Astro2020 Science White Paper

Modeling Debris Disk Evolution

Thematic Areas

☒ Planetary Systems	☐ Formation and Evolution of Compact Objects
☒ Star and Planet Formation	☐ Cosmology and Fundamental Physics
☐ Galaxy Evolution	☐ Resolved Stellar Populations and their Environments
☐ Stars and Stellar Evolution	☐ Multi-Messenger Astronomy and Astrophysics

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Abstract
Understanding the formation, evolution, diversity, and architectures of planetary systems requires detailed knowledge of all of their components. The past decade has shown a remarkable increase in the number of known exoplanets and debris disks, i.e., populations of circumstellar planetesimals and dust roughly analogous to our solar system's Kuiper belt, asteroid belt, and zodiacal dust. Technological advances have also allowed us to image over a dozen exoplanets and spatially resolve more than a hundred debris disks, some around the same stars. Additionally, ground based interferometric observations have revealed the existence of exozodiacal dust around a few stars. Debris disks provide the observable components with which we can study the formation and short- and long-term evolution of extrasolar planetary systems. With the launch of *JWST* and *WFIRST*, the next decade promises to deliver a wealth of new information on the nearest planetary systems. Parallel advances in theoretical/numerical modeling will be necessary to interpret these new datasets fully. Additionally, missions planned to image Earth-like planets directly will also benefit from detailed models of dust production in exozodiacal belts, particularly if they are designed to image these belts as well as planets.

1 Introduction

Within galactic astronomy, the last decade was undeniably the era of exoplanets. With thousands of them discovered, we have substantially increased our knowledge about the innermost regions of planetary systems. The next logical step is to deepen our understanding from the habitable zones (HZ) to the outer icy regions of planetary systems. *To accomplish this goal, we must use all available tools: both observational and theoretical; and also study all components of the planetary systems, not just the planets. Our white paper focuses on the importance of understanding debris disk evolution via modeling efforts to advance this goal.*

Debris disks have often been called the “signposts” of planetary systems; they are that (Meshkat et al., 2017) and really much more. Composed of the remnant planetesimals from planet formation and gravitationally shepherded by planets, they provide direct probes of the composition, architecture, and dynamical evolution of planetary systems. They are also readily observable and some are relatively easily resolved spatially, from the visible to radio, accessing various dust sizes and/or stellocentric locations at various wavelengths. In the next decade a new class of observatories will see first light. In space, *JWST* and *WFIRST* will provide high resolution and high contrast images at optical to mid-infrared wavelengths. These capabilities will enable the imaging of fainter exoplanets and lower surface brightness disks. With *JWST*, we will resolve extrasolar asteroid belts for the first time and also study the spatial variations in dust composition. Spectral studies with *JWST* will also confirm changes in dust crystalline structures in “extreme” (highly variable) systems. From the ground, ALMA is already resolving fine structures in the cold outer planetesimal belts and revealing remnant or collisionally produced gas in some systems (e.g., Kral et al., 2017). Finally, the class of extremely large telescopes (ELT, GMT, TMT) will observe nearby systems, possibly imaging Earth-like planets and/or disks, where modeling of the disks will be necessary to predict confusion levels and to assess the data.

Determining how disks evolved to their current states is difficult, requiring complex numerical models that follow short timescale effects for long time periods. Importantly for the next decade, three dimensional models will be crucial for rendering the new resolved structures we will observe. While disk structures result from dynamical interactions with their environments, the fact that we can observe them at all is due to continuous dust production, a result of collisional activity within the disks themselves. These evolutionary processes occur on greatly different timescales, complicating matters even more. *To maximize the return on the observational investment, we must support the development of sophisticated models and modeling tools.*

2 Extrasolar circumstellar debris belts

The general evolution of debris systems is often based on an understanding of the most well known, circumsolar, debris system as a proxy. Our circumsolar system consists of two belts of planetesimals, the asteroid and Kuiper belts, and a zodiacal cloud that is mostly a product of cometary transport of dust into the inner regions and asteroid collisions. A simple toy model explains the debris system architecture as shaped by the larger planets. The asteroid belt is a result of Jupiter stabilizing certain orbits and disrupting others, while the inner edge of the Kuiper belt is maintained by Neptune. In turn, the locations where the gas and ice giant planets form are likely influenced by condensation points during their formation (e.g., Kennedy & Kenyon, 2008). Based on this model, we would expect all debris disks to follow this archetypal architecture (see Fig. 1). In reality, we observe only around 30% of disk systems hosting a double belt (e.g., Ballering et al., 2013).

