WISE DETECTIONS OF DUST IN THE HABITABLE ZONES OF PLANET-BEARING STARS

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ABSTRACT

We use data from the \textit{Wide-field Infrared Survey Explorer} (\textit{WISE}) all-sky release to explore the incidence of warm dust in the habitable zones around exoplanet-host stars. Dust emission at 12 and/or 22 μm (\(T_{\text{dust}} \sim 300\) and/or \(\sim 150\) K) traces events in the terrestrial planet zones; its existence implies replenishment by evaporation of comets or collisions of asteroids, possibly stirred by larger planets. Of the 591 planetary systems (728 extrastellar planets) in the Exoplanet Encyclopaedia as of 2012 January 31, 350 are robustly detected by \textit{WISE} at \(\geq 3\sigma\) level. We perform detailed photosphere subtraction using tools developed for \textit{Spitzer} data and visually inspect all the \textit{WISE} images to confirm bona fide point sources. We find nine planet-bearing stars show dust excess emission at 12 and/or 22 μm at \(\geq 3\sigma\) level around young, main-sequence, or evolved giant stars. Overall, our results yield an excess incidence of \(\sim 2.6\%\) for stars of all evolutionary stages, but \(\sim 1\%\) for planetary debris disks around main-sequence stars. Besides recovering previously known warm systems, we identify one new excess candidate around the young star UScoCTIO 108.

\textit{Key words:} circumstellar matter – infrared: planetary systems – planets and satellites: formation – stars: individual (UScoCTIO 108)

Online-only material: color figures

1. INTRODUCTION

The recent release of the \textit{Wide-field Infrared Survey Explorer} (\textit{WISE}; Wright et al. 2010) all-sky survey provides an opportunity to explore the incidence of warm circumstellar dust for a large sample of stars. The \textit{WISE} data set covers 100% of the sky at four infrared bands W1, …, W4 centered at 3.4, 4.6, 12, and 22 μm wavelengths that are sensitive to thermal emission from objects at temperatures similar to our Earth (\(\sim 300\) K), asteroid belt, and the interior zodiacal cloud (165–250 K). In this work, we use this all-sky data set to search for dust in the habitable zones around exoplanet-bearing stars.

In the last two decades, over 700 exoplanets have been revealed and confirmed, primarily from radial velocity (RV) and transit studies, plus \(\sim 2300\) announced candidates for the \textit{Kepler} mission (Batalha et al. 2012) awaiting confirmation.\textsuperscript{5} The majority of these planets are in systems very different from our own, with Neptune-size or bigger planets, too large and often too close to the host star to be habitable. On the other hand, a significant fraction of planetary debris disks have warm dust (\(T_{\text{dust}} \sim 200\) K). Following up on results from \textit{Infrared Astronomical Satellite} and \textit{Infrared Space Observatory} surveys by the \textit{Spitzer Space Telescope} (Werner et al. 2004) found that many nearby stars are surrounded by dust that is thought to be generated by collisions between asteroids and/or sublimation of comets. Of the \(\sim 350\) debris disks measured individually with \textit{Spitzer} (Chen et al. 2005; Su et al. 2006; Beichman et al. 2008; Trilling et al. 2008; Carpenter et al. 2009; Plavchan et al. 2009), \(\sim 70\) are known to have warm components with \(T_{\text{dust}} > 150\) K (Morales et al. 2011).

Among the \textit{Spitzer} discoveries are the first systems known to have both orbiting dust and exoplanets (Beichman et al. 2005; Bryden et al. 2009). The relationship between planets and debris is unclear except in the general sense that the debris is indicative of planetary system formation, so one might expect to see some association. Several prominent A-type stars with imaged planets also have bright debris disks (Fomalhaut, HR 8799, and \(\beta\) Pic; Kalas et al. 2008; Marois et al. 2008; Lagrange et al. 2009), further suggesting a link between the two phenomena. The question is whether the presence of planets enhances, depresses, or is neutral in terms of the frequency or observability of dust systems.

