Measuring medium sized bodies in debris disks

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Abstract

We model debris disk evolution and compare to observed systems to probe the primordial size distribution of medium-sized planetesimals. Using a simple model with reasonable assumptions and the available relevant dataset, we find that medium-sized bodies (~100 m - ~100 km) appear to fit a differential power law distribution with a slope between -3.5 and -4.0

Introduction

Planets are formed by the conglomeration of small bodies, planetesimals, in young circumstellar disks while the planetesimals' velocity dispersion remains low. The number-size distribution of the planetesimals not incorporated into planets may reveal their dynamic state when conglomeration ends and collisional grind-down begins (e. g. Kenyon & Bromley 2004 (AJ, 128, 1916), Kenyon & Bromley 2008 (2008arXiv0807.1134), Morishima et al. 2008 (ApJ 685, 1247))

Observations of extra-solar systems only see small grains, so modeling the evolution is needed to get information on the larger bodies (e. g. Wyatt et al. 2007 (ApJ 633, 365))

In the Kuiper belt, the largest bodies (~100 - 1000 km) follow a number-size distribution fit by a differential power law with a slope of -4 to -5 (e. g. Fraser et al. 2008 (arXiv:0810.2296), Fuentes & Holman 2008 (AJ, 136, 83)).

Sample

We use the Hillenbrand et al. 2008 (ApJ 677, 630) observational sample of debris disks. They have multiband Spitzer imaging for 25 disks. This provides temperature, and thus semi-major axis estimates. They also provide isochrone ages, updated in Carpenter et al. 2008. (2008arXiv:0810.1003C) Disks poorly fit by a single temperature are identified as having an extended dust distribution. We exclude both the extended disks, for which the semi-major axis fit is poor, and HD 191089, as it misses multiple bands in imaging, and as the age estimate conflicts with β Pictoris Moving Group membership. (Moór et al. 2006's (ApJ 644, 525))

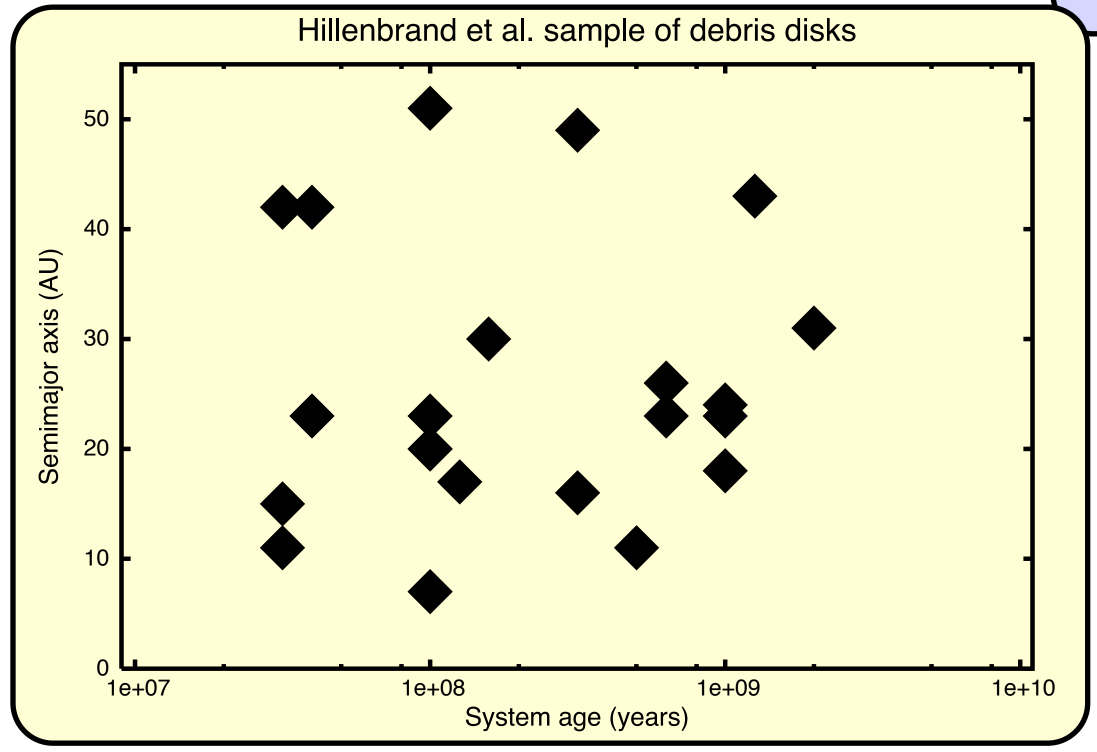

Figure 1. The Hillenbrand et al. 2008 sample uses temperature data to estimate the semi-major axii of the dust. Combined with age data, this provides strong constraints for modeling.

