Transient Heating in the Early Solar Nebula

Formation of some of the Solar System's Oldest Solids

Melissa Morris

April 10, 2010

40th Annual Mid-American Regional Astrophysics Conference

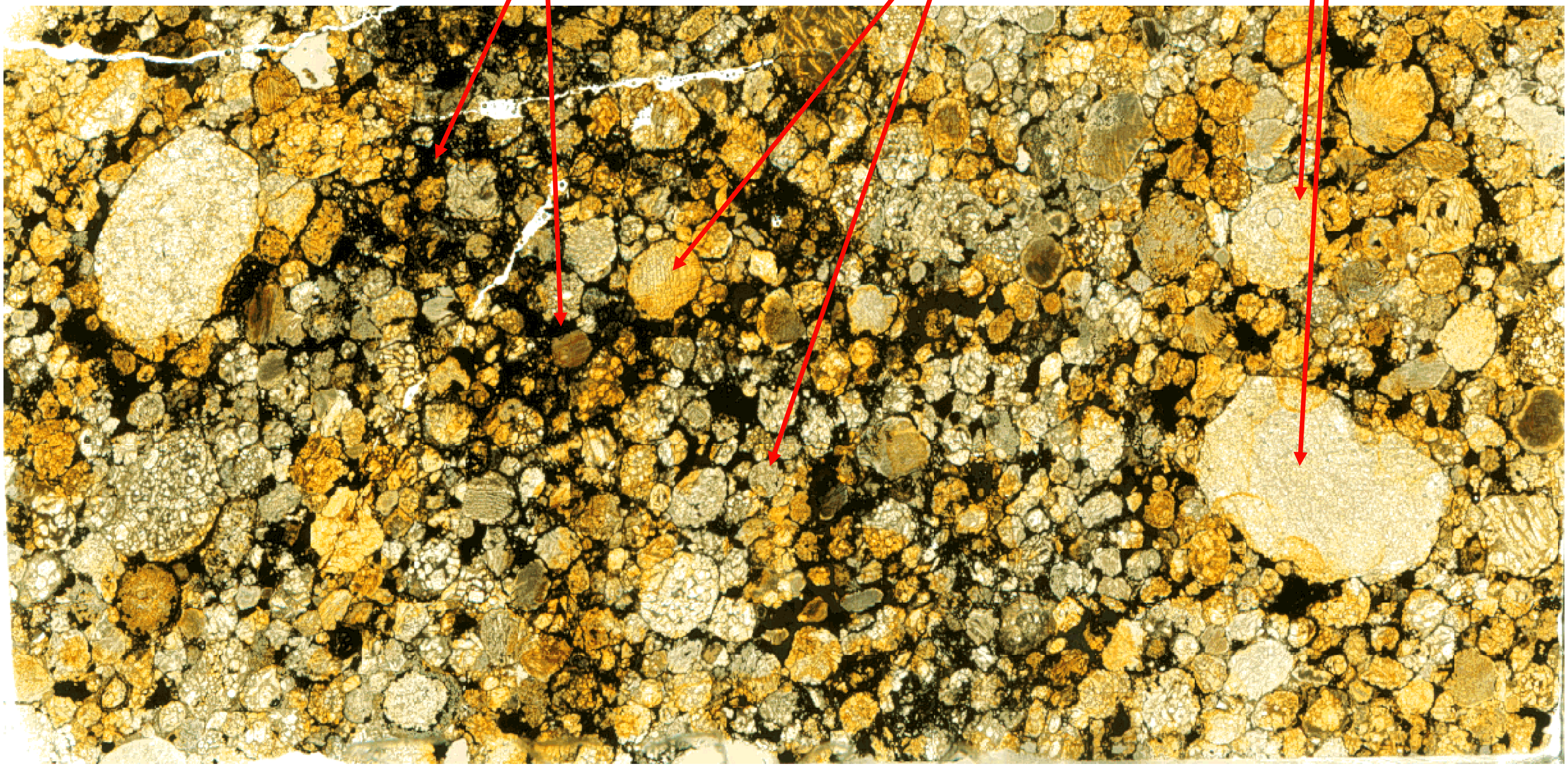
Arizona State University

Missouri State University

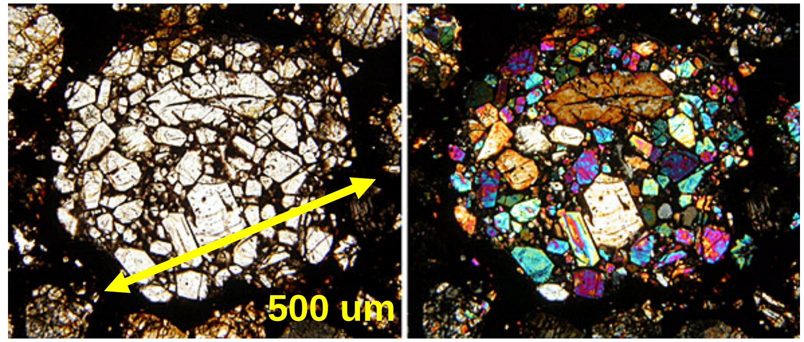
Chondrules & CAIs in Chondrites

Cross section of
Carraweena (L3.9)

MATRIX GRAINS **CHONDRULES** **CAIs**



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.

Observational Constraints for Chondrule Formation Models - Essential Constraints for which a Model Must Account

Constraint	Supporting Observations
High efficiency	high chondrule abundances
Nebular timescales only	isotopic dating
Low ambient temperature	presence of volatiles
Short heating time (minutes)	retention of volatiles
	preservation of relict grains
	experimental reproduction of textures
	lack of isotopic fractionation of S
Peak temperatures $\sim$ 2000 K	experimental reproduction of textures
Short cooling time (hours)	experimental reproduction of textures
	zoning in minerals
	presence of glass
Multiple episodes; recycling	relict grains
	compound chondrules
	igneous rims
Magnetic field	remanent magnetization

adapted from Jones et al. 2000

School of Earth & Space Exploration
Arizona State University

Constraints on Thermal Histories

- Primary sulfur (Rubin et al. 1999)
  - chondrules were cold (< 650 K) before melting event.
- Lack of isotopic fractionation of volatile alkalis (Tachibana & Huss 2005)
  - little evaporation before shock event
  - at temperatures > 1400 K for only minutes before peak heating
- Reproduction of chondrule textures (Hewins et al. 2005)
  - requires near-complete melting of nucleation sites
    - Porphyritic ~ 100-200 K above liquidus
    - Barred ~ 200-400 K above liquidus (peak temperatures 1900 - 2100 K probable)

Missouri State University

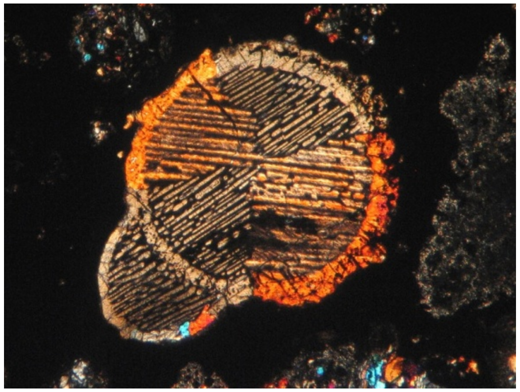
School of Earth & Space Exploration
Arizona State University

