Debris Disks and the Search for Life

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Planetesimals are the building blocks of planets. We can trace them by the dust they produce by collisions and sublimation, which forms a debris disk around the star. This "zodiacal" dust has a variety of scientific connections and implications. It also poses an observational issue for direct planet detection, due to the background noise and confusion it may introduce (Brown 2015; Stark et al. 2014). While zodical emission is an issue for planet-finding at visible and near-infrared wavelengths, the latest information comes from far-infrared observations of dust in the outer reaches of planetary systems. The high frequency of planetesimals around solar-type stars has also sparked renewed interest in lithopanspermia—the distribution of life between planets and even planetary systems.

Planetesimals

The evidence for planetesimals comes from infrared emission in excess of that expected from stellar photospheres. This emission is thought to arise from circumstellar dust. Because the lifetime of the dust grains is <1 Myr, which is much shorter than the age of the star (>10 Myr), we infer that the dust cannot be primordial. It must be steadily or stochastically produced by collisions, disruptions, and/or sublimation of larger bodies—planetesimals (for a review, see e.g., Wyatt 2008; Moro-Martín 2013).

Mid- and far-infrared observations with *Spitzer* (3.6–160 μm) and *Herschel* (70–500 μm) indicate that at least 10–25% of stars of age 0.01–10 Gyr harbor planetesimal disks with radial extent in the range 10s–100s AU. This frequency is a lower limit because the surveys are limited by sensitivity.

We find evidence for planetesimals around A- to M-type stars, and also around the progenitors of white dwarfs (Jura 2007). These stars span orders of magnitude in stellar luminosity, implying that planetesimal formation is a robust process and can take place under a wide range of conditions. This conclusion is consistent with studies that find a correlation between stellar metallicity and the occurrence of massive planets (Santos et al. 2004; Fisher & Valenti 2005). There is, however, no correlation between stellar metallicity and the presence of debris disks (Greaves et al. 2006; Bryden et al. 2006; and Moro-Martín et al. 2015, based on data from the James Clerk Maxwell Telescope, *Spitzer,* and *Herschel* respectively).

Detailed analysis of spectra of infrared excess obtained with *Spitzer* indicates that cold dust disks are common around solar-type (FGK) stars, with a characteristic dust temperature 60–180 K, and with inner disk cavities 10–40 AU in radius (Carpenter et al. 2009). These dust disks are in a regime where the dynamics of the dust particles are mostly controlled by collisions, and therefore the dust traces the location of the planetesimals. These results indicate that most of the planetesimals inferred to exist around mature, solar-type stars are analogous to the Kuiper Belt, in the sense that they have large inner cavities. The inner radius of the Kuiper Belt is ~35 AU.

The sun also harbors a debris disk, produced by the asteroids, comets, and Kuiper Belt objects (Jewitt et al. 2009), with a production rate of dust that has changed significantly with time, having been higher in the past, when the solar system was less than ~700 Myr old. At those earlier times, the asteroid and Kuiper belts were more densely populated; they were depleted by planetary migration. Today, the solar system's debris disk is fainter than the faintest extrasolar debris disks we can observe with *Herschel*, with a 3-σ detection limit at 10–20 times the level of dust in the current Kuiper Belt (Eiroa et al. 2013; Matthews et al., in preparation).

Fractional luminosity and exozodi

Fractional luminosity is a variable commonly used to characterize debris-disk emission. It allows comparison of disks observed at different wavelengths, and it is not strongly model-dependent, as long as the wavelength coverage is good—as is the case for the stars in our sample. Fractional luminosity can also help place *Herschel* observations of debris in the context of the solar system's debris disk.

Figure 1 shows the cumulative frequency of the fractional luminosity of dust, L_{dust}/L_{star}, from an unbiased sample of 204 solar-type stars observed with as part of the DEBRIS and DUNES surveys. The stars in this sample are located at distances <20 pc (to maximize survey completeness), with ages >1 Gyr (to avoid the effect of disk evolution), and with no binary companions within 100 AU, to minimize gravitational disruption. The debris-disk frequency within this unbiased sample is $0.14^{+0.03}_{-0.02}$ (Moro-Martín et al. 2015).

