Understanding Habitability and Characterizing ExoEarths: The Role of Debris Disks

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1 Introduction

The origins of planets lie in collapsing interstellar cloud cores, where angular momentum conservation dictates formation of rotating gas and dust disks around the young stars. Planets grow in circumstellar (CS) disks, interact with them, and implant their signatures on them. The discovery of such disks around nearby stars has provided the opportunity to study planet formation in real time, rather than extrapolating backward from completed or mature systems like the Solar System.

In young, gas-rich disks (protoplanetary disks), gas giant planets are likely forming and the building blocks of terrestrial planets are being assembled. The final stages of terrestrial planet formation and the development of their atmospheres are probably occurring in the older, dust-rich disks (debris disks). These events establish fundamental requirements for life as we know it, such as terrestrial planets with water-rich surfaces. Moreover, disk processes transform interstellar organic material into pre-biotic compounds like those that gave rise to life on Earth.

The extrasolar planetary systems already discovered show surprising diversity compared to the Solar System. Studies of protoplanetary and debris disks are essential to understand the causes of this diversity and to predict what other phenomena might be seen. Debris disks also affect our ability to make new discoveries, through their impact on future efforts to characterize habitable terrestrial exoplanets (aka. exoEarths). Debris dust surrounds our Sun today (zodiacal dust) and a significant fraction of nearby stars have similar dust (exozodiacal dust) at much higher abundance. Exozodiacal dust will likely be the largest source of background flux in direct imaging and spectroscopy of terrestrial exoplanets.

Key Science Questions

- **What are the conditions for – and outcomes of – the planet formation process?** Planets can form around normal stars with spectral types ranging from at least late M to early A, around pulsars, and in multiple star systems (Udry & Santos, 2007, and references therein). Their birth environments are also diverse, varying from low-mass star-forming regions like the Taurus cloud to energetic, high-mass star-forming regions like the Orion nebula. Planet formation models were initially developed to reproduce the Solar System and cannot currently explain the characteristics of many known exoplanets. Improvements are hampered by a lack of basic information about disks, including their initial masses, temperature structure, statistical frequencies and lifetimes around different types of stars in different environments, gas-to-dust ratios, and chemical evolution (for a review, see Roberge & Kamp, 2009).

  We want to understand the prevalence of various kinds of planets around stars of differing metallicity and mass. This will motivate and guide efforts to find and characterize habitable terrestrial exoplanets. In Section 2, we discuss observational studies of debris disks and their implications for terrestrial planet formation.

- **How is habitability established during formation of a planetary system?** The habitable zone (HZ) is the region where liquid water may exist on a terrestrial planet surface (roughly $0.7-1.5$ AU for a G2 star). Examination of the Solar System amply demonstrates that formation of terrestrial planets in the HZ does not by itself ensure habitable planets. Even the Earth might not have been habitable under slightly different conditions. Most models of terrestrial planet formation indicate that the Earth was initially very dry and acquired its surface volatiles fairly late in the formation process (e.g. Raymond et al., 2006). The presumed sources of the Earth's surface volatiles were water-rich bodies formed farther from the Sun. Studies of debris disks will show whether this scenario is generally valid. In Section 3, we discuss key observations of debris disks that will help us understand how habitable conditions are formed on terrestrial planets.

- **How will exozodiacal dust around nearby stars affect direct observations of habitable exoplanets?** When viewed from a distance, the most conspicuous feature of the Sun's planetary system is its debris disk (aka. zodiacal dust), which is tenuous but covers a large surface area. At least $10-20\%$ of nearby stars harbor an outer debris disk much denser than the Solar System's (Beichman et al., 2006). In both images and spectra, light from the zodiacal and exozodiacal dust will likely dominate the exoplanet signal. The magnitude of the exozodiacal emission within the point-spread function of a 4-m telescope is $V \approx 28$, assuming a Solar System twin viewed at 60° inclination. That is two magnitudes brighter than the Earth viewed at quadrature from 10 pc away. On the other hand, debris disks can provide indirect evidence of exoplanets through dust structures caused by gravitational perturbations (see the Astro2010 science white paper by Leisawitz et al.). In Section 4, we discuss current exozodi detection limits and what is needed to observe dust levels relevant for future missions.