Constraints on Thermal Histories

- Lack of elemental fractionation of S (Yu & Hewins 1998)
  - Temperatures above liquidus (1800 K) for only minutes
  - Initial cooling rates ~ 10^3 - 10^4 K/hr (likely ~ 5000 K/hr)
- Chondrule textures
  - Peak temperatures 1770 - 2120 K (Hewins & Connolly 1996)
  - Cooling rates between liquidus and solidus (1400 K)
    - 10 - 1000 K/hr for porphyritic olivines (Hewins et al 2005)
    - 500 - 3000 K/hr for barred olivines (Connolly et al. 1998; Dehart & Lofgren (1991)

Missouri State University

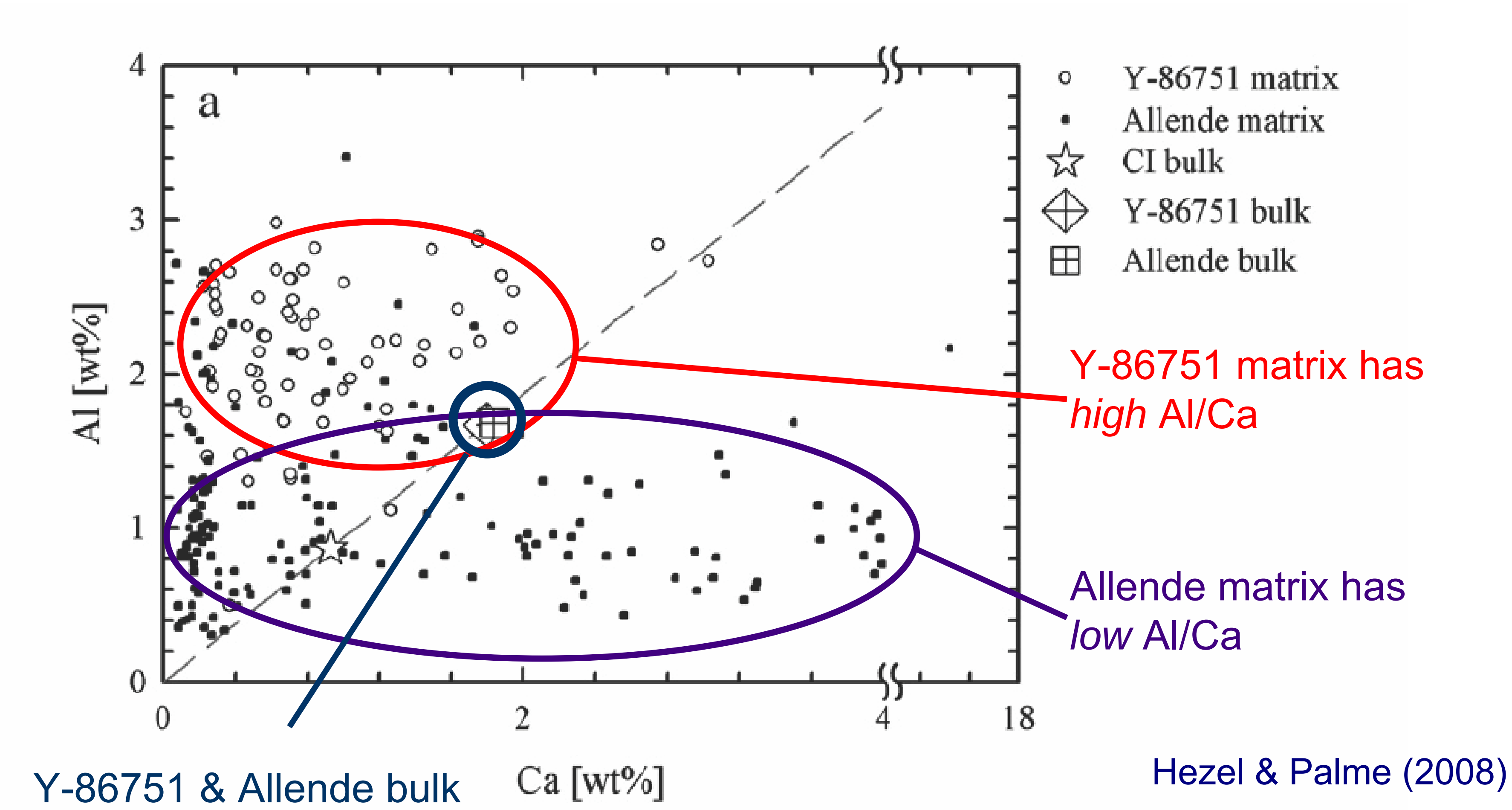
Other Constraints



- About 5% of all chondrules are compound (stuck while molten)
  - chondrule densities ~ 1 - 10 m^{-3} (Gooding & Keil 1981)
- Lack of isotopic fractionation of K, Fe, Mg, Si
  - high vapor pressure where chondrules formed (Cuzzi & Alexander 2006)
  - chondrule-forming region large (> 1000 km) (Cuzzi & Alexander 2006)
  - chondrule densities 1 - 10 m^{-3} (Cuzzi & Alexander 2006)
  - total pressures > 10^{-3} atm (Miura et al. 2002)
- Chemical complementarity of chondrules and matrix (Wood 1985; Palme et al. 1993; Hezel & Palme 2007)
  - are cogenetic and formed in same region

