Diagnosing Circumstellar Debris Disks

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the edge-on debris disk orbiting β Pictoris, from Heap et al (2000)
The debris disk phenomenon (eg, Strubbe & Chiang 2006)

- unseen planetesimals in narrow ring or broad disk collide & generate dust
- radiation pressure or stellar wind lofts small micron-size dust out to \( r \sim \text{hundreds AU} \)
- collisions among dust grains depletes disk

My interest here: 
Are debris disks indicators of ongoing planet-formation? 
Or are they regions of planetesimal destruction?

- planetesimals are seeds of planets, which suggests planet-formation
- but debris disks are resupplied by collisional erosion of planetesimals, which can inhibit planet formation
- could be argued either way...
The model:

- the planetesimal disk is composed of rings that produce dust at various sites in the disk
- dust production rate is a power-law in grain size, \( P(R) \propto R^{-q} \)

Dust orbits are simple functions of grain size parameter \( \beta \):

\[
a(\beta) = \frac{1 - \beta}{1 - 2\beta} r_p \quad \text{and} \quad e(\beta) = \frac{\beta}{1 - \beta}
\]

where \( \beta = \frac{\text{rad. prs. gravity}}{\text{gravity}} \sim \frac{1}{R_{\text{microns}}}. \)

Dust abundance \( N_i(t) = \text{number of grains of size } R_i \text{ in orbit } a_i, e_i, \tilde{\omega}_i \text{ at time } t \) obeys rate equation \( \frac{dN_i}{dt} = \text{dust production rate - collisional destruction rate}, \)

\[
\frac{dN_i}{dt} = P_i - \sum_j \alpha_{ij} N_i N_j
\]

where collision probability rate \( \alpha_{ij} = \text{function(dust sizes, orbits, and strength } Q^*) \)

detailed are in Hahn (2010).
that coupled system of rate equations is solved numerically for abundances $N_i(t)$, providing dust collisional lifetimes $T_c(R)$, and dust optical depth $\tau(r)$ produced by narrow planetesimal ring or broad disk, and disk surface brightness $B(r)$.
Diagnosing the $\beta$ Pictoris debris disk:
fitting model disk to optical HST observations (Golimowski et al 2006) requires:

- broad planetesimal disk, $75 \lesssim r_p \lesssim 150$ AU, comparable to what Wilner et al (2010) infer from mm observations

- heavy dust production, $\dot{M}_d \sim 10 \mathrm{M}_\oplus$/Myr

- dust grains are probably icy & reflective
  I assumed $Q_s = 0.7$ (Saturn’s icy rings), however darker $Q_s = 0.1$ dust
  would require $\dot{M}_d \uparrow \times 50$, because $B \propto Q_s \sqrt{\dot{M}_d}$

- a good fit also requires:
  $q = 2.5$ (shallower than Dohnanyi)
  strong dust, $Q^* \sim 10^8$ ergs/gm,
  asymmetric light scatters, $|g| \simeq 0.7$. 

red & blue curves are disk’s optical surface brightness, black curve is best fitting model
Conclusions, assuming albedo $Q_s = 0.7$:

- dust mass is $M_{\text{dust}} \sim 10$ lunar masses, similar to Holland et al (1998) from sub-mm observations, total dust cross section is $A_{\text{dust}} \sim 2 \times 10^{20}$ km$^2$

- $\beta$ Pic’s age $t_\star \sim 10$ Mys implies a total planetesimal mass $\dot{M}_d t_\star \sim 100$ M$\oplus$ was lost due to collisional erosion, equivalent to 6 Neptunes! $\beta$ Pic’s planetesimal disk is (or was) very massive

- heavy planetesimal erosion in $r > 75$ AU zone may preclude any planet formation there

- however the recent recovery of $\beta$ Pic b at $r \sim 10$ AU (Lagrange et al 2010) shows that the innermost part of this disk did successfully produce a planet
Lastly...

- model details and results are in Hahn (2010), reprint available

- debris-disk model is available online, written in IDL, google ‘SSI’ to find my homepage