2 The Late Stages of Planetary System Formation

The current paradigm for formation of a mature planetary system has three main phases: formation of gas giant planets, formation of terrestrial planets, and removal of most leftover planetesimals (i.e. asteroids and comets). This timeline is represented in Figure 1. On the observational side, disks may be divided into three classes that appear to roughly correspond to each phase. Primordial disks are massive and gas-rich, while transitional disks appear to be clearing material from their inner disks. Debris disks are made of material produced by the destruction of planetesimals and contain little or no unprocessed interstellar material. The young ones are likely in the late stages of terrestrial planet formation, while the older ones correspond to the disk clearing phase. Most of the Earth's surface volatiles were probably delivered during the debris phase by the impact of water-rich planetesimals (e.g. Morbidelli et al., 2000). No significant correlation between the presence of a debris disk and the presence of an extrasolar giant planet or the stellar metallicity has yet been seen (Bryden et al., 2006).

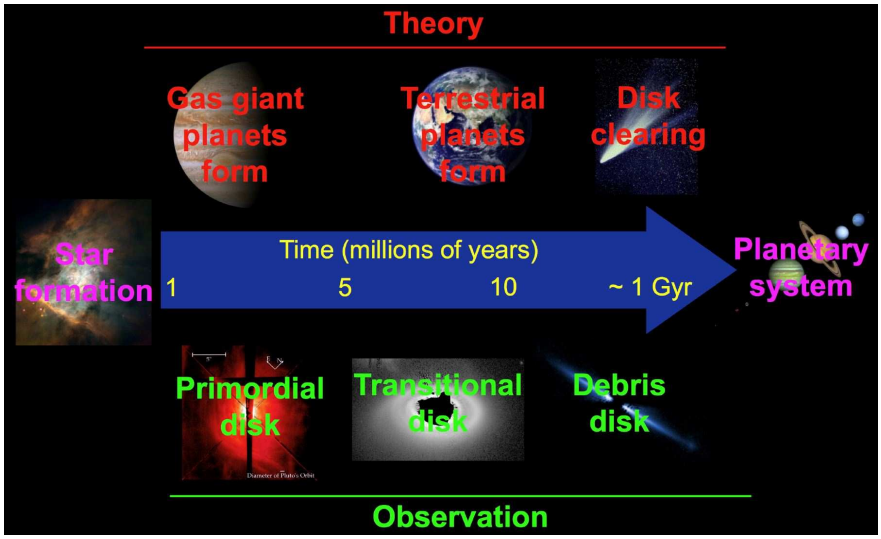

Figure 1: Timeline for planet formation and the evolution of disks. Above the arrow, the main theoretical phases in planetary formation are shown. Below, three classes of CS disks are identified. A coronagraphic image of a disk from each class is shown; AB Aurigae at left (Grady et al., 1999), HD 141569A in the center (Clampin et al., 2003), and AU Microscopii at right (Krist et al., 2005). [Figure credit: A. Roberge]

Currently, there are no observational constraints on the fraction of stars with Earth-like analogs ($\eta_\oplus$). In the next decade, the *Kepler* mission will provide the first estimate of $\eta_\oplus$ and IR radial velocity surveys should find Earth-mass planets around nearby M stars. Teams are exploring instruments to detect and characterize Earth-mass planets in the HZs of nearby solar-type stars (see the Astro2010 science white papers by Kasting et al. and Turnbull et al.). However, these missions likely are at least a decade away. Detailed studies of debris disks can help estimate the prevalence of terrestrial planets by looking for signs of their formation in the solar neighborhood.

Kenyon & Bromley (2006) have developed models of planetesimal disk evolution that indicate terrestrial planet formation begins near the star, where the disk surface density is the highest, and propagates outward with time. Formation of Mars-mass bodies triggers collisional cascades among the remaining planetesimals. The smallest grains in the cascade absorb stellar radiation, producing thermal emission that can be detected at mid-infrared (IR) wavelengths. These models predict that young debris disks should possess IR-bright rings tracing active terrestrial planet formation, which move outward as the disks evolve. The disk fractions found in *Spitzer Space Telescope* surveys of a few star-forming regions are broadly consistent with this model (e.g. Chen et al., 2005). However, the surveys were relatively insensitive to warm dust in terrestrial planet regions of solar-type stars.