The blue, green, magenta, and red lines in Figure 1 are theoretical distributions that assume a Gaussian distribution of fractional luminosity in logarithmic scale, with mean values of 10, 3, 1 and 0.1 times the solar-system value, $L_{dust}/L_{sun} = 10^{-6.5}$, respectively. The 1-$\sigma$ widths (dex) of the theoretical distributions are 0.4, 0.8, 1.18 and 2.0, respectively. We fixed the cumulative frequency of disks with $L_{dust}/L_{star} = 10^{-5} > 10$ at 10%, which is the frequency observed in our sample. The Gaussian distribution

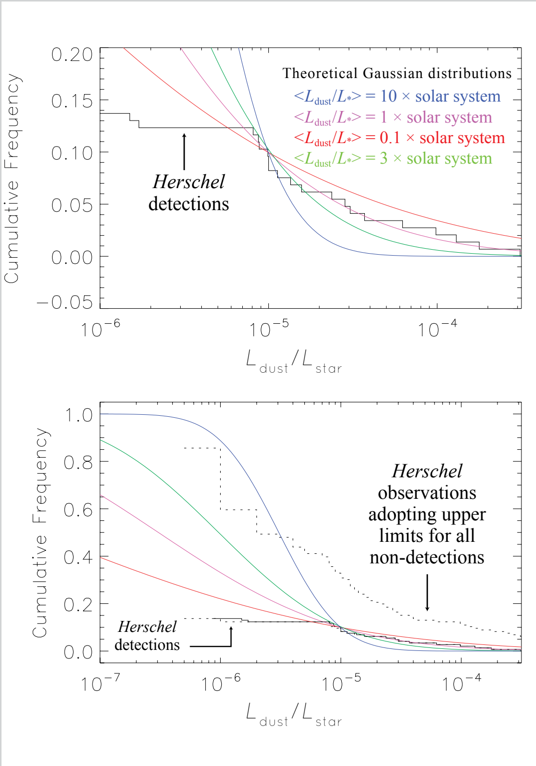

Figure 1: Cumulative frequency of the fractional luminosity observed by (solid line), compared to theoretical distributions that assume a Gaussian distribution in logarithmic scale, centered at 10×, 3×, 1× and 0.1× the solar-system value (colored lines). *Top*: showing only the detected range; there are only three targets with fractional luminosities below 8×10^{-6}, compromising the fit to the data in that low range, because of small-number statistics. *Bottom*: the two dotted lines assume a pessimistic and an optimistic case, respectively, where the adopted fractional luminosities for the targets without excess detections are taken to be zero (pessimistic) or its corresponding upper limit (optimistic).

centered on the solar-system value (magenta line) fits the data well, while one centered at ten times the solar-system debris disk (blue line) exceeds the most optimistic case, so it can be rejected.

Herschel detects emission from cold dust at 10s of AU from the stars with excess emission at 100 µm. The exozodiacal light—reflected starlight from dust at only a few AU—is a related phenomenon. We expect the fractional luminosity of the cold dust and the exozodiacal light to be correlated to some level because the dust in the region of the outer Kuiper Belt is likely one of the sources of the inner, zodiacal dust. This dust has been transported inward by Poynting-Robertson (PR) drag. We further expect the fractional luminosity and zodi to be proportional to the effective optical depths of the relevant dust, along their lines of sight. For debris disks, those optical depths are very small.

In the case of the solar system, the typical fractional luminosity (and optical depth) of zodiacal dust is ~10^{-8}–10^{-7} in the inner system (Dermott et al. 2002) and $10^{-6.5}$ in the outer system. In the case of other planetary systems, if the outer belt were to be the only source of exozodiacal dust—and assuming steady state and dust dynamics controlled by PR drag—one would expect

$$\text{exozodi} \approx \text{zodi} \times (L_{dust}/L_{star}) / (L_{dust}/L_{sun}) \ .$$

Under this assumption, our observations of fractional luminosity, with $L_{dust}/L_{star} < 10 \times L_{dust}/L_{sun}$, are good news for exoplanets, because exozodiacal light at the level of 10 zodis would not measurably reduce the expected performance of a 16m class, *ATLAST*-type telescope.

Ruling out a distribution of fractional luminosities centered at 10× the solar-system level would mean good prospects for finding a large number of debris-disk systems with zodi emission low enough to be appropriate targets for terrestrial-planet searches. This is because, for planetary systems with dust at the solar-system level, PR drag dominates the dust dynamics, and causes the dust to drift inwards to the region where terrestrial planets are expected to occur.

The outer belt is not the only source of exozodiacal dust, however. Comets and asteroids located closer to the star are also sources of dust that can contribute to the zodi emission. For those sources, the long-wavelength observations do not provide constraints. Nevertheless, lower emission from Kuiper Belt-type dust likely implies less populated outer belts, which could reduce cometary activity.