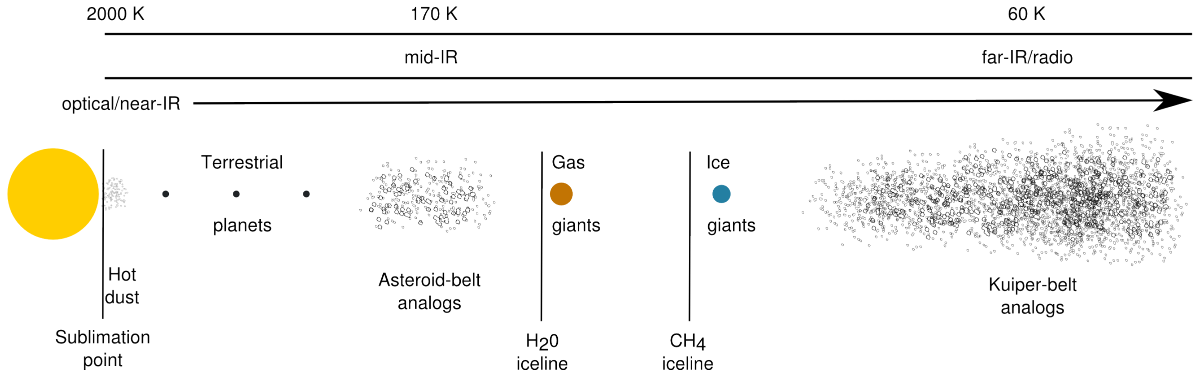

Figure 1: Schematic representation (not to scale) of an "archetypal" debris disk with two belts of planetesimals, analogous to the asteroid and Kuiper belts in the Solar System. Terrestrial planets and the asteroid belt analog are located within the H_2O iceline, while gas and ice giant planets and the Kuiper belt analog are located further out. Such "two-belt" architectures account for around a third of known debris systems.

While the two-belt architecture is not the most common, surveys with the *Spitzer* and *Herschel* space telescopes have shown that planetesimal belts are generally located at these thermal regions (e.g., Ballering et al., 2013). This result hints at a universal process for the formation mechanism for debris disks (e.g., Matrà et al., 2018). As most systems do not have all components and some have gaps within their Kuiper belts (Marino et al., 2018, 2019), the systems must be susceptible to gravitational disruption. Photometric surveys by these telescopes have also shown that disks are more dusty and massive at younger ages, fading away by a few hundred million years (e.g., Rieke et al., 2005; Su et al., 2006; Gáspár et al., 2009). Numerical models of collisional evolution (e.g., Wyatt et al., 2007; Gáspár et al., 2013; Kral et al., 2013) showed that this corresponds to a quasi-steady state evolution and that stochastic events are not necessary to explain the observations.

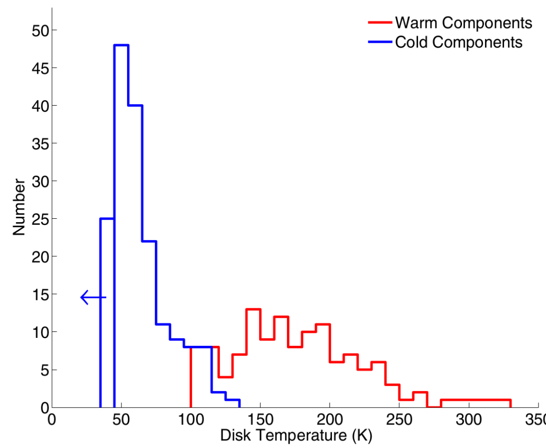

Figure 2: Distribution of debris disks by temperature for 225 systems; 100 of those with only a cold component, 51 with only a warm component, and 74 with both (Ballering et al., 2013).

2.1 Observations in the next decade: Over the last two decades, *Spitzer* and *Herschel* enabled broad statistical studies of debris disks. Observations in scattered light at optical/near-IR (NIR) wavelengths with *HST* (e.g. Kalas et al., 2008; Schneider et al., 2014; Choquet et al., 2016) and at NIR from the ground with GPI (e.g. Currie et al., 2015; Wang et al., 2015; Esposito et al., 2018) and SPHERE (e.g., Boccaletti et al., 2015) provided resolved images of individual bright sources. These images show that each extrasolar system is unique; there is no "one size fits all" model when it comes to details. The 2020 decade will provide a substantial amount of new information on disks. ALMA is already living up to its promise, resolving planetesimal belts around numerous sources. Reviewing approved *JWST* debris disk programs for Cycle 1, and following the commissioning of observatories such as *WFIRST*, ELT, GMT, and TMT, we anticipate exciting results in the next decade. For details, please refer to complementary White Papers by Su et al. and Beichman et al.

