Modeling the Structures of Dusty Disks: Unseen Planets?

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Abstract. One of the legacies of IRAS was to show that some 15% of main sequence stars are surrounded by disks of dust. The dust in these *debris disks* is continually replenished by the destruction of larger planetesimals and so these disks have the potential to tell us a great deal about the outcome of planet formation in their systems. To extract such information the disks need to be resolved. The handful of disks which have had their structure mapped have shown that none of these disks are smooth or axially symmetric. A wide variety of disk structures have been detected, ranging from warped disks of asymmetric brightness to clumpy ring-like disks. Detailed dynamical modeling has identified many of these structures with perturbations from as yet unseen planetary companions. In this paper I review the types of structure that planets can, and indeed have been purported to, impose on debris disks, and look at the evidence we have from modeling of debris disk images that these unseen companions really exist.

CIRCUMSTANTIAL EVIDENCE FOR PLANETS

Before discussing how planets can affect the detailed structure of dust disks, I want to start by considering what information is available from observations of the large scale structure of the disks. Such a discussion is not only necessary to build a coherent picture of what it is that we are observing, but also provides the first circumstantial evidence that planets may have formed in the disks.

Grain Growth

As soon as dust was discovered around main sequence stars it was recognised that this dust cannot be primordial. The reason is that the dust we are seeing is short-lived. Poynting-Robertson (P-R) drag would make the dust spiral onto the star on timescales of around 0.1 Myr. The disks are also so dense that mutual collisions would destroy dust grains on similar timescales. Since main sequence stars have ages in the range 10-10,000 Myr, the dust we are seeing must be continually replenished, presumably by the erosion of an unseen populations of larger planetesimals which have much longer P-R drag and collisional lifetimes.

The nature of this replenishment in the Fomalhaut disk was studied by modeling the spectral energy distribution (SED) of its dust emission [1]. Once the distance of the dust from the star had been constrained by imaging, the SED modeling was able to derive the size distribution of the dust, since smaller grains emit hotter that larger grains at the same distance. This showed that the size distribution is the same as that expected from a collisional cascade, in which planetesimals are continually colliding and getting ground down into smaller particles. Consideration of the collisional lifetime of different sized bodies in the disk showed that what we are seeing is just the bottom half of the cascade (7 μm dust to 20 cm pebbles), and that the cascade is fed by planetesimals a few km in diameter. While nothing could be inferred about the number of planetesimals larger than this, because their collisions are too infrequent to be contributing to the dust we are seeing, this does provide circumstantial evidence for planet formation: grain growth has occurred up to at least km sized planetesimals, so perhaps at some location in the disk, presumably closer to the star, grain growth could have proceeded up to planet sized bodies.

Cavities

Further evidence that such planets may have formed closer to the star comes from the lack of warm dust emission in debris disk systems. This implies that the inner regions, some tens of AU in radius, are relatively empty of dust, a finding supported by imaging for the few disks where this has been possible. The argument put forward for this observation supporting the presence of planets is based on the idea that P-R drag would populate these inner regions with dust created in the outer regions of the system. In the absence of inner planets this would result in a disk with a constant surface density extending in toward the star [2]. Introducing planets, however, would cause the dust grains to be scattered or accreted before they reach the inner regions; some would also be captured into its resonances (see next section). However, while this is one explanation for the inner cavities, other interpretations also exist [3, 4] meaning that the presence of a planet may not be a reliable conclusion based on the presence of a cavity.

STRUCTURES CAUSED BY PLANETARY PERTURBATIONS

If there is a planet orbiting in the disk, then its gravitational perturbations will affect the orbital evolution of material in the disk. This would mean that both the planetesimal disk and the dust disk would contain dynamical structure associated with the planet; this structure may be discernible (or even dominant) in observations of the disks. Planetary perturbations can be broken down into one of two kinds: secular and resonant. These two types of perturbation can be identified with specific mathematical terms in the planet's disturbing function [5], and so it is often possible to find an analytical solution to their effect. They also have specific physical meanings and result in two different types of structure. Secular perturbations act on all material in the disk and can be considered as the long term affect of having a planet in the disk. Indeed these perturbations are equivalent to those from the ring of material created by spreading the mass of the planet evenly along its orbit. Since they affect everything in the disk, secular perturbations result in large scale asymmetries such as offsets and warps. Resonant forces act only at specific radial locations in the disk where an object would have an orbital period which is a ratio of two integers, say $p+q$ and p, times the orbital period of the planet. By

