Debris Disks: Signposts to planetary systems

Prospects for the next decade

A White Paper for the Astro2010 Decadal Survey
Submitted to the "Planetary and Star Formation" Panel

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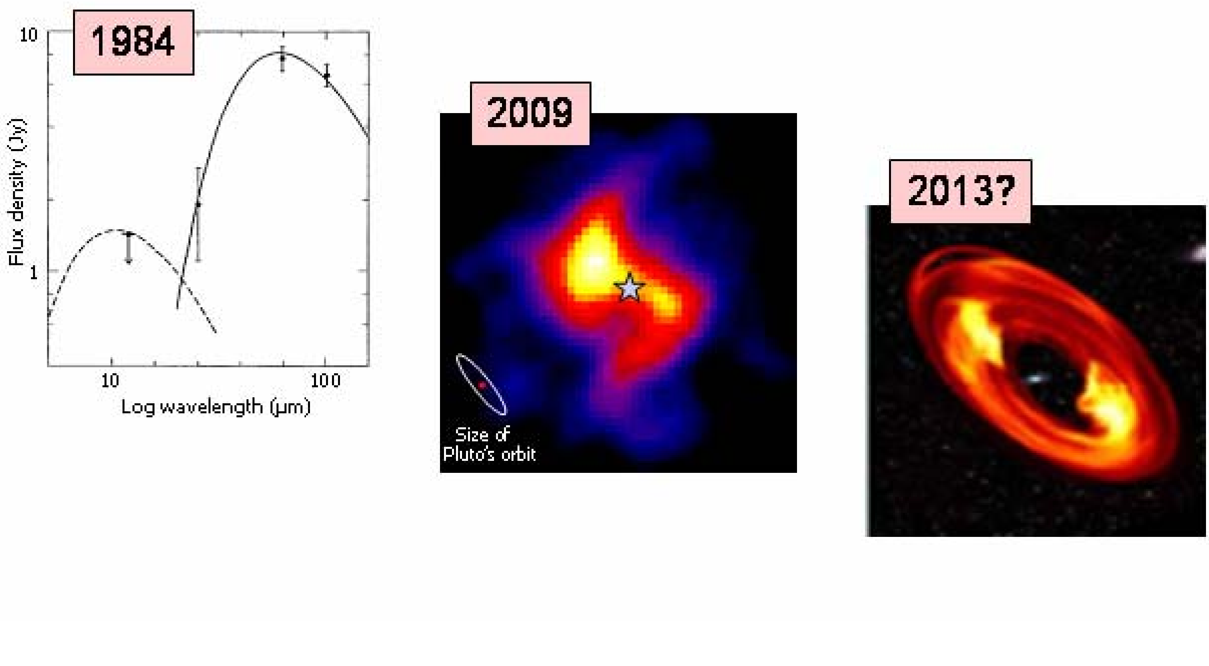

Figure: (left) The spectra energy distribution of Vega as measured by IRAS; (middle) the clumpy Vega debris disk imaged by the SCUBA camera on the JCMT; (right) a simulation of the detail that may be revealed by high angular resolution ALMA observations of the Vega disk (courtesy David Wilner & David Aguilar)

Executive summary

Debris disks are the detritus of comet collisions and their presence around nearby stars is strong evidence that planets also exist in these systems. Debris disks provide a unique way to study how planetary systems form and evolve from their primordial structures. Observations tell us about the scale of regions with planetesimals, locations of perturbing planets and the evolution of the comet population that can affect terrestrial planet habitability. This paper summarises the current status of debris disk studies, and outlines the direction this high profile research area is expected to take over the next decade. Major scientific goals include searching for analogs of our Kuiper Belt around nearby stars to assess whether the Solar System configuration is unique, providing higher resolution images of the disk structures to better constrain the positions of perturbing planets, and to study the physical and chemical properties of the disk material. The paper concludes by recommending facilities that are needed to address these goals, concentrating on studies in the far-infrared and submillimeter. One of the main conclusions is that although ALMA will play a crucial part over the next decade a key role exists for a large single-aperture telescope operating in the far-IR/submm. In particular, a 25-m class submm telescope (200−1000μm), such as the planned Cornell-Caltech Atacama Telescope (CCAT), offers the opportunity of carrying out deep surveys of hitherto undetected cold disks and thus the prospect of detecting true analogs of our Solar System.