3 Elements of disk models

Models of debris disk evolution need to explain two key processes: 1) how dust of various sizes is produced and evolves in number density due to collisions, 2) how the spatial distribution of dust evolves as a function of gravitational and radiative forces. Most models typically address one or the other problem; at best, they treat both, but with one of them in a simplified manner.

3.1 Collisions in disks: The fact that we can observe debris disks at all is a sure sign of ongoing collisional activity, as the particles that we observe are continuously removed and replenished. Numerical models following the size distribution of the particles in a collisional cascade typically calculate the evolution as a particle in a box style code (e.g. Thébault et al., 2003; Krivov et al., 2006; Wyatt et al., 2011; Gáspár et al., 2012a). Simplifications allow these models to be evolved to long timescales (see Figure 3), however, they do not take into account dynamical interactions. Unique approaches have included dynamics, either by evolving the systems as analytically approachable "two body" problems (e.g., Krivov et al., 2006) or by following a limited number of tracer particles (Grigorieva et al., 2007; Thébault, 2012; Nesvold et al., 2013; Kral et al., 2013) for shorter time periods. Recent calculations have also constrained the initial conditions via planetesimal formation models (Krivov et al., 2018), re-evaluating the structures of larger asteroids and total disk masses.

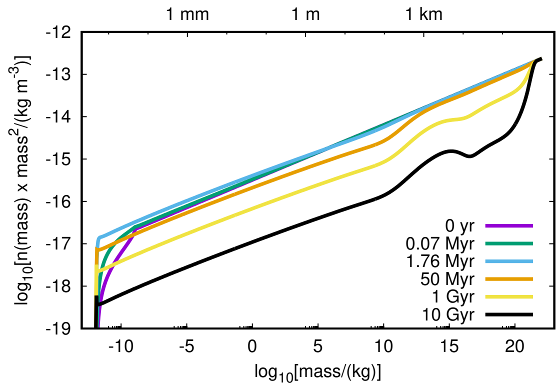

Figure 3: The evolution of a particle mass distribution (from Gáspár et al., 2012b).

3.2 Dynamical evolution: Following the dynamical evolution of the disks is necessary to model the high resolution images we will obtain in the future. While the largest planetesimals are only affected by gravitational forces, the smaller dust particles are further perturbed by a variety of forces intrinsic and extrinsic to the systems. The most important of these is radiation pressure (e.g., Burns et al., 1979; Gustafson, 1994), which removes the smallest dust rapidly. Secondary radiative effects are also crucial. Poynting-Robertson (PR) drag, due to the anisotropic scattering and re-emission of stellar photons, slowly deorbits smaller particles towards the host stars (Figure 4). Late-type and young solar-type (Chen et al., 2005) stars also release significant amounts of charged particles (stellar wind) which has a similar effect as PR-drag, while gas (if present in sufficient quantities) adds another drag component (Lyra & Kuchner, 2013; Marino et al., 2016). Finally, stellar magnetic forces at distances near the sublimation limits may trap nanograins resulting from the sublimation of dust brought in via PR-drag (Rieke et al., 2016; Kirchschlager et al., 2017).

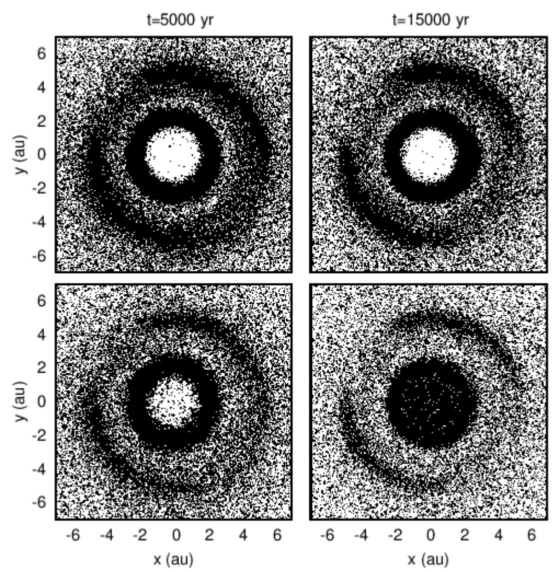

Figure 4: The effects of PR-drag in the solar system for particles between 0.01 and 1000 μm. Top: w/o PR-drag, Bottom: w/ PR-drag.