Once Mars-sized objects have cleared out smaller bodies, they are expected to reach Earth-mass via pairwise collisions (e.g. Chambers & Wetherill, 1998). These giant impacts have consequences for the habitability of terrestrial planets. The Moon probably formed through a glancing collision between a Mars-sized body and the proto-Earth at an age of $\sim 50 - 100$ Myr (Touboul et al., 2009).

The development of life on Earth may have been aided by the presence of a relatively large moon, since it stabilizes the Earth's rotation axis, preventing large, rapid climate shifts. On the other hand, habitability is probably harmed by large impacts at late times that could remove surface volatiles or even developing life. Anomalously large debris disk dust masses probably signify recent giant, possibly moon-forming, impacts (e.g. Rhee et al., 2008).

While *Spitzer* enabled observations of dust thermal emission from many young main sequence stars, its small field of view limited the survey sizes. In addition, it lacked the sensitivity and spatial resolution required for detailed follow-up of most newly discovered objects, which is needed to better constrain the grain sizes and spatial distributions. The *Wide-Field Infrared Survey Explorer* (*WISE*), planned for launch at the end of 2009, will map the whole sky in four bands (3.3, 4.7, 12, and 23 μm) with a sensitivity 500 times better than the last all-sky IR survey mission (*IRAS*). It will allow study of stellar associations not observed with *Spitzer* and be more sensitive to dust in terrestrial planet regions than *IRAS*. Complementing this, the *James Webb Space Telescope* (*JWST*) will provide sensitive near- and mid-IR instruments for detailed photometric and spectroscopic follow-up of disks discovered by *Spitzer* and *WISE*.

3 Volatiles and Organics in Debris Disks

Inevitably, planetary system formation is more complicated than implied in Figure 1. The planet formation stages may be occurring simultaneously in different regions of the same disk. Furthermore, the age ranges of the disk classes apparently overlap, indicating that unknown processes shape the evolutionary pathways of individual systems. A serious hinderance to full understanding of disk evolution is poor knowledge of the gas component. Primordial gas affects the dynamics of all sizes of bodies, from planets to sub-μm dust grains, and its lifetime limits the time available for gas giant planet formation. Gas makes up most of the mass in primordial and transitional disks, but currently is difficult to observe. It seems to vanish by the debris disk phase (within ~ 10 Myr); however, the parameters and causes of the dissipation are unknown. Fortunately, we expect a revolution in disk gas studies over the next decade, largely thanks to the advent of the *Herschel Space Observatory*, the *JWST*, and the *Atacama Large Millimeter Array* (*ALMA*).

The position in a primordial disk beyond which the temperature is low enough for water ice condensation is generally called the "snow line". Outside it, the solid surface density is larger by a factor of ~ 4, allowing coagulation of massive cores that can gravitationally accrete huge gaseous envelopes and become giant planets. Planetesimals formed outside the snow line presumably are the source of Earth's surface volatiles. The exact nature of the planetesimals (asteroids or comets) and the timing of volatile delivery are matters of debate. Most evidence, like the D/H ratio in the Earth's oceans, points to outer belt asteroids perturbed into the inner Solar System (e.g. Morbidelli et al., 2000). Terrestrial planet formation models suggest that the bulk of Earth's water was accreted more than tens of Myr after planetesimal formation (Raymond et al., 2006).

However, this scenario has little outside observational support at present. First, one would expect to observe icy material only beyond the snow lines in debris disks. Enhanced water vapor inside the snow lines would also be expected, accompanied by increased dust production due to collisions between dynamically hot planetesimals. But this leads us to a major nagging question: ***where is the water in debris disks?*** There is no clear observational evidence for snow lines in disks and no signs of ice, water vapor, or its dissociation products, despite a few deep searches (e.g. Liseau & Artymowicz, 1998).