1. Introduction

1.1 History. Many main-sequence stars are surrounded by dusty disks. The dust has a short lifetime due to removal mechanisms such as Poynting-Robertson drag and radiation pressure, and so the disk material must be continually replenished by colliding planetesimals. The presence of such planetesimals leads to the likelihood of larger bodies existing in the systems, such as planets. Debris disks were discovered by IRAS when an unexpectedly high level of infrared excess was detected around Vega (Aumann et al. 1984) − the observation being interpreted as a belt of cool dust in thermal equilibrium with the star. IRAS went on to show that ~15% of nearby stars contained debris (Backman & Paresce, 1993). For more than 20 years β Pictoris (Artymowicz 1997) was the only system where the disk could be resolved and hence studied in more detail. However, over the past decade, advancements in observational capabilities, coupled with the development of sophisticated models to interpret the data, has led to an enormous leap forward in our understanding of such systems.

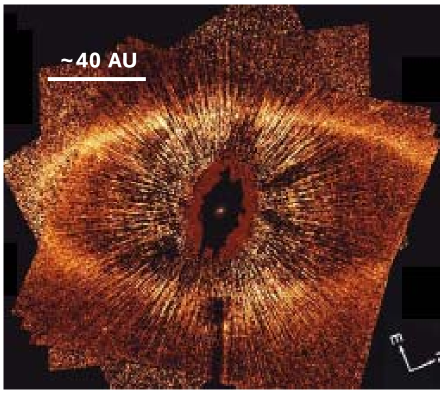

Figure 1: The Fomalhaut debris disk imaged in scattered light with the Hubble Spaces Telescope (Kalas et al 2005).

1.2 Basic characteristics. There are now ~20 resolved disks and the majority of these have been observed in the past few years via scattered light observations using the Hubble Space Telescope (e.g. Fomalhaut in Figure 1). Many of the disks are analogous to the Kuiper Belt in our own Solar System, containing dust grains that are very cold (<40 K) and so emit very little light in the optical/IR. Some of the earliest observations of the thermal emission from disks were provided in the submm by the SCUBA camera. One example is ε Eridani (see Figure 2), a ring of dust containing a number of asymmetric clumps, which have been interpreted as dust trapped in resonance with an unseen planet. Many more unresolved systems have had their physical properties (mass, temperature and radial extent) characterized by spectral energy distributions (SED) via observations from IRAS, ISO and Spitzer (e.g. Sheret et al. 2004, Beichman et al. 2006).

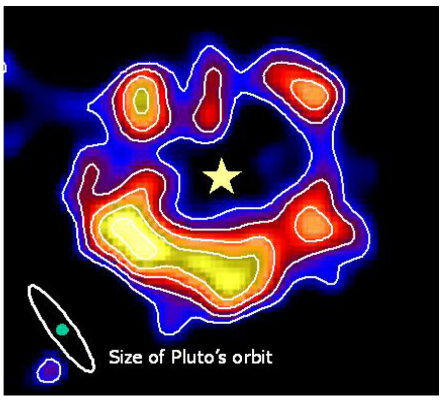

Figure 2: The ε Eridani debris disk from SCUBA observations on the James Clerk Maxwell Telescope (Greaves et al. 1998, 2005).

1.3 Why observe debris disks? The subsequent evolution of sophisticated models to interpret the observations has provided a unique way to study how possible planetary systems form and evolve from their primordial structures. Specifically, studying debris disks tells us about:

(i) *The outcomes of planet formation*. Debris around main sequence stars gives a strong indication of the presence of colliding planetesimals such as asteroids and comets. Knowing the location of planetesimal belts is vital for understanding the outcome of planet formation (e.g. the radius may indicate the outer edge of a planetary system).

(ii) *The uniqueness of our Solar System*. It is unknown whether the Solar System configuration is common or rare. Observing the analogs of our asteroid and Kuiper belts around other stars will allow this question to be addressed.