4 Outstanding Problems

There are a number of unresolved fundamental questions in disk evolution and new data will likely raise additional ones. A list of some of the uppermost ones is given below.

1. **Panchromatic image modeling:** Optical constants not only determine the observable properties of dust (color, albedo, polarization, scattering phase function), but also their dynamical evolution. Fully consistent disk models need to reproduce the panchromatic images (e.g., Ballering et al., 2016) as well as the underlying dynamics of the dust particles, driven by the same optical properties. Panchromatic image modeling will constrain dust chemical composition using the next generation of laboratory and model optical constants (e.g., Arnold et al., 2019).
2. **Exozodi modeling:** Exozodiacal dust in extrasolar planetary systems has been detected by sensitive ground based interferometric observations (e.g., Absil et al., 2013; Ertel et al., 2014; Mennesson et al., 2014; Ertel et al., 2018). Parameterized disk models (Kennedy et al., 2015) are able to interpret such datasets statistically, yielding an understanding of our chances of observing Earth-like planets in the HZ of Sun-like stars. Various approaches have attempted to model exozodi dust production (e.g., van Lieshout et al., 2014; Bonsor et al., 2012), but have been inconclusive. Numerical models will be necessary to interpret individual systems.
3. **Exoplanet disk interactions:** Observations in the next decade will simultaneously image disks and planets, breaking degeneracies in dust location. Disks are perturbed by planets (e.g., Nesvold & Kuchner, 2015; Lee & Chiang, 2016; Yelverton & Kennedy, 2018), clearing gaps and opening cavities (e.g,. Mustill & Wyatt, 2012). Large planets are able to trap exo-Trojan dust in their respective L4 and L5 Lagrangian points, which may be observable (Hippke & Angerhausen, 2015). Finally, the role of planets stirring collisions needs to be further studied (e.g., Kennedy & Wyatt, 2010; Krivov & Booth, 2018). In Figure 4, we show a dynamical model of the Solar System, highlighting the effects: sculpting, Trojan populations, PR-drag, dust size segregation, while in Figure 5, we show a state-of-the-art emission model of the solar system. Fast numerical models will be necessary to test multiple scenarios for individual systems.
4. **Halo production and transport:** Many of the large debris systems we can resolve have a large halo population of micron sized dust particles (Schneider et al., 2014). The halo of Vega (Müller et al., 2010) is likely made of small dust particles on highly eccentric orbits near the blowout limit. Other halos may be a result of planetary scattering (Matrà et al., 2018), much like the solar system's (Geiler et al., 2019). The influence of giant planets on the formation of such halo systems and their retention timescales will need to be studied further in the 2020's.
5. **ISM disk interactions:** Of the few dozen well resolved disks, many show signs of interactions with the interstellar medium (e.g. HD 61005, HD 32297, HD 15115, HD 15745; Schneider et al., 2014). These interactions may remove smaller particles (Pástor, 2017) or sandblast larger particles. ALMA data have revealed larger particles in these regions (MacGregor et al., 2018).
6. **Presence of gas in debris disks:** Radio observations have detected emission from CO molecules in multiple mature disks (e.g., Moór et al., 2015; Matrà et al., 2017), while UV data have revealed atomic C, N, O, and various metals (e.g., Roberge et al., 2006). As these systems are past their gas rich transitional phase, the presence of gas is a clear sign of ongoing continuous collisional activity, releasing CO molecules from volatile rich icy planetesimals (e.g. Moór et al., 2011). The next decade will provide symbiotic measurements on disk gas content with ALMA for many systems. Improved numerical models will complement these observations,