ASU School of Earth & Space Exploration
ARIZONA STATE UNIVERSITY

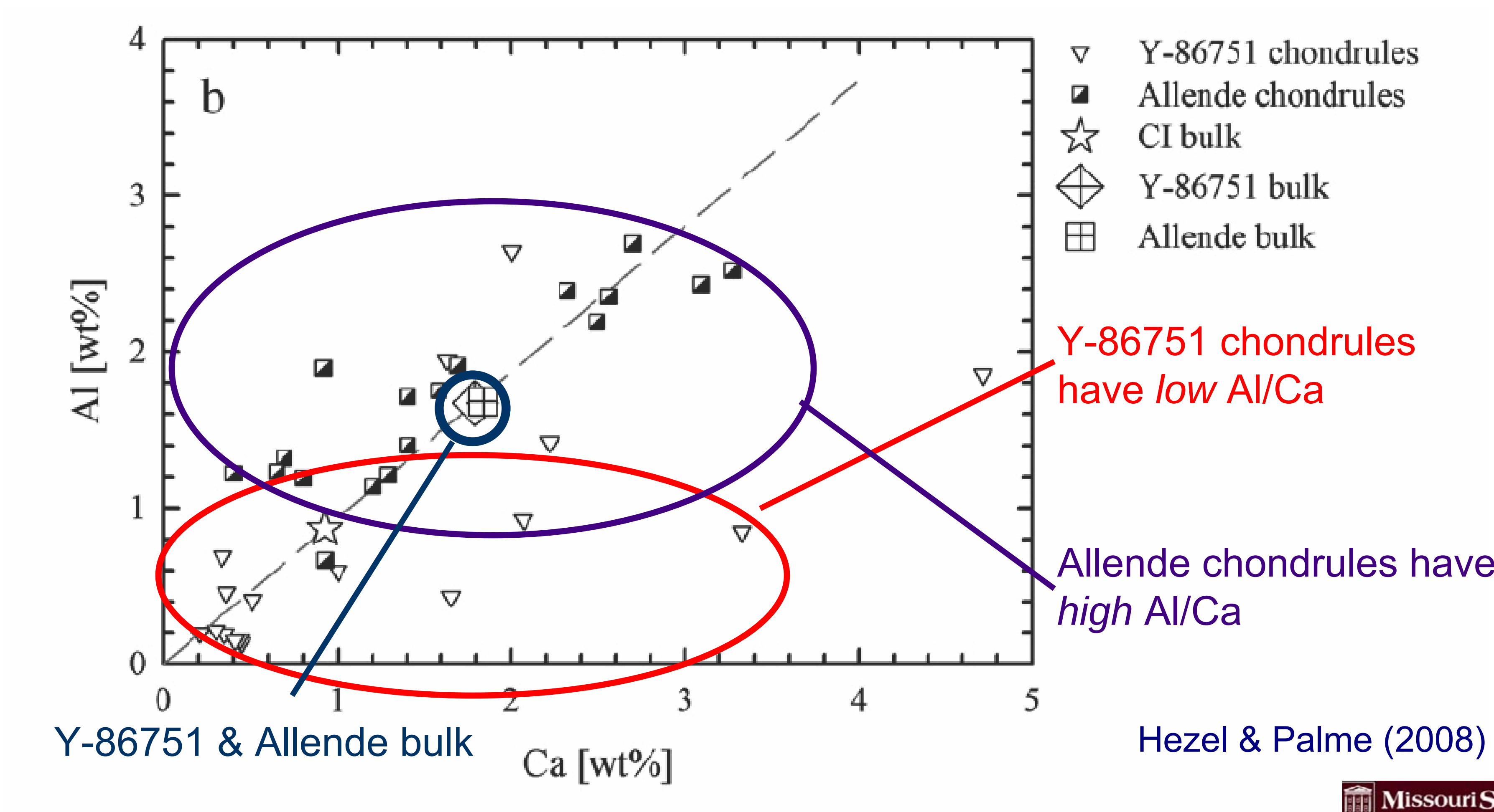
Chondrules and matrix are chemically complementary



Hezel & Palme (2008)

Missouri State University

Chondrules and matrix are chemically complementary



Hezel & Palme (2008)

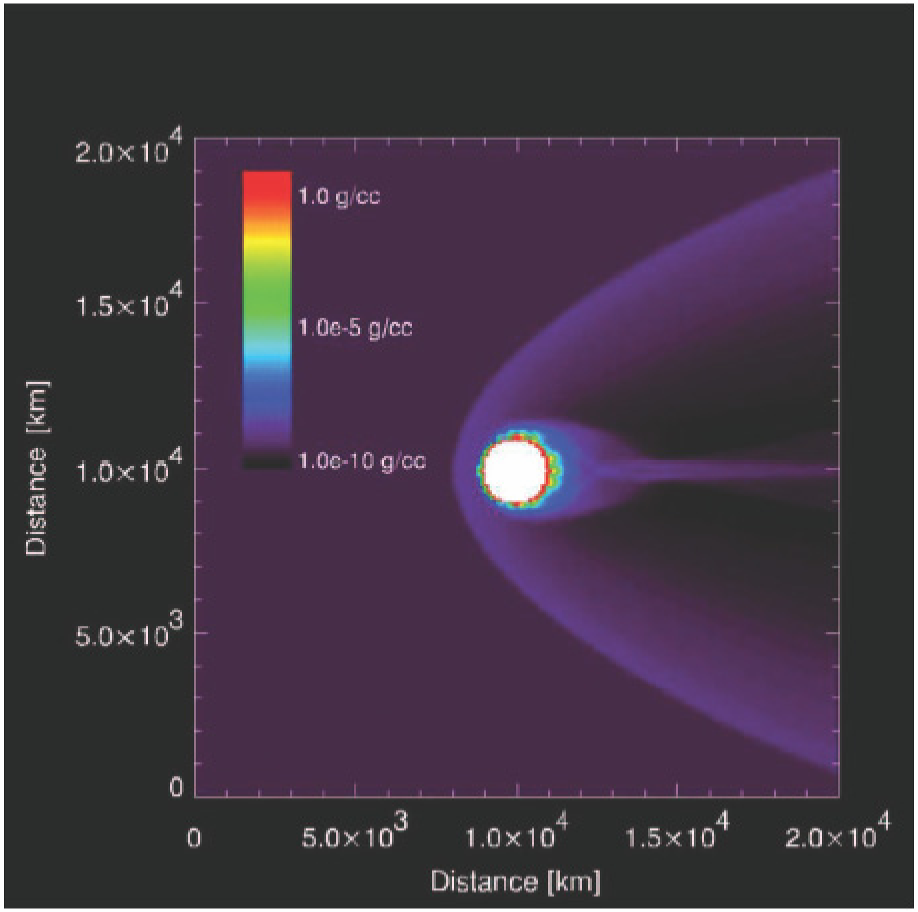
What Do Constraints Tell Us?

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)
  - Shock mechanisms
    - Planetesimal bow shocks
    - X-ray flares
    - Gravitational instability

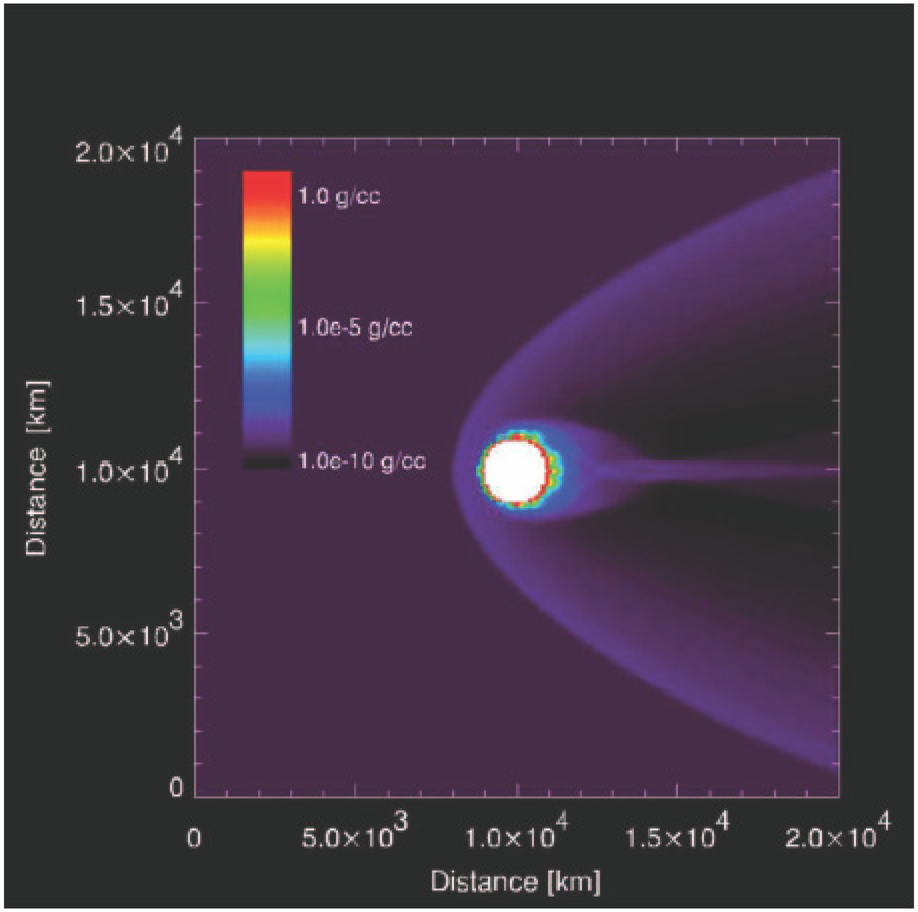
Planetesimal Bow Shocks



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

Ciesla et al. (2004)