(iii) *Locations of planets*. Indirect planet detection is possible via modelling the observed perturbation of debris disk structure. This provides a unique way for finding distant, low-mass planets, very complementary to other planet detection techniques.

(iv*) Habitability of planets*. The presence of a high volume of comets in a system suggests that any planets also present could be subject to constant bombardment. This would have a profound impact on the habitability of terrestrial planets.

The connection with planet hunting, the exploration of extrasolar Kuiper belts and the possibility of making inferences about planet habitability has led to debris disks having a very high public profile.

2. Current status and near-term prospects

2.1 The diversity of resolved debris disks. About 200 disk systems are now known with the majority discovered from their excess far-IR/submm emission. Observations of the (far fewer) resolved disks from facilities such as Spitzer, CSO and JCMT (far-IR/submm), and HST, Gemini and Keck (optical/near-IR), have shown a remarkable variety of disk types and morphologies (see Figure 3). The structures are typically 1−3 times the size of our Solar System and many have central voids – possibly due to dust accretion by an inner planet (or planets). The masses of dust, inferred from submm observations, are typically just a few lunar masses but trace the location of the more massive comet population within the system (Holland et al. 1998). The clumpy structures of some disks suggest the existence of planets on orbits similar to Neptune in our Solar System (Wyatt 2003), and this has led to debris disks becoming a powerful tool for tracing modern-day planets.

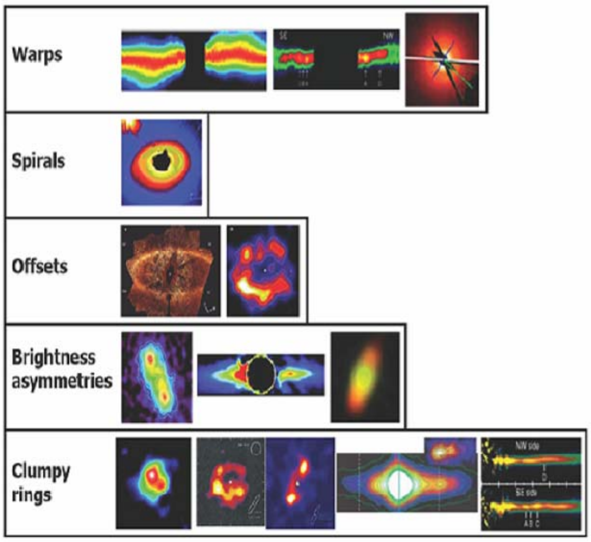

Figure 3: Montage of a selection of resolved debris disks illustrating the remarkable diversity of the observed structures. The images are from scattered light, mid-IR thermal and far-IR/submm thermal emission observations.

2.2 Recent far-infrared surveys. Surveys with ISO and Spitzer have invariably probed dust emission to a much greater sensitivity than was possible with IRAS. In particular, Spitzer has expanded the debris disk census to A−M spectral types (Meyer at al. 2007). It is emerging that the fraction of stars with detectable disks is a function of stellar age (Rieke et al. 2005), spectral type (Habing et al. 2001) and wavelength (Laureijs et al. 2002). A re-analysis of the IRAS and ISO data led to a revision that the fraction of nearby A-type stars with detected 60μm excesses was closer to 25% (Rhee et al. 2007). The "Formation and Evolution of Planetary Systems Legacy" program with Spitzer (Meyer et al. 2006) characterized the evolution of circumstellar gas and dust around 328 solar type stars between ages of 3 Myr to 3 Gyr. The results included a census of warm debris (Meyer et al. 2008), the identification of possible Kuiper Belt analogs (Hillenbrand et al. 2008), and an investigation that revealed no significant correlation on the presence of debris disks around stars with known planets (Moro-Martin et al. 2007).

2.3 Model interpretations – are there planets? The morphology and mass of debris disks provides crucial information about the outcome of planet formation and is revolutionizing our understanding of formation processes. Crucial to this interpretation has been new types of dynamic models that can explain the observed structure, composition and evolution of the disks. Models of the resolved disks (Wyatt et al. 2002) have been used to pinpoint the location of unseen planets, such as the asymmetric clumpy structure seen in the submillimetre around Vega (see Figure 4). The models also contain explicit assumptions about a disk's past history, such as planet migration. The Vega disk is an example that requires the migration of a planet to explain the asymmetric disk structure (Wyatt 2003). Further enhancements have included how the disk structure is expected to vary with grain size (Wyatt 2005) and predict that a significant change in disk structure for observations in different wavebands (which sample different grain sizes). So far this has been successfully applied to the Vega disk which is smooth and significantly extended in the mid- to far-IR (Su et al. 2005) whilst more compact and clumpy at submm wavelengths (Holland et al. 1998, − see also section 3).

