A Preliminary Assessment of Chondrule Cooling Rates in Planetesimal Bow Shocks, Including H_2 Recombination

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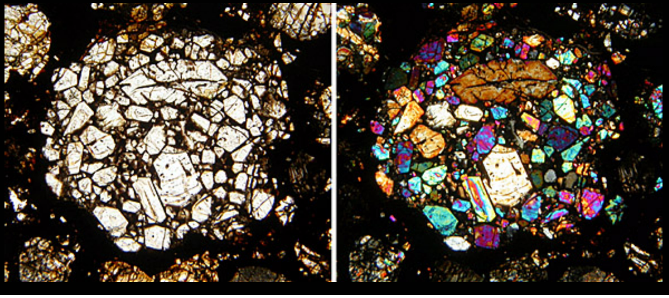
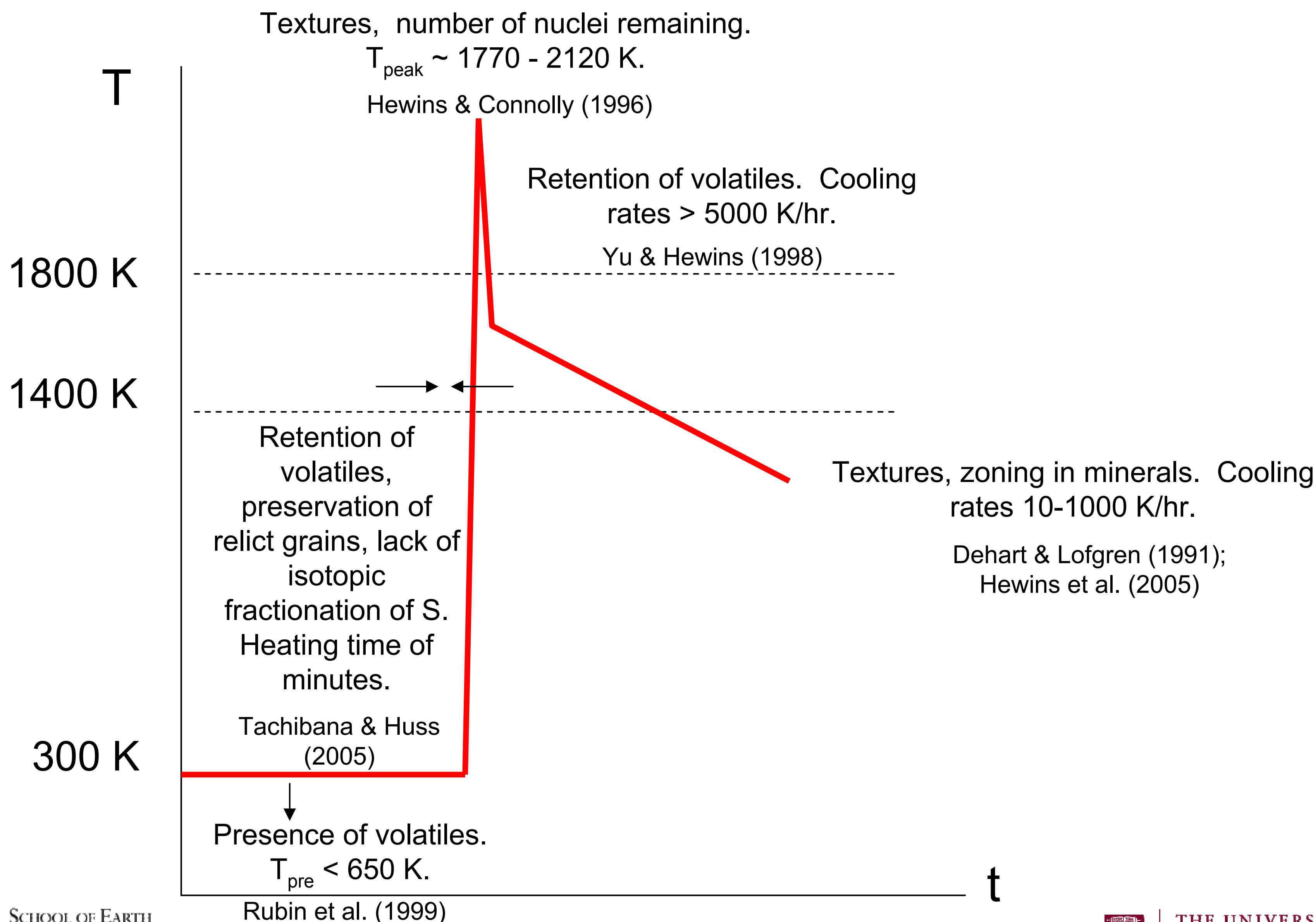
Chondrules



- Igneous textures - crystallized from ferromagnesian silicate melts
- What process could have melted ~ 10^{27} g of rock in the solar nebula?
- Constraints on thermal histories from
  - Retention of volatiles
  - Textures
  - Zoning in minerals
  - Etc.