Planetesimal Bow Shocks

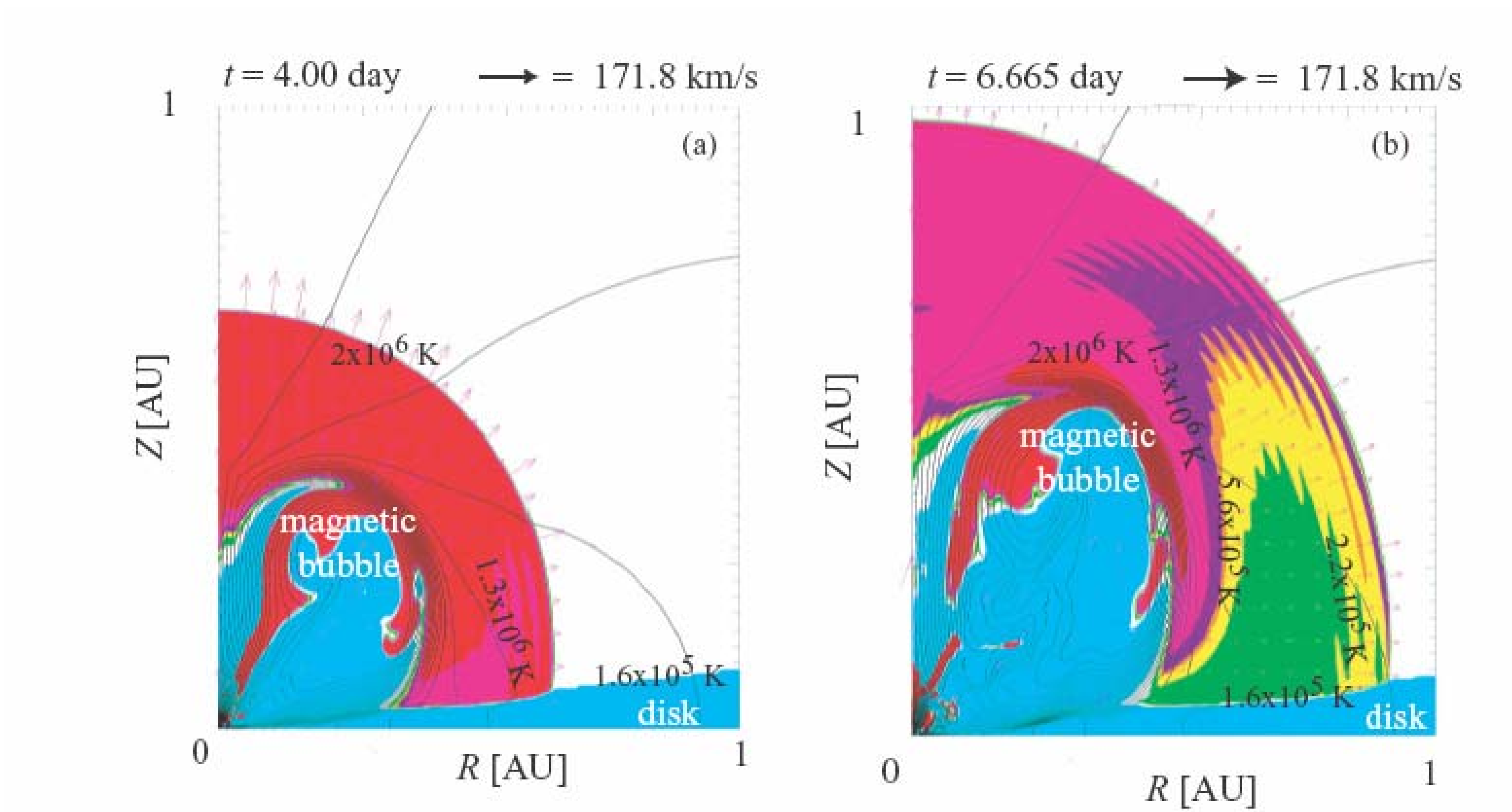


Problems: The size of the bow shock will be comparable to the size of the planetesimal, which places constraints on the fraction of the nebula affected and how long any entrained solids are heated.

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)