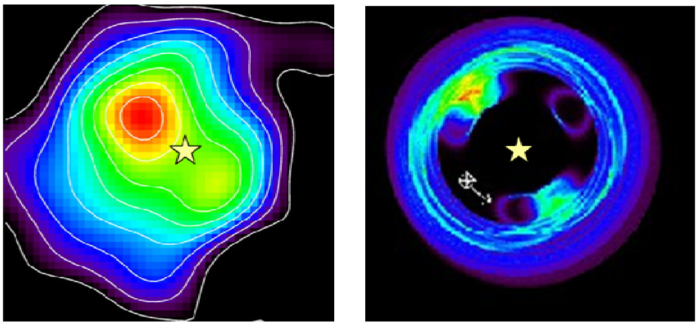

Figure 4: (left) The clumpy structure of the observe debris disk around Vega (Holland et al, 1998); (right) Dynamical model showing the higher density of dust is trapped in resonance with an unseen planet, where the planet position is illustrated by the crossed square (Wyatt 2003).

2.4 Near-term future work. The studies carried out so far of resolved systems have been for a relatively small number of disks. Comparing the observation and model in figure 4 illustrates the shortcomings of the data, in that it lacks sufficient angular resolution to fully constrain the model. Furthermore, sensitivity limitations have led to current surveys being somewhat biased in their target selection. Despite the shortcomings a number of fundamental questions that have emerged out of recent studies:

(i) How do debris disks evolve? How a star's debris disk evolves is indicative of the evolution of its planetesimal belts which in turn may be influenced by the planet formation process. Although a steady-state collisional evolution seems to dominate in the disks around A-type stars and some solar-types, it does not explain all the observed systems (Wyatt 2008). It seems some disks must have had a stochastic component to their evolution which may, or may not, be explainable by debris produced in a large single collision. Further work is now explaining the observables such as how debris disks increase and decrease in brightness following the protoplanetary disk dispersal (Kenyon and Bromley, 2008). The increase is most likely due to ongoing planet formation whilst the subsequent decline happens as grains are eventually removed from the system by drag and radiation forces.

(ii) *What can debris disks tell us about planetary systems*? Although not necessarily a unique interpretation, debris disk structures have the potential to reveal planets in a region of parameter space currently inaccessible to other techniques (e.g. regions comparable to the orbit of Neptune and beyond in our Solar System). This is illustrated in Figure 5 which summarises the properties of all known exoplanets. Although relatively small in number, especially compared to planets discovered by the radial-velocity method, the debris technique is starting to produce a significant number of results. This will continue to improve only with enhanced sensitivity and improved angular resolution from new facilities.

(iii) *Is there a population of cold disks hitherto undetected?* Cold disks will be analogous to the Kuiper belt in our own Solar System and so their study is fundamental in addressing questions such as whether the Solar System configuration is common or rare. Recent results (Rhee et al. 2007) show that the overall frequency of debris disks may now be as high as 25% as there is likely a population of disks that are either of too low a mass or too cold to have been detected by IRAS, ISO or Spitzer.

(iv) *Are there environmental factors that affect the presence of dust?* There is no strong evidence to support an increased incidence of disks around stars with increased metallicity (Greaves et al. 2006). However, these results are largely based on studies of luminous A stars. Another important question that is now being addressed is how binarity affects the dust disk properties and evolution. A study of the excess emission from a sample of A and F stars with Spitzer at 24−70μm has revealed that the incidence of disks is around 50% for binary systems with small (<3 AU) and with large (>50 AU) separations (Trilling et al. 2007).