Constraints on Thermal Histories



What Do Constraints Tell Us?

Chondrules **were *transiently heated*** in an otherwise cold environment

Chondrule Formation Models

- Lightning

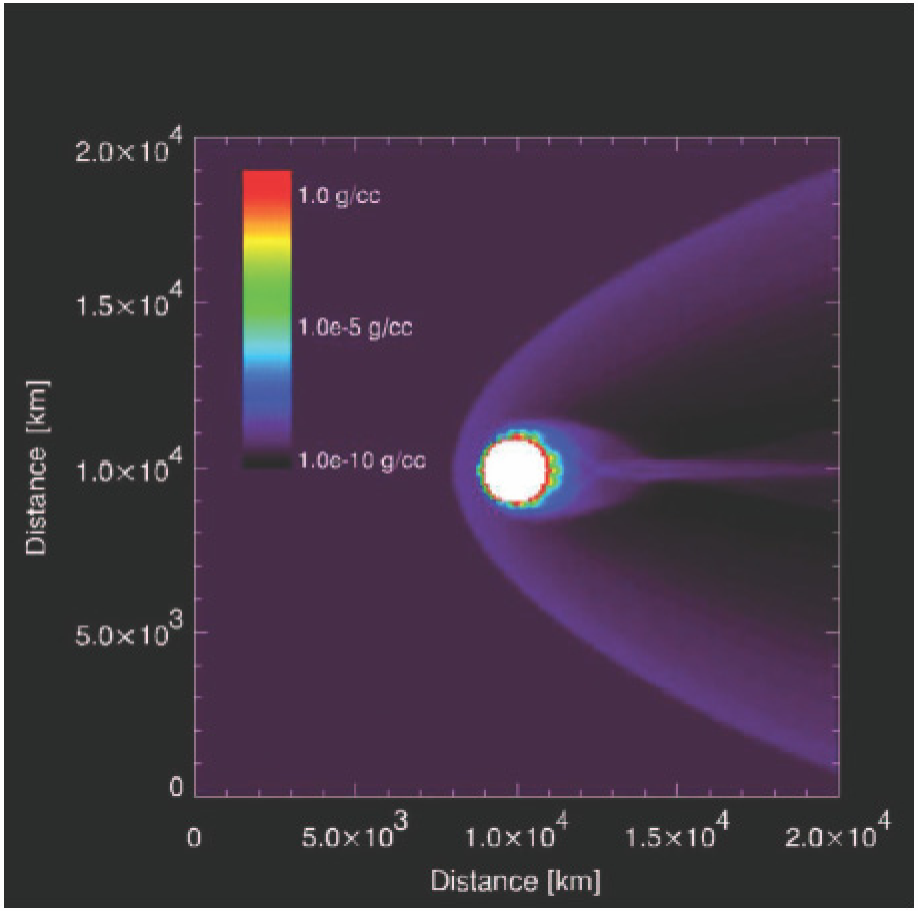
  Cameron 1966, Pilipp et al. 1998, Desch & Cuzzi 2000, others
- Interaction of Planetary Bodies

  Brezina 1885, Urey & Craig 1953, Lugmair & Shukolyukov 2001, others
- Interaction of Precursors with Early Active Sun

  Liffman & Brown, 1995; 1996, Shu et al. 1996; 1997; 2001, others
- Nebular Shocks (most likely)

  Desch & Connolly 2002 (DC02), Ciesla & Hood 2002 (CH02), Iida et al. 2001 (INSN), Miura & Nakamoto 2006 (MN06), Morris & Desch (2010)
  - Shock mechanisms
    - Planetesimal bow shocks
    - X-ray flares
    - Gravitational instability