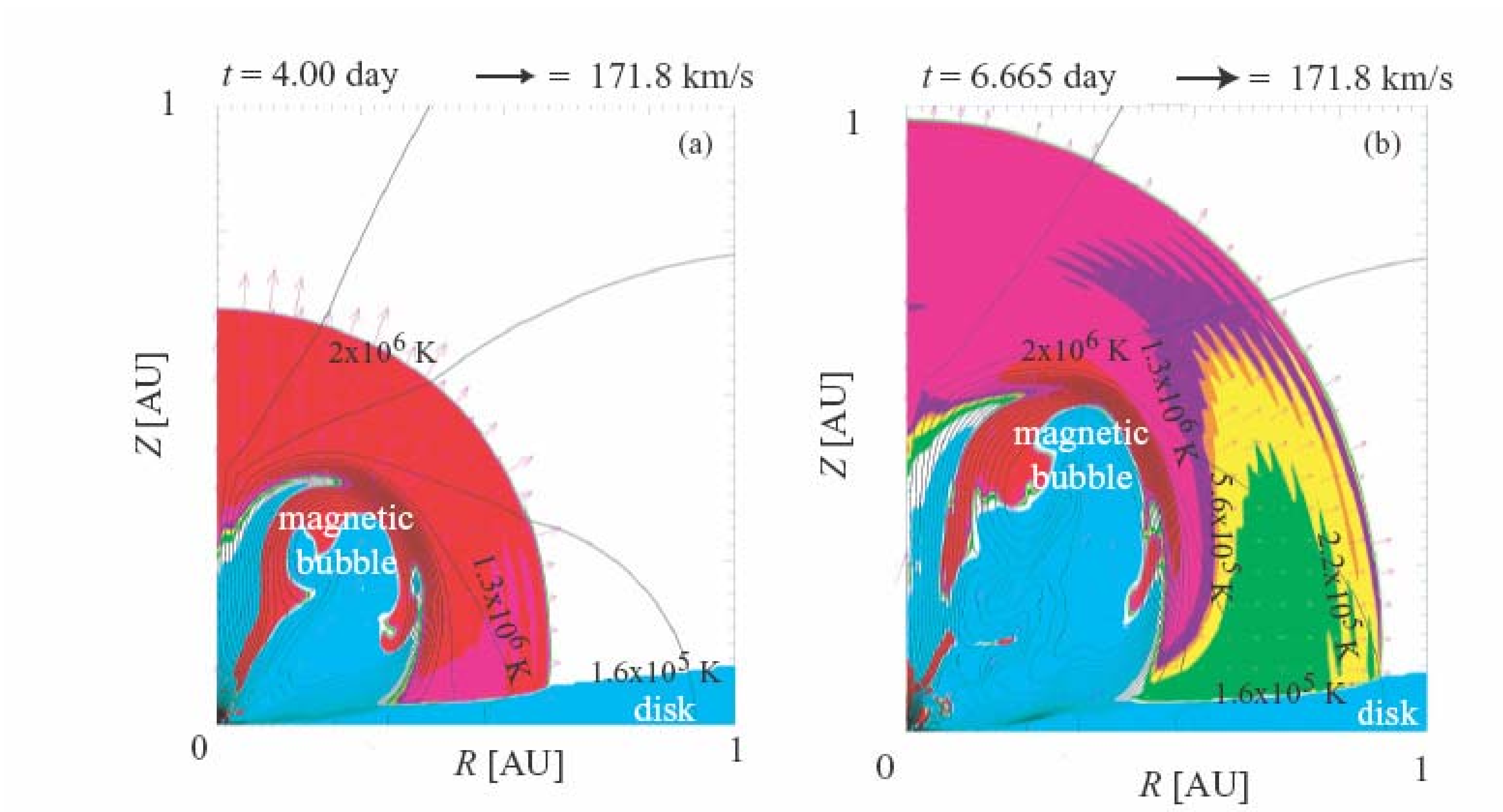
X-ray Flares



The major part of the momentum flows upward, but a small fraction of it flows toward the disk, which generates shock waves in the disk.

Nakamoto et al. (2005)

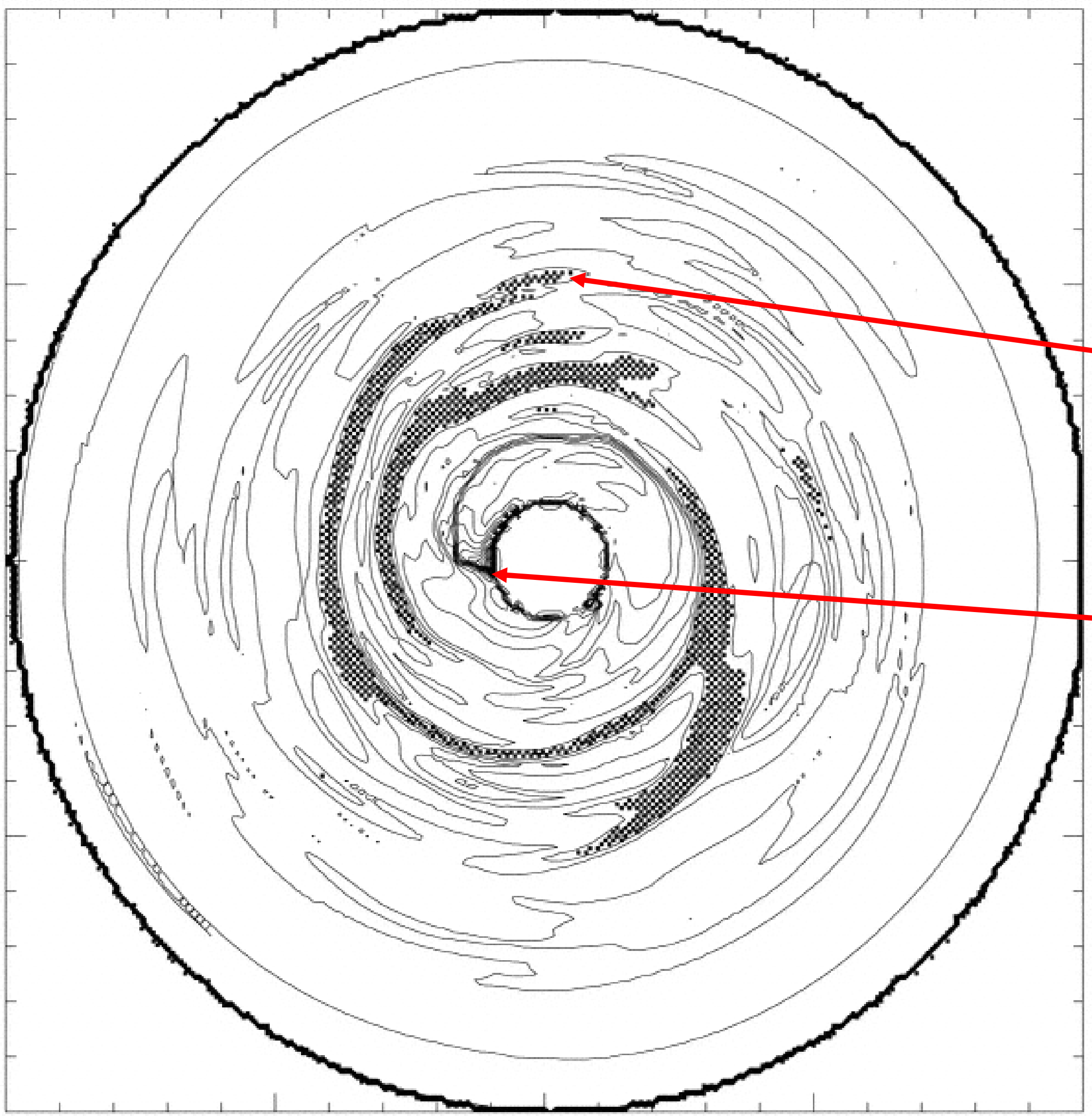
X-ray Flares



Problems: X-ray flares probably only affect material high above the midplane of the disk, where micron-sized dust may be heated, but chondrule precursors are not likely to exist, due to settling to the midplane.

Nakamoto et al. (2005)