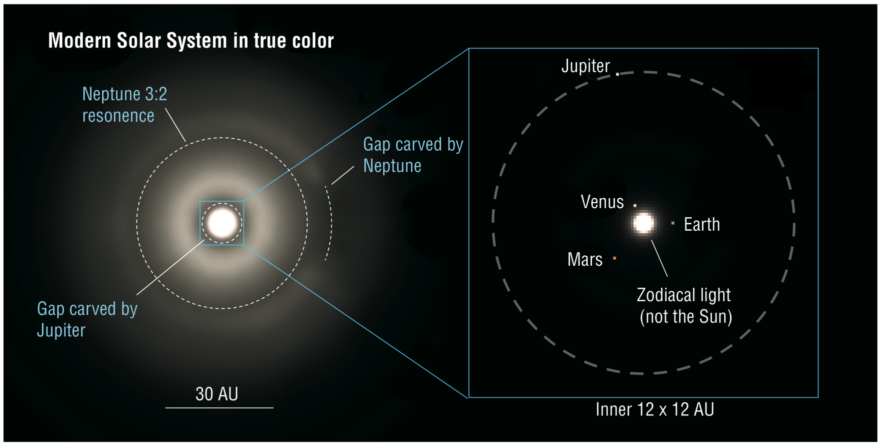

Figure 5: Model image of the solar system produced from empirical inner (Kelsall et al., 1998) and numerical outer (Kuchner & Stark, 2010) disk calculations (Roberge et al., 2017, and the Haystacks team). Note the perturbation effects of the planets (gaps and cavities) as well as the bright zodiacal dust cloud.

providing upper limits on the amount of gas planetesimal collisions are able to provide. For more information on gas rich systems, please see the Decadal White Paper by Luca Matrà et al.

7. **Stochastic events/extreme disks:** The frequency of stochastic events and their influence on the disks is an open question. Short ($\sim$ 1-2 year) semi-periodic bursts of dust production have been observed in a few younger "extreme" (highly variable) systems (e.g., Meng et al., 2014; Su et al., 2019). The nature of these systems is still uncertain (e.g., Thebault & Kral, 2018) and detailed models will be necessary to understand them. Extreme disks are further complicated by the likely presence of optically thick dust, requiring flux calculations via radiative models. Scattered light observations have also revealed, for example, fast moving dust structures in the AU Mic system (e.g. Boccaletti et al., 2015; Sezestre et al., 2017; Chiang & Fung, 2017).

5 Summary

Observational astronomy is on a track that will provide a wealth of new information on extrasolar planetary systems in the next decade. Upcoming space missions with high-contrast coronagraphs, such as *JWST* and *WFIRST*, will be attempting to image extra-solar planets and low-surface brightness circumstellar disks close to their host stars. Higher performance dedicated coronagraphic missions will more deeply probe disks and disk/planet interactions, if appropriately designed. These capabilities will revolutionize our understanding of planetary system evolution. However, without equal advances in theoretical modeling, the observations of the next decade will not fully realize their potential. The models necessary to explain future observations will need to follow both the spatial and size evolution of debris particles. These are two physically distinct processes with greatly different timescales; however, they exert feedback on each other. Additionally, in extreme systems, large scale stochastic events may also need to be followed. Fast and efficient numerical models will be necessary, which enable multiple scenarios, collisional prescriptions, stellar parameters, tensile strengths, and compositions to be tested for individual systems. Models developed to execute on High Performance Computer (HPC) Clusters and/or Graphical Processing Units (GPUs) are required to solve such rigorously complex problems. While HPC clusters/GPUs are generally accessible, either via NASA computing time or infrastructure available at individual institutions, all encompassing models are not. *We call on the decadal survey to emphasize the need for supporting modeling efforts in all astronomical fields, especially in disk science.*

Complementary White Papers

Direct Imaging and Spectroscopy of Exoplanets with the James Webb Space Telescope
Charles A. Beichman et al.
Direct imaging of exoplanets in nearby multi-star systems
Ruslan Belikov et al.
The Critical, Strategic Importance of Adaptive Optics-Assisted, Ground-Based Telescopes for the Success of Future NASA Exoplanet Direct Imaging Missions
Thayne Currie et al.
Cold Debris Disks as Strategic Targets for the 2020s
John Debes et al.
Debris disks: Exploring the environment and evolution of planetary systems
Wayne Holland et al.
Planet formation – The case for large efforts on the computational side
Wladimir Lyra et al.
Exocometary Science
Luca Matrà et al.
Interplanetary dust around main sequence stars: origin, magnitude, and implications for exoplanet habitability searches
Bertrand Mennesson et al.
Community Endorsement of the National Academies "Exoplanet Science Strategy" and "Astrobiology Strategy for the Search for Life in the Universe" Reports
Peter Plavchan et al.
Exoplanet Yields of Future Direct-Imaging Space Telescopes: Sensitivity to Mission Design
Christopher Stark et al.
Probing Unseen Planet Populations with Resolved Debris Disk Structures
Kate Y. L. Su et al.
A Strategy for Understanding Planet Formation
Alycia Weinberger et al.

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