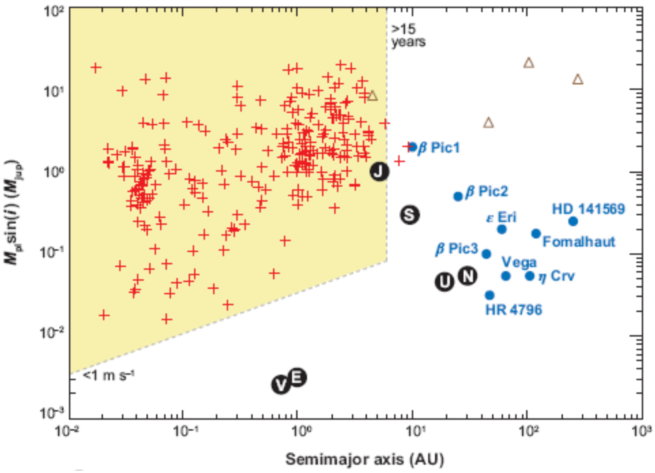

Figure 5: Distribution of planet masses and semi-major axis (from Wyatt 2008). Red crosses represent planets discovered by the radial velocity method, triangles via transit studies and blue circles indicate planets inferred from debris disk studies. The planets in our Solar System are also marked.

All of these questions will be addressed by more sensitive surveys and higher angular resolution imaging. For example, the SCUBA-2 Debris Disk survey (Matthews et al. 2008) will carry out an unbiased survey of 500 nearby main-sequence stars, 100 of each in the A, F, G, K and M spectral types, searching for debris signatures at 850μm. SCUBA-2 will provide the unique detection statistics and will be supplemented by 100 – 500μm fluxes from Herschel to give a complete far-IR/submm SED. The SED then allows temperatures and masses to be determined, from which, for example, a collisional cascade can be derived to give an estimate of the parent body population. The main goals of the observational programs using JCMT/SCUBA-2 and Herschel are to:

(i) Determine unbiased statistics on the incidence and properties (mass, grain size/temperature, radii) of disks around nearby stars
(ii) Discover the relationships between these properties, stellar history and environment
(iii) Provide targets for future programs with ALMA, JWST and optical extremely large telescopes to investigate at the detailed disk structure (perhaps also including spectroscopy)
(iv) Provide limits on the presence of dust for future planet-finding missions (e.g. Darwin/TPF)

The issue of angular resolution to better resolve clumpy structure, and so provide improved constraints for theoretical models, is also starting to be addressed. Facilities like the Smithsonian Millimeter Array (SMA) and Combined Array for Research in Millimeter-wave Astronomy (CARMA) are producing images with angular resolutions of a few arcseconds. A recent example of the current capabilities is shown in Figure 6. The 3 arcsecond resolution of CARMA at a wavelength of 1.3mm resolves the disk around HD107146 into clumps, somewhat similar to that seen around the much closer ε Eridani. SMA and CARMA will continue to image the brighter debris disks, but the next generation telescopes are required to image the fainter, Kuiper Belt analogs around nearby stars.

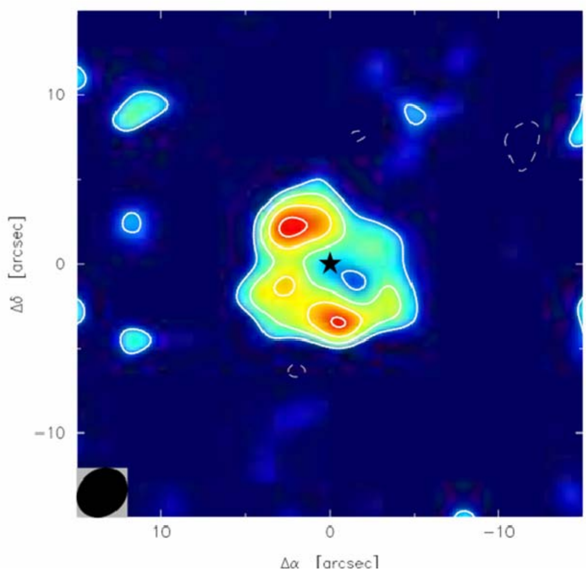

Figure 6: The resolved debris disk around HD 107146, a 100 Myr solar analog from observations with CARMA (Corder et al. 2009).

