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Formation and Evolution of Planetary Systems: Placing Our Solar System in Context with Spitzer

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Abstract. We summarize the progress to date of our Legacy Science Program entitled *The Formation and Evolution of Planetary Systems* (FEPS) based on observations obtained with the Spitzer Space Telescope during its first year of operation. In addition to results obtained from our ground–based preparatory program and our early validation program, we describe new results from a survey for near–infrared excess emission from the youngest stars in our sample as well as a search for cold debris disks around sun–like stars. We discuss the implications of our findings with respect to current understanding of the formation and evolution of our own solar system.

1. Introduction

Is our solar system, and the potential for life to arise that it represents, common or rare among sun–like stars in the disk of the Milky Way galaxy? In order to help answer this question, planetary scientists use the properties observed today in our solar system to infer its evolutionary history and initial conditions of formation. Astronomers have a different approach, observing sun–like stars at a variety of ages in an attempt to constrain the range of paths taken by evolving planetary systems that might surround these stars. Only by synthesizing results from studying our solar system and observations of disk evolution around ensembles of sun–like stars can we address the question posed.

Few researchers dispute that most stars are surrounded by circumstellar accretion disks at birth. Recent near–infrared (1–4 μm) photometric studies have indicated that this accretion phase lasts between 1–10 Myr with 50 % of sun–like stars losing their inner accretion disks ($R_{disk} < 0.1$ AU) within 3 Myr (Haisch et al. 2001). Yet the gas and dust content of remnant disks at larger radii is unconstrained by these observations. Cooler dust at larger radii will emit at longer wavelengths characteristic of the appropriate blackbody temperature (Beckwith, 1999). As a result, we can consider that different wavelengths trace different radii in the disk It is extremely important to conduct photometric studies from 1–1000 μm as a function of age in order to constrain the geometric distribution of dust from 0.1–100 AU and how it may evolve over time.

Observations of accretion disks surrounding T Tauri stars have established that they are optically–thick from a few to > 30 μm (Beckwith et al. 1990; see also D'Alessio et al. 2001). It is from these disks that we think planets form.

As they do, material in the disk is either incorporated into larger objects or dispersed leading to the optically–thin disks observed around older main sequence stars. How much material is required for optical–depth unity perpendicular to the disk? If the disk interior to 0.1 AU were optically–thick and the opacity were dominated by gas, that would imply a mass accretion rate $> 10^{-7}$ $M_{\odot}$/yr (Meyer et al. 1997; see also Muzerolle et al. 2003). If the opacity is dominated by dust, it would take roughly a few times the mass of the asteroid Ceres distributed interior to 0.1 AU in micron–sized particles to reach optical depth unity. In the mid–infrared, it would take approximately one Earth mass of micron–sized grains between 0.1-1 AU for the dust to be optically–thick. And in the far–infrared, approximately one Jupiter's worth of small grains distributed between 1–10 AU would correspond to $\tau = 1.0$.

It is often assumed that optically thin disks correspond to debris disks rather than primordial disks, though this need not be the case. What do we mean by these distinctions and how can we discern them? We will refer to a disk as *primordial* if the opacity in the disk is dominated by interstellar dust grains incorporated into the disk as a by–product of the star formation process. We will refer to a disk as *debris* if the opacity is dominated by grains generated through collisions of larger parent bodies. While these definitions are helpful in clarifying the terminology, they are not very practical. We might hope to tell the difference observationally by constraining the amount of remnant gas in a disk, thereby invoking timescale arguements (P–R drag and radiation pressure blowout) to infer that the dust we see must be continuously replenished (Backman and Paresce, 1993) or detecting solid–state spectral features that suggest dust generated from a differentiated parent body.

In what follows, we review some recent results concerning the evolution of circumstellar disks surrounding sun–like stars in the pre–Spitzer era, describe briefly our Legacy Science Program, provide an overview of our initial results, and discuss their implications. Our main goals in carrying out this program are to constrain theories for the formation and evolution of planetary systems, and to provide insight into whether solar systems like our own are common or rare surrounding sun–like stars in the disk of the Milky Way.