Planetesimal Bow Shocks

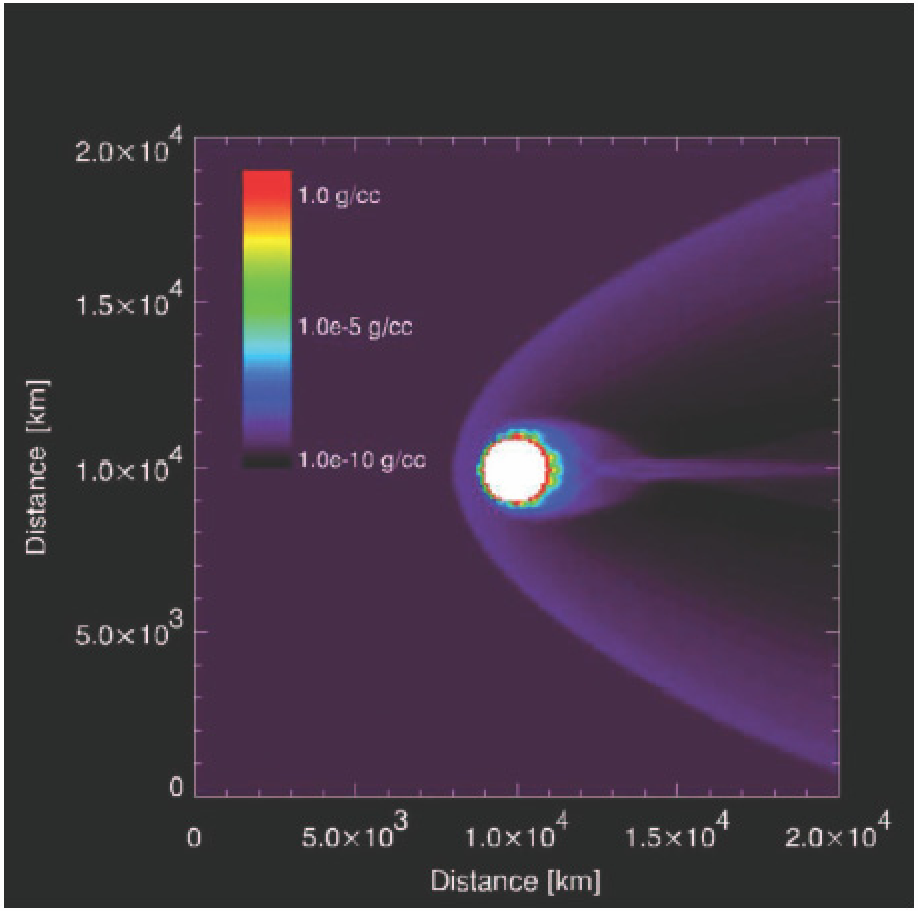


A planetesimal in an eccentric orbit (while gas is still present in the disk) orbits faster than the gas, creating a bow shock around the planetesimal.

Planetesimals at 3 AU on eccentric orbits will drive shocks with speed of 5-10 km/s (depending on eccentricity).

Ciesla et al. (2004)

