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Dust Clumps in Fomalhaut and Other Debris Disks

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Abstract. Here we present a 450 μm image of Fomalhaut's debris disk taken with SCUBA at the JCMT. The increased resolution over previous 850 μm images permits the detection of a clump embedded in the disk containing 5% of the total flux. Clumps are also a common feature of other debris disks. We discuss the origin of these clumps in the light of a tentative observation that clump mass remains constant with disk age.

1. New 450 μm Observations of Fomalhaut's Disk

While debris disks are known to exist around some 15% of main sequence stars, the true nature of most of these disks has remained elusive; so far only a handful have had their structure resolved. At 7.7 pc, Fomalhaut has one of the closest and brightest debris disks. Previous imaging at 850 μm with SCUBA at the JCMT showed two lobes of emission straddling the star consistent with a $\sim$ 150 AU radius ring of dust that is being seen close to edge-on (Holland et al. 1998). Recently Fomalhaut was re-observed with SCUBA. Some of the highest quality sub-mm weather on Mauna Kea and a system substantially improved in sensitivity meant that it was possible to obtain a map of the disk's 450 μm emission (Holland et al. 2002; Fig. 1a). The greater spatial resolution of the shorter wavelength (7.5 arcsec, equivalent to 50 AU) allowed the detection of small-scale structure in the disk — there is a distinct bend in the emission connecting the lobes, an effect which is also visible in the new (deeper) 850 μm image. Subtraction of a smooth axisymmetric ring model (Fig. 1b) from the 450 μm observation shows that this asymmetry can be explained by a clump embedded in the smooth ring containing $\sim$ 5% of the total flux (Fig. 1c; Holland et al. 2002). At 30 mJy this clump stands out significantly above the noise in the image and it is statistically very unlikely that this is a background source.

2. Possible Origins of Debris Disk Clumpiness

Fomalhaut is not the first star to have had clumps discovered in its disk. In fact all the disks that have had their structure resolved, regardless of the age or spectral type of the stars they formed around, appear to be clumpy or asymmetric at some level. It is thus crucially important to find the origin of this structure, especially as several authors have shown that it could provide evidence for the presence of an unseen planetary system (e.g, Wyatt et al. 1999). The properties of the four systems for which imaging has shown that their debris disks could

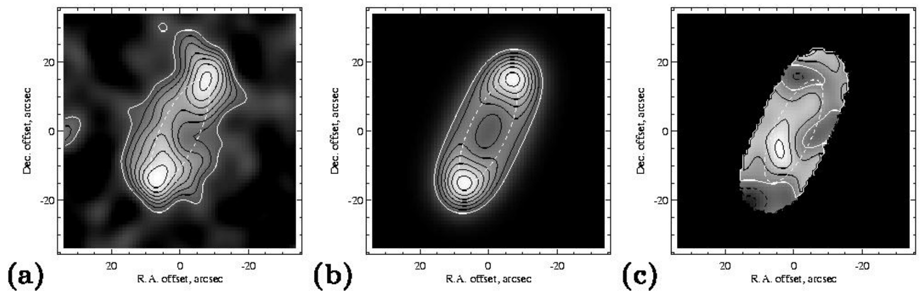

Figure 1. 450 μm images of Fomalhaut (Holland et al. 2002): **(a)** observation, **(b)** smooth axisymmetric ring model, **(c)** residual clump.

be described as *Kuiper belt-like rings* (as opposed to extended disks) are shown in Table 1. While the number of such disks is small, it is noticeable that the properties of the disks around early-type stars[1] seem to follow a pattern — the rings around older stars are both fainter and appear more clumpy, but the mass of dust in their clumps remains roughly constant at a few thousandths of an Earth mass. Since the dust we see in the rings originates in a collisional cascade starting with km-sized planetesimals (Wyatt & Dent 2002), the reduction in disk brightness with age can be understood as evidence of the decay of the population of km-sized planetesimals that feed the cascade. For heuristic purposes we discuss below possible explanations for the uniform clump mass in such disks.