Gravitational Instabilities

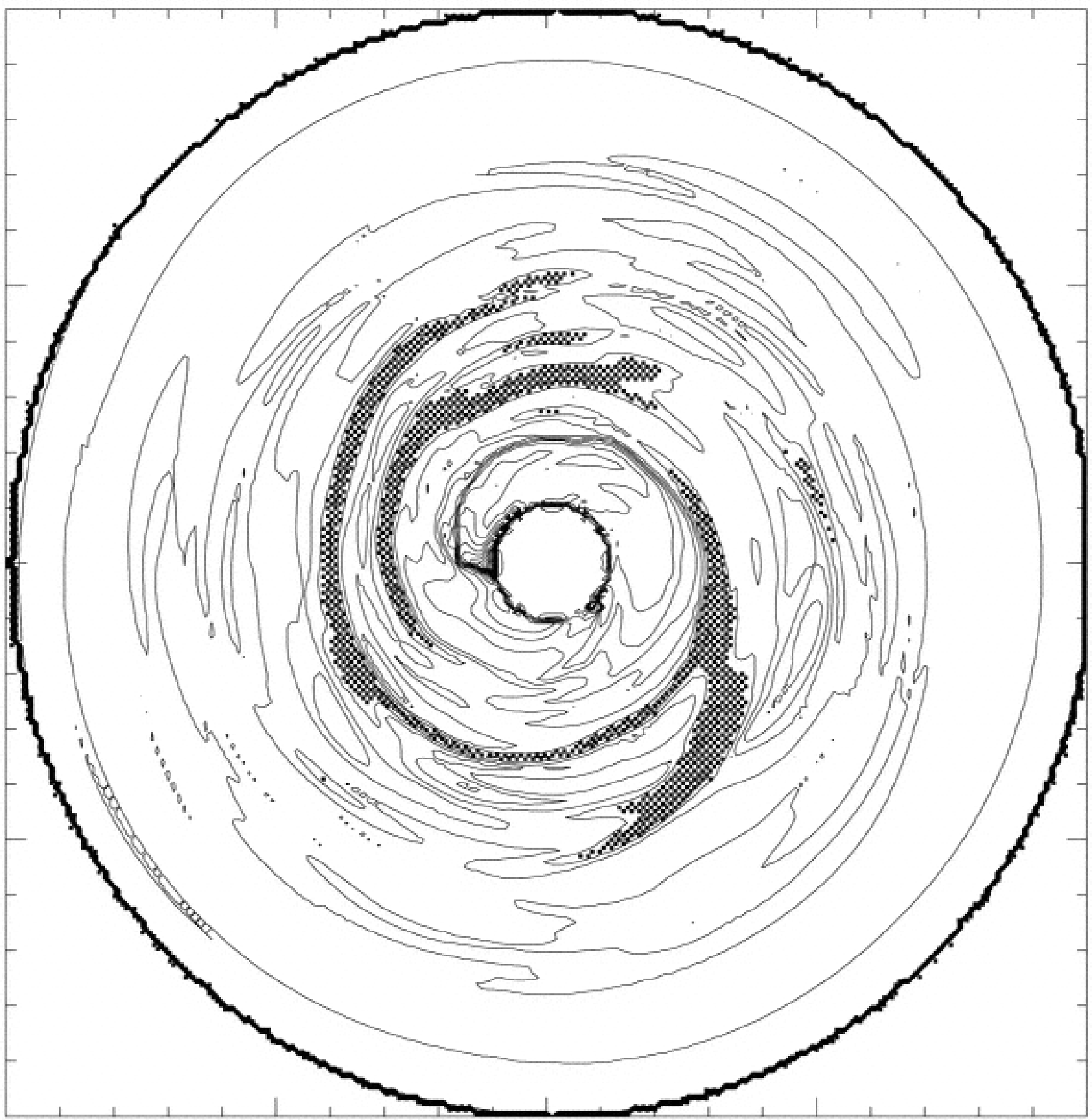


spiral-density waves

shock front at 2-3 AU, propagating at about 5 -10 km s^{-1} relative to surrounding gas

Boss & Durisen (2005)

Gravitational Instabilities



Problems: The simulations of Boley & Durisen (2008) predict, however, that high-speed shocks (5 - 11 km/s) should be rare, and must be triggered inside 2 AU.

Disk needs to remain unstable up to 2 My to coincide with chondrule formation, which requires massive disk …but see Desch (2007).

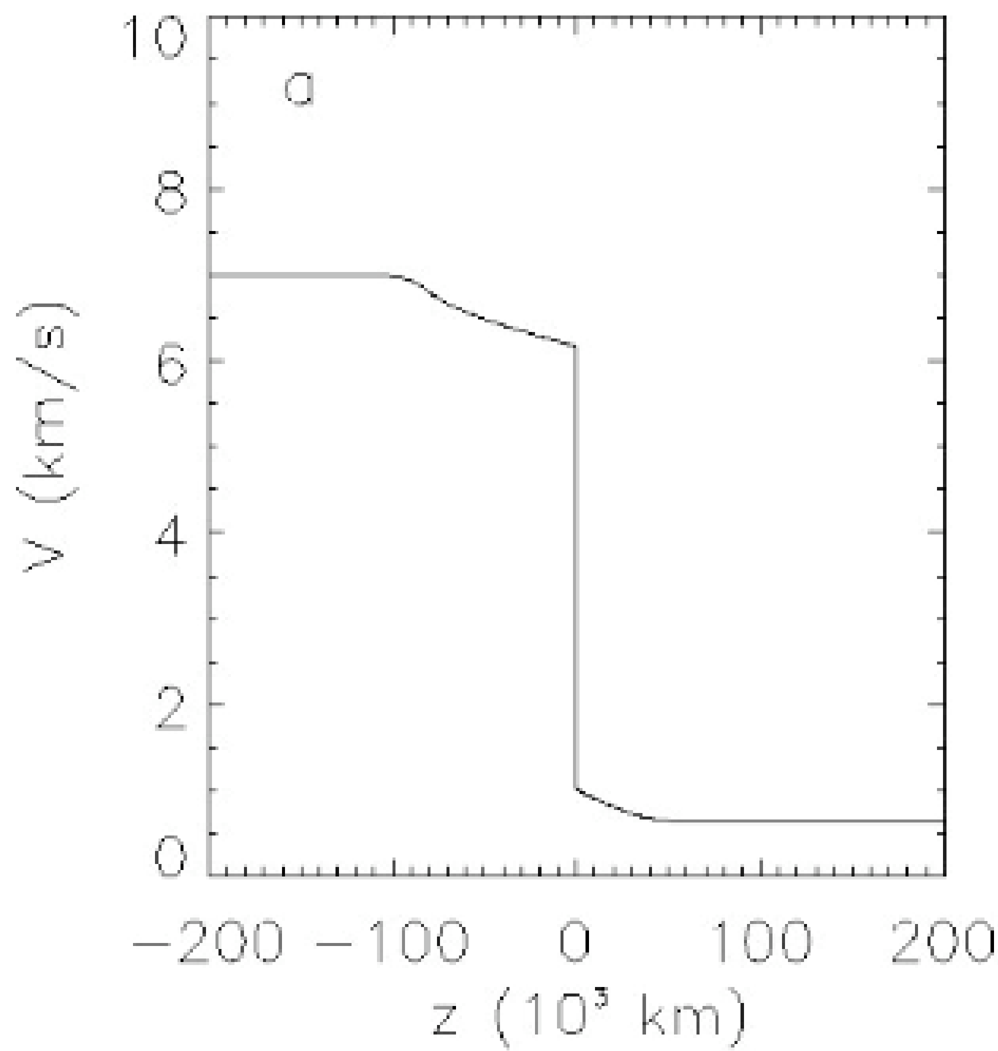
Boss & Durisen (2005)

Chondrule Formation in Shocks

- Upon passage through the shock wave, gas is slowed, compressed, heated.
- Solids are heated by thermal exchange, by friction (as they are slowed to the post-shock gas speed), and by absorbing IR radiation emitted by other solids.