Here, we use \textit{WISE} data to attempt to find evidence of comet/asteroid activity in the habitable zones of stars known to harbor exoplanets, and thereby examine the link between planets and debris. Several groups have already searched for similar planet–debris relationships using \textit{WISE}. Krivov et al. (2011) used data from the preliminary \textit{WISE} release, covering 57% of the sky, to search for dust around 52 systems with transiting exoplanets finding zero \(3\sigma\) excess detections in any single \textit{WISE} band (where \(\sigma\) refers to the fractional infrared excess statistical significance). But by combining \(< 3\sigma\) excesses in W3 and W4, Krivov et al. (2011) identify two candidate excess detections that remain to be confirmed. With the Kepler Objects of Interest (KOI) Catalogue of candidate transiting exoplanets (not necessarily planet bearing), Lawler & Gladman (2012) find the fraction of stars with warm excesses to be \(\sim 3\%\) using the recently released all-sky \textit{WISE} survey. Also using the all-sky \textit{WISE} release and \textit{Kepler}'s KOIs, Ribas et al. (2012) identify 13 transiting planet systems with IR excess (>\(2\sigma\)) at 12 and/or 22 μm, out of a 546 star sample. Only four are \(\geq 3\sigma\) detections for a corresponding detection rate of \(\sim 0.7\%\).

Unlike the previous work, our study makes use of the \textit{WISE} all-sky release and focuses on the set of confirmed exoplanets, including not just transiting planets, but also those detected by RV measurements or by direct imaging. We do not consider the \textit{Kepler} candidate objects, but our sample does overlap with...
Krsov et al. (2011) and Ribas et al. (2012) for a handful of confirmed transiting systems.

For comparison, Padgett et al. (2012) searched for circumstellar warm dust using the WISE all-sky data set, while considering all Hipparcos stars within 120 pc, as well as Tycho stars with proper motions $>$ 30 mas yr$^{-1}$. Their results suggest that the frequency of warm excess emission associated with stellar sources is $\lesssim$2% at the WISE sensitivity limits.

In Section 2, we describe the data for our chosen sample of target stars. Based on this data, we next (Section 3) determine which planet-bearing stars have evidence for warm dust by fitting the spectral energy distribution (SED) and visually inspecting the WISE images. In Section 4, we interpret the results and summarize our findings in Section 5.

2. SAMPLE SELECTION AND THE WISE DATA

Our starting target list consists of 591 planetary systems (with 728 extrasolar planets) given in the Exoplanet Encyclopaedia as of 2012 January 31 (Schneider et al. 2011). The Schneider et al. compilation includes planetary-mass companions detected using all methods presently utilized, i.e., RV or astrometry, transit studies, micro-lensing, pulsar timing, and direct imaging. Searching through the WISE all-sky catalog (which includes all data taken during the WISE full cryogenic mission phase), we find 350 individual planet–star systems that have WISE photometric data within a 5$''$ search radius. The vast majority are well within an arcsec. In addition to the WISE flux measurements from profile-fitting photometry, each WISE catalog entry gives positions, astrometric and photometric uncertainties, and flags for reliability, which we used to decide which flux measurements in W1,...,W4 are used or discarded during the batch-processing analysis described below. The remaining 241 stars are too faint for the WISE 5$\sigma$ point source sensitivity limits of $\sim$0.08, 0.11, 1, and 6 mJy in bands W1,...,W4 (WISE, Wright et al. 2010). Figure 1 is a color–magnitude diagram color-coded by planet discovery method, to illustrate how stars with infrared excess emission can be initially identified. Most stars do not have excess (i.e., $[3.4] - [22] \sim 0$), but the WISE fluxes reveal an interesting sample of objects with $[3.4] - [22] > \sim 0.2$.

3. ANALYSIS

3.1. SED Fitting

To measure excess emission at the WISE wavelengths, we require a precise method to subtract off the stellar photosphere. We start by compiling near-IR Two Micron All Sky Survey (2MASS) data (cross-correlated with the WISE catalog) and optical Tycho photometry (Hög et al. 2000) from the NASA Exoplanet Archive.2 For the SED fitting, we use previously developed advanced tools built to study large samples of debris disks as seen by Spitzer (Morales et al. 2009, 2011). These tools $\chi^2$ fit the SEDs of each of the 350 exoplanet-bearing stars to derive the photosphere and disk contributions. The latter can be approximated by a blackbody corresponding to the characteristic temperature of the dust grains, and NextGen models are used to model the contribution of the stellar photospheres.

While our expectation is to find dust emission primarily at longer wavelengths, our SED fitting method can detect excess emission at any dust temperature (it is sensitive to any WISE waveband, not just W3 and W4).

