DEBRIS DISKS AND THE FORMATION OF PLANETS:
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Debris Disks: An Overview

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Abstract. An overview regarding planetary debris disks: First, more history to complement Low and Aumann's summary appearing elsewhere in this volume. Then, commentary on the nature of debris disks and what we've learned from them: properties of the original "Fabulous Four" archetypes, results from surveys showing that a large fraction of ordinary stars may be hosts for debris disks, and relatively detailed discussion of β Pictoris, the most prominent disk. Finally, discussion of the connection between debris disks, our solar system's Kuiper Belt, and the zodiacal dust cloud. Open questions about these objects will be highlighted which can lead on to the remainder of the proceedings.

1. A Bit Of History

Vega's infrared excess first detected by IRAS in 1983 (Aumann et al. 1984) was completely unexpected but was quickly understood to be due to solid material orbiting the star. In January 1984 Fred Gillett gave a talk at the Protostars & Planets II meeting in Tucson based on his IRAS team's continued work finding and studying other stars which showed excesses. I was in the audience for that presentation; in his characteristic style, and instead of going directly to the punch line of his 10-minute contributed talk, Fred first displayed the uninteresting spectral energy distributions (SEDs) of Sirius, Altair, Procyon, and ϵ Indi, approximately the same spectral types as the "Fabulous Four" stars Vega, Fomalhaut, β Pictoris, and ϵ Eridani, but showing completely normal Rayleigh-Jeans photospheric distributions. Of course Fred knew that the plain far-IR SEDs of the first four stars provided the only reason to conclude that the spectra of the Fab 4 were so far out of the ordinary.

When Fred Gillett displayed SEDs of the Fab 4 (Figure 1; Gillett 1986), each showing enormous far-IR excesses relative to extrapolated photospheric spectra, it caused quite a stir. We have become used to seeing these SEDs, but at the time they were astonishing. The β Pic disk is 400 times brighter at 60 μm than the stellar photosphere, yet all that infrared flux can come from only 0.1 $M_\oplus$ of dust! Clearly, to detect planetary material, infrared is the place to be: that small mass was easily detected by IRAS across 20 parsecs.

Kuiper Airborne Observatory (KAO) observations by Harper et al. (1984) confirmed that Vega's excess emission extended to 160 μm. The analyses in their paper plus a theoretical paper by Weissman (1984) based on the IRAS observations showed that the only reasonable explanation for the IR excess is that it comes from dust grains orbiting the stars that cannot be primordial.

Timescale arguments indicated that the dust IRAS detected is much younger than the respective system ages: the lifetimes of dust grains in the Fab 4 systems against destructive processes of Poynting-Robertson (PR) drag and mutual collisions range from 10^5 to about 10^7 years, in each case significantly less than the respective system ages (Backman & Paresce 1993). And, we know we are not seeing transient events because debris disks are too common for that to be the case (see below).

This is central to the definition of a debris disk: that the emission we detect comes from "2nd generation" material released after planetesimals and perhaps planets have formed. The strong IR signal possible from collisional debris of planetesimals assembling into planets was first predicted by Witteborn et al. (1982) who searched with pre-IRAS ground-based sensitivity for warm debris disks around 300 Myr-old stars in the Ursa Major Stream. Further defining characteristics of debris disks (e.g. Lagrange et al. 2000) include little or no gas at the location of the dust, so dust dynamics are not controlled by gas drag, and dust optically thin to stellar radiation even along the disk midplane.

2. The Fabulous Four

IRAS also gave us barely resolved but nevertheless clearly extended scan profiles of the Fab 4 which helped Fred Gillett and George Aumann conclude that extended objects centered on the visible stars were producing the IR excesses. It took 15 years before resolved images of the thermal emission from these objects appeared (Holland et al. 1998; Greaves et al. 1998).