Planetesimal Bow Shocks

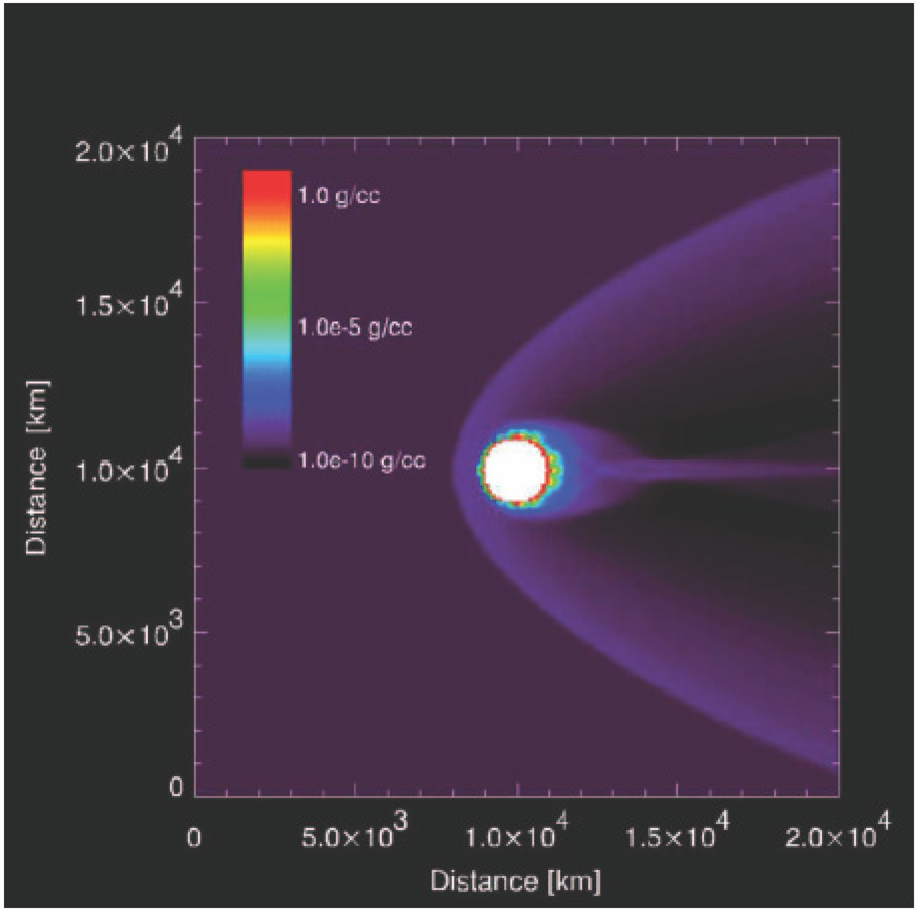


Problems: The size of the bow shock will be comparable to the size of the planetesimal, which places constraints on the fraction of the nebula affected and how long any entrained solids are heated.

Ciesla et al. (2004) have shown that solids pass through a bow shock in < three minutes, resulting in cooling rates > 10^3 K/hr, inconsistent with the thermal histories of chondrules.

Ciesla et al. (2004)

Planetesimal Bow Shocks?



Morris & Desch (2010) have shown recombination of hydrogen buffers the effects of molecular line cooling (factors of 2-10).

We have conducted preliminary assessment using shock code of Morris & Desch (2010).

Ciesla et al. (2004)

Preliminary Assessment

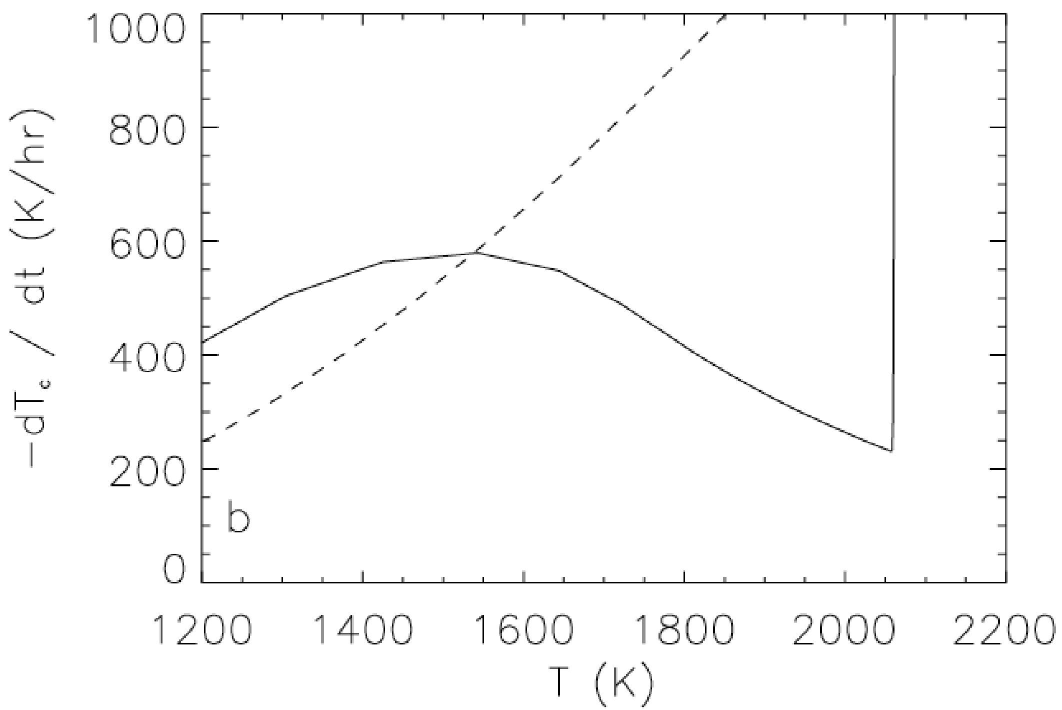
- Chondrules of interest are assumed to be surrounded by a cloud of chondrules at same temperature ➔

$$J = B(T_{bkgrnd})\exp(-\tau) + B(T_{ch})[1 - \exp(-\tau)]$$

- Cloud assumed ~ 2 times size of planetesimal
- Shock speeds 8-10 km/s
- Gas density, $\rho_g = 10^{-9}$ g cm^{-3}
- Chondrule densities 0.004 - 0.75 times ρ_g

Preliminary Results

- Effects of H_2 dissociation/recombination reduces cooling rates by factor of ≈ 2, near 1800 K