In order to identify a significant amount of excess emission, the total signal-to-noise ratio ($S/N$) can be expressed as

$$\left(\frac{S}{N}\right)_T = \frac{F_* + F_d}{\sigma} = \left(\frac{S}{N}\right)_d + \left(\frac{S}{N}\right)_d,$$  \hspace{1cm} (1)

where the uncertainty, $\sigma$, is a combination in quadrature of the uncertainty in the WISE photometry and calibration. Thus, the

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7 http://exoplanetarchive.ipac.caltech.edu/
fractional excess can be expressed as

$$\frac{F_d}{F_\star} = \left[ \left( \frac{S}{N} \right)_d - 1 \right]^{-1}.$$  

(2)

These expressions hold under the assumption that the observational uncertainties are much greater than the uncertainty of the SED fit. Objects detected by WISE with an S/N of 5, for example, allow us to measure excess emission ($F_{\text{dust}}/F_\star$) down to a factor of 1.5 above photospheric emission levels (with 3σ significance on dust), while we can detect fainter excesses in brighter objects.

By applying these equations, we find that 23 of the 350 planet-host stars result in an S/N of 3 or greater for the dust emission, ($S/N)_{\text{dust}} \geq 3$, in W3 and/or W4. The remaining 327 planet-bearing stars have photospheric SEDs, where no statistically significant excess is observed at the WISE bands. Of the 23 planet-bearing stars studied here, most lack excess emission in the W1 and W2 WISE bands, except for a small subsample of young stellar sources where excess is seen in all WISE bands. Subsequently, young systems are modeled using the Robitaille grid (Robitaille et al. 2006, 2007) for young stellar sources.

Figure 2 shows the SED fitting results of four representative objects of the 23 planetary systems yielding ($S/N)_{\text{dust}} \geq 3$.

The 23 systems show IR excess when using the W1, W3, W4 photometric measurements available in the WISE catalog. However, because WISE is an all-sky survey, it is certain that some of its photometry, obtained via an automatic profile-fit pipeline, will suffer from background contamination, so our next step is to inspect the WISE images.

### 3.2. Visual Inspection

We downloaded fits files from the IRSA archive for the 1.4×1.4 regions surrounding each of the 23 SED-fit candidate disks. Although the WISE all-sky release source catalog provides four-band photometry at the location of each W1 (3.4 μm) point source, a large number of objects with cataloged fluxes have no evidence of a corresponding point source in W3 and/or W4. After a visual inspection of the WISE images on the 23 WISE excess candidates identified via SED fitting, we find 9 stars with planetary mass companions (β Pic, ε Eri, HR 8799, 2M1207, CT Cha, GQ Lup, LkCa 15, USco CTO 108, and HD 139357) are bona fide point sources at the location of the WISE...
Table 1

<table>
<thead>
<tr>
<th>Name</th>
<th>Spectral Type</th>
<th>K (mag)</th>
<th>Dist (pc)</th>
<th>Age (Myr)</th>
<th>(N_{pl})</th>
<th>Planet</th>
<th>(W3)</th>
<th>(W4)</th>
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<td></td>
<td></td>
<td>(F_{\nu})</td>
<td>(F_{\nu}/F_{*})</td>
<td>([S/N]_d)</td>
<td>(T_d) (K)</td>
<td></td>
<td></td>
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<tr>
<td>(\beta) Pic</td>
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<td>3.5</td>
<td>19</td>
<td>12</td>
<td>1</td>
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<td>-</td>
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<tr>
<td>(\epsilon) Eri</td>
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<td>1.8</td>
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<td>660</td>
<td>1</td>
<td>RV</td>
<td>5.689</td>
<td>-</td>
</tr>
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<td>HR 8799</td>
<td>A5V</td>
<td>5.2</td>
<td>39</td>
<td>60</td>
<td>4</td>
<td>Imaging</td>
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**Main-sequence stars**

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<th>Age (Myr)</th>
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<th>Planet</th>
<th>(W3)</th>
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<td>([S/N]_d)</td>
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<td>2M1207</td>
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<td>8</td>
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<td>4.2</td>
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<td>K7eV</td>
<td>7.1</td>
<td>140</td>
<td>1</td>
<td>1</td>
<td>Imaging</td>
<td>0.534</td>
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<tr>
<td>LkCa 15</td>
<td>K5V</td>
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<td>2</td>
<td>1</td>
<td>Imaging</td>
<td>0.152</td>
<td>8.2</td>
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<tr>
<td>U Sco CTIO 108</td>
<td>M7</td>
<td>12.5</td>
<td>145</td>
<td>11</td>
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**Young stars**

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<th>Dist (pc)</th>
<th>Age (Myr)</th>
<th>(N_{pl})</th>
<th>Planet</th>
<th>(W3)</th>
<th>(W4)</th>
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<td></td>
<td>(F_{\nu})</td>
<td>(F_{\nu}/F_{*})</td>
<td>([S/N]_d)</td>
<td>(T_d) (K)</td>
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<td>3100</td>
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**Evolved star**

