Extrasolar Analogues to the Kuiper Belt

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Abstract. Debris disks are found around some 15% of main sequence stars and their dust is thought to be continually replenished in collisions between planetesimals in extrasolar Kuiper belts. While they were discovered in 1984 by IRAS, it is only with more recent imaging that their true nature has been revealed. This paper discusses recent debris disk images and their impact on our understanding of extrasolar systems. Importantly these images confirm the extrasolar Kuiper belt hypothesis for most (but not all) debris disk candidates and show that the planetesimals within these disks must have grown to at least a few km. Asymmetries in imaged disk structures also provide information about the planetary systems orbiting inside these planetesimal belts. The impact of debris disk studies on our understanding of the evolution of our own Kuiper belt, as well as their potential to solve puzzles such as the origin of the missing mass and the outer edge of the Kuiper belt, is also discussed.

Keywords: Circumstellar matter, extrasolar planets

1. Introduction

While most of the mass of the solar system is tied up in its planets, these are not always the most readily observable components of an extrasolar system. A relatively small mass of dust ($< 1M_\oplus$) can be easily detected around nearby stars because of its large surface area. The infrared satellite IRAS found that some 15% of nearby main sequence stars exhibit far-IR emission in excess of that expected from the star itself (Backman & Paresce 1993; Lagrange et al. 2001). The first such discovery was of excess emission toward Vega (Aumann et al. 1984). The spectral energy distribution (SED) of Vega's excess could be fitted well with a 95 K black body (Walker & Wolstencroft 1988), implying that the star is surrounded by relatively cold dust grains and so, in regions $\sim$ 80 AU from the star, are analogous to the Kuiper belt. Since the dust contributing to the excess has a lifetime due to P-R drag and collisions that is much shorter than the age of the star, it could not be a remnant primordial disk, rather it has to be continually replenished. This replenishment was postulated to come from the collisional grinding down of a population of much larger bodies which have longer lifetimes; similar arguments also apply to the other excess stars. Thus these excesses are thought to be indicative of extrasolar Kuiper belts (hereafter XKB) around the stars. Further evidence that these excesses are caused by XKBs comes from the lack of hot dust close to the stars. This inner cavity is thought to be caused by clearing of a planetary system, since without such a mechanism the dust created in the XKB would repopulate the inner region due to P-R drag, although other mechanisms have been proposed that could cause such a hole such as the interaction of dust grains with a gaseous disk (e.g., Takeuchi & Artymowicz 2001).

2. Debris Disk Images

Analysis of the IRAS database has now uncovered ~ 300 debris disk candidates. However, the poor resolution of IRAS (~ 1 arcmin) means that only limited information about the disks is available from their SEDs: their temperature and luminosity. The ring-like geometry of the disks, the radius of the XKBs, and any defining features in their structure can only be determined by imaging. Luckily, some of the debris disk candidates are close enough and bright enough to be imaged. However, despite significant effort, images have only been made of six disk candidates. These images have been made using a variety of techniques, ranging from optical and near-IR coronographic imaging of the starlight scattered by the disk (e.g., Smith & Terrile 1984; Schneider et al. 1999) to mid-IR, sub-mm and mm imaging of the disks' thermal emission (e.g., Telesco et al. 2000; Holland et al. 1998; Wilner et al. 2002). In the following subsections we discuss images of the thermal emission of four of these disks[1], in age order.

2.1. HR4796

The HR4796 disk is the only one that has been well resolved in the mid-IR (apart from β Pictoris). The challenge with mid-IR imaging is that the disks are cold, so their emission is falling off quickly on the Wien side of the black body curve; extrapolation from the IRAS far-IR fluxes is thus very uncertain. In addition it is often difficult to untangle the disk emission from that of the stellar photosphere which can be brighter than the disk at these wavelengths. In its favour, though, the high resolution of the mid-IR means that XKB disks have the potential to be resolved out to at least > 100 pc.

