ORIGIN OF INTERPLANETARY DUST THROUGH OPTICAL PROPERTIES OF ZODIACAL LIGHT

HONGU YANG AND MASATERU ISHIKURO

Department of Physics and Astronomy, Seoul National University, 599 Gwanak-ro, Gwanak-gu, Seoul 151-742, Korea;
hongu@astro.snu.ac.kr, ishiguro@astro.snu.ac.kr

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ABSTRACT

This study investigates the origin of interplanetary dust particles (IDPs) through the optical properties, albedo and spectral gradient, of zodiacal light. The optical properties were compared with those of potential parent bodies in the solar system, which include D-type (as analogs of cometary nuclei), C-type, S-type, X-type, and B-type asteroids. We applied Bayesian inference to the mixture model composed of the distribution of these sources, and found that >90% of the IDPs originate from comets (or their spectral analogs, D-type asteroids). Although some classes of asteroids (C-type, X-type, and B-type) may make a moderate contribution, ordinary chondrite-like particles from S-type asteroids occupy a negligible fraction of the interplanetary dust cloud complex. The overall optical properties of the zodiacal light were similar to those of chondritic porous IDPs, supporting the dominance of cometary particles in the zodiacal cloud.

Key words: comets: general – interplanetary medium – minor planets, asteroids: general – zodiacal dust

1. INTRODUCTION

The purpose of this study is to investigate the origin of interplanetary dust particles (IDPs) while taking into account the optical similarities and diversities between zodiacal light and the reflections from minor bodies in the solar system, such as comets and asteroids. An enormous number of IDPs are distributed in interplanetary space. They are observable as scattered sunlight in the optical wavelength (zodiacal light) and as thermal radiation in the mid- and far-infrared wavelengths (zodiacal emission). The IDP cloud, occasionally referred to as the zodiacal cloud, erodes on a time scale of 10^3–10^7 years (depending on the size and orbit, <1/100 of the age of the solar system) due to Poynting–Robertson drag, mutual collisions among IDPs, and planetary perturbations (Gor’kavyi et al. 1997; Dikarev et al. 2001; Mann et al. 2006). The mass-loss rate around Earth’s orbit is estimated to be ≈10^7 kg s^{-1} (Grun et al. 1985; Mann & Czechowski 2005). It is therefore natural to suppose that ongoing dust production, through mechanisms such as impacts or ice sublimation, is compensating for the erosion of the zodiacal cloud.

The origins of IDPs have been studied through the spatial distribution of the zodiacal light. Early research attempting to explain the spatial distribution expected a large contribution from asteroidal origin IDPs (see, e.g., Dermott et al. 1996). Later, Hahn et al. (2002) compared the surface brightness distribution of zodiacal light, taken with the Clementine spacecraft on board camera, to the inclination distributions of comets and asteroids and suggested that a significant fraction of dust particles at 1 AU are of cometary origin. Nesvorný et al. (2010) further performed a numerical simulation for dust particles ejected from six different orbital groups (asteroid families, main belt asteroids, Jupiter family comets (JFCs), dormant JFCs, Halley-type comets, and Oort cloud comets), and compared the brightness distribution of the modeled zodiacal emission to that of zodiacal emission observed by an infrared space telescope. They suggested that 85%–95% of IDPs observable as zodiacal emission originate from JFCs.

Although these recent studies on the brightness distribution favor cometary sources, little is known about the origin of IDPs in terms of their optical properties. Recently, Ishiguro et al. (2013) derived the geometric albedo of IDPs by comparing the brightness of the Gegenschein, a part of the zodiacal light enhanced by backward scattering enhancement, to the infrared model (Kelsall et al. 1998). The research provided the possibility of studying the origins of IDPs from a different perspective than previous studies. In this study, we considered the origin of IDPs through a comparison of the albedo and spectral gradient of zodiacal light with those of the potential parent bodies, and present a discussion based on previous studies.

2. METHODOLOGY

The size distribution of IDPs was studied through lunar microcrater counting and in situ flux measurements (Grun et al. 1985; Divine 1993). These studies suggested that the effective cross-section of IDPs around Earth’s orbit is dominated by large (10–100 μm) particles. The opposition effect found in Gegenschein supports the idea that IDPs, which make up the zodiacal light, are significantly larger than the optical wavelength (Buffington et al. 2009; Ishiguro et al. 2013). Accordingly, we can assume that the optical properties of IDPs are similar to those of big objects, such as comets and asteroids. Thus, in the following discussion, we postulate the albedo (A) and the spectral gradient (S’) of the IDPs based on those of the potential dust sources.