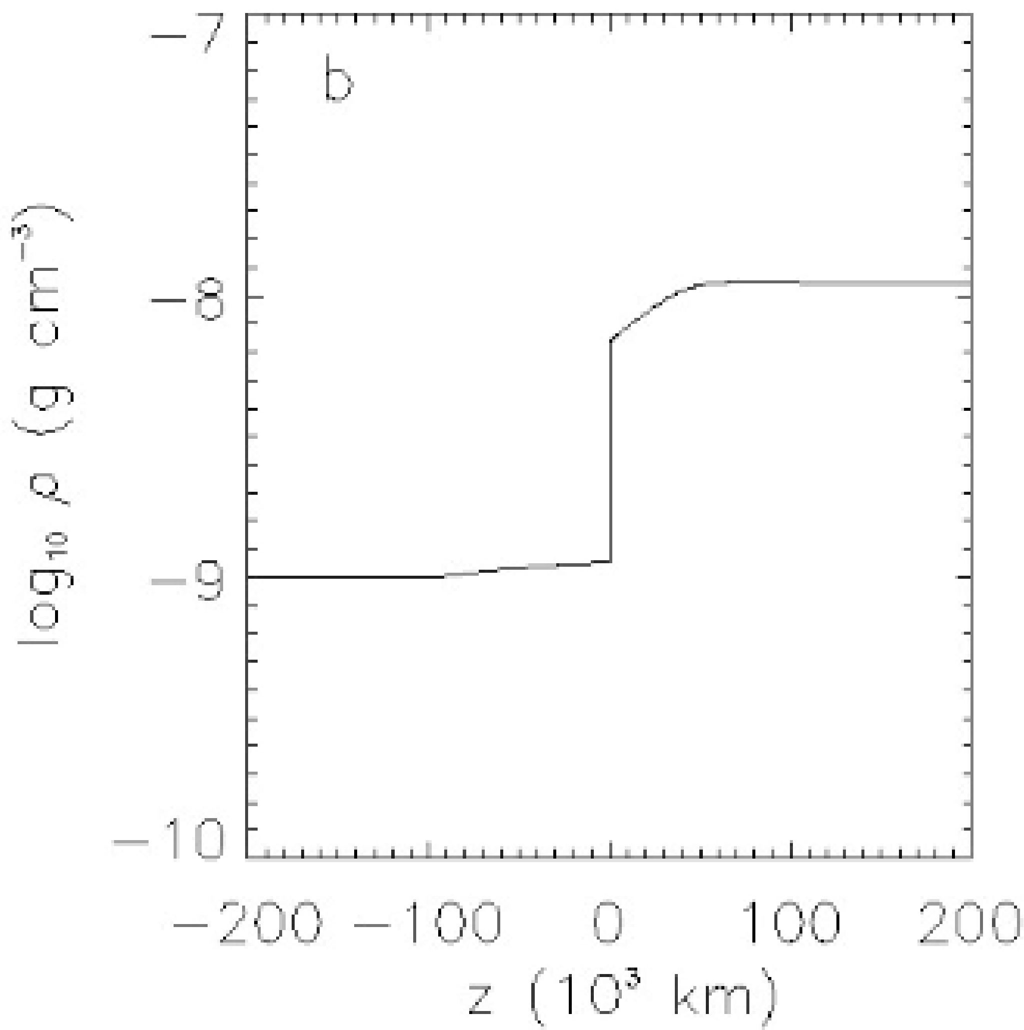
Chondrule Formation in Shocks

- Models of chondrule formation in shocks have been developed (Iida et al. 2001; Desch & Connolly 2002 (DC02); Ciesla & Hood 2002; Miura & Nakamoto 2006, Morris & Desch 2010)
- DC02 includes gas (H, H_2, He), chondrules, and dust
  - solves steady-state 1-D equations of mass, momentum & energy
  - includes radiative transfer and radiative heating / cooling of chondrules
- Morris & Desch (2010) improves upon the DC02 model
  - Proper jump conditions and lower final temperature
  - Proper treatment of opacity and dust evaporation (evaporates over a range near 1500 K, not 2000 K)
  - Loss of energy due to line cooling by water molecules



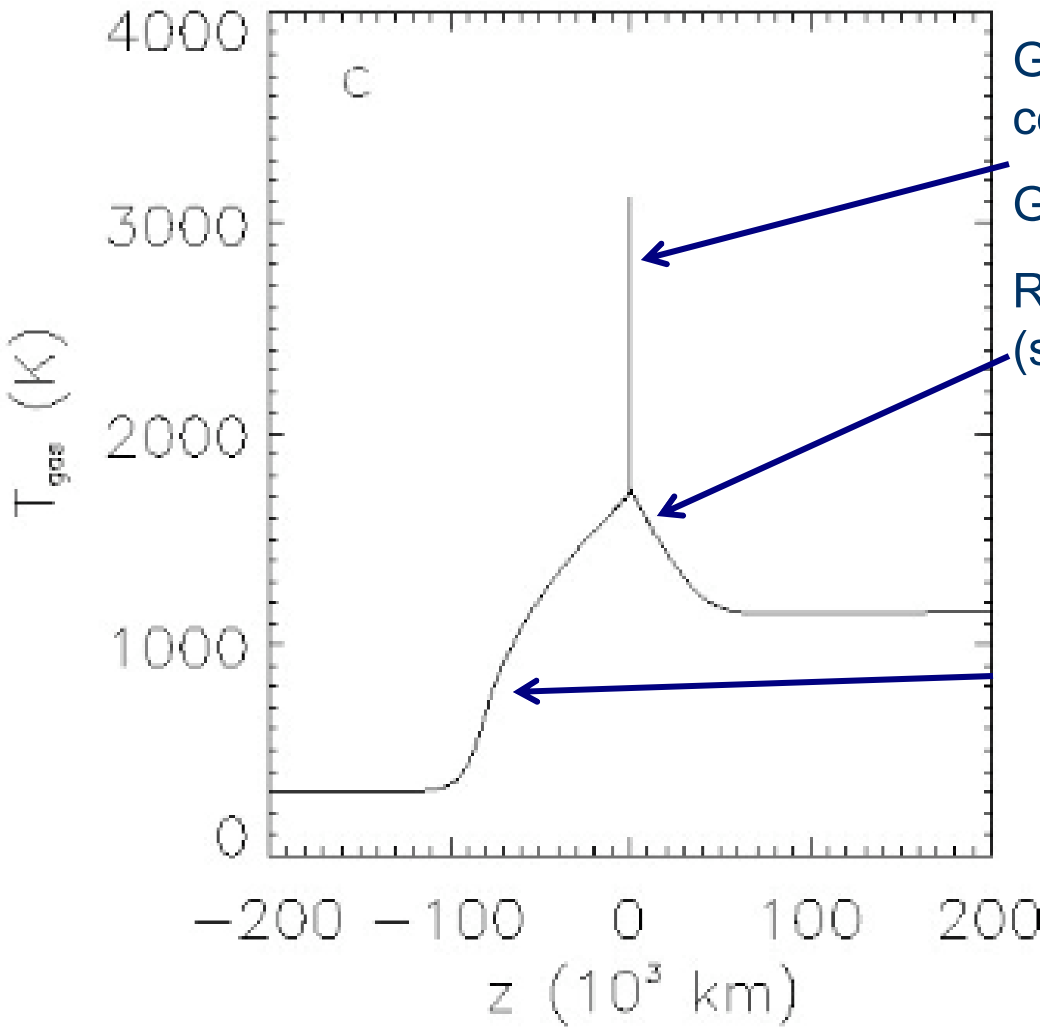
Gas is suddenly slowed at shock front

Desch & Connolly (2002)