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[1] The other two well resolved disks are those around β Pictoris and HD141569. These are not discussed partly because their emission distribution is found to be radially extended from tens to several hundred AU, thus complicating any discussion of their XKBs, but also to limit the length of the review.

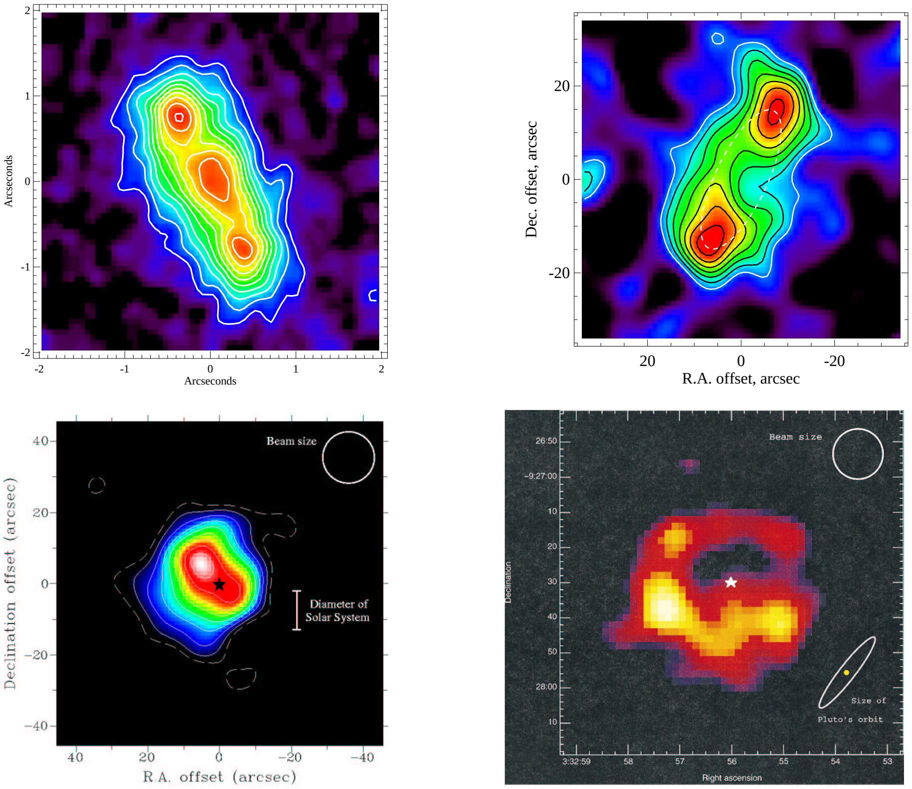

Figure 1. Debris disk images: **(a)** HR4796 at 18 μm (Telesco et al. 2000); **(b)** Fomalhaut at 450 μm (Holland et al. 2003); **(c)** Vega at 850 μm (Holland et al. 1998); **(d)** ϵ Eridani at 850 μm (Greaves et al. 1998).

HR4796A is a 10Myr-old A0V star at 67 pc. The 18 μm disk image shown in Figure 1a was taken using the mid-IR camera OSCIR on Keck (Telesco et al. 2000), and images of this disk have also been made in the near-IR (Schneider et al. 1999); unresolved sub-mm observations of the disk determined its mass to be $\sim 0.25M_\oplus$ (Greaves, Mannings & Holland 2000). The central peak in the mid-IR image is emission from the stellar photosphere, but once this has been subtracted the remaining double-lobed structure is characteristic of an edge-on disk, in this case with $\sim$ 70 AU radius. Importantly the images confirm the dust ring with a central cavity interpretation of the SED, though there remains debate about the existence of an additional zodiacal cloud-like hot dust component close to the star (Augereau et al. 1999; Li & Lunine 2003). One of the most exciting discoveries from the imaging was of an asymmetry in the disk structure: the NE lobe is $\sim$ 5% brighter than the SW lobe. Wyatt et al. (1999) showed that this asymmetry would be expected if there is a planet in the hole that has an eccentric orbit. The reason is that long-term gravitational perturbations from the planet would have imposed an eccentricity on the disk particles causing one lobe to be closer to the star and so hotter and brighter than the other, an effect they called *pericenter glow.*

