Its predictions in the various filters are given in Table 2. The best-fit parameters are given in Table 3.

The contributions by mass are 50% amorphous olivines, 30% amorphous pyroxenes, and 20% crystalline olivines. The actual masses in these small grains range from 0.7 to \( 1.7 \times 10^{22} \) g. Obviously, most of the mass would be in the blackbody grains. A minimum mass for these can be set by selecting the minimum grain radius for one of the above grains to look like a blackbody or \( \sim 30 \mu m \). Then, the minimum mass is \( 6 \times 10^{23} \) g.

4. DISCUSSION

The remarkable results of the Spitzer data are the lack of cold dust—all of the 70 \( \mu m \) emission arises from the same close-in population of dust producing the bright 8–30 \( \mu m \) silicate features, and that the dust that does orbit the star is extremely close-in—within 1 AU. It is the most dusty star for its age known and the one with the warmest dust.

There are now about 10 known “warm” debris disks around FGK stars (Rhee et al. 2008; Moór et al. 2009; Fujiwara et al. 2010; Melis et al. 2010). Most of these have dust temperatures of \( \sim 150–200 \) K and \( L_{IR}/L_\star < 5 \times 10^{-4} \). For stars older than 1 Gyr, BD +20 307 has more than two orders of magnitude more dust opacity than the others. The closest star in terms of dustiness is the much younger Pleiades member HD 23514.

The timescales over which the BD +20 307 disk should evolve are short. The treatment of radiation pressure on small silicates in Burns et al. (1979) and scaled to the slightly larger mass and luminosity of BD +20 307 suggests that all grains smaller than 0.5 \( \mu m \) will be blown away on an orbital timescale, which at 0.85 AU, assuming a central mass of 2.2 \( M_\odot \), is 0.5 yr.

Taking the model fit \( L_{IR}/L_\star = 0.032 \) as the surface density of the grains yields a collision time of 2.4 yr. This is only a few times longer than the orbital time, so the small grains observed in the spectrum will be created and then lost nearly immediately. Wyatt et al. (2007) argue that massive planetesimal belts grind themselves down by collisions quickly, so it is not possible to maintain very large amounts of dust in the terrestrial planet region of old stars. They included BD +20 307 in the list of stars for which it was impossible to generate the present dust through collisional grinding, even using the IRAS 60 \( \mu m \) upper limit to constrain the cold planetesimal population and for an age of 300 Myr. At the current best estimate of its age of at least 1000 Myr, its maximum \( L_{IR}/L_\star \) in steady state (see their Equation (20)) is \( 7.4 \times 10^{-5} \). Recently, Heng & Tremaine (2010) confirm the Wyatt et al. (2007) result that BD +20 307 cannot be from a steady-state collisional cascade, although their models allow most of the other warm disk sources to come from a warm planetesimal cascade.

We do not detect any cold dust; our best-fit model for the hot dust actually overpredicts the measured 70 \( \mu m \) flux density and is slightly higher than the 1\( \sigma \) upper limit at 160 \( \mu m \) (Figure 3). A check on the reasonableness of the lack of cold dust is that if we take the average flux density in the IRS spectrum of 0.4 Jy and extrapolate this as a Rayleigh–Jeans falloff from the mean wavelength of the IRS spectrum, 20 \( \mu m \), we would predict a 70 \( \mu m \) flux density of 0.032 Jy, which is again higher than measured.

We can place a conservative upper limit on the amount of cold dust by finding the luminosity of a dust ring whose spectrum peaks at 160 \( \mu m \) (i.e., temperature of 33 K) and produces no more than a 10% increase in the flux density at 70 \( \mu m \)—such a cold disk would produce an additional 6 mJy at 160 \( \mu m \), which would still fall under the measured 3\( \sigma \) upper limit and would have a \( L_{IR}/L_\star = 3 \times 10^{-5} \). Therefore, in the context of the Wyatt et al. model for planetesimal belt self-grinding, the

Table 3

| Component       | \( A \) | \( T \) (K) | \( L_{IR}/L_\star \) |
|-----------------|--------|------------|---------------------|
| Amor. Olivine   | 1.0    | 460        | 0.010               |
| Amor. Pyroxene  | 0.653  | 462        | 0.006               |
| Crys. Olivine   | 0.821  | 508        | 0.004               |
| Blackbody       | 1.64e-4 | 358      | 0.011               |
| Distance        | 0.85 AU | · · ·      | · · ·                |

Note. These coefficients, defined in Section 3.2, are normalized such that Amor. olivine is 1.0.

Figure 2. Best-fit model to the Spitzer spectrum (black line), derived as described in the text. The various dust components (purple: amorphous olivine, cyan: crystalline olivine, dark blue: amorphous pyroxene, and red: blackbody grains) sum to make the total spectrum (gold line). All components are situated at the best-fit distance of 0.85 AU.

(A color version of this figure is available in the online journal.)
The permanent. The Planet V models of Chambers (2007) show that vapor pressure conditions where the molten silicate cooled that the observed dust is largely amorphous suggests that the impact heated the bulk of the material to temperatures ~1000 K and that any recondensation took place under low vapor pressure conditions where the molten silicate cooled quickly and therefore did not re-anneal into crystalline form. A terrestrial planet system may be stable over a Gyr but not permanent. The Planet V models of Chambers (2007) show that in a configuration such as the solar system’s, a fifth planet can survive in the inner solar system for a Gyr and create collisions of terrestrial planets at many hundreds of millions of years after the system formed. The configuration of the exoplanet system will determine how long it lasts; small planets further from the star take longer to go unstable (J. E. Chambers 2010, private communication). In the case where a tenuous asteroid belt still remains in a planetary system, the trajectory of a rogue planet can destabilize the belt and produce collisions between planetesimals or bombardment of the planets. Over several Gyr, our current terrestrial planet system may be unstable and result in collisions between the planets (Laskar & Gastineau 2009).