Smith and Terrile (1984) took their visible-wavelength coronagraph to Las Campañas in an attempt to detect new moons around Uranus prior to Voyager's arrival there in 1986. Someone from LPL who was at the PPII conference phoned them with Fred's results. They pointed their instrument at β Pic and the now-famous disk image essentially popped right out. In fact, according to Rich Terrile that disk is so bright that, knowing the position angle, one can recognize it in the eyepiece of the 100-inch at Las Campañas without the aid of a coronagraph. Beta Pic's was the first, and so far one of the few debris disks detectable in scattered light at optical / near-IR wavelengths, primarily because it is so much denser than the others (see below; Kalas and Jewitt 1996).

3. Surveys and Statistics

I was lucky enough to become Fred Gillett's post-doc about a year after he gave his talk at PPII. Figure 2 shows some work I did with him, a plot of 25/60 μm versus 12/25 μm flux ratios for a sample of main sequence stars from the Yale Bright Stars Catalog. A star with no dust would have colors at the upper right hand corner of the diagram, but would be plotted further down and to the left as more and more dust emission is added to the SED. The curves connect colors of Fab 4 disk analogs as the amount of dust is increased or decreased while keeping the spatial scales and structures constant. It can be seen that there are many stellar systems that fit the color-color characteristics and thus the morphology of the debris disk archetypes.

