Theoretical modelling of debris disk structure

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Outline

(I) Radial structure
   • Flux vs radius and wavelength
   Most can be explained by dust produced in steady-state collisional evolution of planetesimal belts...

(II) Non-axisymmetric structure
   • Clumps and asymmetries
   Most can be explained by perturbations to that evolution...

(III) ...
    ... but there are EXCEPTIONS
(1) Radial structure

The axisymmetric structure of debris disks can be explained as the consequence of a belt of planetesimals orbiting the star.

- No need to know origin of planetesimals or why they are confined to a ring.
- But understanding interplay between collisions and radiation forces is essential.
Collisions

Existence of dust implies collisions are destructive and so the planetesimal belt has been stirred:
\[ e, l > 10^{-3} - 10^{-2} \] (e.g., talk by Kenyon)

Collisions result in collisional cascade with a size distribution:
\[ \sigma(D) \propto D^{-1.5} \]

Collisional lifetime \( t_{\text{col}} \propto D^{0.5} \)
Radiation forces

Small grains interact with stellar radiation resulting in a force characterised by:

\[ \beta = \frac{F_{\text{rad}}}{F_{\text{grav}}} \approx \frac{0.4}{D} \left( \frac{L_*}{M_*} \right) \]

1. **Radiation pressure**

   - \( \beta > 0.5 \) blown out on hyperbolic orbits
   - \( 0.1 < \beta < 0.5 \) put on eccentric orbits

2. **Poynting-Robertson drag**

   All dust grains spirals toward star on timescale
   \[ t_{\text{pr}} = \frac{400}{M_*} r^2 / \beta \text{ years} \]
P-R drag is insignificant...

Distribution of dust due to loss in collisions and migration by P-R drag depends on \( \eta_0 = \frac{t_{pr}}{t_{col}} \propto D^{0.5} \)

If \( \eta_0 \gg 1 \) for the smallest particles (\( \beta=0.5 \)) then all dust remains confined to the planetesimal belt

Wyatt (2005)
but stellar wind drag may be significant for M stars

Stellar wind forces also result in a pressure and drag component, and these can be characterised by $\beta_{sw}$.

In the solar system $\beta_{sw}/\beta_{rad} = 1/3$, but in M stars $\beta_{sw}/\beta_{rad} \gg 1$ as low luminosity and high mass loss rate (Plavchan et al. 2005, Strubbe & Chiang 2006, Augereau & Beust 2006).
Disk particle categories

Particles of different sizes have different dynamics:

- $\beta \ll \beta_{pr}$, large, confined to belt
- $\beta \approx \beta_{pr}$, P-R drag affected, little depleted by collisions on way in
- $0.1 < \beta < 0.5$, $\beta$ critical, bound, but extended distribution
- $\beta > 0.5$, $\beta$ meteoroid, blown out on hyperbolic orbits

Not all types of particles exist in every disk.
Collision dominated disk: simple model

Simple treatment of expected size distribution often suffices and is MUCH better than assuming single grain size

The emission spectrum of Fomalhaut, for which radius is well known, implies collisional cascade size distribution (Wyatt & Dent 2002)
Collisional evolution models: wavy size distribution

Collisional evolution for realistic cascades is followed numerically showing details

Lack of $\beta > 0.5$ dust causes a wave (Thebault, Augereau & Beust 2003)

Abundance of $\beta > 0.5$ dust eroded the smallest bound grains (Krivov, Mann & Krivova 2000)

Size dependence of planetesimal strength causes wave at 150m (Bottke et al. 2005)
Details can be important

Short wavelengths probe smallest grains and so are dominated by the details.

