The Fomalhaut debris disk: what it tells us about planetesimal collision models

Sarah Maddison
Swinburne Centre for Astrophysics and Supercomputing

Lucca Ricci, Caltech & ESO
Leonardo Testi, ESO & INAF
David Wilner, CfA
Introduction: what are debris disks?

- Old disks (>10 Myr) of dust (little/no gas)
- Several hundred debris disks discovered in IR
  - excess IR emission from thermal dust
  - Vega & β Pic discovered by IRAS in 1984 → “Vega phenomena”

- Rad pressure (+ PR drag) remove dust in few Myrs
  - dust replenished by collisional grinding
  - unseen population of asteroid-sized bodies
Introduction: why study debris disks?

• Important phase in disk evolution

Disk evolution:
“primordial” TTS disks $\rightarrow$ “transitional” disks $\rightarrow$ “secondary” debris disks

(Adapted from Currie 2010)
Introduction: why study debris disks?

- Important phase in disk evolution
- Planets already formed $\rightarrow$ morphology hints at unseen planets

<table>
<thead>
<tr>
<th>Warps</th>
<th>Spirals</th>
<th>Offsets</th>
<th>Brightness asymmetries</th>
<th>Clumpy rings</th>
</tr>
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All of these structures can be explained by dynamical perturbations from unseen planets orbiting the star

(from Wyatt 2006)
Introduction: why study debris disks?

- Important phase in disk evolution
- Planets already formed → morphology hints at unseen planets (and in some cases planets have been found!)

Planet: 8 Mj @ 8 AU

Age ~ 12 Myr


June 2010 (data: Nov 2009) (Lagrange et al. 2010)
Introduction: why study debris disks?

• Important phase in disk evolution

• Planets already formed $\rightarrow$ morphology hints at unseen planets (and in some cases planets have been found!)

• Can also probe unseen planetesimal population
  
  - Thermal dust emission probes grain sizes similar to $\lambda_{\text{obs}}$
    
    - small grains effected by stellar $P_{\text{rad}}$
    
    - pebbles dominated by collisions & gravity

$\Rightarrow \lambda$–mm trace their parent planetesimal population

[Bonus: (sub)mm emission also optically thin so provide mass estimate]
Introduction: collisional models

• Highly destructive planetesimal encounters triggered by:
  – interaction with planet(s) (Mustill & Wyatt 2009)
  – or self-stirring (Wyatt 2008)
  – produce grain size distribution, down to sub-µm grains

• Size distribution tells of planetesimals – differs depending on:
  – dynamical state (velocity distribution, Pan & Schlichting 2011)
  – physical conditions (tensile strength, Durda & Dermott 1997)

➤ Grain size distribution can distinguish b/w collision models
➤ Can use (sub)-mm SED to determine size distribution

More details to follow…
Fomalhaut debris disk

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<tr>
<th>Fomalhaut</th>
<th>Dust belt: (Kalas 2005)</th>
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(Kalas et al. 2005)
Fomalhaut debris disk

Fomalhaut
- Sp. Type: A4
- Mass: 2.0 M$_{\text{sun}}$
- Distance: 7.66 ± 0.04 pc
- Age: ~200 Myr

Dust belt: (Kalas 2005)
- very sharp inner edge 133 AU
- dust belt ~24 AU
- eccentric (e~0.11)
- offset from star ~15 AU
  → suggests planet shaping morphology

Fomalhaut b
- Mass: < 3M$_{\text{jup}}$
- SMA: 115 AU
- ecc: 0.11

(Kalas et al. 2008)

But is it really a planet??
Fomalhaut: sub-mm images

new SCUBA/JCMT 450 & 850 μm
(Holland et al. 2003)

SCUBA/JCMT 850 μm
(Holland et al. 1998)

JCMT = 15-m single dish

- Thermal dust maps: disk emission resolved in sub-mm
- Move to longer $\lambda$, probe colder dust further out in the disk*
- Is the disk symmetric?

*Note: longer $\lambda$ less resolution but more sensitivity
Modelling a hidden planet

Simulated 450 μm with E=0.4, 2 Mj planet, disk i=70° (Deller & Maddison 2005)

450 μm SCUBA (Holland et al. 2003)
350 µm image shows very symmetric emission – first clearly “ring-like” morphology

Resolution enhanced with Maximum Correlation Method deconvolution (Aumann et al. 1990)

SHARC II/CSO 350 µm
Marsh et al. (2005)

CSO = 10.4-m single dish
Fomalhaut is one of the closest and brightest debris disks

Use ATCA to:

(1) image Fomalhaut at 7mm, longest wavelength ever
   → probe location of the unseen planetesimals

(2) determine mm spectral index & dust opacity index
   → determine grain size distribution
   → distinguish between collisional models
ATCA observations

