Collisional and dynamical evolution of debris disks

I. Debris disk theory primer
II. Theories to explain evolution statistics
III. Theories to explain anomalous systems
IV. Theories to explain asymmetries

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Debris disk primer

Simplest debris disk model has planetesimals orbiting the star confined to a belt (no assumptions about their origin of why they are confined to a ring)

What we see from this belt is the result of the interplay between collisions and radiation forces
Collisions and Radiation Pressure

Collisions grind planetesimals into smaller and smaller fragments resulting in a collisional cascade with a size distribution:

\[ n(D) \propto D^{-3.5} \]

Radiation pressure truncates the collisional cascade at small particles:

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

- \( \beta > 0.5 \) blown out on hyperbolic orbits
- \( 0.1 < \beta < 0.5 \) put on eccentric orbits
**P-R drag dominated disks**

Dust spirals toward star resulting in distribution dependent on
\[ \eta_0 = \frac{t_{\text{pr}}}{t_{\text{col}}} = 10^4 \tau_{\text{eff}} \left( \frac{r}{M_*} \right)^{0.5} \]

Debris disks detected by IRAS have \( \eta_0 > 10 \) and those by Spitzer \( \eta_0 > 1 \) so P-R drag usually negligible (Wyatt 2005)

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**KQ1: How does P-R (or SW) drag influence disk structure?**
Different-sized particles have different dynamics, explaining axisymmetric structures.

- Solar System
  P-R drag dominated

- Extrasolar debris
  Collision dominated

KQ2: What is planetesimal distribution in imaged disks?

Simple steady state collisional evolution model

Simple debris disk theory predicts steady state size distribution evolution
\[ \frac{dM_{\text{disk}}}{dt} = -M_{\text{disk}}/t_{\text{col}} \]
\[ M_{\text{disk}} = M_0 \left[1 + t/t_{\text{col}} \right]^{-1} \]

Disk mass and fractional luminosity fall off once largest objects collide on a timescale which depends on initial mass and radius (Wyatt et al. 2007a)
Steady-state population model

24&70μm stats explained with population models (Wyatt et al. 2007b; Löhne et al. 2008):

• All stars have one planetesimal belt that evolves in steady state from t=0

• Distributions of: initial mass=that of proto-planetary disks; radii= \( n(r) \propto r^{-0.8} \)

KQ3: Is evolution dominated by steady state collisions, or does it just look like it?

KQ4: What sets the radius distribution?
Numerical models of size distribution evolution

Wiggle from small-size cut-off (Thebault & Augereau 2001)

Change in slope from strength-gravity scaling (O’Brien & Greenberg 2005)

Wiggle from that change in slope (Durda et al. 1998)

Turn-over at late times when P-R drag becomes important (Booth & Wyatt in prep.)

Slower evolution of mass compared with area (Löhne et al. 2008)
The birth of A star debris disks

After protoplanetary disk dispersal in <5 Myr (Kennedy & Kenyon 2009), the 24 μm excess of A stars peaks at 10-15 Myr (Hernandez et al. 2007; Currie et al. 2008)

This is typically interpreted as self-stirring (Kenyon & Bromley 2008)
Self-stirring models

Self-stirred disks brighten after growth of Plutos within the disk, which takes longer at larger radii (Kenyon & Bromley 2008)

Resulting brightness evolution fitted empirically using steady-state evolution after delay (Kennedy & Wyatt)

\[ t_{\text{stir}} = 400r^3 \eta^{-0.5} M_*^{-1.5} \]
Revised KQ4: What sets distributions of inner and outer radii and are these correlated?

Fit improved and trends reproduced if belts are self-stirred

But not possible to fit if stars have extended disks (mostly from 70μm stats)
Secular perturbations of eccentric planet

The secular perturbations of a planet on an eccentric orbit make the eccentricity vectors of planetesimals precess around a forced eccentricity with a rate that is slower for planetesimals further from planet.
Secular-stirring in the $\varepsilon$ Eridani disk

The secular perturbations of a planet in the shaded region would stir the disk at 60AU on timescales shorter than the 850Myr system age, and the known planet at 3.4AU would do this in 40Myr (Mustill & Wyatt 2009)

KQ5: What stirs debris disks?

KQ6: Are debris disks fed by km-sized or Pluto-sized planetesimals?
Predictions for surface brightness profiles

Different models make different predictions for surface brightness profiles.

Self-stirring can’t fit optical depth in β Pic disk (Telesco et al. 2005), but stirring by planet at 10AU can if planetesimals are smaller than 5km (Kennedy & Wyatt, in prep)
Surface brightness profiles with low stirring

A low eccentricity planetesimal belt causes a sharper outer edge, as seen in HR4796 (Thebault & Wu 2008)

Collisions and radiation pressure cause smallest dust to be vertically extended at H/R~0.04 even if planetesimals aren’t (Thebault 2009)

KQ7: Could the level of stirring in debris disks be very low?
Transience of hot dust

Simple steady state evolution models predict a maximum luminosity (and mass) that a belt of given radius and age can have (Wyatt et al. 2007a)

\[ f_{\text{max}} = 1.6 \times 10^{-4} r^{7/3} t_{\text{age}}^{-1} \]

The hot dust (1AU) of 2Gyr systems like HD69830 and η Corvi have a luminosity >1000f_{\text{max}} and so cannot be produced in a steady state asteroid belt

KQ8: What is the origin of the “transient” hot dust at <3AU?
Ongoing terrestrial planet formation origin

Terrestrial planet formation models predict mid-IR emission observable (Kenyon & Bromley 2004), but understanding of Earth-Mars collisions, debris lifetime, quiescent level, population models incomplete

HD172555 spectrum best fit with silica suggesting massive collision (Lisse et al. 2009)

KQ9: What’s probability of seeing collision during planet formation?
Alternative explanation for origin of hot dust is an LHB-like instability.