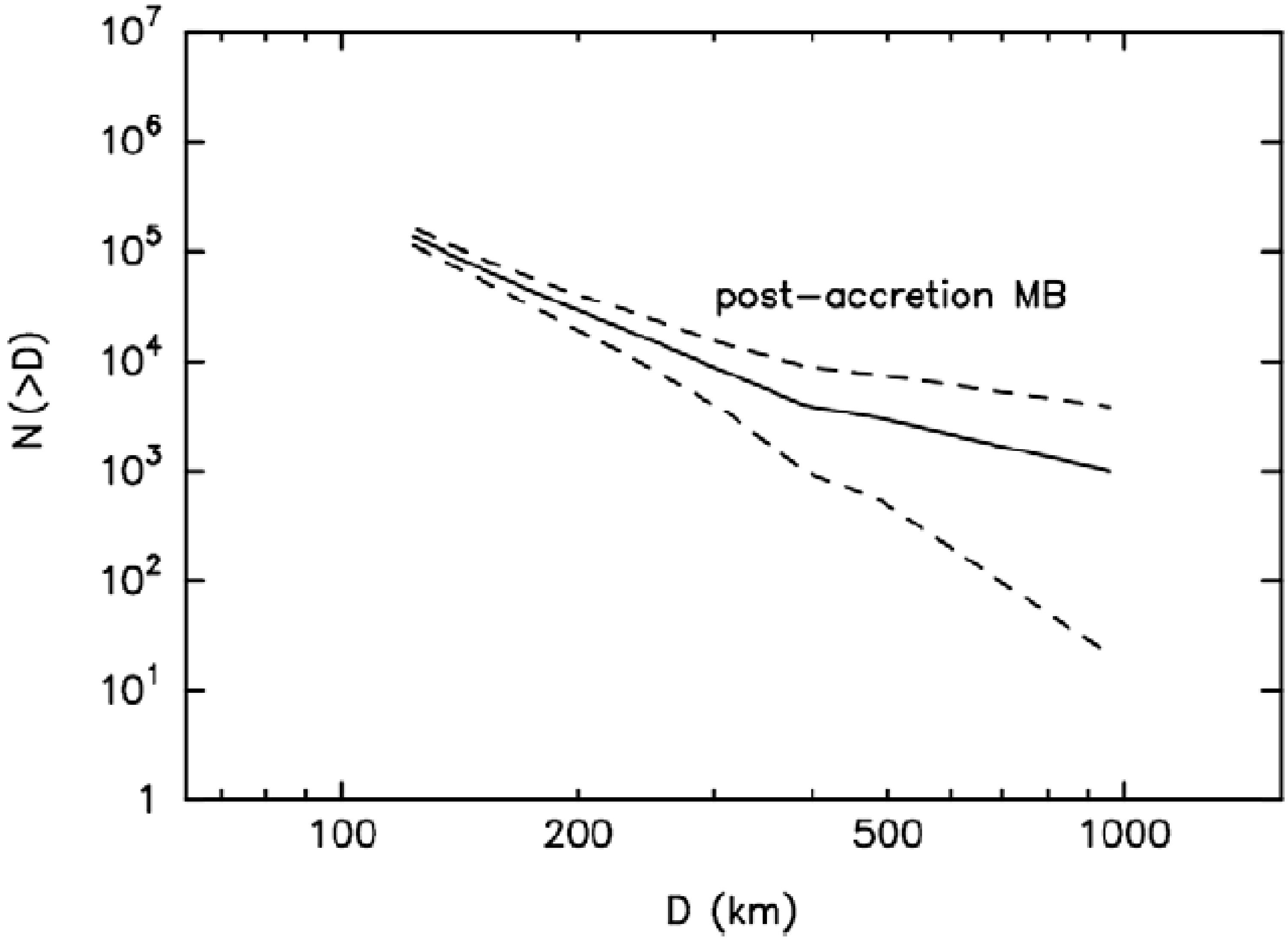


V_s = 10 km/s
C = $0.1\rho_g$
τ = 3

Preliminary Results

- $\tau = 3$
  - Much higher than standard parameters
  - Requires some combination of:
    - Large planetesimal (D > 1000 km) ?
    - High chondrule concentration □
    - High gas density □
- Need 100s of bodies to melt volume of material necessary to produce abundance of chondrules we see today.

Primordial Asteroid Belt



Morbidelli et al. (2009)

Primordial Asteroid Belt

- Mass deficit in current belt > factor of 1000
  Morbidelli et al. (2009)
- D ≥ 500 km, number likely ≈ 7400
  Morbidelli et al. (2009)
- D ≥ 1000 km, number likely ≈ 3800
  Morbidelli et al. (2009)

If small fraction of D ≥ 1000 km planetesimals (~ 10%) in eccentric orbits, provides needed hundreds of bodies

Further Progress Requires:

2-D Hydrodynamic Modeling!

In progress…stay tuned…