2.2. FOMALHAUT

A disk which looks very similar to the HR4796 disk is that around Fomalhaut, a 200 Myr-old A3V star at 7.7 pc. It is too cold to image in the mid-IR, but was bright enough to be imaged in the sub-mm (Holland et al. 1998; Holland et al. 2003). Because of the cool temperature of these disks, the sub-mm has been the most fruitful wavelength range for imaging them, and the sub-mm bolometer array, SCUBA, working on the JCMT, has been the most prolific debris disk imager to date. Sub-mm imaging has the benefit of avoiding confusion with stellar photospheric emission, which is much fainter than the disk at such wavelengths, but the drawback is resolution: SCUBA has a resolution of 14 arcsec in the most sensitive waveband of 850 μm. This means that only the closest disks, say those within 25 pc, can be resolved using this instrument.

The early results (Holland et al. 1998) showed that Fomalhaut has an edge-on ring, characterised again by a double-lobed feature, this time with a larger radius of 135 AU (which explains why it is not hot enough to image in the mid-IR). More recently Holland et al. (2003) obtained images of the disk at 450 μm (reproduced in Fig. 1b), again with SCUBA which images at 850 and 450 μm simultaneously. The shorter wavelength gives better spatial resolution (7.5 arcsec), and so shows the structure of the disk in much greater detail. As well as characterising the size and inclination of the dust ring with much greater accuracy, this image also uncovered a warp in the emission distribution between the lobes.

The fact that the radial location of the dust was so well constrained meant that modelling of the SED of the dust emission was able to show that the size distribution of grains 7 μm - 20 cm in diameter is exactly the same as that expected from a collisional cascade (Wyatt & Dent 2002); smaller grains are blown out of the system by radiation pressure and larger grains contribute little to the SED. Further, extrapolating the collisional cascade distribution back and considering the collisional lifetimes of different sized planetesimals showed that the cascade starts with planetesimals a few km in diameter. Any larger planetesimals, should they exist, would have to be primordial given the 200 Myr age of the system. In this way the imaging allowed a picture to emerge

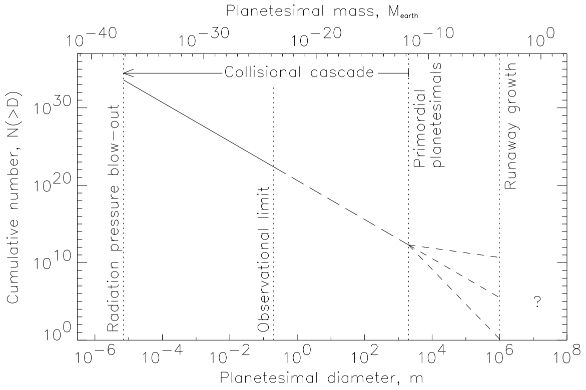

Figure 2. Size distribution of planetesimals in Fomalhaut's debris disk (Wyatt & Dent 2002).

of the parent bodies of the observed dust disk (Wyatt & Dent 2002; see Fig. 2). Wyatt & Dent (2002) also inferred a mass of $20M_\oplus$ for the collisional cascade, much more than the $0.02M_\oplus$ derived from the sub-mm emission which doesn't see material larger than 20 cm.

The warp in Fomalhaut's disk could not be explained by *pericenter glow*, since a warp of this magnitude would cause a lobe brightness asymmetry which is not observed. Rather the warp is caused by a clump seemingly embedded in the dust ring that contains 5% of the flux of the disk and has a mass of at least $0.001M_\oplus$ (Holland et al. 2003). Wyatt & Dent (2002) looked into the possibility that this was caused by the recent collision of two asteroids in the disk, but concluded that this is unlikely, since such a collision would have to have involved two asteroids at least 1400 km in diameter. While such planetesimals may exist, too few are expected for their clump to have been observed given that this clump would last for just 30,000 yr before spreading into the background disk. It is more likely that the clump is caused in some way by resonant trapping by a planet (see Kuchner, these proceedings), but as yet the origin of this structure remains obscure.