2.1. Albedo and Spectral Gradient of Zodiacal Light

The albedo of IDPs has been measured using several methods. Hanner (1980) compared the zodiacal light brightness to the IDP model derived from lunar microcrater records. Lumme & Bowell (1985) derived the albedo value of IDPs, which can explain the polarization distribution of zodiacal light. Dumont & Levasseur-Regourd (1988) compared the optical and infrared brightness at a solar elongation of 90°. Recently, Ishiguro et al. (2013) directly measured the geometric albedo of zodiacal light by comparing the optical and infrared (Kelsall et al. 1998) flux at the anti-solar point. They deduced that the albedo of the smooth zodiacal light component is A = 0.06 ± 0.01, after subtracting weak fine-
scale features associated with asteroidal collisional families, namely, asteroidal dust bands. In this paper, we adopt the albedo value from Ishiguro et al. (2013).

Small bodies in the solar system generally show linear spectra in a range of 4500–7500 Å. It is useful to express the spectral index using the normalized reflectivity gradient, \( S' \): 

\[
S' = \frac{dS}{S d\lambda},
\]

where \( S \) is the reflectance, defined as the flux density of an object divided by the flux density of the Sun at a wavelength \( \lambda \), and \( S' \) and \( dS/d\lambda \) denote the average reflectance and spectral gradient in the wavelength range, respectively. The spectra of zodiacal light have primarily been measured at infrared wavelengths from space (Matsuura et al. 1995; Matsumoto et al. 1996; Fixsen & Mather 2002; Reach et al. 2003; Ootsubo et al. 2009; Tsumura et al. 2010). Since there is no spectrographic data available in the optical wavelength range, we derived the optical spectral gradient \( S' \) by a log-linear fitting using compiled photometric data taken at different wavelengths around 4600 Å (Leinert et al. 1998). The regression formula for the ratio between the solar spectrum and the zodiacal light spectrum is given by

\[
I_{\lambda} \propto \left[ 1.0 + 0.9 \times \log \left( \frac{\lambda}{5000 \text{ Å}} \right) \right] I_{\odot},
\]

where \( I_{\lambda} \) and \( I_{\odot} \) denote the flux densities of zodiacal light and the Sun at wavelength \( \lambda \), respectively. Equation (2) is applicable for zodiacal light in the spectral range of \( \lambda \leq 5000 \) Å at a solar elongation of >90º (Leinert et al. 1998). From Equation (2), we obtained the spectral gradient of IDPs as \( S' = 8.5 \pm 1.0\% \cdot 1000 \text{ Å}^{-1} \) at 4600 Å. Note that we derived \( S' \) at 4600 Å in order to match the measured wavelength of the albedo (Ishiguro et al. 2013).

2.2. Data Sources

Turning now to the IDP sources, we assume that they originate from asteroids and comets. In addition, some IDPs may originate from interstellar space (Hahn et al. 2002). For asteroids, we considered five major taxonomic types, namely, C-, X-, S-, B-, and D-types (DeMeo & Carry 2013), as input data. Since the optical properties of cometary nuclei are similar to those of D-type asteroids (one taxonomic type of asteroids), we do not discriminate between D-type asteroids and cometary nuclei. We thus assumed that IDPs consist of dust particles from six populations: C-type, X-type, S-type, and B-type asteroids, as representatives of asteroids, cometary nuclei (including D-type asteroids), and interstellar dust.