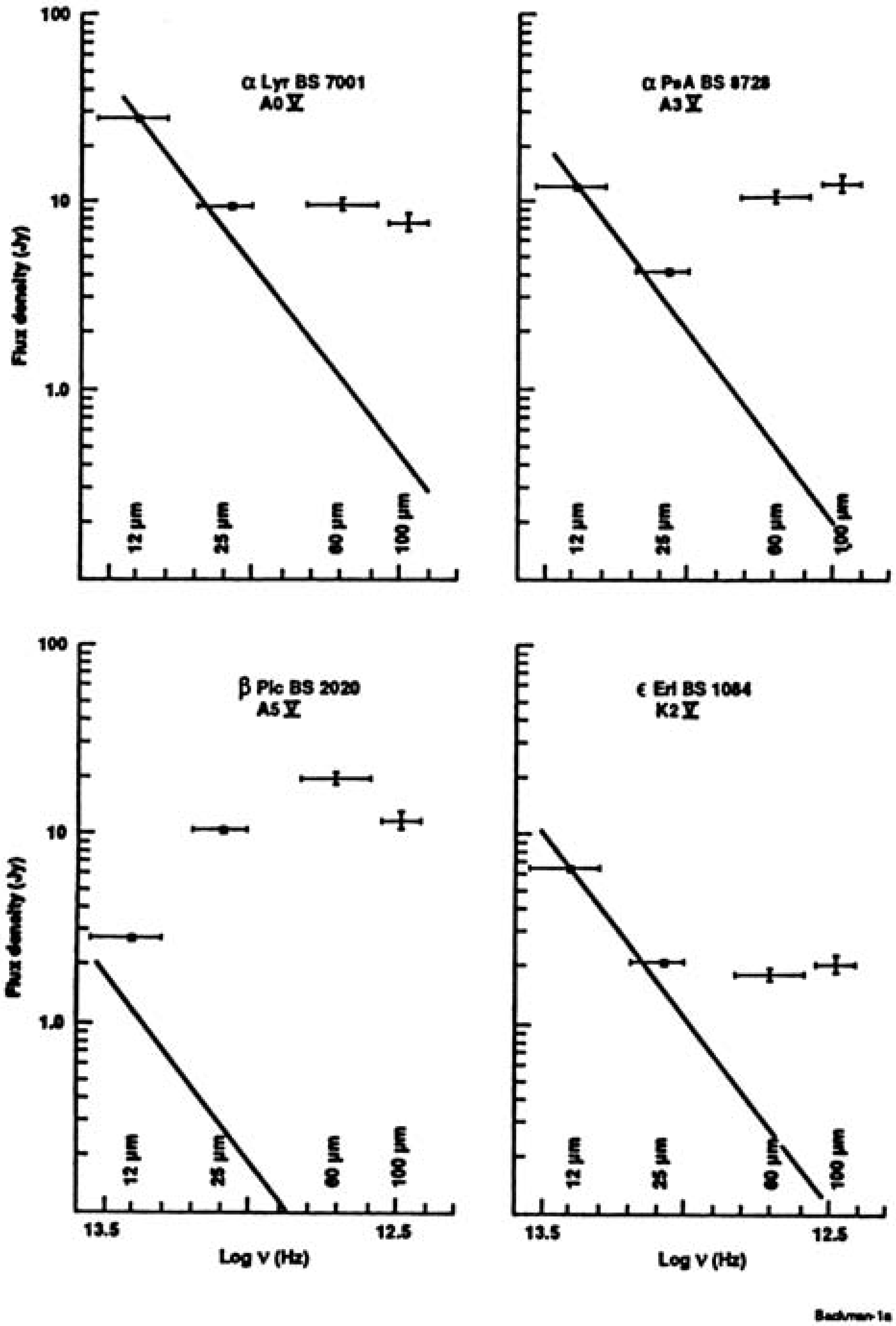

Figure 1. IRAS spectral energy distributions of the "Fabulous 4" debris disks. The diagonal lines represent Rayleigh-Jeans extrapolations of photospheric emissions from near-infrared data.

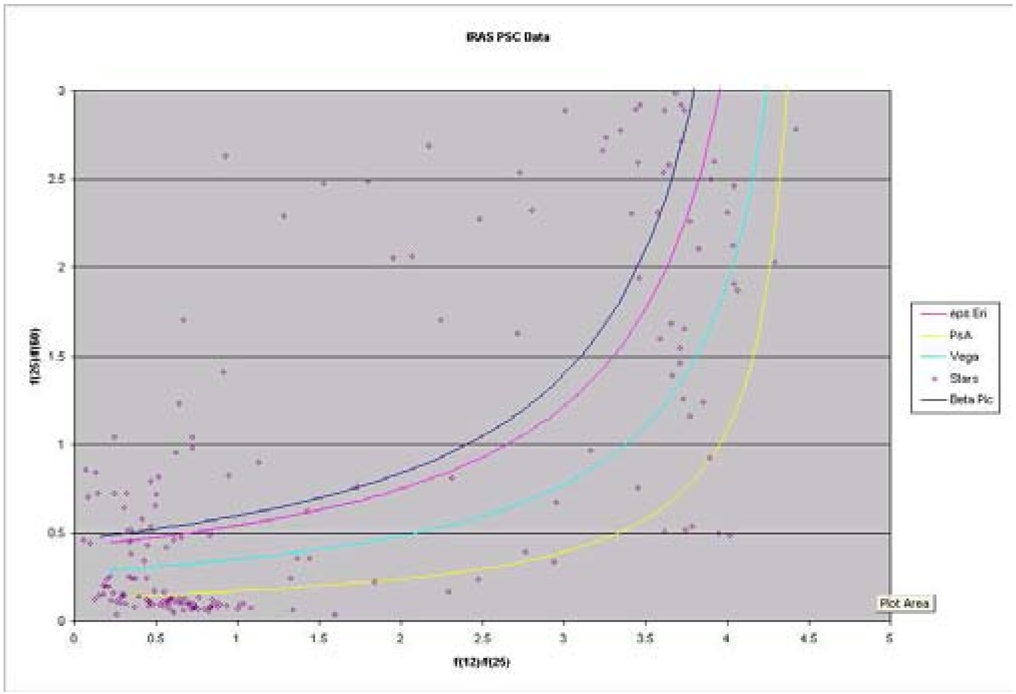

Figure 2. Data points represent far-infrared color ratios af main sequence stars of spectral classes B8 through K5 in the Yale Bright Star Catalog, showing excess IR flux in IRAS Point Source Catalog data. The curves represent loci of colors traced by taking the "Fab 4" systems and varying the dust-to-star luminosity ratios but leaving the respective morphologies, i.e. temperature ranges, constant (from top to bottom, beta Pic, Vega, Fomalhaut, and eps Eri). Pure photospheric colors would be off the plot to the upper right.