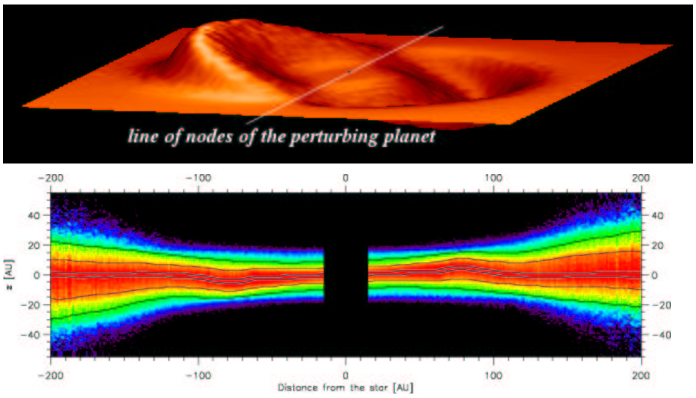

FIGURE 1. Long term effect of introducing a planet on an inclined orbit into a planetesimal disk [10]. Left: orbital planes of planetesimals at different distances from the star. On intermediate timescales planetesimals closer to the orbit of the planet have their orbits aligned with the planet, while those further away retain their primordial orbits. Right: model showing how this effect would cause the β Pictoris disk, which is viewed edge-on, to appear warped.

analogy with the dynamical structure of the solar system, resonant orbits can be either over- or under-populated, and a simple discussion of their geometry (see later) shows that such orbits can result in a clumpy disk.

Offsets and Warps: Secular Perturbations

One of the first discoveries of structure within debris disks came from images of β Pictoris. These showed that its disk, which is seen edge-on, is both warped and contains brightness asymmetries, even when asymmetries which can be attributed to observational effects (such as starlight being scattered by dust grains in a forward rather than backward direction) have been taken into account [6, 7]. A brightness asymmetry is also observed in the HR4796A disk. The emission from this disk comes from a narrowly confined ring, also seen edge-on. As expected, the disk appears in the image as two lobes straddling the star, but one lobe is 5% brighter than the other [8]. Both warps and brightness asymmetries have been modeled as being due to the secular perturbations of unseen orbiting planets [9, 10].

Warps

One of the long term effects of introducing a planet into a planetesimal disk is to make the orbital planes of those planetesimals precess about the planet's orbital plane. After a few precession timescales, the orbital planes of nearby planetesimals are mixed so that the planetesimal disk has its plane of symmetry aligned with the orbital plane of the planet. As the precession is faster for orbits which are closer to the planet, on intermediate timescales the disk can appear warped, with planetesimals close to the planet having their orbits aligned with the planet, while those further away still having

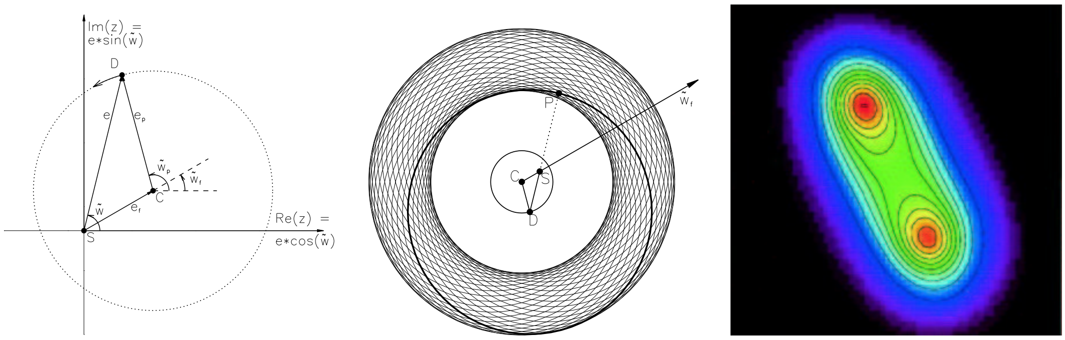

FIGURE 2. The consequence of introducing a planet on an eccentric orbit into a planetesimal disk [9, 8]. Left: the eccentricities, e, and pericenter orientations, $\tilde{\omega}$, of planetesimals precess about a point called the forced eccentricity (defined by e_f and $\tilde{\omega}_f$). Middle: on long timescales the eccentricities and pericenters appear evenly distributed about the circle centered on the forced eccentricity resulting in a disk with a center of symmetry (C) that is offset from the star (S). Right: model of the HR4796A disk showing how when such a disk is viewed edge-on, a brightness asymmetry occurs because one of the disk lobes is closer to the star, and so hotter and brighter, than the other one.