By including details, extended structure of AU Mic explained by dust created in a narrow belt at \(~40\text{AU}\) (Augereau & Beust 2006; Strubbe & Chiang 2006)

Understand this model before considering non-axisymmetric structure

Extended dust distribution does not mean planetesimals are extended
(11) Non-axisymmetric structure

Different types of structures observed in debris disk images (talk by Greaves):

<table>
<thead>
<tr>
<th>Structures</th>
<th>Images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warps</td>
<td><img src="image1.png" alt="Images" /> <img src="image2.png" alt="Images" /> <img src="image3.png" alt="Images" /></td>
</tr>
<tr>
<td>Spirals</td>
<td><img src="image4.png" alt="Images" /> <img src="image5.png" alt="Images" /> <img src="image6.png" alt="Images" /></td>
</tr>
<tr>
<td>Offsets</td>
<td><img src="image7.png" alt="Images" /> <img src="image8.png" alt="Images" /> <img src="image9.png" alt="Images" /></td>
</tr>
<tr>
<td>Brightness asymmetries</td>
<td><img src="image10.png" alt="Images" /> <img src="image11.png" alt="Images" /> <img src="image12.png" alt="Images" /></td>
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<tr>
<td>Clumpy rings</td>
<td><img src="image13.png" alt="Images" /> <img src="image14.png" alt="Images" /> <img src="image15.png" alt="Images" /></td>
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</tbody>
</table>

All of these structures can be explained by dynamical perturbations from unseen planets orbiting the star.
Planetary perturbations

Planetary system dynamics predicts exactly this set of features

Two types of perturbations:

(1) Secular perturbations
  • eccentric planet
  • young disk = spiral
  • old disk = offset = brightness asymmetry
  • inclined planet
  • young disk = warp
  • multiple planets in old disk = warp

(2) Resonant perturbations
  • multiple planets = cleared region
  • individual planet = clumps
Impact of sudden introduction of planet on eccentric orbit is to impose an eccentricity on nearby planetesimals.

Precession rates are slower for planetesimals further from planet which means dynamical structure evolves with time:

\[ t_{sec(3:2)} = 0.651 \frac{t_{pl}}{M_{pl}/M_{star}} \]

Wyatt (2005)
$0.001 t_{sec}(3:2)$
Spiral Structure in the HD141569 Disk

• HD141569A is a 5 Myr-old B9.5V star at 99 pc

• Dense rings at 200 and 325 AU with tightly wound spiral structure (Clampin et al. 2003)

• Spiral at 325AU explained by $0.2 M_{\text{Jupiter}}$ at 250AU with $e=0.05$ (Wyatt 2005)
Perturbations at late times in narrow ring

After many precession periods, orbital elements distributed around circle centred on forced eccentricity

This translates into material in a uniform torus with centre of symmetry offset from star by $a_{e_f}$ in direction of forced apocentre

Wyatt et al. (1999)
Applications of pericentre glow

First predicted in dust ring of HR4796 (A0V, 10Myr) from 5% brightness asymmetry, implying a forced eccentricity of 0.02 (Wyatt et al. 1999)

First detected in Fomalhaut, a 133AU ring offset by 15AU implying a forced eccentricity of 0.11 (Kalas et al. 2005) (Talk by Kalas)
Further constraints on planets

Quillen (2006) model the Fomalhaut ring and conclude:

• Planet is at $a_{pl} = 119$ AU with $e_{pl} = 0.1$

• Inner edge from resonance overlap
  $da/a_{pl} = 1.3(M_{pl}/M_*)^{2/7}$

• Eccentricity dispersion at the inner edge affects its slope

• Observed sharpness of inner edge implies eccentricity dispersion <0.013 and so $M_{pl} < M_{\text{saturn}}$
Secular perturbations: warps

Secular perturbations of a planet also affect the inclinations (i.e., orbital plane) of nearby planetesimals.

Introducing a planet into the disk on an orbit inclined to the disk midplane causes a warp to propagate away from the planet.

Augereau et al. (2001)

This causes disk near planet to become aligned with the planet, but that far away keeping the initial symmetry plane.
Warp in $\beta$ Pic

The warp in $\beta$ Pic can be explained in this way by a $1-2M_{\text{Jupiter}}$ planet at 10AU inclined by $3^0$ to the disk mid-plane which causes a warp at 70AU at 20Myr.