To create a template of the optical properties of the six potential dust sources, we made use of catalogs of albedos and the spectra of asteroids and comets. For asteroids, we used the Asteroid Catalog Using AKARI (AcuA) catalog as a data set of albedos (Usui et al. 2011) and the SMASSII catalog as data sets of spectral gradients (Bus 1999; Bus & Binzel 2002b; Binzel et al. 2004). We found 274 C-type, 222 S-type, 191 X-type, 40 B-type, and 33 D-type asteroids archived in both catalogs. For C-type, B-type, and D-type asteroids, which show no obvious absorption, we used the spectral gradient values measured between 4350 and 9250 Å (Bus & Binzel 2002b; Binzel et al. 2004). For S-type and X-type asteroids, which may have an absorption band around >7000 Å, we used the data at 4400–7000 Å (Bus 1999). Albedos and spectral gradients of 10 cometary nuclei were compiled from various previous studies, shown in Table 1. For interstellar dust, we used the optical properties of average galactic dust particles at 4600 Å, that is, \( A = 0.67 \) and \( S' = -23 \pm 1\% \cdot 1000 \text{ Å}^{-1} \) (Draine 2003). We ignored some taxonomic types of asteroids, such as K-type, L-type, and V-type asteroids, as discussed in Section 4.

Figure 1 shows the relationship between the albedos and spectral gradients for the IDPs and the potential parent bodies described above. In the diagram, the datum for IDPs is located within the population of comets and its spectral analog, D-type asteroids, suggesting that the major constituents are of cometary origin. In the following section, we further investigate the contribution of each population using statistical analysis.

2.3. Bayesian Analysis

When we chose objects from a type of population and calculated the correlation coefficients between the albedos and spectral gradients, the absolute values were as low as −0.14, −0.04, 0.16, −0.36, and −0.11, for the C-type, S-type, X-type, B-type, and D-type asteroids, respectively. Therefore, we considered these two properties, the albedo and spectral gradients, as independent of each other, and treated a probability of observed values as a product of probabilities of albedo and spectral gradient. Within a population, we simply assumed that the albedo follows a log-normal distribution, whereas the spectral gradient has a Gaussian distribution. We fit the distributions shown in Figure 1 to the model distributions shown in Figures 2 and 3. Because interstellar dust particles, which make only a limited contribution to IDPs, have optical properties that are very different from those of solar system objects, we assumed that the interstellar dust particles have a fixed albedo value of \( A = 0.673 \) and a spectral gradient of \( S' = -23.2 \pm 0.8\% \cdot 1000 \text{ Å}^{-1} \), and we did not consider their statistical distributions in the following analysis.

We made a 2% grid for the possible combinations of fractional contributions from the source populations. Then, through linear combination of the probability distributions of the source populations according to the given contribution, we were able to generate a mixture probability distribution for an optical property of a single dust particle. Different populations were weighted according to their average albedos. From the probability distribution for a single particle, we calculated the expected average values of both the albedo and spectral gradient for the IDP complex using Monte Carlo (MC) simulations. At every grid point, MC simulations with 500 sample particles were generated 3000 times. Under these conditions, the expected average values follow a Gaussian distribution with a standard deviation of less than 10% of the uncertainty on the zodiacal light measurement. At each grid point, we compared the average value distributions in the MC simulations with the measured values of the zodiacal light with errors, and therefore derived probability that an observation of hypothetical IDPs cloud from the grid point resulted in the measured values. The probability was regarded as the probability of the grid point representing the real fractional contributions through a Bayesian analysis with a flat prior.
Table 1: Optical Properties of Cometary Nuclei

| Name               | Type            | Albedo | Spectral Gradient | References |
|--------------------|-----------------|--------|-------------------|------------|
| 1P/Halley          | Halley type     | 0.043  | 7.5               | (a), (c), (g) |
| 2P/Encke           | Encke type      | 0.050  | 11                | (h), (j), (r) |
| 9P/Tempe1 1        | Jupiter family  | 0.056  | 12.5              | (q)        |
| 10P/Tempe 2        | Jupiter family  | 0.022  | 20                | (e), (f)   |
| 28P/Neujmin 1      | Jupiter family  | 0.025  | 11.8              | (b), (k), (p) |
| 49P/Arend-Rigaux   | Jupiter family  | 0.028  | 10.4              | (d), (i)   |
| 67P/Churyumov-Gerasimenko | Jupiter family | 0.047  | 10                | (o), (s), (t), (u) |
| 103P/Hartley 2     | Jupiter family  | 0.045  | 8.1               | (v)        |
| 162P/Siding Spring | Jupiter family  | 0.034  | 9.2               | (m), (n)   |
| C/2001 OG114 (LOMEOS) | Halley type    | 0.040  | 9                 | (l)        |

Note. (a) Sagdeev et al. (1986), (b) Campins et al. (1987), (c) Keller et al. (1987), (d) Millis et al. (1988), (e) A’Hearn et al. (1989), (f) Jewitt & Luu (1989), (g) Thomas & Keller (1989), (h) Luu & Jewitt (1990), (i) Luu (1993), (j) Fernández et al. (2000), (k) Campins & Fernández (2002), (l) Abell et al. (2005), (m) Campins et al. (2006), (n) Fernández et al. (2006), (o) Lamy et al. (2006), (p) Campins et al. (2007), (q) Li et al. (2007), (r) Boehnhardt et al. (2008), (s) Lamy et al. (2008), (t) Tubiana et al. (2008), (u) Kelley et al. (2009), (v) Li et al. (2013).