their primordial orbit alignment (Fig. 1 top). This was the basis of a model which showed that the β Pictoris disk warp could be explained by the introduction of a 3 Jupiter mass planet at 10 AU on an orbit inclined by just 3° to the primordial disk [10] (see Fig. 1 bottom). Within the context of this model, it is the product of the planet's mass and its orbital radius squared which are constrained, and the warp is observed because of the relative youth of the *beta* Pictoris system. More recent mid-IR images of β Pictoris indicate that there are at least three planes of symmetry within its disk [11, 12]. Multiple planes of symmetry can also be explained using secular perturbations, since if there is more than one planet in the disk, and these planets orbit on different planes, then the symmetry plane will vary throughout the disk. Warps in multiple (non-coplanar) planet systems arise regardless of the age of the system.

Offsets

The lobe brightness asymmetry seen in the HR4796A disk was explained to be the result of the secular perturbations of a planet on an eccentric orbit in the disk [9]. The reason is that these perturbations affect the eccentricities and pericenter orientations of planetesimals in the disk; they impose a forced eccentricity and forced pericenter orientation on the planetesimals (Fig. 2 left). This means that on long timescales the disk looks like an eccentric ring, with the forced pericenter side being closer to the star than the corresponding forced apocenter side (Fig. 2 middle). While the offset between the two sides was proposed to be very small in the HR4796 disk (1-2 AU), this effect was observed in the mid-IR images, because this caused the lobe on the forced pericenter side to be hotter and so brighter than the other lobe (Fig. 2 right). The interesting thing about this model is that a planet as small as a few Earth masses orbiting with an eccentricity of just 0.02 could be causing this asymmetry. However, the nature of secular perturbations meant that the model could not constrain the mass or orbit of the planet, and it is even

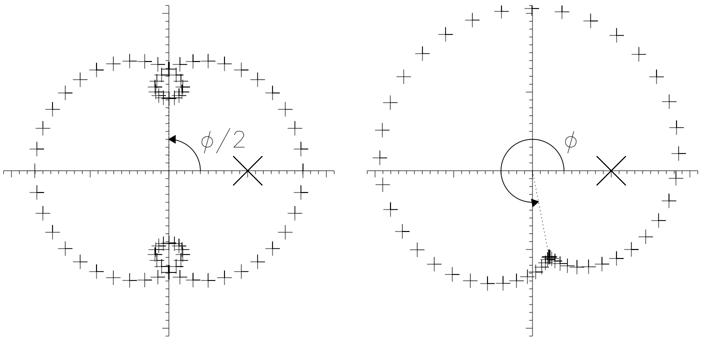

FIGURE 3. Paths of resonant orbits in the frame corotating with the planet [27]: 3:2 (left) and 2:1 (right) resonances. The resonant object is plotted with a plus at equal timesteps along its orbit which has an eccentricity of 0.3. The orientation of the pericenter with respect to the planet, which is shown with a cross, is determined by the resonant argument, ϕ.

possible that the asymmetry is caused by the M star binary companion HR4796B, the orbit of which is as yet unknown. Perhaps the most promising method of testing this model is to look for the offset asymmetry which should exist between the lobes; the orbit of the binary companion must also be constrained to ascertain its effect on the disk structure.

Clumps: Resonant Perturbations

The most common feature of debris disks is that they are clumpy: the Vega [13, 14], ϵ Eridani [15], and Fomalhaut [16] disks are all clumpy. The only feasible explanations put forward so far for this clumpiness have involved planetary resonances.