At ~800Myr the inner solar system underwent a period of heavy bombardment which has been explained as result of dynamical instability when Jupiter and Saturn crossed 2:1 resonance (Gomes et al. 2005).
Solar System debris detectability

The Nice model predicts that the Solar System would have been detectable before the LHB at both 24 and 70um, but not afterward (Booth et al. 2009)

LHBs like ours are rare (<12% of stars) and if optimistic we might expect just 1/413 of the Sun-like stars surveyed at 24um to be going through one

KQ10: How best to couple collisional and dynamical evolution?
Characteristics of a mid-LHB system

A mid-LHB system has dust at a range of distances and so emission at a range of temperatures (Booth et al. 2009)

Imaging breaks degeneracy of SED interpretation in η Corvi which may be undergoing an LHB

KQ11: How does cometary sublimation affect debris disks?
Is a long-lived eccentric disk the solution?

Consider the steady-state evolution of a planetesimal belt with pericentre fixed at 1 AU, but increasing eccentricity:

Collisional timescale increases, so mass remaining at late times also increases (Wyatt et al. submitted)

Most collisions occur at pericentre, and the wind of particles blown out by radiation pressure from pericentre can be detectable
A plausible model for $\eta$ Corvi?

The emission spectrum and all imaging constraints (Wyatt et al. 2005; Smith et al. 2008; Smith et al. 2009) can all be explained with a planetesimal belt with a pericentre at 0.75AU and an apocentre at 150AU and current mass $5M_{\text{earth}}$:

Tests:

- deep mid-IR imaging to detect extended wind
- lack of planets >0.75AU (Lagrange et al. 2009)

BUT, how could such an eccentric planetesimal belt form?
Formation of eccentric planetesimal disk

N-body simulations of planetesimals remaining after HD69830 planets migrated in from 3, 6.5 and 8 AU (Alibert et al. 2006) ends with significant eccentric planetesimal population (Payne et al. 2009)

KQ12: Are extreme populations dynamically plausible?
Extrasolar debris disks are asymmetric

- **Warps**
- **Spirals**
- **Offsets**
- **Brightness asymmetries**
- **Clumpy rings**

This set of structures is that expected to arise from dynamical perturbations from unseen planets orbiting the star.
Perturbed debris disk theory

Consider the planetesimal belt + one planet

Simple planetary system dynamics predicts non-axisymmetric structures

1. Secular perturbations of eccentric planet

young disk = spiral
old disk = offset+
brightness asymmetry

2. Secular perturbations of inclined planet

young disk or multiple planets in old disk = warp

3. Resonant perturbations

near planet = cleared
far from planet = clumps
Resonant trapping by planet migration

Outward migration can trap planetesimals into the planet’s resonances.

The resonant structure depends on planet mass and migration rate (Wyatt 2003) and eccentricity (Reche et al. 2008).

The outward migration of a Neptune mass planet (○) around Vega sweeps many comets (*) into the planet’s resonances.
The geometry of resonant orbits makes the disk clumpy. Resulting clumpy structure depends on planet mass, migration rate and eccentricity, and so these parameters can be constrained from observations of a clumpy disk.

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
Asymmetries also size-dependent

The structure of a disk perturbed by a planet depends on particle size; e.g., radiation pressure causes small particles fall out of resonance losing clumpy structure of larger grains (Wyatt 2006)

Observations at different wavelengths are sensitive to different grain sizes and so may see different structures

KQ13: What is origin of Vega’s high level of blow-out grains?
Debris disks as planet detection tool

Comparison of planets inferred from debris disks with those found from other methods

Direct confirmation of planets predicted from debris disk imaging

KQ14: How accurate are debris disk planet predictions?
History of Fomalhaut-b prediction

Brightness asymmetry in HR4796 disk (Telesco et al. 2000) ...

... explained if disk is offset due to perturbations of eccentric planet (Wyatt et al. 1999)

13AU offset observed to Fomalhaut implying $e_f = 0.1$ (Kalas et al. 2005) ...

... and constraints on planet mass and orbit from shape of inner edge caused by resonance overlap (Quillen 2006)
Disk modelling constrains planet mass

Planet discovered by direct imaging (Kalas et al. 2008) broadly speaking in the predicted orbit

Modelling of shape of radial profile shows $M_{pl} < 3M_{Jup}$ (Chiang et al. 2009)

Outstanding questions: mass and orbit, circumplanetary disk, origin of planet

KQ15: Should debris disk theorists be planet formation modellers?
Key questions

(1) How does P-R (or SW) drag influence disk structure?
(2) What is planetesimal distribution in imaged disks?
(3) Is evolution dominated by steady state collisions, or just look like it?
(4) What sets distributions of inner and outer radii and are these correlated?
(5) What stirs debris disks?
(6) Are debris disks fed by km-sized or Pluto-sized planetesimals?
(7) Could the level of stirring in debris disks be very low?
(8) What is the origin of the "transient" hot dust at <3AU?
(9) What's probability of seeing collision during planet formation?
(10) How best to couple collisional and dynamical evolution?
(11) How does cometary sublimation affect debris disks?
(12) Are extreme populations dynamically plausible?
(13) What is origin of Vega’s high level of blow-out grains?
(14) How accurate are debris disk planet predictions?
(15) Should debris disk theorists be planet formation modellers?