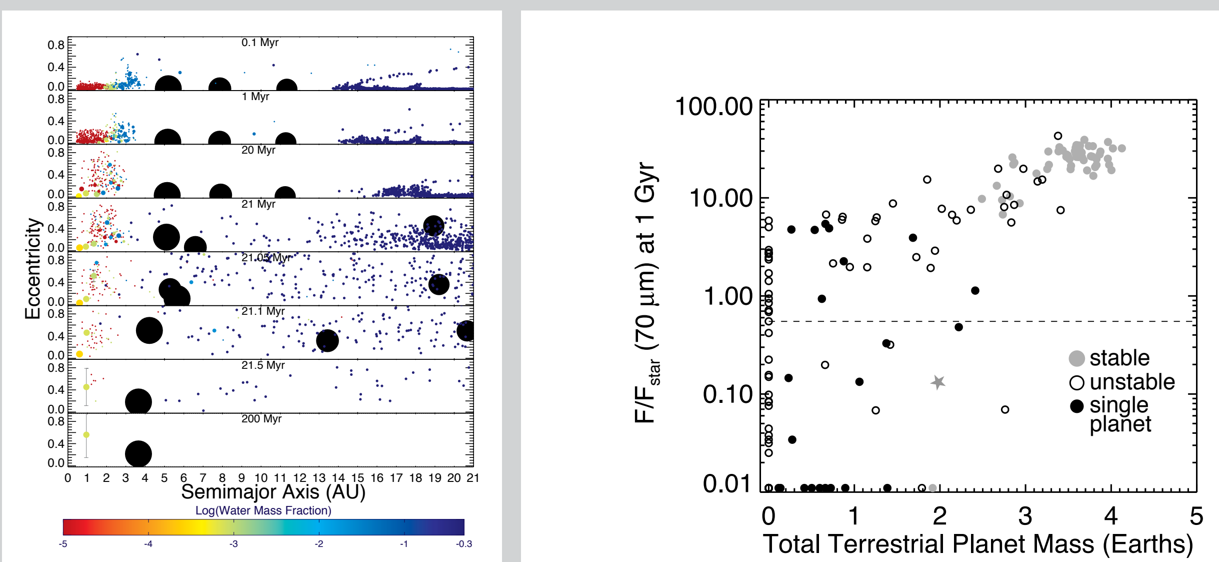

Figure 2: *Left*: Sample simulation showing that dynamically active, high-mass planets tend to destroy both the outer, dust-producing planetesimal belt and the building blocks of the terrestrial planets. *Right*: The dust-to-stellar flux ratio at 70 µm after 1 Gyr of dynamical and collisional evolution, plotted as a function of the total mass in terrestrial planets. Figures from Raymond et al. (2011).

There is more to the story, however.

Even though the planetesimals detected by *Herschel* in the far infrared are located far from the terrestrial-planet region, their presence indicates an environment favorable to the growth and survival of terrestrial planets. The planetesimals indicate that the system has experienced a calm dynamical evolution, as opposed to an environment of dynamically active, high-mass planets. Such an environment would tend to destroy both the outer, dust-producing planetesimal belt and the planetesimals that might otherwise build the terrestrial planets.

Figure 2 shows the results from extensive dynamical simulations by Raymond et al. (2011, 2012), consisting of high-mass planets, embryos, and inner and outer belts of planetesimals. These simulations find that there is a strong correlation between the presence of cold dust in the outer planetary system, and the presence of terrestrial planets in the inner region. Thus, a system with low levels of Kuiper-Belt dust emission might also imply a dynamical history not amicable to terrestrial planets. In this case, the solar system would be an outlier, with a low level of Kuiper-Belt dust but a high number of terrestrial planets. It would be of great interest to further explore this correlation by extending the Raymond et al. (2011, 2012) simulations to cover a wider range of initial conditions. This could shed light on the target selection for an *ATLAST*-type mission.

Lithopanspermia

Another link between debris and the search for life is the exchange of debris between young planetary systems, which may be more efficient than previously assumed. The phenomenon of dynamical transfer via chaotic, near-parabolic orbits makes lithopanspermia a viable hypothesis.