To understand why resonances result in clumpy structures one needs to consider two things. First of all, when plotted in the frame corotating with the planet, the pattern traced out by a resonant orbit is such that the object in resonance spends longer at certain longitudes relative to the planet (Fig. 3). This is because the pattern repeats itself after an integer number of orbits, which means that when the object reaches pericenter the planet can be at one of a few longitudes relative to the object. The orientation of those pericenters relative to the planet are defined by the resonant argument, ϕ. The second point is that while in resonance, resonant forces cause the object's resonant argument to librate (i.e., undergo a sinusoidal oscillation). Since the angle about which ϕ librates is the same (or rather varies in a consistent way) for all objects in the same resonance, all such objects are most likely to be found at the same longitudes relative to the planet.

Two different types of model exist to explain the clumpiness of dust disks in terms of planetary resonances, and they differ in the mechanism which puts the dust in the resonances: in one model dust migrates into the resonances by P-R drag, and in the other the parent planetesimals of the dust grains were captured into the resonances when the planet migrated outward.

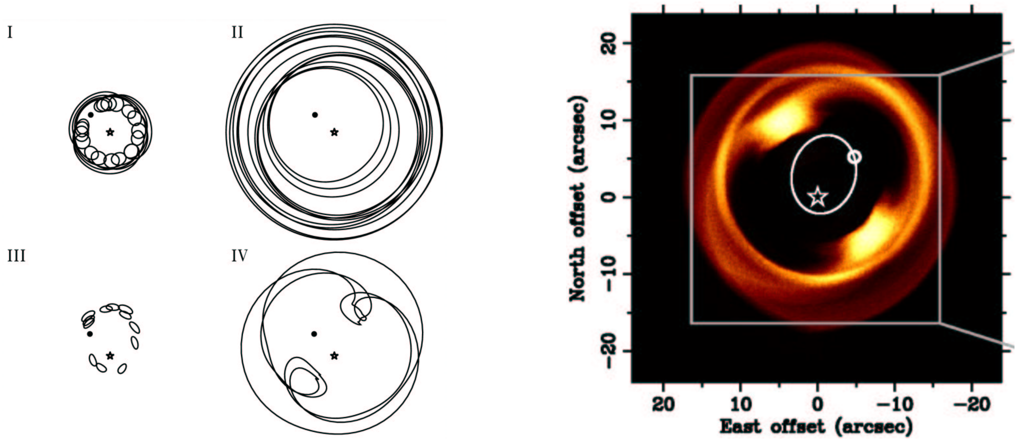

FIGURE 4. Structures resulting from dust migrating into a planet's resonances. Left [22]: four basic structures resulting from (I) low mass planet on a low eccentricity orbit, (II) high mass planet on a low eccentricity orbit, (III) low mass planet on a moderate eccentricity orbit, (IV) high mass planet on a moderate eccentricity orbit. Right [14]: model of Vega's two asymmetric dust clumps resulting from dust trapped into the resonances of a 3 Jupiter mass planet with an eccentricity of 0.6.

Dust Migration into Resonance

After a dust grain is created P-R drag makes a dust grain migrate in toward the star. On its passage inward, if there is a planet on an orbit interior to it, the dust grain will encounter the planet's resonances. Resonant forces can halt the migration causing the particle to be trapped in the resonance. While trapped the particle's eccentricity is pumped up, and eventually it leaves the resonance, then continuing its passage toward the star. The trapping causes a concentration of dust at a distance from the star similar to that of the planet's orbit. For reasons already described the resulting *resonant ring* is clumpy. Such resonant rings exist in the Solar System: one has been detected in the structure of the zodiacal cloud, associated with dust trapped in resonance with the Earth [17], and Neptune is also predicted to have such a ring [2].

This effect was first applied to extrasolar systems to provide an explanation of the radial distribution of dust observed in the β Pictoris disk [18]. Later this effect was used to explain the clumpy structures observed in the Vega and ε Eridani disks [19]. These models showed that it is possible to explain the clumpy structures in terms of dust migrating into the resonances of a 2 Jupiter mass planet orbiting at 40-60 AU from the Vega, and a 0.2 Jupiter mass planet at 55-65 AU from ε Eridani. The models made testable predictions: the planets should be detectable with ground-based observations (none has been detected yet at limits slightly above the masses proposed [20]); and the clumpy structures should orbit the star with the orbital period of the planet, i.e., at $0.6-1.6^\circ$/year, motion which should be detectable on timescales of order a decade.