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<th>Dist (pc)</th>
<th>Age (Myr)</th>
<th>(N_{pl})</th>
<th>Planet</th>
<th>(W3)</th>
<th>(W4)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>(F_{\nu})</td>
<td>(F_{\nu}/F_{*})</td>
<td>([S/N]_d)</td>
<td>(T_d) (K)</td>
<td></td>
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<td>Fomalhaut</td>
<td>A4V</td>
<td>0.9</td>
<td>7.7</td>
<td>430</td>
<td>1</td>
<td>Imaging</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HD 10647</td>
<td>P9V</td>
<td>4.3</td>
<td>17.3</td>
<td>4800</td>
<td>1</td>
<td>RV</td>
<td>0.600</td>
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**Notes.** Table listing nine planetary systems with significant WISE excesses, \((S/N)_{dust} \geq 3\), at 12 (W3) and/or 22 \(\mu\)m (W4) using the all-sky WISE data release. Our detections of IR excesses are divided into three categories: main-sequence debris disks, young disks, and dust around an evolved star in the giant phase. An entry of "-" under the \(W3\) columns corresponds to values not used in fits due to saturation problems and thus no excess is computed. An entry "-" under the \(W4\) column means that a single dust temperature is not computed since young stars with disks are modeled with a wide distribution of dust temperatures. The last two entries, Fomalhaut and HD 10647, are known to harbor warm dust emission \(\sim 20\ \mu\)m from Spitzer studies, but are below the detection limit of the WISE W4 band.

4.1. Young Disks

Five of the nine warm excess systems in our sample are young stellar sources, 2M1207, CT Cha, GQ Lup, LkCa 15, and U Sco CTIO 108, and all show warm dust excess emission at both W3 and W4 wavebands. Using Spitzer, these objects have been previously known to harbor warm dust (Riaz et al. 2006; Manoj et al. 2011; Kessler-Silacci et al. 2006; Espaillat et al. 2007), except for U Sco CTIO 108. This star, a young stellar source in the nearest OB association Scorpius–Centaurus, is an 11 Myr old M7 type star, 142 \(\pm 2\) pc away (Pecaut et al. 2012). Discovered by direct imaging, U Sco CTIO 108 is orbited by at least one substellar-mass companion \((M = 16.5^{+2.3}_{-2.0} M_J)\) at a distance of 670 AU from the star (Béjar et al. 2008). A simple SED fit (Figure 2) to the WISE data using the Robitaille grid suggests that this object has an optically thick disk. It has excess flux ratios \((F_3/F_4)\) of 4.0 in W3, and greater than 20 times the expected photosphere in W4. We estimate a disk mass accretion rate \(\dot{M} \sim 1.3 \times 10^{-10} M_{\odot} \text{yr}^{-1}\), a T$_{\text{disk}}$ of \(\sim 0.016 L_{\odot}\), a disk mass of \(M_{\text{disk}} \sim 6.73 \times 10^{-5} M_{\odot}\), assuming an inclination angle of \(\sim 76^\circ\) and \(A_V = 1.63\).

4.2. Main-sequence Debris Disks

Our search yields three planetary systems around main-sequence stars that have measurable WISE excesses at levels \(\geq 20\%\) above that expected from the photosphere in the W4 WISE band: \(\beta\) Pic, \(\epsilon\) Eri, and HR 8799. With \((S/N)_{dust} \geq 5\), all three star–planet systems are already known to harbor warm dust emission (Wahhaj et al. 2003; Backman et al. 2009; Su et al. 2009).
4.3. Dust around Evolved Stars

There is one evolved star in our final excess candidate list, HD 139357, with spectral type K4 III and 121 pc from the Sun. It is orbited by a giant planet discovered using the RV technique; a 9.8 ± 2.2 $M_J$ exoplanet at 2.4 ± 0.2 AU (Döllinger et al. 2009). The SED fit in Figure 2 of HD 139357 suggests the presence of excess emission at 22 μm, but this star is bright ($K = 3.4$ mag), with photometry above the WISE saturation levels in W1, W2, W3 which are thus not used in the fitting analysis. Although the photometric extrapolations for W1, W2, W3 are provided in the WISE all-sky catalog and the WISE images show this giant star as a point source in infrared emission, the accuracy of the W1, W2, W3 measurements are highly uncertain. With a borderline $S/N_{dust} = 3$ in W4 and because it survives our discriminating filters, this star remains in Table 1 but is still inconclusive until its photometry can be more accurately measured. One possible explanation for warm dust around giants comes from Jura (2004) and Jones (2008), who propose that as stars ascend the red giant branch and become more luminous, thermal sublimate from comet-like bodies in an analog to the Kuiper Belt could occur and therefore dust would be released into the surroundings.