3. Debris disks studies beyond the near-term

Despite the promise of the upcoming surveys with JCMT and Herschel, and the emergence of the SMA and CARMA, there remains both a sensitivity *and* angular resolution problem to make further progress. Debris disks, particularly those to be found around Solar-type stars (and also later spectral types e.g. M stars), have a low surface brightness often with extended structures covering up to a few arcminutes in diameter. Observations with current single aperture telescopes have also revealed the problem of confusion in that disk features could be contaminated by other sources such as background galaxies. Beyond the near-term surveys and the arcsecond resolution imaging with current interferometers, there are four areas in which the study of disks will develop to a new level:

(1) *Unbiased surveys for Solar System analogs.* Although SCUBA-2 will likely find several Solar System analogs (after very lengthy integrations), it will not produce valuable statistics on their occurrence. As illustrated in Figure 7 the sensitivity of either current (e.g. Spitzer) or near-term facilities (e.g. SCUBA-2) will struggle to probe Solar System dust levels even at the distance of the nearest stars. To carry out deeper surveys approaching Solar System dust levels around nearby stars requires a 10-m class telescope (scaled-up Spitzer or SPICA, e.g. SAFIR concept) for the far-IR and a 25m-class telescope operating in the submm (e.g. CCAT). Such facilities would not only have the ability to survey large number of solar-type analogs but would also provide high enough angular resolution to show significant sub-structure in the disks. The more interesting of these detected systems would then be followed up with interferometers such as ALMA and with JWST at shorter IR wavelengths. For example, a 25-m class submm telescope, coupled with a highly sensitive imaging camera, is perfectly suited to this role. With 4× improved resolution and 64× the search volume of current single-dish telescopes, hundreds of solar-type stars could be studied to reveal the true picture of disk population. Confusion levels would be lower than for existing telescope which would also reduce the possibility of true disk structure being masked by background objects (such as high-z galaxies).

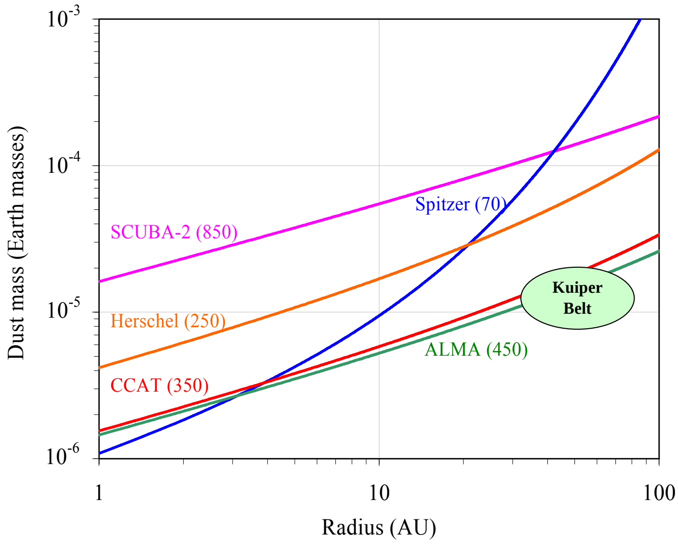

Figure 7: The dust mass sensitivity (5-σ, 10-hr) as a function of radius from the star (distance of 10pc) for a selection of current and new facilities. The mass sensitivity is for unresolved sources.

(2) High resolution imaging of the disk structure to determine the fraction of dust trapped in planetary resonances. The low surface brightness of the majority of debris disks will remain a challenge for existing interferometers, particularly when trying to detect sub-structure at high S/N such as dust clumps trapped in planetary resonances. Sensitivity and angular resolution are also issues for studying dust in the terrestrial planet region (which as not been done before – analogous to our asteroid belt). Higher angular resolution studies, particularly at sub-arcsec levels, will better constrain models (see example for simulated ALMA observation in Figure 8). Another intriguing prospect is that facilities like ALMA or a 25-m single dish would have sufficient