More recently two papers showed how the Vega and ε Eridani dust structures may also be caused by dust migrating into the resonances of planets on eccentric orbits [14, 21]. The proposed masses and orbital radii of the perturbing planets are not significantly different to those proposed previously; the orbits have eccentricities of 0.6 (for Vega's planet, see Fig. 4 right) and 0.3 (for ε Eridani's planet). However, introducing an

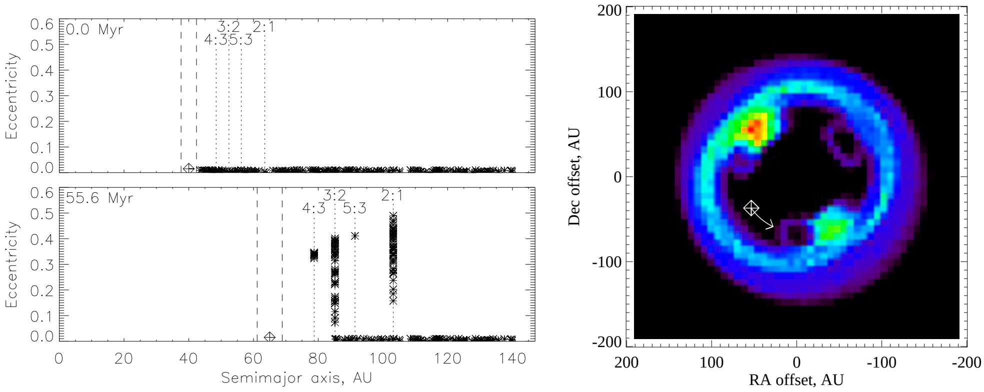

FIGURE 5. Impact of the outward migration of a Neptune mass planet on a planetesimal disk around Vega [27]: orbital distribution of planetesimals at the beginning (top left) and end (bottom left) of the migration; spatial distribution of those planetesimals at the end of the migration (right).

eccentricity into the planet's orbit meant that the dust is trapped into different orbital resonances. This led to the prediction that the structure would also change as it orbits the star, and in the case of Vega's structure, this would orbit at half the orbital speed of the planet. This type of model, and in particular the different types of structure caused by dust migration into the resonances of a high/low mass planet on a circular/eccentric orbit, was summarized in a recent paper [22] (see also, Fig. 4 left).

Planetesimal Trapping by Planet Migration

One problem encountered by the dust migration model is that the disks which have been observed are very dense. This means that their dust grains do not migrate far from their source before they are destroyed in a collision with another dust grain. One paper proposing dust migration into resonance suggested that this may mean that the sources of the dust are themselves already in resonance with the planet [14].

One reason why planetesimals may be in resonance with a planet is evident from the Solar System. Many objects in the Kuiper Belt, including Pluto, are found to be trapped in resonance with Neptune [23], and this configuration is thought to be because Neptune's orbit actually started much closer to the Sun, at about 23 AU, then migrated outward to its current 30 AU orbit [24]. This migration is thought to have been caused by angular momentum exchange when Neptune scattered the remnant planetesimal disk and to have taken about 50 Myr [25]. As its resonances swept through the primordial Kuiper Belt, many planetesimals became trapped in the resonances and migrated out with Neptune, while at the same time having their eccentricities pumped up. This scenario has been expanded significantly and now explains many of the dynamical features of the current Kuiper Belt [26].

The different kind of dynamical structure you can get from planet migration in extrasolar systems was recently modeled and it was found that with this model it is possible to reproduce the observation of two clumps of asymmetric brightness around Vega [27] (Fig. 5). To do this the model assumed a planet with a mass similar to that of Neptune, and with an orbit that expanded from 40 to 65 AU over a period of about 56 Myr. Within the context of the model, tight constraints were set on these parameters, since only a small range of planet mass and migration rate resulted in the majority of the planetesimals being trapped into the 3:2 and 2:1(u) resonances (Fig. 5 left).

Again the model made testable observational predictions: the orbital motion of the clumps (1.1°/year); the location of the planet (SW of the star if the orbital motion is anticlockwise, as depicted in Fig. 5 right, NE if the motion is clockwise); and the high resolution structure of the disk, which is predicted to include a faint clump on the opposite side of the star from the planet (Fig. 5 right).