- ATCA + CABB digital filter bank (Wilson et al. 2011)
- 15-17 Sept 2011 7mm-band observations
- double side-band continuum (BW=4 GHz):
  $\nu_1 = 42$ GHz, $\nu_2 = 44$ GHz $\rightarrow$ mean $\lambda = 6.66$ mm
- compact H75 array configuration (baselines: 31-89 m)
- $T_{\text{int}} \sim 12$ hours (over 3 days)
- Angular resolution $\sim 14''$ (synthesised beam FWHM)
- FoV $\sim 65''$ (primary beam FWHM)
- RMS noise $\sigma \sim 23 \mu$Jy/beam

$\approx 850 \mu$m single-dish

~15% ATCA abs flux uncertainty @ 7mm
Results: 7mm image

ATCA 7 mm image
-- similar to 850 µm image (morphology, PA and peak surface brightness)
-- contours at (-2, 2, 4, 6) × σ, σ ≈ 23 µJy RMS

★ Fomalhaut star
★ Disk center
(~2” or 15 AU offset, agrees with HST offset)

(Ricci et al. 2012)
Results: grain size distribution

- Slope of SED $\alpha$ ($F_\nu \propto \nu^\alpha$) related to dust opacity index $\beta$ ($\kappa_\nu \propto \nu^\beta$)

  -- thermal dust in debris disks optically thin:

  $$F_\nu \propto \frac{B_\nu (T_{dust}) \kappa_\nu M_{dust}}{d^2}$$

  where:

  $$\kappa_\nu \propto \nu^\beta$$

  $$B_\nu (T_{dust}) \propto \nu^{\alpha_P}$$

  $\alpha_P$ depends on $T_{dust}$

  $\alpha_P = 2$ in Rayleigh-Jeans limit

- $\beta$ related to slope of grain size distribution $q$ [ $dn(a) \propto a^{-q} da$ ]

  $\beta \approx (q-3) \beta_s$ (Drain 2006) $\beta_s$: dust opacity index in small particle limit

- Combine (1) and (2):

  $$q = \frac{\alpha - \alpha_P}{\beta_s} + 3$$

  $\beta_s = 1.8 \pm 0.2$

  $\alpha_P = 1.84 \pm 0.02$

  assumes grain comp. similar to ISM

  Mie theory to model dust emission (IR + sub-mm)

- measure $\alpha$ and determine $q$
Results: SED

\[ F_\nu \propto \nu^{2.70\pm0.17} \]

- 350 µm Marsh et al. (2005)
- 450+850 µm Holland et al. (2003)
- 1.3 mm Chini et al. (1991)

(Ricci et al. 2012)
Results: grain collision models

- Using SED: \( q = 3.48 \pm 0.14 \)
- Different collision models predict different grain size distribution
  - Steady-state collisional cascade give \( q = 3.51 \) (Dohnanyi 1969)
  - Theoretical collisional cascades: **single constant tensile strength & single velocity disp.**, regardless of size
  - Recent num. models investigating what parameters most affect \( q \) → slope of **tensile strength** (Gaspar et al. 2011)
  - If strength curve varies with size \( a^{-1} \) or steeper, Gaspar et al. suggest \( q \geq 3.82 \) for Fomalhaut’s age

→ Our obs rule out steep tensile strength curves > 95% confidence
  - Extension to classical coll. cascade allowing a **size-depend. velocity distrib.** found \( v(a) \propto a^{0.5} \) and very steep \( q = 4 \) (Pan & Schlichting 2011)

→ Our obs rule out such a high \( q \) to > 99% confidence
Conclusions

- Longest wavelength image of Fomalhaut debris disk - clearly resolved and well matches sub-mm images
- Investigate spectral index and constrain power-law grain size distribution: $q = 3.48 \pm 0.14$ for grains $\sim 1\text{mm}$
  - consistent with classical predictions of steady-state collision cascade
  - inconsistent with collision models with vel. distribution or tensile strength a strong function of body size
Fomalhaut seen by ALMA

“This leads us to favor shepherd planets as the explanation for the ring’s morphology.”

Composite HST optical (blue) & ALMA @ 850 µm (orange)

(Boley et al. 2012)
“The belt around Fomalhaut is a prototypical example of a steady-state collisional cascade. The dust particles are fluffy aggregates…the planetesimals at the top of the collisional cascade are in fact comets.”

Herschel PACS @ 70 μm

(Acke et al. 2012)
Planet or not planet??

- Fomalhaut b discovered with HST optical (600 + 800 nm), but IR non-detections (Gemini 3.8 µm + Keck H-band) (Kalas et al. 2008) → expect opposite
- 2006 HST brightness nearly half that of 2004
- Non-detection with Spitzer/IRAC 4.5 µm in 2010-11 (Janson et al. 2011) → Thus:
  -- not a planet, or
  -- much less massive and older planet (hence no IR)

Pre-Spitzer: \( M \sim 2-3 \, M_{\text{jup}}, \quad \tau \sim 200 \, \text{Mys} \)
Post-Spitzer: \( M < M_{\text{jup}}, \quad \tau \sim 400 \, \text{Myrs} \)

[Mamajek (2010) suggests \( \tau \sim 360\pm50 \, \text{Myrs} \)]

Also see Bhattacharjee (2012)