3. RESULTS

Table 2 shows the resulting contributions from the individual sources to the IDP cloud. To derive the ranges (which are shown as plus and minus signs in the Table 2), we created contours with the same probability in the six-dimensional grid, calculated the total probability within the contours around the most probable case, and derived a range with a 68.3% confidence interval. We found that comet nuclei (including D-type asteroids) are the primary contributors (~94%) to the IDP cloud, as predicted in the Section 2.2. The remaining part (~6%) originates from the C-type, X-type, and B-type asteroids. S-type asteroids and interstellar dust make an insignificant contribution to the IDPs (~0%). Figure 4 shows the marginalized probability distributions of the four major populations.

Figure 1. Spectral gradients $S'$ with respect to the albedos $A$ of asteroids, comets, and zodiacal light. Uncertainties of albedos are appended in the plot. The 1σ measurement uncertainties in spectral gradients are ordinarily about 0.7% - 1000 Å⁻¹.

4. DISCUSSION

4.1. Feasibility of the Method

To assess the feasibility of our approaches described above, let us discuss the three following points.

First, we should consider the validity of the source populations. There is a wide variety of objects in the solar system, however, only six types of sources (five types of asteroids, comets, and interstellar dust particles) are considered in this paper. Recently, the mass fractions from different taxonomic types of asteroids were studied using new multi-filter photometric survey data. DeMeo & Carry (2013) suggested that C-type asteroids account for more than 50% of the mass in the main belt. Although S-types, P-types, B-types, and V-types have moderate fractions (~10% each of the total mass of asteroids in the main belt), other asteroids, such as K-types, L-types, and A-types, only have minor contributions of <1%. P-types are included in X-types in our assumption. Thus, we considered all but one, namely, V-types, of the major asteroids in this paper. We conjecture that V-types cannot contribute to the IDP cloud because they have very large albedos ($A = 0.30$, Usui et al. 2011). In addition, the mass fraction of V-types is very small (0.01%) when we exclude the largest objects in the taxonomic type (i.e., (4) Vesta). Meanwhile, the photopolarimeters on the Pioneer 10 and 11 spacecraft revealed that the zodiacal light brightness is negligible beyond 3.3 AU (Toller 1981). Those observations suggest that the contribution from outer objects such as Kuiper-belt objects (KBOs) may not be as large as those from asteroids when we consider the previous dynamic studies pointing out that the dust particles from KBOs have peak densities outside of the Jovian orbits (Poppe & Horányi 2012; Vitense et al. 2014). The optical properties of the Centaurs show bimodality. Inactive Centaurs show ultra-red spectra similar to KBOs, and active Centaurs have colors and albedos similar to cometary nuclei (Stansberry et al. 2008, pp. 161–179; Melita & Licandro 2012). In this paper, inactive ultra-red Centaurs were ignored along with KBOs, and active Centaurs were treated as cometary nuclei. Some cometary nuclei have optical properties that are different from those of D-type asteroids, as in the cases of 95P/Chiron and 107P/Wilson–Harrington. We did not include these kinds of objects in this study. We do not know
how many of such objects exist, but these non D-type asteroidal nuclei are similar to other kinds of asteroidal groups in terms of their optical properties. Therefore, each population of an asteroidal group should be understood to include possible cometary nuclei whose optical properties are similar to the group. If we subdivide the X-type asteroids into E-type, M-type, and P-type asteroids, the results remains same, with only the confidence interval worsening because the optical

Figure 2. Albedo distribution of C-type, S-type, X-type, and B-type cometary nuclei (including D-type asteroids; Usui et al. 2011). Black solid lines are histograms for the given types. Red dashed lines are the log-normal distributions calculated from the mean and standard deviation of logarithms.
properties of P-type asteroids are similar to those of D-type asteroids.