Other important general properties of debris disks were gleaned from follow-up surveys using IRAS and ground-based observations. Aumann and Probst (1991) examined objects with suspect IRAS 12 μm excesses. They confirmed only two warm debris disks in their sample, so the occurrence of terrestrial temperature (asteroidal/zodiacal) dust systems is rare – it is much more common to see temperatures that are Kuiper Belt-like. Aumann and Good (1990) defined a sample of nearby G stars, combined the coadded flux densities of all the stars in the sample (prior to the IRAS Faint Source Catalog) and compared the result to the sum of extrapolated photospheric emissions. They concluded that, on average, field G stars have a small 100 μm (T $\sim$ 30 K) excess, possibly due to Kuiper Belt-like systems. Arguing from the Copernican point of view, our Solar System should not be strange and this, indeed, is what they found.

4. Fractional Bolometric Luminosity

In the past, there has been some confusion between the symbols used for fractional luminosity and for optical depth of the dust, and I am substantially to blame. The face-on surface density, σ, is equivalent to the fractional area coverage,

σ = individual grain cross-section area $\times$ n(dust) per unit disk area.

The face-on or perpendicular optical depth, τ_{perp}, is $\sigma \times \epsilon$, where ϵ is an absorption efficiency factor that in general depends on wavelength. In the case of the debris disks, a typical grain is much larger than the wavelength of the input stellar radiation, so the absorption efficiency is $\sim$ 1 and independent of wavelength, therefore $\tau_{perp} \sim \sigma$.

Since we don't in general observe the disks face on, how do we determine τ_{perp}? If we define the fractional luminosity 'f' as the ratio of dust bolometric luminosity to the bolometric luminosity of the star,

$$f = L_{dust}/L_{star} = \int_{r_1}^{r_2} [\sigma(r_1)/2r][r/r_1]^{\gamma}\, dr \tag{1}$$

$$= [\sigma(r_1)/2\gamma][(r_2/r_1)^{\gamma} - 1] \tag{2}$$

when $\gamma \neq 0$, where r_1 is the inner radius, r_2 the outer radius, and γ is the (negative-valued) power law exponent for decrease of disk surface density with distance from the star. For $r_2 >> r_1$, f $\sim$ 0.5 σ (r_1)/ $|\gamma|$ $\sim$ τ_{perp} (r_1) / $|\gamma|$. Since observations show that γ is generally between 0 and -2, then the fractional luminosity 'f' and the inner edge dust surface density will be the same within factors of order unity. It is also worth noting that the mid-plane optical depth τ_{para} is approximately $\sim \tau_{perp}(r_1)/\theta$, where the opening angle θ is independent of radius for a PR-controlled disk.

The combination of f and T_{dust} required for IRAS detection of material indicates IRAS could have found the ϵ Eri disk only out to about 8 pc due to the low luminosity of the star, yet that is one of the densest disks we have yet seen. We were fortunate in that there are lots of disks so some of them are nearby enough to be detected by IRAS. Since ISO did not much extend the detection limits of IRAS, we don't have much information about the abundance of disks out beyond about 25 pc. SIRTF (Spitzer) will do much better!

Some over-all results from IRAS and ISO together (Backman and Paresce 1993; Lagrange et al. 2000):
1) 100+ candidate debris disks are known, unresolved except for the Fab 4;
2) there is no strong dependence of debris disk frequency on star spectral type;
3) average dust density decreases with age of the star;
4) some examples are found around giant stars, but they are rarer than around corresponding main sequence progenitors;
5) very few warm (Earth-temperature) disks are found – most are cold.

5. β Pictoris

Kalas and Jewitt's (1995) Figure 1 shows a beautiful 0.9 μm ground-based coronagraph image of the entire β Pic disk. Multiple warps or asymmetries in this disk are quite apparent. The disk extends to about 1000 AU, with the central lower-density zone about 200 AU in diameter. Kalas and Jewitt (1996) did model calculations showing that the β Pic disk's edge-on aspect is less important than density in explaining its prominence. The reason that β Pic was so easily detected in the optical is because it has 100x the density of the Vega disk and about 10x the other two Fab 4 disks. Of the Fab 4, β Pic is the youngest system, with an age of 20 ± 10 Myr estimated from the age of two M stars which share the same space motion, even though they are separated on the sky by a large angle (Barrado y Navascués et al. 1999).