Modeling

We model disks with a primordial power-law distribution, $\frac{dn}{ds} \propto s^{-q}$, for particles from 100 m - 1000 km. Particles are evolved via catastrophically destructive collisions, calculated with the two regime (material strength-bound & gravity-bound) criterion of Benz and Asphaug 1999 (Icarus 142, 5). The chance of collision is calculated as a particle-in-a-box. Bodies break into smaller fragments until they are unbound by radiation pressure (~μm).

The evolution can be understood with a simple analytic model, similar to Löhne et al. 2008 (ApJ 673, 1123). Bodies remain in their primordial configuration until they collide ~once, at which point they obey an equilibrium distribution. As small bodies are held together by material strength, large bodies by gravity, they obey a broken power law distribution. Evolution during ages of 10^7 to 10^{10} years proceeds with gravitationally bound bodies entering equilibrium. Unlike similar models, we use a much larger maximum planetesimal size (1000 km) and thus do not experience a final 1/time phase of luminosity evolution.

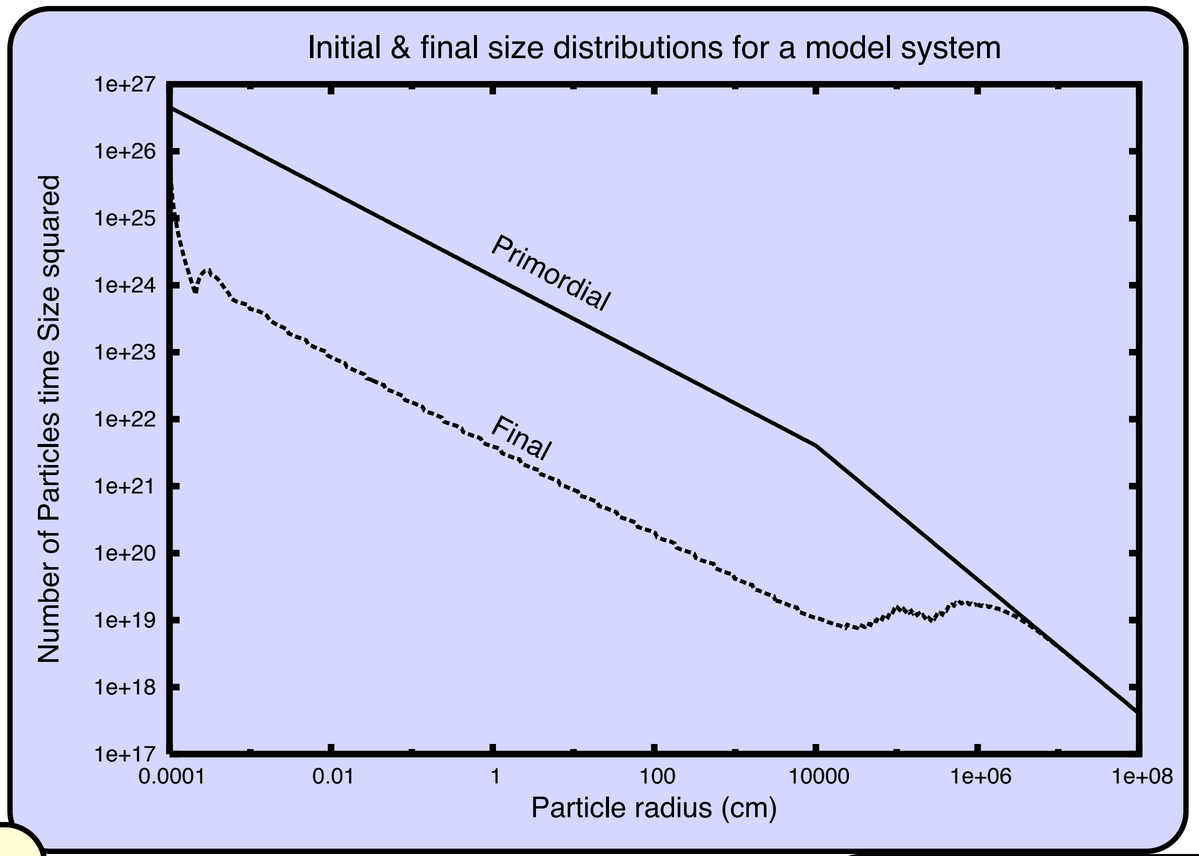

Figure 2. Initial and final particle distribution for a model disk, with primordial q = 4. The small and medium-size bodies obey different equilibrium number-size distribution, owing to their different disruption criteria. The largest bodies stay in their primordial distribution. During the population evolution, particles obey these distributions, while the size at which bodies transition from the primordial distribution to the middle, gravity bound distribution increases.