Model explains all observations by dust produced by planetesimals, including effects of radiation pressure.

Warp can be present in old systems too if there are two planets on different orbital planes (Wyatt et al. 1999)
Geometry of resonance

- Resonances are special because of the periodic nature of the orbits and the way that planet and planetesimal have encounters

3:2 Resonance
A comet in 3:2 resonance orbits the star twice for every three times that the planet orbits the star

- Planet
- Comet in 3:2 resonance

Inertial frame
Rotating frame
Capture by migrating planet

Planetesimals can become captured into the resonances of a migrating planet.

Resonances which can be populated depend on planet mass and migration rate.

![Diagram showing the capture process and resonances](image)
The outward migration of a Neptune mass planet (○) around Vega sweeps many comets (*) into the planet’s resonances.

**Diagram:**
- **Eccentricity** vs. **Semimajor axis, AU**
- **Time:** 0.0 Myr
- Resonances marked: 2:1, 5:3, 3:2, 4:3
- Other points: Sun (○) and migrating planet (○)

**Legend:**
- Sun: Yellow
- Migrating planet: Blue
- Comets: Black dots
The trapping of comets in Vega’s disk into planetary resonances causes them to be most densely concentrated in a few clumps.

Time: 0.0 Myr
Constraints on Vega’s planetary system

- This model can explain the clumpy structure of Vega (350 Myr, A0V at 7.8 pc) seen in sub-mm (Holland et al. 1998) and mm (Wilner et al. 2002; Koerner et al. 2002)

- Infers $1M_{\text{Neptune}}$ which migrated 40-65 AU over 56 Myr (although $1M_{\text{Jupiter}}$ over 3 Myr also possible, see poster by Martin)

- See also poster by Reche for migration of eccentric planet

Predictions:
- orbital motion of structure (Poulton et al. 2006)
- multiwavelength structure
Particle populations in a resonant disk

Radiation pressure causes dust created from resonant planetesimals to fall out of resonance; smallest grains are removed on hyperbolic orbits.

<table>
<thead>
<tr>
<th>Grain Size</th>
<th>Population</th>
<th>Spatial distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>I</td>
<td>Same clumpy distribution as planetesimals</td>
</tr>
<tr>
<td>Medium</td>
<td>II</td>
<td>Axisymmetric distribution</td>
</tr>
<tr>
<td>Small</td>
<td>III</td>
<td>$\tau \propto r^{-1}$ distribution</td>
</tr>
<tr>
<td>IIIa</td>
<td></td>
<td>Spiral structure emanating from resonant clumps</td>
</tr>
<tr>
<td>IIIb</td>
<td></td>
<td>Axisymmetric distribution</td>
</tr>
</tbody>
</table>

Wyatt (2006)
Multiwavelength imaging predictions

Observations in different wavebands sample different grain sizes and so should show different structures.
... and comparison with observations

Mid- to far-IR images should exhibit spiral structure emanating from clumps

Not detected at present, but resolution of published Spitzer observations may not have had sufficient resolution to detect this (Su et al. 2005)

Meanwhile 350\(\mu m\) imaging shows evidence for 3 clump structure (Marsh et al. 2006)

Possible evidence for a different size distribution of material in 4:3 resonance?
Dust migration into planetary resonances

Resonances can also be filled by inward migration of dust by P-R drag, since resonant forces can halt the migration.

For example dust created in the asteroid belt passes the Earth’s resonances and much of it is trapped temporarily (~10,000yrs).
Structures of resonant rings

The structure expected when dust migrates into planetary resonances depends on the planet’s mass and eccentricity (Kuchner & Holman 2003)

However...
- P-R drag is not important in detectable debris disks

Will be important when disks in which P-R drag is important can be detected (e.g., JWST, ALMA, TPF/Darwin)
(III) Exceptions: Vega!