There is stable gas in the β Pic system, although the gas and dust are not co-located. Figure 4 in Lagrange et al. (2000)'s review article shows gas absorption in Ca II K, with a broad absorption due to the rotating photosphere and the narrow line(s) to circumstellar gas. This is also seen in the ultraviolet where there is absorption in e.g. Fe II. It has been determined from the line ratios that this gas is likely to be located about 1 AU from the star whereas the dust is much farther away, with peak density occurring about 50–100 AU from the star. An interesting question is how can this happen? In a series of papers summarized by Lagrange et al. (2000) the Grenoble-based French spectroscopy group successfully modeled the gas as being replenished by evaporating comets. If the density of comets in this system is ~ 100 times that in the Solar System, a stable gas shell can be maintained close the star independent of the dust disk. In addition, the French group reports transient redshifted absorption events which they model as being consistent with the spectroscopic appearance of an infalling comet of reasonable mass and compositon evaporating near the star, hence their designation as FEBs (Falling Evaporating Bodies).

Figure 8 in Heap et al. (2000) clearly shows a warp in the disk within about 30 AU of β Pic, best explained by gravitational perturbation from a Jupiter-sized planet orbiting the star at an angle to the plane of the debris disk.

6. Connections to The Kuiper Belt

The Kuiper Belt is sometimes called the "Edgeworth–Kuiper Belt", since Edgeworth, a geologist, proposed the existence of matter orbiting the Sun beyond Neptune independently about the same time as Kuiper did. The Kuiper Belt was not actually discovered until after the IRAS mission. Currently, more than

600 objects have been found in the few 100 km size range, the range most easily detected. We infer that there must be $> 10^8$ objects with diameters > 1 km in order to explain the observed frequency of comets with periods < 200 years and low-inclination orbits (reviews by Jewitt & Luu 2000; Malhotra et al. 2000).

The largest orbital semi-major axis yet detected for a Kuiper Belt object at this writing is ~ 85 AU, and that might represent the outer edge of the belt; the inner edge is at Neptune's orbit, 30 AU. Stern and Colwell (1997) showed that there must have been at least 10 $M_\oplus$ in the KB for the growth of 100 km bodies to have proceeded on a time scale less than the age of the Solar System. There is currently no more than about 0.1-1 $M_\oplus$ in the KB (Backman et al. 1995; Teplitz et al. 1999). Most of the original mass has been gravitationally perturbed and ejected or collisionally eroded.

Aumann and Good's (1990) model of a typical G star, as determined from their statistical search of nearby field stars, has τ_{perp} in the range 10^{-5} or 10^{-6} for radii between about 100 and 1000 AU. Interestingly, one of these 'typical' dust disks with the central G star replaced with a Vega-like star would have about the luminosity and temperature of the Vega debris disk.

We do not know the optical depth of dust in our KB but we can put limits on it. There is a minimum amount that should be produced because there is definitely a population of KBOs to act as dust parent bodies. Landgraf et al. (2002) claim detection of inbound KB dust based on data based on data from collisions of dust grains with the Ulysses spacecraft. An upper limit on dust density can be determined from the upper limit on the as-yet undetected cold component of the zodiacal emission. The KB's dust density τ_{perp} must be $< 10^{-6}$ or we would have detected a cold excess from the KB relative to zodiacal dust emission.

One can produce models of KB-like structures around Vega and β Pic in which dust is produced by collisions between parent bodies and destroyed by PR drag or dust collisions. To match the fractional luminosity for β Pic would require 100 $M_\oplus$ of cometary objects, about the mass of Saturn, and the Vega disk can be modeled by a 10 $M_\oplus$ KB, of order the mass of Uranus or Neptune. These are all reasonable numbers, indicating that young KBs may, in fact, be the explanation of what we are seeing in the Fab 4 and other observed debris disks.