2. The Pre–Spitzer Era

While the IRAS satellite provided powerful evidence for circumstellar accretion disks surrounding newly formed stars (Rucinski et al. 1985) as well as debris disks surrounding nearby luminous main sequence stars (Aumann, 1985), many gaps remain in our understanding of how to connect these two phenomena. Several studies undertaken with the Infrared Space Observatory (ISO), have helped make these connections (see review by Meyer and Beckwith, 2000; van Dishoeck, 2003) and focus attention on unresolved questions: 1) do debris disks diminish with the mass in small grains as t^{-2} expected if the dominant removal mechanism for grains is P–R drag (e.g. Spangler et al., 2001; see however Decin and Dominik 2003); 2) how long do gas–rich disks persist in circumstellar disks (e.g. Thi et al. 2001); 3) can we infer the presence of massive planets in disks based on spectral energy distributions (SEDs) (e.g. Bouwman et al. 2003);

and 4) can we trace the evolution of grain size and dust composition through observations of solid state features in the remnant dust (e.g. Meeus et al. 2001).

Recent ground–based studies undertaken in preparation for the Spitzer Space Telescope have also furthered our understanding. Mamajek et al. (2004; see also Weinberger et al., 2003 and Metchev et al., 2004) conducted sensitive mid–infrared photometric studies in order to constrain the evolution of dust in the terrestrial planet zone. These preliminary results suggest that optically–thick disks between 0.1–1.0 AU evolve on timescales comparable to the cessation of accretion. Further, the limits placed on the amount of optically–thin debris disks appear inconsistent with simple extrapolations of our own solar system zodiacal dust disk to ages of 10–30 Myr (Mamajek et al. 2004). Sub–millimeter surveys for cool dust surrounding sun–like stars (e.g. Carpenter et al. 2005) provide quantitative constraints on the evolution of dust mass from 3–30 Myr. Following up a rare dust detection towards the 100–300 Myr old G star HD 107146, Williams et al. (2004) tentatively resolved the 450 μm emission and modelled the disk with a large inner hole. Ardila et al. (2005) have confirmed aspects of this model with images of the disk in scattered light with the ACS on HST. Finally, Kessler et al. (2005) describe ground–based efforts to extend work done on evolution of the silicate emission features observed toward Herbig Ae/Be stars with ISO (Meeus et al. 2001) to sun–like stars from the protostellar phase through to the debris disk phase.

3. Overview of the FEPS Program

In coordination with guaranteed time programs, general observer programs, and other Legacy Science Programs, the FEPS project attempts to address: 1) how optically–thick accretion disks transition to become debris disk systems; 2) when the molecular gas from which giant planets form is removed from circumstellar disks around sun–like stars; and 3) the diversity of planetary architectures inferred from infrared observations of main sequence stars. Our sample consists of approximately 300 stars with masses between 0.7–1.5 $M_\odot$ spanning a range of ages from 3 Myr to 3 Gyr. Roughly 50 stars were selected in six equally spaced bins of log–age. Care was taken to choose the closest targets available in the lowest IR background regions from the parent samples available within the constraints of our program. Each of our target stars is observed with every Spitzer instrument: IRAC photometry in the near–infrared, IRS low resolution spectroscopy in the mid–infrared, and MIPS photometry in the far–infrared. A sub–set of our sample is observed with the IRS at high spectral resolution in order to discern the amount of remnant gas in disks through a variety of atomic and molecular species (see Hollenbach et al., this volume). Additional details concerning the FEPS program can be found in Meyer et al. (2005).

4. New Results

We received our first Spitzer data in December, 2003, as part of the Legacy Validation Program in order to insure that our observing proceedures were suitable for our program given the measured in–flight performance and modified operation protocols. Although minor modifications were made to the overall program based on these data, we succeeded in: 1) confirming the presence of a debris disk surrounding the 30 Myr old sun–like star HD 105, 2) discovering a new debris disk surrounding HD 150706, a G star with age 700 $\pm$ 300 Myr, and 3) placing stringent upper limits on dust mass in three older systems. For the two debris disks, inner holes ranging from 20–45 AU were inferred based on the observations. The limits on the amount of warm debris suggest that the dust surface density drops by x100 inside the inner hole radii. While these inner holes could be maintained collisionally, depending on the assumptions made concerning the dust, they are also consistent with a model requiring the presence of gas giant planets (Moro–Martin et al., 2005).