In fact, we have little information on debris disk composition generally. Mid-IR spectra of a few debris disks show silicate dust emission features superimposed on the dust continuum emission; the features have often been modeled using grains similar to Solar System comet dust. However, the mid-IR spectra of most debris disks are featureless, providing little information on the typical grain composition (Chen et al., 2006). Another way to get information on dust composition is to look at the broadband colors of debris disks in coronagraphic scattered light images; this has been done for at least 7 debris disks (e.g. Debes et al., 2008). No changes in albedo with radius that might be associated with snow lines have been seen. Somewhat surprisingly, about half of the disks show red colors suggestive of grains coated with organic material.

Although debris disks contain little or no primordial gas, at least some have gas recently produced from planetesimals, just like the dust. Spectroscopy of debris gas can in principle convey a great deal more information on the composition of parent planetesimals than dust observations, much as remote studies of Solar System comets do. The one disk whose gas has been well-inventoried (β Pictoris) shows no water vapor, OH, or enhanced oxygen. Instead, its gas is extraordinarily carbon-rich, while the central star has solar metallicity (Roberge et al., 2006). The parent planetesimals appear to be losing volatile organic material, but not producing much water vapor.

The keys to solving these puzzles lie in UV, IR, and sub-mm spectroscopy with high spectral resolution. Far-UV absorption spectroscopy of edge-on systems is sensitive to small amounts of atomic, ionic, and molecular gas; this has been the most fruitful technique for detecting debris gas. Ice, PAH, and other solid state features can be revealed in IR and sub-mm spectra, preferably spatially resolved to show changes in composition with radius. These observations may be provided by *JWST* and *ALMA*. However, there is no firm plan for UV spectroscopic capability after *HST*.

4 Exozodis and ExoEarths

Zodiacal dust is interplanetary dust interior to the Solar System's asteroid belt; it comes from asteroid collisions and comet comae, just like the dust in any debris disk. Exozodiacal dust around nearby stars impacts a mission intended for direct characterization of exoEarths largely through increases in integration time. Missions in both the visible and IR are similarly affected (details may be found in Hinz et al., 2009). The amount of dust in a debris disk is usually quantified using the total dust emission luminosity relative to the stellar luminosity ($L_{\rm IR}/L_\star$); the zodiacal dust has

$L_{\rm IR}/L_\star \approx 10^{-7}$ (Dermott et al., 2002). In the context of direct detection of exoplanets, debris dust abundances are typically described in units of "zodis." If the exozodiacal dust has exactly the same properties as the zodiacal dust, a one zodi disk has the same total mass and surface brightness as the zodiacal dust. In practice, one zodi simply corresponds to a dust disk with $L_{\rm IR}/L_\star = 10^{-7}$.

The most important current mission for debris disk surveys is *Spitzer*, although these observations will no longer be possible after exhaustion of the cryogenic supplies. For solar-type stars, the lowest $L_{\rm IR}/L_\star$ value that can be detected is about 10^{-4} for 360 K dust, which would be located at around 1 AU (Beichman et al., 2006). This limit corresponds to about 1000 zodis. For cooler dust between about 5 – 10 AU from solar-type stars, *Spitzer* can detect $L_{\rm IR}/L_\star \gtrsim 10^{-5}$.

How do these limits compare to the requirements for direct imaging and spectroscopy of exoEarths? First, a dust measurement at 5 – 10 AU probably cannot be used to predict the dust present at 1 AU, since the dust dynamics depends on the details of the system architecture (e.g. the locations of planetesimal belts and planets). Direct measurements of exozodiacal dust in the HZs of nearby stars are needed. Preliminary calculations by groups planning future large space telescopes for direct exoEarth observations suggest that new designs can tolerate several tens of zodis in the HZs (e.g. Defrere et al., 2008; Turnbull et al., 2009). This is more than an order of magnitude below our current detection limits for such dust. A further complication is that confusion between spatially unresolved exozodi dust clumps and planets has not yet been thoroughly addressed.