Habing et al. (2001) presented statistical evidence that debris disk densities decrease slowly with age then transition to a more rapid decrease at very roughly 400 Myr, about the time that the "Heavy Bombardment" phase would have ended in the Solar System. The "Heavy Bombardment" may have represented a clearing out of our Solar System after the completion of the outermost planets. The same discontinuity in evolution at roughly 400 Myr thus may be true of other G and K stars.

Liou and Zook (1999) have modeled the distribution of dust which would be produced in our KB and gravitationally perturbed by Neptune. Their results (especially Figure 4a) very closely match the observed structure in ϵ Eri (Greaves et al. 1998) providing strong evidence for the presence of a Neptune-like body in that system.

7. Zodi and Exozodi

Fred Gillett got into this business with his Ph.D. thesis regarding the properties of the zodiacal cloud, our local debris disk. Figure 3 shows Fred working on a U. of Minnesota balloon-borne IR photometer to observe the zodiacal cloud; this reputed to be the only case where a real live astronomer appeared in Ap.J. (Gillett et al. 1964).

Our zodiacal dust cloud has a "wedge" morphology and surface density approximately constant with radius. These characteristics are consistent with dynamical control by PR drag, further reason to consider our zodi cloud as a very low density debris disk. Dynamical perturbation of the dust distribution by the Earth can be seen in COBE data, showing a resonant ring of enhanced density at 1 AU, together with a wake that is 10-20% denser than the resonant ring (Dermott et al. 1994). Observations of these kinds of structures can provide indirect, but strong evidence for the presence of planets. SIRTF will plow right through this wake, so we will have additional observations in the near future.

8. Open Questions

IRAS' and ISO's photometric sensitivity limits did not survey for debris disks over large enough volumes to yield good statistics on, for example, frequency of debris disks versus age and stellar type. SIRTF observations, especially by Legacy and Guaranteed Time teams, should yield answers to the following significant questions:

(1) What is the frequency of debris disks in the density range 1-100 zodis (1 zodi is defined the surface density of our zodiacal cloud near the Earth), i.e. f $\sim$ 10^{-7} - 10^{-5}, below IRAS' and ISO's limits? For comparison, Vega, the thinnest of the prototype disks, has a density of 100 zodis and β Pic has 10,000 zodis. At Spitzer sensitivity, will all or most main sequence stars be found to have debris disks?

(2) Is it really true that the average G star has a faint cold dust disk?

(3) What about M dwarfs? Disks around these stars are faint because the star, itself, is not bright. If the average M star has a debris disk, then such disks are, indeed, very common in the Universe.

(4) What is the normal evolution of debris disks over time? There is some disagreement between Habing's result, represented in these proceedings by Carsten Dominik's paper, of a transition in frequency at an age of about 400 Myr, versus the results from the UCLA ISO group, represented by Murray Silverstone's paper, which seem to indicate a monotonic decline of density with age consistent with collisional evolution of the planetesimal parent bodies.

(5) What about debris disks in open clusters, which will have well-defined ages? IRAS and ISO did not have the sensitivity to detect disks like the prototypes in even the closest of these clusters.

(6) Is there a correlation between systems with debris disks and systems in which planets have been detected by the radial velocity method? So far, at IRAS/ISO sensitivity, there is only one star (ϵ Eri) in common between these two lists.

Figure 3. Fred Gillett, possibly the only human to appear in an ApJ figure, working on the balloon gondola used for his thesis observations of the zodiacal cloud.

(7) What about warm zodiacal dust? At IRAS/ISO sensitivity, there are very few examples of Earth-temperature material detected around pre-main sequence and main sequence stars.

(8) What is the composition of debris disk material? We have good information about the grain composition in only a few of the brightest and hottest examples of true debris disks, e.g. β Pic and 51 Oph (Knacke et al. 1993; Fajardo-Acosta et al. 1993).

(9) What is the connection of the debris dust to circumstellar gas? Does the gas disappear on one timescale and the dust appear on another, longer time scale? It seems that is the case, but more observations are needed to resolve this question that is crucial to our understanding of the evolution of planetary systems.

(10) Finally, what about our own KB? We would like to detect and study the dust there to relate the amount of KB grains to the number of parent bodies, to confront our models of extrasolar systems.

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