Our “archetype” is exceptional!

Why? because of the large dust mass being blow-out by radiation pressure

Pop. III grains removed at $2M_\odot$/Myr

What is the origin of the observed high mass loss rate?
Origin of large mass loss in Vega

(1) Initially a very massive disk
• $2M_{\text{earth}}/\text{Myr}$ for $350\text{Myr} \rightarrow M_{\text{disk}}/M_* = 0.1$
• Collisional processing in pop I is $\sim 2M_{\text{earth}}/\text{Myr}$
  BUT... why so many small grains produced in collisions?

(2) Mass is not being lost
• These are bound grains, e.g., on highly eccentric orbits,
  BUT... must reproduce $\tau_{24,70} \propto 1/r$ and temperature of $2-18\mu m$ grains
  Perhaps low $T_{\text{equator}}$ of star important (Aufdenberg et al. 2006)?

(3) Mass loss is recent/transient
• Recent collision, or recent ignition of collisional cascade
  BUT... why so many small grains produced in collisions?
Rieke et al. (2005) suggested that debris around A stars is transient. Model population of 10,000 debris disks with:

- Initial masses inferred from protoplanetary disk mass distribution
- Initial radii inferred from 70μm/24μm flux distribution
- Subsequent collisional evolution...

Statistics can be explained by steady-state evolution in collisions.
Detailed comparison of disk stats

- More quantitative proof that the statistics can be explained by steady-state evolution in collisions:

- Testable by predictions at 70\(\mu\)m – comparison with poster by Su

Vega is exceptional in A star population in showing evidence for transience

Wyatt et al. (in prep)

Fraction of disks in different age bins with \(F_{24}/F_*\) in range

![Graph showing fraction of disks in different age bins over time, with 'No disk', 'Intermediate disk', and 'Massive disk' categories.](image)

Wyatt et al. (in prep)
**(III) Exceptions: Hot dust around FGK stars**

2% of sun-like stars have 25μm excess indicative of dust <10AU (Bryden et al. 2006; Hines et al. 2006; Laureijs et al. 2002; Gaidos 1999)

This dust cannot be produced in a planetesimal belt coincident with the dust, rather it must be **transient** (Wyatt et al., submitted)

**Why?**

There is a maximum luminosity (and mass) that a belt can have: 
\[ f_{\text{max}} = 0.16 \times 10^{-3} \frac{r^{7/3}}{t_{\text{age}}} \]

HD69830, η Corvi, HD72905, BD+20307, and HD128400 have \( f \) > 1000\( f_{\text{max}} \)
Origin of transient event?

(1) Recent collision in massive asteroid belt
   • Too few big enough objects remain
   • Chance of witnessing collision <1:10^5

(2) In situ planetesimal belt
   • Mass loss rate too high
   • Mass remaining at ~1AU at this age implies duration << 1Myr
   • 2% detection fraction implies 100Myr duration

(3) Scattered in from outer planetesimal belt
   • e.g., in event akin to Late Heavy Bombardment

Gomes et al. (2005)
Constraints in $\eta$ Corvi

An outer planetesimal belt is known to exist around $\eta$ Corvi and could be feeding the hot dust closer in.
Constraints in HD69830

Far-IR upper limit does not rule out the existence of an outer planetesimal belt

Planetary system at <0.8AU provides potential for dynamical instability (Lovis et al. 2006)

The presence of hot dust around Vega (Absil et al. 2006; talk by Absil) could indicate the system is undergoing a similar transient phase of evolution?
Conclusions

Most of the radial structure of debris disks explained by steady-state evolution of a planetesimal belt due to collisions and radiation forces

Must be taken into account when interpreting observations

Non-axisymmetric structures explained as perturbations to this model, particularly due to planets

Rare exceptions may be systems undergoing periods analogous to Late Heavy Bombardment

Bottom Line: Modelling of debris disks can tell us about the origin and evolution of planetary systems