2.3. VEGA

Vega's is a more obvious example of a clumpy debris disk because it is seen face-on. Vega is in many ways similar to Fomalhaut: it is at 7.8 pc, it is 350 Myr-old, and is an A0V star. Sub-mm imaging at 850 μm showed a symmetrical disk structure, consistent with a face-on interpretation, but the emission is dominated by two clumps of unequal brightness straddling the star at about 70 AU projected separation (Holland et al. 1998; see Fig. 1c). The total mass of the disk was estimated from its sub-mm flux to be $\sim 0.01 M_\oplus$ (Holland et al. 1998). The structure of the disk was recently mapped with even higher spatial resolution (3 arcsec) using millimeter interferometry (Koerner, Sargent & Ostroff 2001; Wilner et al. 2002). While such observations are not sensitive to the disk's larger scale structure, they did show that a significant fraction of the millimeter emission could be resolved into the two clumps, both $\sim$ 9 arcsec NE and SW of the star, with more flux in the NE clump.

Two models have been proposed to explain the origin of Vega's clumps, both involving the resonant gravitational perturbations of a planet orbiting inside the ring. One of the models is explained in detail in these proceedings by Kuchner (see also Kuchner & Holman 2003). The salient points are that dust is trapped in the 2:1 and 3:1 resonances of a 3 Jupiter mass planet orbiting with an eccentricity of 0.6 (Wilner et al. 2002). The dust becomes trapped when it migrates in toward the star due to P-R drag.

In the other model, the dust is trapped in the 3:2 and 2:1 resonances of a Neptune mass planet on a circular orbit (Wyatt 2003). The dust is in the resonances because the parent asteroids were trapped there when the planet's orbit migrated out early in the history of the system. The asymmetric flux of Vega's clumps arises in the model because of an asymmetry in the number of planetesimals trapped in the 2:1(u) and 2:1(l) resonances. A fit to the image showed the planet started at 40 AU and ended up at its current location of 65 AU after $\sim$ 56 Myr. This migration could have been caused by the scattering of the residual planetesimal population, the same mechanism thought to be the origin of the populations of Kuiper belt objects that are found in Neptune's resonances (see Chiang these proceedings). If this model is correct, the implication is that Vega's system both formed and evolved in a very similar way to the solar system.

2.4. ϵ ERIDANI

Another disk with obviously clumpy structure is that around ϵ Eridani, which is again seen close to face-on. This is more Sun-like than the others: it is an 800 Myr K2V star and is one of our nearest neighbours at 3.2 pc. Despite its proximity, and the fact that it has $0.01 M_\oplus$ of dust, it was still very difficult to image, taking 12 hours of observations (Greaves et al. 1998). The difficulty arises because the star is not very luminous, and as such the dust only emits at 35 K despite it being relatively close at 60 AU from the star. The 850 μm image (see Fig. 1d) shows the ring-like structure of the disk, and also shows that this appears to be significantly clumpy. Only the brightest clump in this image was claimed to be real in Greaves et al. (1998), although many authors have taken the other features in the ring to be real as well. More recent sub-mm images do show, however, that many of these features are real (Greaves priv. comm.).

Several models have appeared in the literature interpreting the structure of this disk in terms of dust migrating into planetary resonances due to P-R drag (Ozernoy et al. 2000; Quillen & Thorndike 2002). Such a planet is predicted to orbit ~ 40 AU from the star and have a mass and eccentricity of $33M_\oplus$ and 0.3. Interestingly these models, as do all models in which debris clumps are caused by planetary resonances, predict that the whole structure would orbit the star with the planet (slightly different orbital periods are predicted in some models, see Kuchner these proceedings). This motion is sufficiently large that it should be detectable within the next decade. We should point out that a 0.86 Jupiter mass planet orbiting at 3.4 AU with an eccentricity of 0.6, has also been inferred from its effect on the radial velocity of the star (Hatzes et al. 2000). However, this inner planet is too distant to have any effect on the structure of the outer disk imaged in the sub-mm.