Implications for Planet Formation around Vega

The different models for the origin of Vega's clumps (Figs. 4 right and 5 right) have very different implications for how Vega's planetary system formed. All predict the presence of a planet orbiting some 40-65 AU from Vega, but the dust migration models predict this planet to be relatively massive at ~ 3 Jupiter masses, and to have an orbital eccentricity up to 0.6. Such a planet has very different characteristics to any currently known and so would provide an important additional constraint to planet formation models which attempt to explain all the observed endstates of planet formation in a consistent manner ([28]). The planet migration model, on the other hand, predicts a relatively low mass planet, about Neptune mass, on a circular orbit, and with an evolutionary history similar to that proposed for our own Neptune [25, 26]. While the origin of the migration of such a planet remains debatable [25, 28], based on this model it is possible that this system formed and evolved in a similar manner to our own.

Of course, the similarity of the proposed planetary system to our own, or lack thereof, should not be a factor in deciding which model is correct. For that the different observational predictions of the two models need to be borne out. First the orbital motion of the structure needs to be confirmed (a prediction of both models). Then predictions about the higher resolution structure of the disk must be tested. Searches for light from the planet itself will also help determine which model is correct. Finally, it should be pointed out that the physical processes affecting debris disk structure are extremely complicated, with the current models focusing only on specific aspects of those processes. Neither model yet gives a complete description of the disk, and further development of both models, and their implications, is sure to proceed as more observations are obtained.

STRUCTURES NOT CAUSED BY PLANETS

Not all structures in debris disk images are caused by planetary perturbations. To avoid over-interpreting debris disk images it is important that all possible causes of observed structure are explored before a planetary interpretation can be confirmed. Here I consider just four possible sources of structure which fall into one of two categories — either those which have already been purported to have been detected in debris disks (structure from binary companions, or a stellar flyby) and those which are known to have the potential to cause structure (planetesimal collisions, and interaction with the interstellar medium):

- Just as planetary companions can affect the structure of the dust disk, so can the presence of a stellar companion. Many systems with dusty disks are known to be binary systems, but in many cases, particularly in wide binary systems, the orbit is not known. Recently modeling has shown that spiral structure observed in the HD141569 disk can be explained by the secular perturbations of its binary companion [31].
- The passing of a star close to the disk is also a method of causing structure. Clumps which have been detected in the β Pictoris disk have been explained as the consequence of perturbations from a star which passed 700 AU from β Pictoris about 0.1 Myr ago [32]. A variety of structures, including clumps and warps, are possible from stellar flybys [33]. However, the probability of a star passing close enough to a debris disk to cause observable perturbations is thought to be very small given the density of stars in the solar neighbourhood.
- The evolution of the Asteroid Belt is punctuated by sudden brightness increases caused by the destruction of single asteroids. Indeed the products of a few such collisions may make up a significant fraction of the dust in the present day zodiacal cloud [29]. The possibility that the clump observed in the Fomalhaut disk was created in a collision between two large planetesimals was considered [1], but it was shown that this is unlikely to be the case: the very fact that we can see the dust clump means it is very massive, and collisions between planetesimals massive enough to produce the clump should be too infrequent for us to be likely to witness such an event.
- Substantial asymmetries can arise if the erosion of a planetesimal disk is affected by the sandblasting of those planetesimals by interstellar dust grains [30]. However, because of the repulsion from the star of such grains by radiation pressure, this erosion is only thought important at large distances from the star (> 400 AU).

CONCLUSIONS

If there are planets in disks then they will affect the structure of those disks in a variety of ways, introducing clumps, warps and offsets. Modeling the observed structures of debris disks can be used to identify the presence of an unseen perturbing planet and set constraints on its location, mass, orbit and even evolutionary history. However, planets are not the only cause of structure in debris disks: binary companions, stellar flybys, planetesimal collisions and sandblasting by interstellar dust grains all play a role to some extent in shaping the disk. In most cases the contribution of these effects to the observed structures can be ruled out leaving the only feasible explanation as the presence of planets. For this planetary interpretation to be accepted, though, the observational predictions of the models, such as the orbital motion of the clumpy structures, and high resolution structure of the disks, must be confirmed.

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