To prepare for future missions, we need to know how many nearby solar-type stars have $\lesssim 100$ zodis of exozodiacal dust in their HZs. These observations require substantial removal of light from the central star, since stellar photospheres cannot currently be modeled with adequate precision. Ground-based mid-IR nulling interferometry can, in principle, probe low levels of dust in HZs. A Keck Interferometer (KI) survey of nearby stars for exozodiacal dust is complete; the observations have a 1σ sensitivity of ~ 100 zodis (R. Millan-Gabet, pers. comm.). The Large Binocular Telescope Interferometer (LBTI), scheduled to begin operations in 2010, will have reduced thermal background and improved stellar suppression compared to KI. LBTI should reach a 3σ limit of 10 zodis for a sample of nearby stars. Another strategy is space-based high-contrast imaging at optical, near-IR, or mid-IR wavelengths, which can reveal disk structures as well as detect low dust levels in HZs. Some proposed moderate size missions, which will be discussed in the second round of Astro2010 white papers, could potentially achieve our goals.

5 Summary of Goals & Requirements

The next decade promises to be an exciting one for debris disks studies. *IRAS*, *HST*, and *Spitzer* have laid the groundwork on debris disk frequencies and morphology. But we have only scratched the surface of debris disk composition and begun to fully understand their implications for terrestrial planet formation and habitability. Major new facilities – including *WISE*, *Herschel*, *JWST*, and *ALMA* – will dramatically advance these topics. These studies require a multi-wavelength

approach, so coordination between diverse missions and facilities will be needed. Further, there are two critical areas where progress is somewhat uncertain. One area is study of gas in debris disks, which to date has relied on high-resolution far-UV spectroscopic capability. Many fields of astronomy will benefit from a far-UV successor to *HST*.

The other area is measurement of exozodiacal dust in the HZs of all the potential targets for a future mission to directly characterize exoEarths. While LBTI is a crucial first step that will detect low exozodi levels around some northern stars, it cannot observe enough of the potential targets. A major effort from a southern hemisphere facility is called for. In addition, the sensitivity of LBTI exozodi observations is greater for A, F, and G stars than K and M types. The optimal targets for optical and IR direct characterization missions are G and K stars. For many targets of a future exoEarth mission, sufficiently sensitive exozodi observations will likely require a space-based precursor mission. We advocate a more robust community program of mid-IR photometry and high-contrast optical/IR imaging of exozodis around nearby stars.

References

Beichman, C. A., et al. (2006). ApJ *639*, 1166–1176

Bryden, G., et al. (2006). ApJ *636*, 1098–1113

Chambers, J. E. & G. W. Wetherill (1998). Icarus *136*, 304–327

Chen, C. H., et al. (2005). ApJ *634*, 1372–1384

Chen, C. H., et al. (2006). ApJS *166*, 351–377

Clampin, M., et al. (2003). AJ *126*, 385–392

Debes, J. H., A. J. Weinberger, & G. Schneider (2008). ApJ *673*, L191–L194

Defrere, D., et al. (2008). A&A *490*, 435–445

Dermott, S. F., et al. (2002). In B. Warmbein (Ed.), *ESA SP-500: Asteroids, Comets, and Meteors: ACM 2002*, pp. 319–322

Grady, C. A., et al. (1999). ApJ *523*, L151–L154

Hinz, P., R. Millan-Gabet, & Exoplanet Forum 2008 Exozodiacal Disk Characterization Group (2009). In *2008 Exoplanet Forum Report*

Kenyon, S. J. & B. C. Bromley (2006). AJ *131*, 1837–1850

Krist, J. E., et al. (2005). AJ *129*, 1008–1017

Liseau, R. & P. Artymowicz (1998). A&A *334*, 935–942

Morbidelli, A., et al. (2000). Meteoritics and Planetary Science *35*, 1309–1320

Raymond, S. N., T. Quinn, & J. I. Lunine (2006). Icarus *183*, 265–282

Rhee, J. H., I. Song, & B. Zuckerman (2008). ApJ *675*, 777–783

Roberge, A., et al. (2006). Nature *441*, 724–726

Roberge, A. & I. Kamp (2009). In S. Seager (Ed.), *Exoplanets*. Univ. of Arizona Press, submitted.

Touboul, M., et al. (2009). Icarus *199*, 245–249

Turnbull, M. C., et al. (2009). ApJ, in prep.

Udry, S. & N. C. Santos (2007). ARA&A *45*, 397–439