Another puzzle about this disk is its SED, which shows evidence of a lack of small grains: the radial location of the dust measured from the images is incompatible with the temperature of the SED if the grains have the collisional cascade size distribution used in Wyatt & Dent (2002) (Sheret, Dent & Wyatt 2003). Slight deviations from the single power law distribution for small grains are expected (Thébault, Augereau & Beust 2003), but a lack of small grains may also turn out to be prediction of at least one of the planetary resonance models (Wyatt 2003).

2.5. BOGUS DEBRIS DISKS

Imaging is also useful for weeding out bogus debris disks from lists of candidates determined by IRAS. The 1 arcmin beamsize of IRAS means that occasionally an excess thought to be associated with a star actually arises from a nearby background object. The excess toward 55 Cancri was shown by sub-mm imaging to be resolved into 3 point sources offset by 30 arcsec from the star, two of which have R band identifications and so are probably background galaxies (Jayawardhana et al. 2002). Similarly HD123160 (which we would not class as a debris disk now anyway since its luminosity classification has changed from a main sequence star to a giant) has its excess originating in a point source which is offset by about 10 arcsec (Sheret et al. 2003), and which coincides with a nearby galaxy (Kalas et al. 2002). Also, the excess for

HD155826 was found from mid-IR imaging to originate in a background carbon star (Lisse et al. 2002).

2.6. NEW DISK IMAGES

It is noticeable that there have been more discoveries of bogus disks in the last few years than of real disks. All of the disks we just presented were discovered in 1998, even if more detailed images are available now from more recent observations. Apart from the problem of bogus disks, these disks are also at the limit of the sensitivity and resolving power of current technology. Compounded with uncertainties in the anticipated flux which are inherent in extrapolations from the far-IR excesses measured by IRAS, this means that long integrations are required with no guarantee of an image. Luckily this appears to be just a hiatus and a new wave of discoveries is set to be published in the coming year as a result of sub-mm searches. These include the presence of a disk around τ Ceti (Greaves et al., in prep.) and η Corvus (Wyatt et al., in prep.). The former is particularly interesting, since this star is even more Sun-like than ϵ Eridani. It is a 7 Gyr-old G8V star at 3.6 pc and the images show its disk to be ~ 55 AU in radius and have a dust mass of $5 \times 10^{-4} M_\oplus$ (Greaves et al., in prep.).

3. Comparison to Solar System

It is instructive to compare the observed properties of debris disks with that of the solar system, both for the implications for how these systems evolve as well as their potential to solve outstanding mysteries such as the fate of the missing mass of the Kuiper belt and the origin of its outer edge (see Morbidelli, these proceedings). While the massive members of the Kuiper belt are relatively well characterised, its dust population remains poorly constrained. Current estimates based on its non-detection by COBE are that it has a mass of $< 10^{-5} M_\oplus$ (Backman, Dasgupta & Stencel 1995), and models of the evolution of dust grains created in collisions between Kuiper belt objects show that its emission is expected to peak at 30-50 AU (Moro-Martín & Malhotra 2002). Thus it appears from the last section that the confirmed debris disks are both more massive and larger than our own. They also tend to be found around stars that are younger than our solar system which has an age of 4.5 Gyr.

However, we must remember that very few debris disks have been imaged. As such these images could be just the extreme members of their population. Also, there is an observational bias in that most

Table I. The circumstellar environments of all main sequence F, G and K stars within 6 pc, including both binary companions and dusty debris disks.