Having only one example of a habitable planet, there is little certainty regarding the frequency and timescale of abiogenesis once the conditions for life are met. Life could arise *in situ*, or it could be transferred from somewhere else. The exchange of meteoroids between the terrestrial planets in our solar system is a well-established phenomenon. The identification of a handful of meteorites on the moon and Mars has given rise to the concept of lithopanspermia: the transfer of life from one planet to another via the exchange of meteoroids. Nevertheless, the idea of lithopanspermia between different planetary systems—as opposed to between planets in the same system—has had a serious problem: extremely low transfer probabilities.

Until now.

Encouraged by the high frequency of planetesimals around solar-type stars, we have revisited the issue of lithopanspermia between planetary systems. We found that the transfer probabilities are greatly increased when considering quasi-parabolic, chaotic orbits (a.k.a. “weak transfer”; Belbruno et al. 2012). This mechanism, illustrated in Figure 3, could allow the exchange of large quantities of solid material between young planetary systems, when the stars were still embedded in the birth cluster. The efficiency of the exchange depends on the masses of the stars involved. For stellar masses between

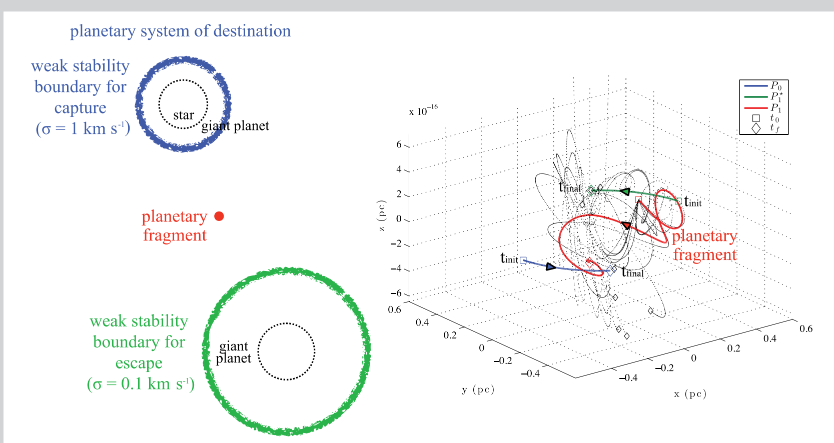

Figure 3: *Left*: Schematic representation of the weak-transfer process. It consists of a meteoroid weakly escaping from a planetary system and its subsequent weak capture by a neighboring planetary system in the stellar cluster. The meteoroid flies by the planet and weakly escapes the central star at approximately the location of the weak stability boundary created by the gravitational perturbation of the other N–1 stars in the cluster. The motion in this region is chaotic and lies in the transition between capture and escape. Then the neighboring cluster star weakly captures the meteoroid. *Right*: Few examples of the million Monte Carlo realizations carried out, showing the chaotic trajectory of a meteoroid that is successfully captured (in red), and others that are not captured (dotted black lines).

0.5 M_{Sun} and 1 M_{Sun}, we find that about 0.05–0.15% of the meteoroids that leave the first planetary system on nearly parabolic orbits are trapped by the second planetary system (its nearest neighbor in the cluster). This capture efficiency is a billion times larger than was found by previous studies using hyperbolic orbits to transfer meteoroids between the Sun and its nearest neighbor—after the stars have left the birth cluster (Melosh 2003). At that point, the relative velocities of the meteoroids are several km s^{-1} larger than the 0.1–0.3 km s^{-1} that we considered to be characteristic of open clusters.

For lithopanspermia to be a hypothesis worth considering, the increased transfer probability is not enough; there needs to be a viable mechanism for weak transfer to take place after abiogenesis (see Figure 4), and the time for survival of microorganisms in deep space needs to be longer than the characteristic transfer time. In Belbruno et al. (2012), we explored the case of the Earth. We asked the question: could life on Earth have developed before the cluster dispersed? From the isotopic ratio of oxygen found in zircons, there are indications that liquid water was present in the crust of the Earth when the solar system was as young as 164 or 288 Myr, depending on the study, which indicates that habitable conditions might have been present early on. Other studies show that the isotopic ratio of carbon in old sedimentary rocks indicates evidence of biological activity when the solar system was only 718 Myr. If this age estimate is correct, it means that life may have been present very shortly after the end of the era of the "late heavy bombardment."