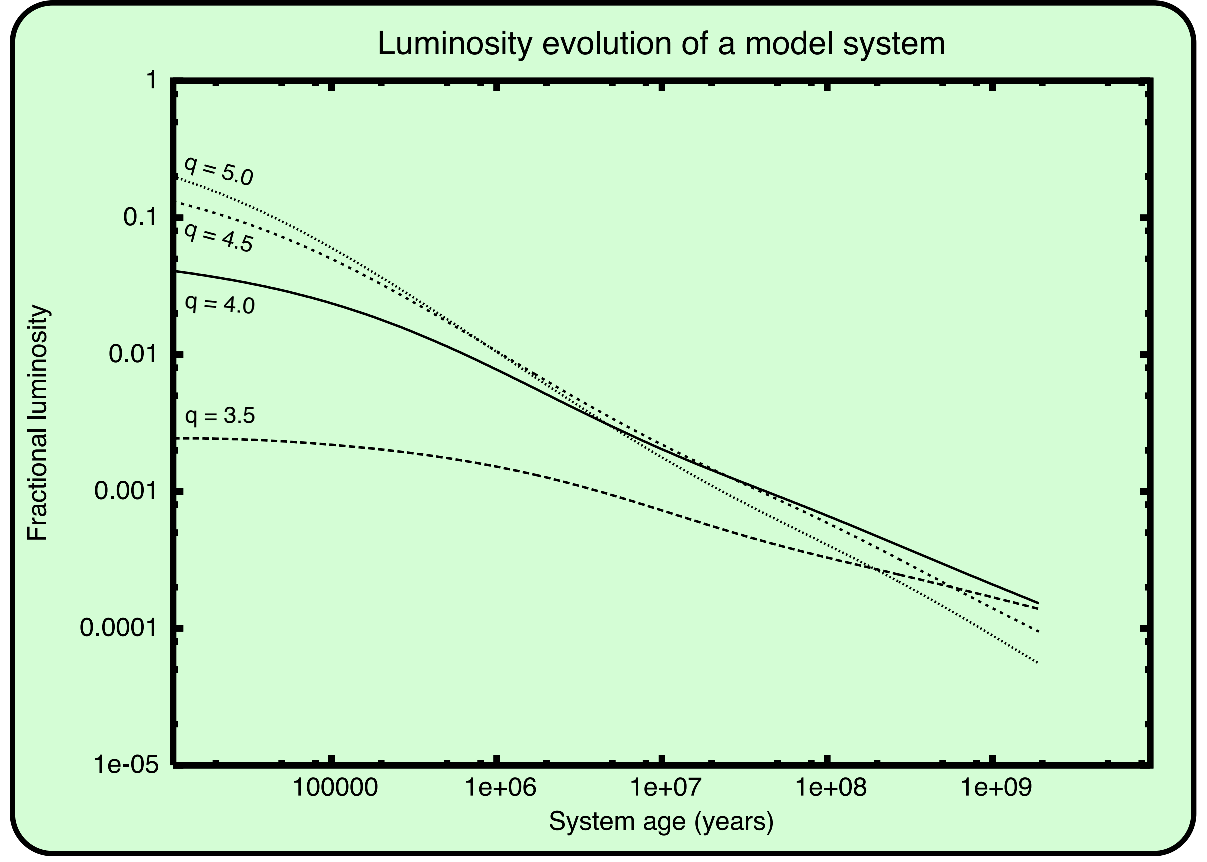

Figure 3. Luminosity evolution tracks of a model disk with four different primordial number-size distributions. All other properties of the disks are identical. While the final luminosities are all similar (~10^{-4}), the differing luminosity decline rates allow measurement of the primordial slope by taking measurements at different times (which is achieved with systems of different ages).