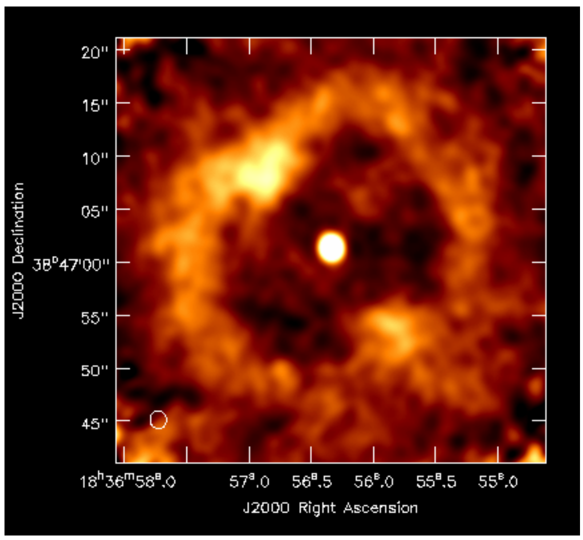

Figure 8: Simulation of a 12-hr observation of the Vega debris disk with ALMA (figure courtesy of Rob Reid).

angular resolution to detect the evidence of rotating clumps within nearby disks on periods of order a year – another constraint on planetary system models.

(3) Investigation of the wavelength dependence of the debris structure. Recent models (Wyatt 2006) predict that the observed structure of debris disks changes with grain size due to radiation pressure. Hence images taken of the same debris disk will look different at different wavelengths. This is because the balance of radiation pressure and gravity means dust of different sizes are trapped differently, with small grains feeling more radiation force so short-wavelength data show more blow-out (see Figure 9). The submm is ideal for imaging perturbations since it is sensitive to large(ish), well-trapped dust grains.

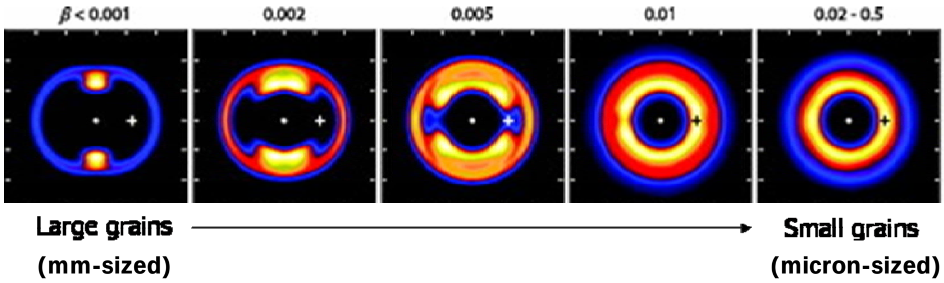

Figure 9: Surface density of dust grains of different sizes created in the collisional destruction of planetesimals trapped in resonance with a 30M(Earth) planets (Wyatt 2006).

Different structures are seen that give an insight into the properties of debris (e.g. perhaps a recent catastrophic collisions in a system) and of the planet. Therefore, such studies require a facility (or facilities) that provide the essential coverage from the far-IR to long submm wavelengths to investigate the wavelength dependence. This model has so far been successfully applied to multi-wavelength data on the Vega debris disk which predicts that the submm image will appear clumpy whilst at mid-IR wavelengths it will appear smooth (see Figure 10). Since the transition from smooth to clumpy depends on planet's mass this could provide a very powerful way of determining physical characteristics of the perturbing planet.

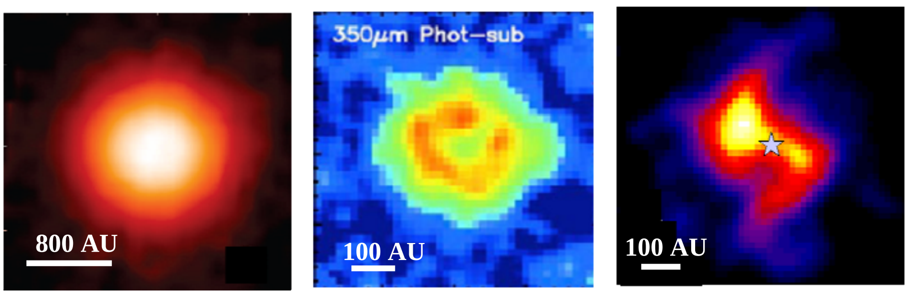

Figure 10: Observations of the Vega debris disk: (left) at 70μm with Spitzer (Su et al. 2005), (middle) at 350μm with CSO (Marsh et al. 2006); and (right) at 850μm with JCMT (Holland et al. 1998). Note the large difference in scales between the Spitzer image and the submm observations.