Recently, Matranga et al. (2010) suggested that the changing separation of close binaries due to angular momentum loss could sweep resonances across planetary systems and destabilize their planetesimal belts. The stars in BD +20 307 are separated by 0.06 AU at present (Weinberger 2008), and thus the disk radius is 14× the binary separation. They have likely been in a tight circular orbit for billions of years (Weinberger 2008) and their relatively low X-ray activity likely makes their angular momentum loss relatively slow.

How common are giant collisions amongst sun-like stars? We can estimate the number of giant impacts per star N\_\text{f} = f\_\text{\textit{i}} A L\_\text{\textit{i}}^{-1}, where f\_\text{\textit{i}} is the fraction of stars observed to have hot dust, L\_\text{\textit{i}} is the lifetime of the collision products, and A is the age of the stars surveyed.

To estimate the lifetime of the dust, we invert the Wyatt et al. (2007) expression for the amount of dust that can be produced by a collisional cascade over time (their Equation (20)) to solve for the lifetime of a collision that starts in a giant impact. The most significant unknown is the internal strength of the large planetesimal(s) involved, but the binding energy is likely closer to that of a differentiated planet than a pure rubble pile, i.e., more like 2×10⁷ than 200 J kg⁻¹. Therefore, a planet-sized impact could generate a cascade that lasts up to 80,000 years. This result is similar to the 100,000 year lifetime for a collisional cascade started by planetary embryos as calculated by Melis et al. (2010).

Surveys with Spitzer have looked at all Sun-like stars within 25 pc (Koerner et al. 2010), for a sample of about 800. The average age of this population is ≥3 Gyr but it includes a small fraction of much younger stars (Wright et al. 2004). While there are five stars with warm dust in this sample, we note that these have 24 μm flux densities \lesssim10 times their photospheres and L\_\text{IR}/L\_\text{\textit{i}} \lesssim 10^{-3}, and so are not nearly as extreme as BD +20 307. Moreover, their average age is <1 Gyr. Their warm dust may either be from young planetesimal belts (e.g., β Pic, which is in this group) or from collisions fed by outer belts and constrained by planets (e.g., η Corvi; Wyatt et al. 2007).

IRAS was capable of detecting every A−G star with as much hot dust as BD +20 307 out to ~280 pc, although it is possible some of these would not have been noticed. There are ~600,000 stars of earlier spectral type than K0 in that volume. Four stars (including BD +20 307) have F\_24/F\_\text{\textit{i}} > 10. This fraction of host dust stars implies a giant impact rate greater than 0.2 impacts/star during its main sequence lifetime, i.e., implies that such impacts are common. Obviously, these are small number statistics. The WISE mission currently surveying the sky at mid-infrared wavelengths will greatly improve the statistics. Its sensitivity is 30 times better than IRAS at ~24 μm (Wright et al. 2010), and so it should provide a truly complete census of isolated hot dust sources out to a few kpc.
It is difficult to search for planets around BD +20 307 with the radial velocity technique because of the spectroscopic binary. However, if planets do encircle this star, they may trap small bodies in resonance. An enhancement in the planetesimal density might increase the likelihood of a destructive collision such as the one observed. The star HD 69830, also an IRAS source, and >1 Gyr old, was shown with Spitzer to harbor a ring very similar in size and temperature to that around BD +20 307, but containing 150 times less dust (Beichman et al. 2005). A system of three Neptune mass planets was then found to encircle HD 69830, with the dust either residing between the second and third planets from the star or exterior to all three (Lovis et al. 2006).

Whatever the scenario that originated the collision in the BD +20 307 system and others, it is interesting to note that the spectra of other warm dust systems are not identical. HD 69830, for example, has much more prominent 20 μm crystalline silicate peaks (Beichman et al. 2005) and HD 23514 has an unusual broad spectral feature at 9 rather than 10 μm (Rhee et al. 2008). HD 172555’s narrow 8 μm peak and featureless 20 μm regions have been attributed to SiO. These various compositions may result from a combination of progenitor composition, which would affect the primordial abundances of different types of silicates, and geometry of the impact, which can change the melt fraction and condensation properties of its debris.

5. CONCLUSIONS

We have detected a large amount of small silicate dust at 0.85 AU from the >Gyr old star BD +20 307 but no cold dust that could be generated tens or hundreds of AU from the star. A catastrophic collision of two rocky, planetary-scale bodies in the terrestrial zone is the most likely source for this warm dust because it does not require a reservoir of planetesimals in the outer system. Furthermore, the high amorphous silicate content of the dust suggests that the impact must have caused a high melt fraction and amorphization of what was likely a largely crystalline parent body.

This work is based on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. Support for this work was provided by NASA through an award issued by JPL/Caltech and a contract to Ames Research Center for the SOFIA program. We acknowledge support from NASA's Astrobiology Institute to the UCLA and CIW nodes. John Chambers and Sarah Stewart provided insightful conversations on the topic of giant impacts.

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