Results

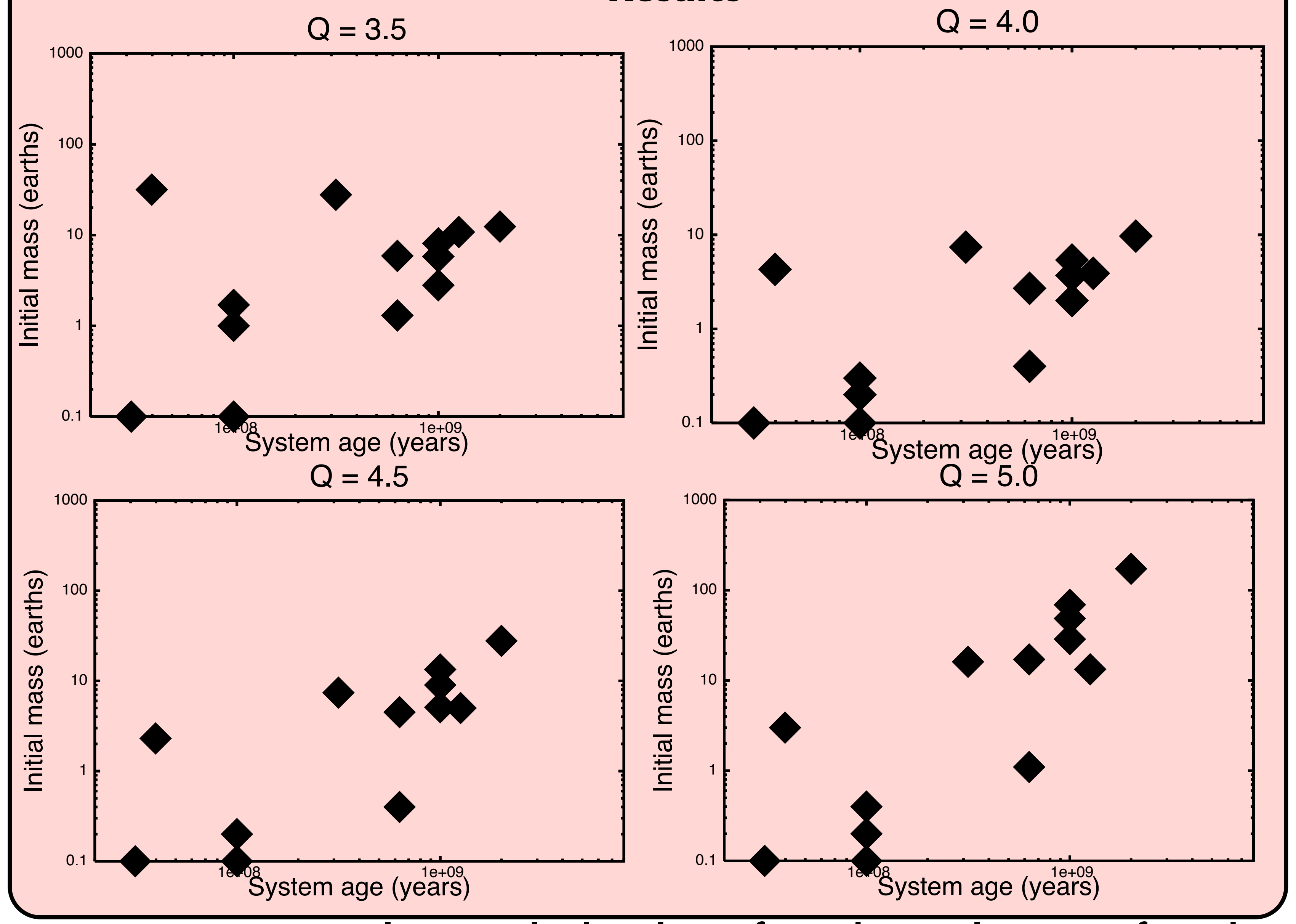

Figure 4. We simulate and plot the inferred initial mass of each system against its age. Where our assumed value of q is correct, we expect the maximum inferred mass to be constant at all ages. From this, we infer the differential number-size distribution best fits a power law with a slope between -3.5 and -4.0, at medium sizes (~100m - ~100km).

Discussion

The slope of the number-size distribution of planetesimals may encode information about their evolution. Outside the solar system, this value cannot be measured directly, but can be inferred with simple numerical modeling. Good measurements of the system age, and multiband photometry to measure the dust temperature are both needed. We find that the number-size distribution slope is roughly 3.5 < q < 4.0; the small sample of debris disks available for our study is the greatest uncertainty.

Assumptions that have gone into the modeling may not be correct; if the primordial number-size distribution does not have a power law form, our results will not be accurate.