Second, we should consider the time-evolution of the optical properties via space weathering. We assumed that the optical properties of dust particles resemble those of the source objects. However, this may not be true in some populations. Since the Poynting–Robertson lifetime of silicaceous dust particles 1 mm in size is about $2 \times 10^7$ years when released into a circular orbit.
from 2.5 AU (Mann et al. 2006), while the timescale of space weathering is more than an order of magnitude shorter than this lifetime (Shestopalov et al. 2013, $\sim 7 \times 10^5$ years for S-type asteroids), it is reasonable to assume that surfaces on both silicate IDPs and S-type asteroids are altered by space weathering and therefore have similar optical properties. However, the space weathering of C-type, X-type, and B-type asteroids is not well known, although there are studies, e.g., Moroz et al. (2004). Therefore, we cannot clearly discuss the optical surface maturation of IDPs originating from these asteroids. Furthermore, cometary dust particles remain within the interplanetary space longer than the active lifespan of cometary nuclei (Levison & Duncan 1997; $\sim 12,000$ years for the ecliptic comets); therefore, the relation between the optical properties of cometary dust particles and the surfaces of active cometary nuclei is not direct. If we regard the cometary nuclei and D-type asteroids as identical, then there are studies that imply that the spectra of D-type asteroids would not change significantly over time. D-type asteroids were found in the inner main belt (DeMeo et al. 2014), and Phobos, possibly a captured D-type asteroid, has the optical properties of a D-type asteroid after remaining in the inner solar system for billions of years (Pajola et al. 2013, 2014). Even though these objects have albedo values slightly higher than the average for D-type asteroids, their albedos and spectral gradients are still in the range of D-type asteroids. In another direction, according to the laboratory experiments on the Targish Lake meteorites, which have spectra similar to D-type asteroids, the continuum spectrum moved in the bluer direction after being exposed to laser radiation (Hiroi & Sasaki 2012). If these results can be applied in our case, then the contribution of cometary nuclei would increase. If we think about the cometary contribution which is dominant even now, then we can conclude that this assumption does not alter the conclusion of this paper.

Third, we should consider the effects of simplification in this study. We assumed that optical properties are randomly dispersed within a population, however, this may not be true. As shown in Usui et al. (2013), there is a relation between orbital elements and optical properties. We want to emphasize that the differences in the optical properties between different types of sources are an order of magnitude larger than the differences between the sub-groups of different types of sources, as shown in Figure 1. Furthermore, we ignored the weak correlation between the albedo and the spectral gradient. This relation was non-negligible for B-type asteroids. There is a possibility that the interstellar dust, which entered the solar system, has a different composition compared to the average dust particles in the Milky Way galaxy (Mann 2010), but we ignored this possibility. However, we justify these simplifications because the contributions from B-type asteroids and interstellar dust are almost negligible. The SMASSII catalog is not bias-free (Mothé-Diniz et al. 2003), and we do not know the optical properties of unbiased populations, but we ignored the effect of bias. We hope that the large measurement uncertainties in the optical properties of zodiacal light cover the consequences of the bias.

### 4.2. Comparison with IDP Samples

Today, IDPs are collected in the Antarctic ice or in the stratosphere around 20–25 km altitude using aircrafts, and they are well studied through laboratory investigations (Brownlee 1985; Engrand & Maurette 1998). Because such particles should contribute to the zodiacal light before they arrive on Earth, it is important to compare our result to IDP samples. It is known that there are two major IDP groups, referred to as “chondritic smooth” (CS) and “chondritic porous” (CP). CS IDPs are composed of low-porosity materials, predominantly hydrated layer silicates (Sandford & Walker 1985). CP IDPs have large porosities of about $\sim 70\%$. CP IDPs are dominated by anhydrous minerals. It is likely that CP IDPs originate from comets based on their mineralogical and petrographical properties (Bradley 2003). When the Earth passed through the dust stream of 26P/Griel–Skjellerup (one of the JFCs), it was expected that 1%–50% of the total collected dust larger than 40 $\mu$m could originate from that comet (Messenger 2002).