Several other studies are underway based on data collected during the first year of Spitzer operations, some of which was delivered to the Spitzer Legacy Science Archive in October, 2004. In a follow–up study concerning the lifetime of inner dust disks surrounding young stars, Silverstone et al. (2005) confirm and extend the results from Mamajek et al. (2004). In a sample of 74 stars ranging in age from 3–30 Myr, only five stars were found to exhibit emission in excess of that expected from the stellar photosphere at wavelengths of 3.6, 4.5, and 8.0 μm. While four of the excess stars have ages from 3–10 Myr, only one star with excess was found with an age from 10–30 Myr. In all cases the excesses arise from optically–thick disks with 4/5 stars exhibiting spectroscopic evidence for active disk accretion. No stars in the sample were found to have optically–thin excess emission with constraints of $< 10^{-5}$ Earth masses of dust in micron–sized grains inferred for non–detections. This suggests that: 1) dust from 0.1–1.0 becomes extremely optically–thin on timescales of 10 Myr; and 2) the timescale to transition between optically–thick and thin is < a million years.

Hollenbach et al. (this volume; 2005) describe the search for remnant gas using the IRS high resolution mode to search for emission lines of atomic and molecular species expected to dominate the cooling of gas disks. Non–detections towards the 30 Myr debris disk candidate HD 105 suggest upper limits of < 0.1 $M_{JUPITER}$ in remnant gas, ruling out the future formation of gas giant planets in that system. Hines et al. (this volume; 2005) describes the search for warm debris disks detected with the IRS including the unusual ring of material surrounding HD 12039 emitting at 110 K. Assuming the emission comes from large blackbody grains, models suggest that the material is confined to a narrow ring from 4–6 AU not unlike the asteroid belt in our own solar system.

Kim et al. (2005) present new data for five cold debris disks surrounding sun–like stars analogous to the dust generated in our solar system by collisions of Kuiper Belt objects. In all cases, limits are placed on the amount of warm inner debris and estimates are made for the sizes of the inner disk holes inferred as a function of assumptions made concerning the grain properties. There is a degeneracy in the models such that the SEDs observed can be explained either through large (blackbody) dust grains at radii from 20–50 AU, or small grains near the blowout size at radii > 100 AU. Minimum dust masses inferred are consistent (within a factor of x3) with extrapolations based on a toy model for the evolution of the Kuiper Belt (Backman et al. 2005). While models where the inner holes are maintained by collisional evolution and radiation pressure blowout cannot be ruled out, the data are also consistent with inner holes maintained by the presence of gas giant planets. We plan to distinguish between