(4) Spectroscopy of transitional and debris disks. In debris disks the structure and dynamics are dominated by solid bodies. However, in transitional disks (i.e. those disks between the protoplanetary and debris phases), hydrodynamics and chemistry become very important. Spectroscopic probes can address questions such as how do disks finally lose their gas, and are there planets in the gas-rich transition phase? Facilities such as ALMA and Herschel will have the potential to carry out spectroscopy on a number of different scales to probe the inner and outer disk structures. Also vital is the development of continuum and line radiative transfer models to fully interpret the observations. For debris disks it may also be possible with increased sensitivity to measure the CO emission within the disks – perhaps from a narrow ring of evaporating comets.

4. Summary and recommendations

Debris disks provide a unique way to study how planetary systems form and evolve from their primordial structures. Observations of such disks tell us about the scale of regions with planetesimals, locations of perturbing planets and the evolution of the comet population that can affect terrestrial planet habitability. Over the next few years the observation and interpretation of debris disks in the far-IR/submm will accelerate. The JCMT/SCUBA-2 survey will identify dozens of new disks and Herschel and SOFIA will provide physical characteristics by pinning down dust temperatures and masses. Other facilities, such as the Large Millimeter Telescope, will also provide crucial imaging and SED information. Surveys of (unresolved) disks will show how the disk mass evolves, how disk incidence varies with stellar mass, binarity, metallicity, exoplanet parameters etc. All detected systems will be subsequent targets for ALMA, which will remove the degeneracy from SED measurements alone, and detail the perturbed structure on sub-arcsecond scales.

However, there are a number of limitations to the new surveys with existing facilities. For example, although JCMT/SCUBA-2 will image disks ~50 times faster than before, there will remain issues with coarse angular resolution and confusion. For main sequence stars, the clumps and cavities within disks will continue to be seen coarsely on scales >20AU. These are even more serious issues for Herschel and SOFIA, and will not be addressed even with facilities like SPICA over the next decade. Hence, there exists a real niche for both a space borne 10-m aperture for the far-IR (e.g. SAFIR concept) and CCAT − a 25m-class single-dish telescope operating with 2−4 arcsecond angular resolution in the 200−500μm wavelength regime. Indeed, CCAT will be the only telescope to provide high angular resolution imaging in the crucial 200−250μm windows. Such a telescope will provide the full picture of disk sizes, incidence of perturbing planets, frequency of comet collisions etc. It will have the sensitivity to detect true analogs of our Solar System and by imaging the cometary dust trapped in planetary resonances can solve unambiguously for the mass, position and eccentricity of unseen planets – even the time-resolved orbital motion of the clumps can be detected over periods of ~1 year. For main sequence stars, the clumps and cavities within disks will be imaged down to 2AU – pinpointing the regions of influence of planets and the extent of the outer cometary belts (a source of hazard to life on terrestrial planets).

Making further advances in the study of debris disks not only requires new telescopes but also the continued development of highly-sensitive, state-of-the-art instrumentation for both imaging and spectroscopy. With disks typically being of order an arcminute in size, a large field-of-view is not a critical driver for new instruments. More crucial for disk studies is having the sensitivity to detect very small amounts of emission (typically a lunar mass or less for a system at 10pc). This requires detectors that have sky background-limited sensitivity throughout the waveband of interest with typical noise equivalent powers in the 10^{-17} – 10^{-16} W/√Hz range. Another critical requirement for any new instrumentation, particularly for a ground-based instrument operating in an environment of changing sky conditions, is the ability to produce a fully-sampled image as quickly as possible (i.e. close-packed array configuration). This is essential to maintain a high level of image fidelity – important when looking for sub-structure within disks that could pinpoint possible planets. The development of Transition Edge Sensor detector arrays, with an emphasis on extending designs to operate at higher frequencies in the submm, should be a top priority for the next decade.

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