Star	Sp. Type	Dist, pc	Companions	Debris Disk
Sun	G2V	0	-	$< 10^{-5}M_\oplus$, 30-50AU
α Cen A+B	G2V+K0V	1.34	Orbit 24AU	-
ϵ Eri	K2V	3.23	-	$0.01M_\oplus$, 60 AU
Procyon	F5IV/V	3.50	Orbit 14AU	-
61 Cyg A+B	K5V+K7V	3.50	Orbit 88AU	-
ϵ Ind	K5Ve	3.63	T2.5 at 1460AU	-
τ Cet	G8Vp	3.64	-	$5 \times 10^{-4}M_\oplus$, 55AU
HD88230	K7V	4.86	-	-
40 Eri A	K1Ve	5.03	M4.5 at 417AU	-
70 Oph A+B	K0Ve+K5Ve	5.10	Orbit 25AU	-
σ Dra	K0V	5.76	-	-
HD131977	K5Ve	5.89	M1V at 130AU	-
η Cas A+B	G3V+K7V	5.94	Orbit 71AU	-
36 Oph A+B	K1Ve+K1Ve	5.97	Orbit 84AU	-
36 Oph C	K5Ve	5.97	At 4370AU	-

imaged systems are around A stars, these being more luminous and heating the dust to higher temperatures. So when we ask the question "is the solar system anomalously small and undusty?" or alternatively "are the debris disk systems abnormally big and dusty?", we should really compare similar systems. Table 1 lists all F, G and K stars within 6 pc along with any known stellar companions and an estimate of their dust content. None of the stars with stellar companions has a dust disk. This is not surprising, since planetary formation would have been disrupted in these systems by the gravitational perturbations of the companion. The two nearest systems without companions are ϵ Eri and τ Cet; both have debris disks that are 50-1000 times as massive as, and on similar (though slightly larger) scales to, that of the solar system. The remaining two, HD88230 and σ Dra, have no far-IR excess measured by either IRAS or ISO. It is difficult to use the 60 μm and 100 μm upper limits to derive dust mass upper limits, since the dust around such low luminosity stars could simply be too cold to have been detected in the far-IR (Wyatt, Dent & Greaves 2003). However it appears likely that any disk in these systems would have to be less massive than that of τ Cet which was detected by both IRAS and ISO but is only slightly closer. Thus, depending on the dust content

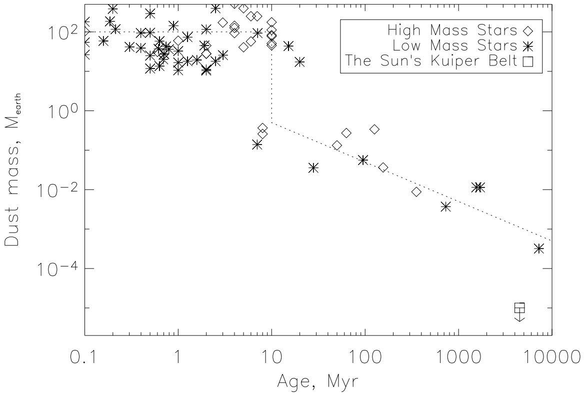

Figure 3. Evolution of the dust mass of debris disks inferred from their sub-mm flux and dust temperature (adapted from Wyatt, Dent, & Greaves 2003). High mass stars (A stars) are plotted with a diamond and low mass stars (F, G, and K stars) are plotted with an asterisk. The dotted line shows the evolution implied by this plot (for illustrative purposes only).

of these last two stars, the Kuiper belt is either relatively undusty or about average compared with the XKBs of nearby F, G or K stars.

Part of the reason why the Kuiper belt is relatively undusty could be evolutionary — the Sun could lack dust because it is old. Supporting this idea, a study of disk detection rates using ISO (Habing et al. 2001) showed that disks are found predominantly around stars younger than 400 Myr (Habing et al. 2001). However, more recently Greaves & Wyatt (2003) combined disk detection statistics from a range of surveys and found that disks can be found at any stage up to the end of the star's main sequence life, and that the epoch of detectability lasts ~ 500 Myr, but not necessarily at the beginning of the star's life, nor necessarily all at the same time. In another ISO study, the average disk mass was found to decline $\propto t^{-2}$ between 10 to a few 100 Myr (Spangler et al. 2001), which they suggested was caused by the collisional erosion of the XKB parent bodies. The trend of lower disk mass with increasing age is certainly evident when the masses of disks detected in the sub-mm (but not necessarily imaged) is plotted as a function of their age, although the mass loss looks more like $\propto t^{-1}$ (Figure 3). An even shallower mass decline, $\propto t^{-0.5}$, was found by Greaves & Wyatt (2003) when considering the detection statistics of nearby young and old G stars.