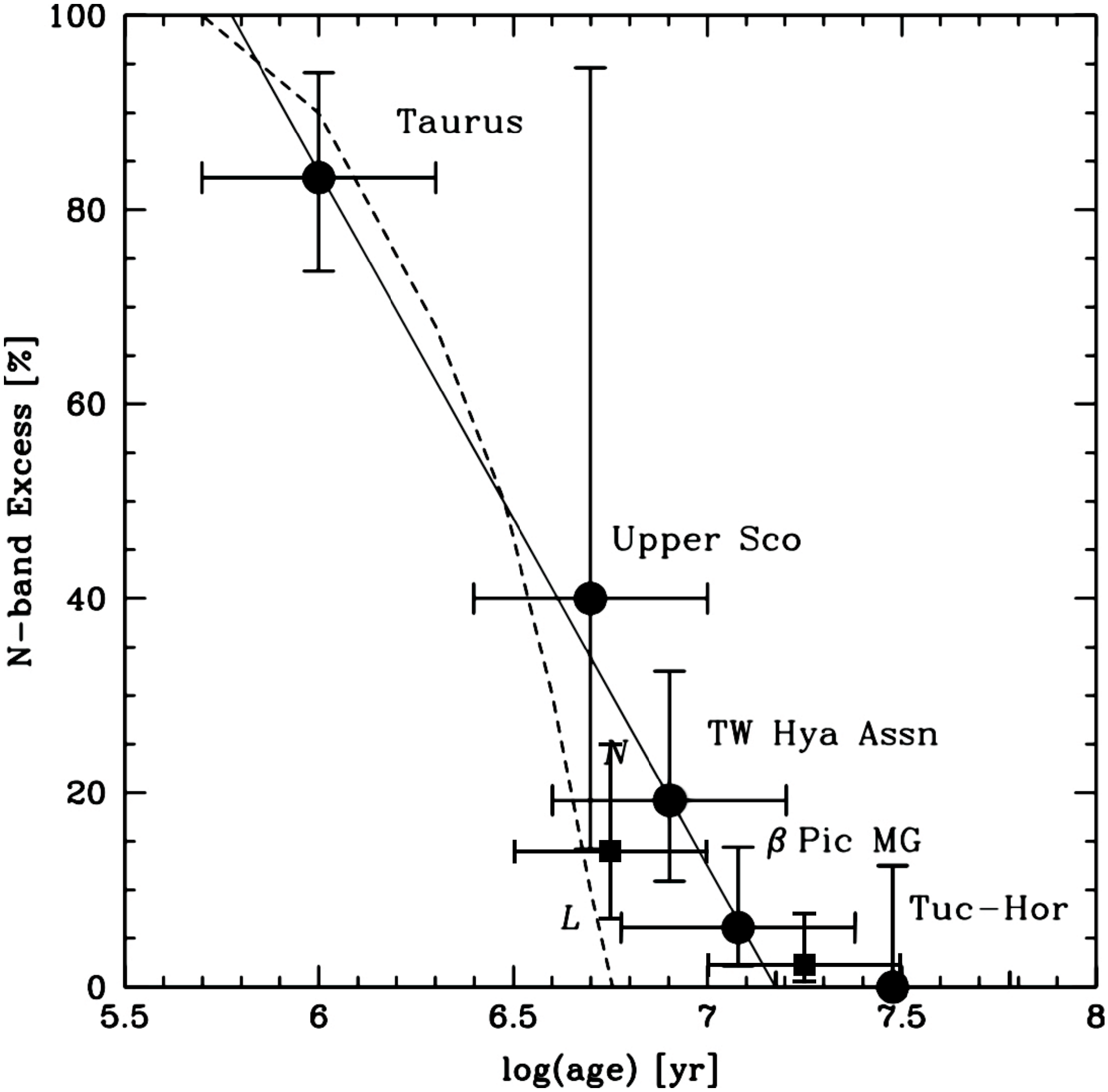

Figure 1. Frequency of stars in clusters or associations with detectable mid–infrared excess versus cluster age. Filled circles are data taken from the literature while the filled squares are new results from Silverstone et al. (2005).

these models by: 1) attempting to directly detect gas giant planets surrounding the youngest and nearest cold debris disks in our sample (e.g. Masciadri et al., 2005), 2) coronagraphic imaging of the outer dust disks in scattered light (e.g. Kalas et al. 2005), and 3) resolved observations of the thermal emission using nulling interferometry on large ground–based telescopes equipped with adaptive optics (e.g. Liu et al. 2004).

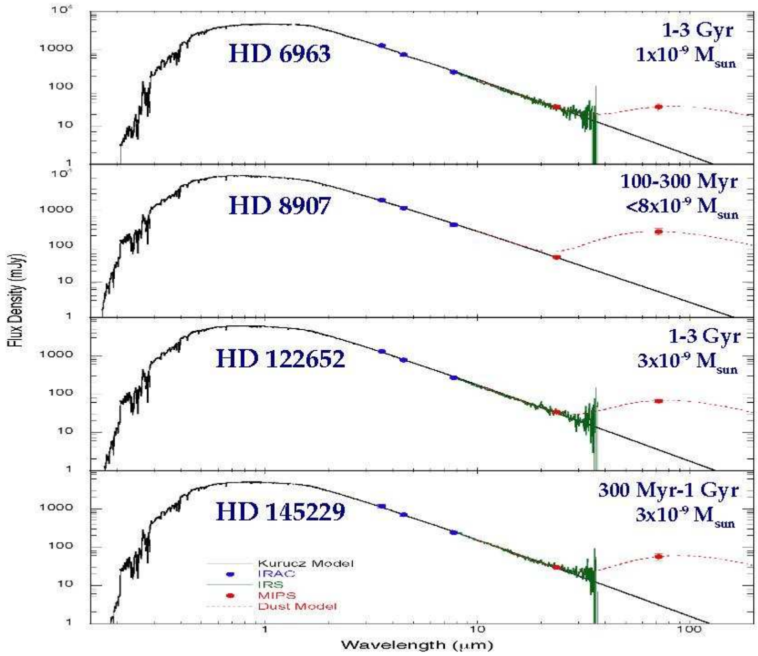

Figure 2. Spitzer SEDs for debris disks surrounding sun–like stars from Kim et al. (2005). Expected photospheric emission based on our model fits are shown as solid lines, with best fit models for the excess emission indicated with a dashed line. The ages and estimated dust masses for each system are also given.