A collisionally produced disk is expected to be intrinsically clumpy, since a clump would be created in a collision between two planetesimals. While such clumps would eventually disperse into the ring, there must be some clump mass at which the frequency of their forming events is high enough that at least one clump of this level would always be present in the ring. Wyatt & Dent (2002) showed that Fomalhaut's clump, if collisional in origin, could only have been

[1] Disks around late-type stars would have evolved differently to those around early-type stars due to the inability of radiation pressure to remove small grains in less luminous systems.

Table 1. Characteristics of *Kuiper belt-like* debris disks. Clumpiness is the fraction of the disk's total flux in its brightest clump. The mass of dust in that clump is derived from its sub-mm flux (Holland et al. 1998), although there could be additional mass in large planetesimals which emit inefficiently in the sub-mm. For HR4796 we assumed that the lobe brightness asymmetry is caused by a clump in the NE lobe.

Star	Sp. Type	Age, Myr	$f = L_{ir}/L_\star$	Clumpiness	Clump Mass
HR4796	A0V	10	5×10^{-3}	0.5%	$10^{-3} M_\oplus$
Fomalhaut	A3V	160	8×10^{-5}	5%	$2 \times 10^{-3} M_\oplus$
Vega	A0V	350	2×10^{-5}	25-50%	$3 \times 10^{-3} M_\oplus$
ϵ Eridani	K2V	730	8×10^{-5}	7%	$0.2 \times 10^{-3} M_\oplus$

produced in a collision between two runaway planetesimals, both larger than 1400 km diameter. Collisions between such runaways would be an attractive solution to the origin of clumps, since runaway growth is a natural consequence of planet formation, and the presence of runaways may be required to gravitationally stir debris disks sufficiently to initiate a collisional cascade (e.g., Kenyon & Bromley 2001). Also, a uniform clump mass could result from the most massive runaways in all systems having similar mass. However, the number of suitably massive runaways that can form *in situ* in Fomalhaut's 50 AU wide ring at 150 AU is limited to ~ 100 (Wyatt & Dent 2002). That number could be as much as ~ 1000 if the runaways that formed closer to the star were scattered out to larger orbital radii where dynamical friction then circularized their orbits. However, even with this additional population, the time between runaway-runaway collisions ($1 - 100$ Myr) would still be at least an order of magnitude more than the duration of the resulting clump (~ 0.1 Myr). Thus to witness one of these clumps, we would have to observe a disk only at special times in its evolution. This clearly cannot be the case for all disks, and this possibility is even more unlikely given that multiple clumps are seen in the Vega and ϵ Eridani disks.

Perhaps a more plausible explanation for these clumps is that some of the planetesimals in these rings are trapped in resonance with a planet orbiting just inside the rings. The geometry of resonant orbits is such that resonant planetesimals, and so the dust resulting from their destruction, would be concentrated at certain locations relative to the planet, thus readily explaining the presence of (multiple) clumps. A resonant population would only be expected if the planetesimals were trapped there either by their inward migration or by the outward migration of the planet. In fact we expect planets to migrate after they form due to the angular momentum exchange caused by clearing of the residual planetesimal disk. Furthermore, simulations show that the migration of the outermost planet of a planetary system is normally outwards (Hahn & Malhotra 1999). A migration/resonance origin for the clumps could also explain the constant clump mass seen in young massive disks: Since the resonant population exerts a torque opposing the planet's migration, this migration would be slowed considerably once the mass of the resonant population is comparable to that of the planet. At this stage migration would continue, but only at a rate which replenishes the mass lost from the resonant population by collisional destruction; migration would finish once the planetesimal disk is sufficiently depleted. Thus the constant clump mass in the systems in Table 1 could indicate that all systems contain similar mass planets that are still migrating due to the clearing of the planetesimal disks in which they formed.

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