However, it must be remembered that dust mass is but a small fraction of the total disk mass (Wyatt & Dent 2002). Its evolution may be indicative of that of the total mass, but in general much of this mass may be inherently unobservable if it is locked into large planetesimals which do not even contribute to the collisional cascade. Their presence (or rather their collisional destruction) may, however, cause significant temporal variations in the dust mass. This could be why disks such as τ Cet are presently observable, despite their high age. However, other possibilities for high disk masses at late times are the delayed ignition of the collisional cascade due to long planetesimal growth timescales (Kenyon & Bromley 2002b) or stirring by a recently scattered failed planet core (Thommes et al. 2002). Stirring by a recent stellar passage appears unlikely given the relative infrequency of such events and the duration of the resulting dusty phase (Kenyon & Bromley 2002a), although it is noteworthy that structure in the β Pictoris disk has been attributed to a stellar flyby (Kalas et al. 2000). Greater statistics on the evolution of dust mass, as well as details in the imaged structure, will certainly help resolve the issue of how these systems evolve and so shed light on the fate of missing mass of the Kuiper belt.

Information about the evolution of the radial extent of debris disks is even more scarce. The mean radius of the disks is only known for the imaged debris disks, since this is poorly constrained from the dust temperature alone (Sheret et al. 2003). This radius shows no evolutionary trend. This is not surprising, since the observed radius is indicative of the disk's inner edge (where the dust is hotter) which is set by the radius of the putative planetary system. In terms of the origin of the edge of the Kuiper belt, however, it may be important that in our sample of nearby solar-type stars (Table 1), the disk of ϵ Eridani extends out to 100 AU (Greaves et al. 1998), while that of the τ Cet does not extend beyond 55 AU (Greaves, in prep.). This may indicate that the outer edge of the system is set up relatively late on in the system's evolution (e.g., by a random event such as a stellar flyby), although a sharply defined outer edge to the 10 Myr-old HR4796 disk has been inferred from near-IR coronographic imaging (Schneider et al. 1999)[2].

4. Conclusion

In conclusion, disk imaging is vital to our understanding of debris disks: it proves the IRAS excesses really are from dust rings, proves the existence of the central hole and links the dust to its origin in the collisional destruction of km-sized planetesimals. Imaging also provides further evidence that these systems have planets, however the exact nature of these planetary systems remains debatable; models with Jupiter or Neptune mass planets, on eccentric or circular orbits, are possible.

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[2] Note that the large outer edges observed for the HD141569 and β Pictoris disks are probably due to radiation pressure which causes the dust disks to extend further out than their parent planetesimal disks.

Clearly a very different interpretation of the evolution of these systems results from the different models. It will be possible to distinguish between the models once higher sensitivity and resolution observations of these systems have been performed, as well as observations separated by a sufficient time interval to detect orbital motion.

The small number of disks that have been imaged means that we do not yet fully understand how these disks evolve. Since debris disks do appear to be extrasolar Kuiper belt analogues, it should be possible to use their inferred evolution to answer questions about the evolution of our own Kuiper belt, such as "is disk mass usually removed in a single event such as a stellar flyby (and if so when) or in gradual erosion due to collisions?" To find the answers to such questions, a larger sample of disk images is required. As well as the anticipated sub-mm images, we can also look forward in the near future to imaging in the mid-IR using MICHELLE and TRECS as well as in the far-IR using observatories such as SIRTF and SOFIA.

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