5. Implications

What sort of picture is emerging concerning the formation and evolution of planetary systems around sun–like stars based on the early results from FEPS? Our results suggest that not only are inner disks surrounding post–accretion T Tauri stars devoid of detectable disks out to a few AU, but also that the dust production rates in any remnant planetesimal belts are lower than predicted by simple models for the early evolution of our solar system. Whether these systems lack planetesimal belts all together, or have yet to be dynamically stirred by the presence of larger bodies remains to be seen. We cannot yet distinguish whether outer debris disks are best fit with a diminution of dust mass as t^{-2} or t^{-1} characterisic of P–R drag and collisional blowout dust removal mechanisms, respectively. What is clear is that there is a large dispersion in dust masses at all ages. Rieke et al. (2005) present evidence that the typical disk evolution around intermediate–mass (A–type) stars could be punctuated by rare collisions that temporarily raise observed dust signatures by orders of magnitude.

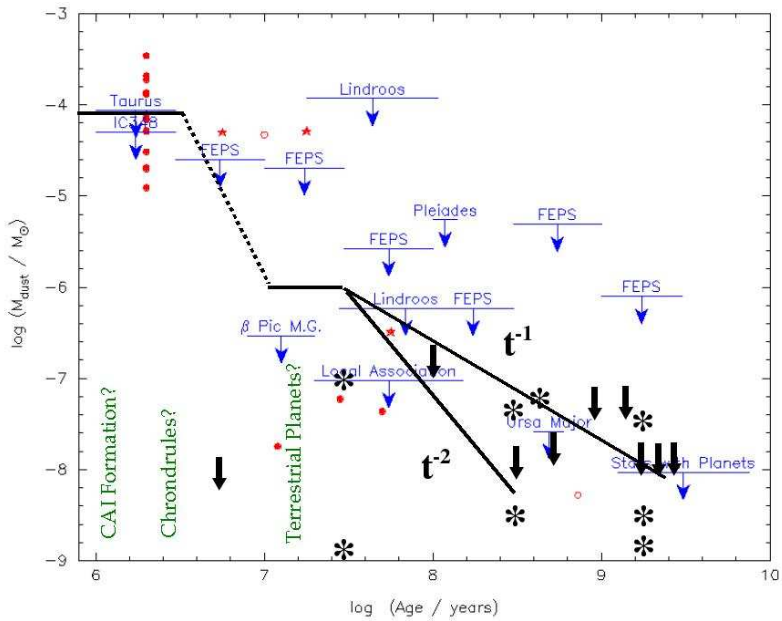

Figure 3. Dust mass versus age with sub–mm observations of Carpenter et al. (2005) compared with 70 μm detections (and upper limits) from Meyer et al. (2004) and Kim et al. (2005). Also shown are two models for dust diminution with time. Evolution with t^{-2} represents the P–R drag model while t^{-1} indicates collisional blowout removal.

Future work includes: 1) a study of dust excess surrounding G stars in the 100 Myr old Pleiades open cluster (Stauffer et al.), 2) the properties of warm debris disks in our FEPS sample (Bouwman et al.), 3) the spectral energy distributions and solid state spectra of long–lived accretion disks uncovered in our sample (Bouwman et al.), and 4) upper limits to the lifetime of gas–rich disks based on our survey of 10 stars with the IRS in high resolution mode (Pascucci et al.). Of paramount importance will be development of a model for the dust production rates in our own solar system as a function of time so that we can ascertain whether our solar system is consistent with the observed dispersion in evolutionary properties for disks surrounding sun–like stars. In this way, we hope to address one piece of the puzzle in understanding whether solar systems like our own are common or rare in the Milky Way.

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