The timescales for abiogenesis are thought to range from 0.1–1 Myr for hydrothermal conditions at the deep sea, to 0.3–3 Myr for warm-puddle conditions in shallow water, to 1–10 Myr for subaeric conditions in the soil—all at least an order of magnitude less than the lifetime of the stellar cluster. If life arose on Earth shortly after liquid water was available on its crust, the window of opportunity for life-bearing rocks to be transferred to another planetary system in the cluster opens when liquid water was available (64–288 Myr), and ends by the cluster dispersal time (135–535 Myr; Adams 2010). Within this timeframe, heavy bombardment ejected large quantities of rocks from Earth. This bombardment period lasted from the end of the planet–accretion phase until the end of the late heavy bombardment 3.8 Gyr, when the solar system was approximately 770 Myr old (Tera et al. 1974; Mojzsis et al. 2001; Strom et al. 2005).

The bombardment is evidence that planetesimals were being cleared from the solar system several hundred million years after planet formation (Strom et al. 2005; Tsiganis et al. 2005; Chapman et al. 2007). This period of massive bombardment and planetesimal clearing completely encompassed the "window of opportunity" for the transfer of life-bearing rocks, providing a viable ejection mechanism for weak transfer to occur.

For lithopanspermia to work, the time for survival of microorganisms in deep space needs to be longer than the characteristic transfer timescale. Microorganisms can be sheltered from the hazards of outer space (ultraviolet light, x-rays and cosmic rays) if hidden below the surface of the rocks. Survival for millions of years cannot be tested with direct experiments (e.g., experiments testing the survival on the surface of the Moon lasted only a few years), but there are computer simulations that model the conditions in outer space for extended periods of time. A study based on these simulations (Valtonen et al. 2009) found that the survival times range from 12–15 Myr (for rocks with sizes of

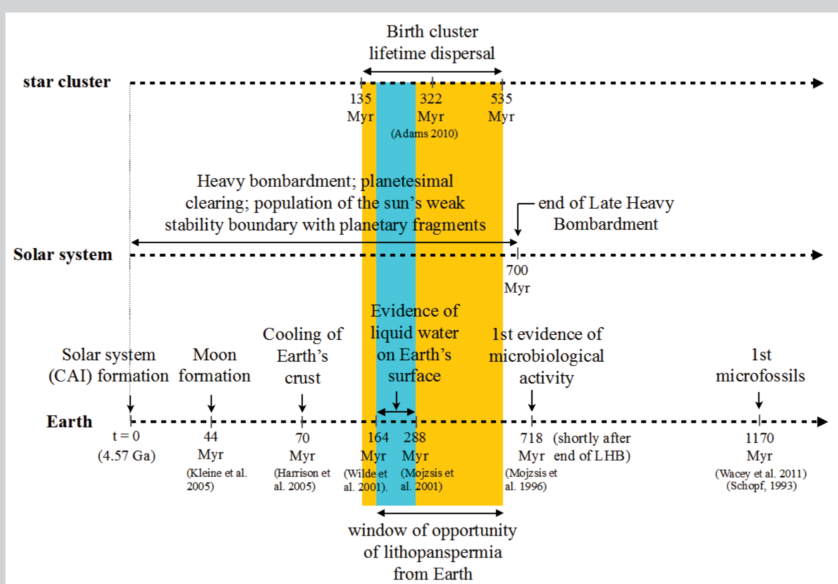

Figure 4: Window of opportunity for lithopanspermia.

0.00–0.03 m), 15–40 Myr (0.03–0.67 m), 40–70 Myr (0.67–1.00 m), 70–200 Myr (1.00–1.67 m), 200–300 Myr (1.67–2.00 m), 300–400 Myr (2.00–2.33 m), and 400–500 Myr (2.33–2.67 m). Given the timescales involved in the weak-transfer mechanisms, including the time it might take to land on a terrestrial planet, we find that microorganisms could survive the long interstellar journey hidden in meteoroids larger than about one meter.

It is therefore possible that life on Earth could have been transferred to other planetary systems when the Sun was still embedded in its stellar birth cluster. But could life on Earth have originated beyond the boundaries of our solar system? Our results indicate that, from the point of view of dynamical transport efficiency, life-bearing extrasolar planetesimals could have been delivered to the solar system via the weak-transfer mechanism if life had a sufficiently early start in other planetary systems, before the solar maternal cluster dispersed. An early microbial biosphere, if it existed, would likely have survived the Late Heavy Bombardment. Thus, both possibilities remain open: that life was "seeded" on Earth by extrasolar planetesimals, or that terrestrial life was transported to other star systems via dynamical transport of meteorites. Regarding the search for life beyond our solar system, this opens a new world of possibilities to dream about, given how many extra-solar planetary systems are out there and how tremendously diverse they are.

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