4.4. On the Overall Sample

For the seven cases of directly imaged substellar-mass companions (two main-sequence and five young stars), the warm dust is inferred to be located interior to the imaged planet(s), where the dust is asteroidal in temperature and the planets are gas giants. On the other hand, the planetary companions detected using the RV technique around $\epsilon$ Eri and HD 139357 are exoplanets found within a few AU ($\sim$3.4 and $\sim$2.4 respectively) from the parent stars, and may influence the origin and evolution of the warm dust.

In the case of $\epsilon$ Eri (K2V), the planet (1.55 ± 0.24 $M_J$) is only 3.4 ± 0.4 AU from the star and an asteroidal belt is thought to be unstable. According to Reidemeister et al. (2011), the observed warm dust can stem from the outer “Kuiper Belt,” get transported inward by Poynting–Robertson drag, and the inner planet may have little effect on the distribution of warm dust.

5. SUMMARY AND CONCLUSIONS

In summary, of the 591 planetary system (728 extrasolar planets) in the Exoplanet Encyclopaedia as of 2012 January
31, 350 are robustly detected by WISE, and nine stars have mid-IR excesses (\(S/N_{\text{dust}} \geq 3\)) measurable with WISE at 12 and/or 22 \(\mu\)m (W3 and/or W4). The excess emission is indicative of dust at characteristic temperatures that correspond to the habitable and/or terrestrial zones around the stars.

Overall, the \(\sim 2.6\%\) incidence of warm dust emission from planet-bearing stars is lower than that of \(\sim 4\%\) from unbiased samples studied with the Spitzer Space Telescope (Bryden et al. 2006; Trilling et al. 2008; Lawler et al. 2009; Carpenter et al. 2009). Note that Spitzer determinations may go to dust fractional excesses as low as \(\sim 10\%\), where with WISE we achieve \(\geq 20\%\) above the photosphere (Fomalhaut and HD 10647 in Table 1, for example, have fractional excess \(< 20\%\) at \(\sim 20 \mu\)m as seen by Spitzer but are only \(\sim 2\sigma\) with WISE W4). Also, some of the stars in our sample are fainter than the corresponding Spitzer targets. Thus, it is not surprising that the incidence of warm dust around planet-bearing stars as seen with WISE is somewhat lower than the pointed surveys using Spitzer.

The stars considered here can be divided into three categories as a function of their evolutionary state—young, main sequence, and evolved (Table 1). In that case, there are three warm debris disk robustly confirmed by WISE around the \(\sim 350\) main-sequence planet-bearing stars, for an incidence of excess of \(\sim 1\%\) (where for the young stars only, the incidence is closer to \(\sim 38\%\)). The low warm debris disk incidence is in agreement with Padgett et al. (2012), but lower than some recent studies focusing on Kepler candidate planetary system (Ribas et al. 2012; Lawler & Gladman 2012). Based on a detailed analysis of all Kepler-observed objects, Kennedy & Wyatt (2012) conclude that the previous Kepler-based studies were contaminated by background galaxies.

In conclusion, using the WISE all-sky data release,

1. We recover previously known warm excess systems above a dust detection limit of \(F_{\text{d} W4}/F_* > 0.2\); stars just below this threshold (e.g., Fomalhaut and HD 10647) only yield \(\sim 2\sigma\) excesses.

2. We find one unambiguous new excess system around the young stellar source UScoCTIO 108. Although the region around this object shows some low-level background emission, the target is robustly detected at both W3 and W4.

3. The fraction of planet-bearing stars with WISE 12 and/or 22 \(\mu\)m excesses is \(\sim 2.6\%\) including young, main-sequence, and evolved stars, but \(\sim 1\%\) for planetary debris disks around main-sequence stars only.

4. The identification of mid-IR excesses using the WISE all-sky release requires the examination of the images in all cases to confirm the presence of a bona fide point source at the location of the star.

The large number of W3 and W4 entries in the WISE all-sky catalog (170 and 30 million with \(> 2\sigma\) detections in each band), although they are not all high S/N stellar sources, offers a unique opportunity to explore the incidence of warm dust (down to the sensitivity of WISE) for all stellar sources, and not only for those where substantial companions have been identified.

Determining the incidence of warm dust is important to further our understanding of the matter available to form planets in the habitable zones around stars, and the processes by which rocky terrestrial-like bodies form.

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