These were actually CP type IDPs of primitive anhydrous composition, supporting the assumption that CP IDPs are of cometary origin (Busemann et al. 2009). CS IDPs are thought to be derived from primitive (not differentiated) asteroids because comets do not exhibit the spectral signatures of hydrated silicate while asteroids do (McAdam et al. 2015).

Bradley et al. (1996) measured the reflectance spectra of IDP samples in the optical wavelength and found that CS IDPs generally exhibit flat spectra with a weak fall-off from 6000 Å toward 8000 Å (similar to CI and CM meteorites or C-type asteroids with $S' \sim 0$), whereas CP IDPs exhibit upward spectra ($S' > 0$) without remarkable curvature, although these IDP samples have a variety of albedo values and spectral slopes. Figure 5 compares the synthesized spectrum of zodiacal light based on our mixing model of small bodies with those of most typical CS IDPs (W7040A15) and CP IDPs (W030A5; Bradley et al. 1996). In Figure 5, we also show the input spectrum obtained from multi-band photometry in Leinert et al. (1998) and anti-solar point observation (Ishiguro et al. 2013). The synthesized spectrum of zodiacal light is similar to that of CP IDPs (W030A5) in that it shows a low albedo value and positive slope ($S' > 0$), but it is different from that of CS IDPs in that it does not show a positive slope beyond $\sim 6500$ Å. It should be noted that the fall-offs below 4500 Å in IDP signals are artifacts of the measurements caused by small size effects and should be ignored in the comparison (Bradley et al. 1996). The spectral similarity leads to our assumption that the interplanetary dust complex is dominated by CP IDPs (i.e., the dominance of cometary particles in the zodiacal cloud). It is also curious that CP IDPs tend to have cluster structures of 20–100 $\mu$m (Bradley et al. 1996). The size is in agreement with the effective size of zodiacal light dust particles evaluated by the IDP size distribution model (Grun et al. 1985).

There seems to be a difference in the quantitative estimates of IDP origins between laboratory investigations of IDP samples and ours. Bradley (2003) studied 200 chondritic IDPs from the stratosphere and found that about a half of them are
classified as CP IDPs. Similarly, Noguchi et al. (2015) investigated micrometeorite samples in Antarctica and suggested that \(\sim 25\%\) or even less are categorized into CP IDPs. While we acknowledge that these laboratory investigations provide reliable results regarding the fraction of CS and CP IDPs fallen to Earth, we would draw attention to the sampling bias of the laboratory studies of IDPs. Asteroidal dust particles could be collected on Earth more selectively than cometary dust particles because of the orbital properties. The impact cross-section of asteroidal dust particles at Earth is a few times larger than that of cometary ones. Furthermore, the impact cross-section of Earth can be a few thousand times larger for dust particles trapped in quasi-satellite resonance, which favors asteroidal particles (Kortenkamp 2013).

4.3. Comparison with Previous Studies

Our results are in agreement with kinematic, dynamical studies based on the spatial distribution of zodiacal light. The numerical simulations of Nesvorný et al. (2010) concluded that

![Figure 4](image1.png)

**Figure 4.** (a)–(d) Marginalized probability for the fractions of cometary (D-type asteroids), B-type, X-type, and C-type asteroids. The probability of the vertical axis is the values integrated over a 2% bin.

![Figure 5](image2.png)

**Figure 5.** Comparisons of spectra between our synthesized zodiacal light model (thick continuous line) and CS and CP IDPs (dotted and dashed lines; Bradley et al. 1996). The observed reference spectrum of zodiacal light is also shown (see Section 2.1). Note the drop-offs in the IDP spectra for less than 4000 Å artifacts.
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\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig6.png}
\caption{Comparison of near-infrared zodiacal light spectra between our synthesized model and observed data (Matsuura et al. 1995; Tsumura et al. 2010, 2013). The S-220-11 rocket data at an ecliptic latitude of 10° from Matsuura et al. (1995) were used in the figure. The template spectra of each type of asteroid are from Bus & Binzel (2002a), and the solar spectra are from Gueymard (2004). The templates, synthesized spectra, and the data from Tsumura et al. (2010) are normalized at 1.5 μm, and the data from Matsuura et al. (1995) and Tsumura et al. (2013) are scaled to match our model spectrum at 1.8–2.5 μm.}
\end{figure}
The Astrophysical Journal, 813:87 (9pp), 2015 November 10

Yang & Ishiguro

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9