Gas is compressed at shock front

Desch & Connolly (2002)

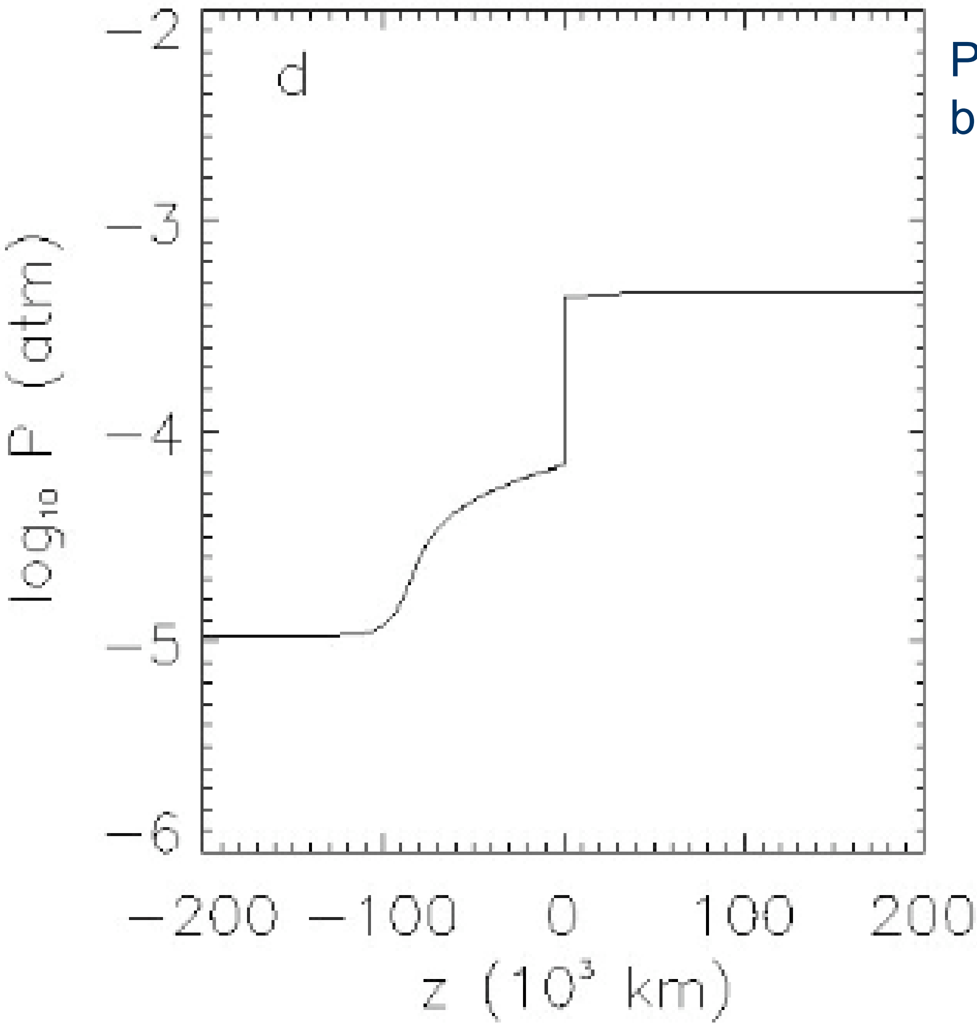


Gas peak heating right after shock, cools in seconds by H_2 dissociation.

Gas / chondrules cool by radiation.

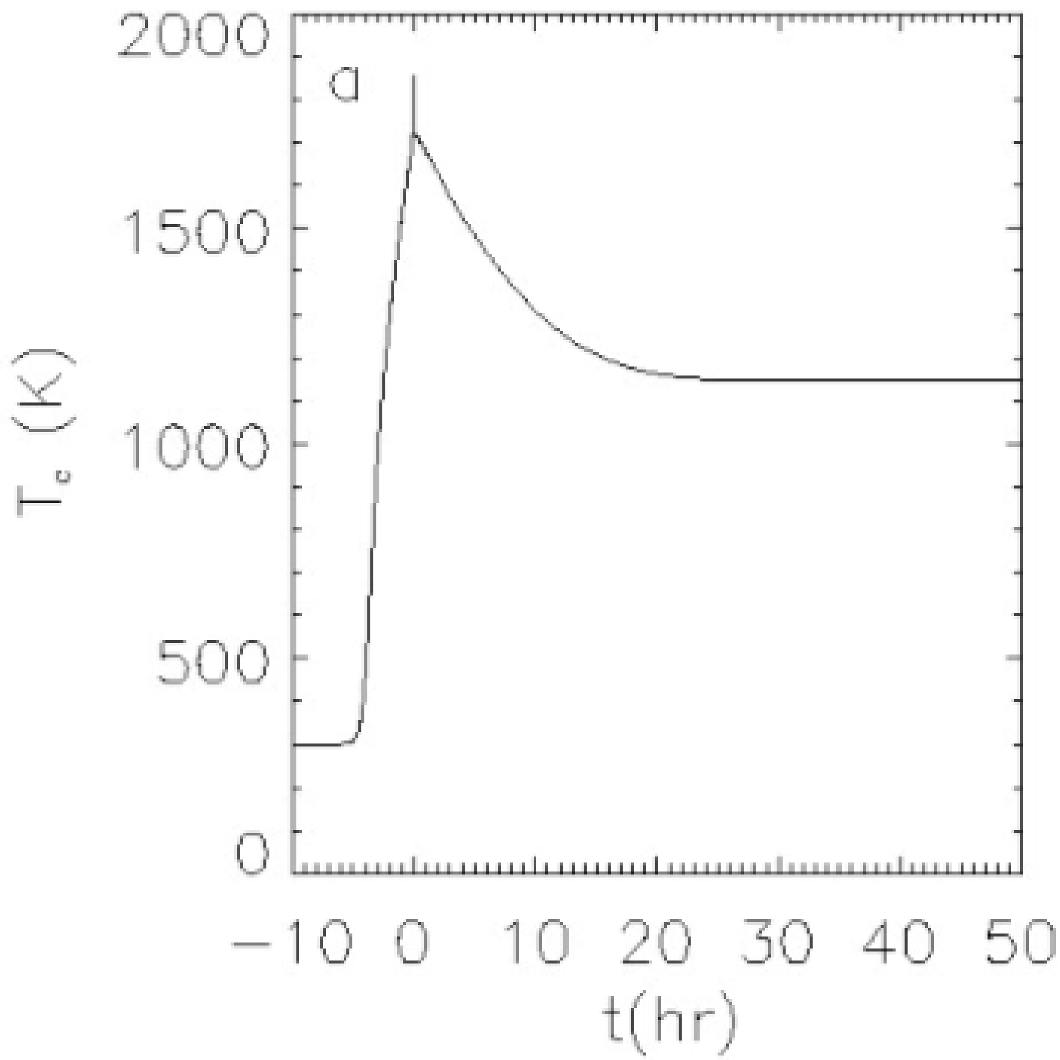
Radiation leaks into pre-shock region (stationary Marshak wave).

Desch & Connolly (2002)



Pre-shock heating raises pressure before shock front

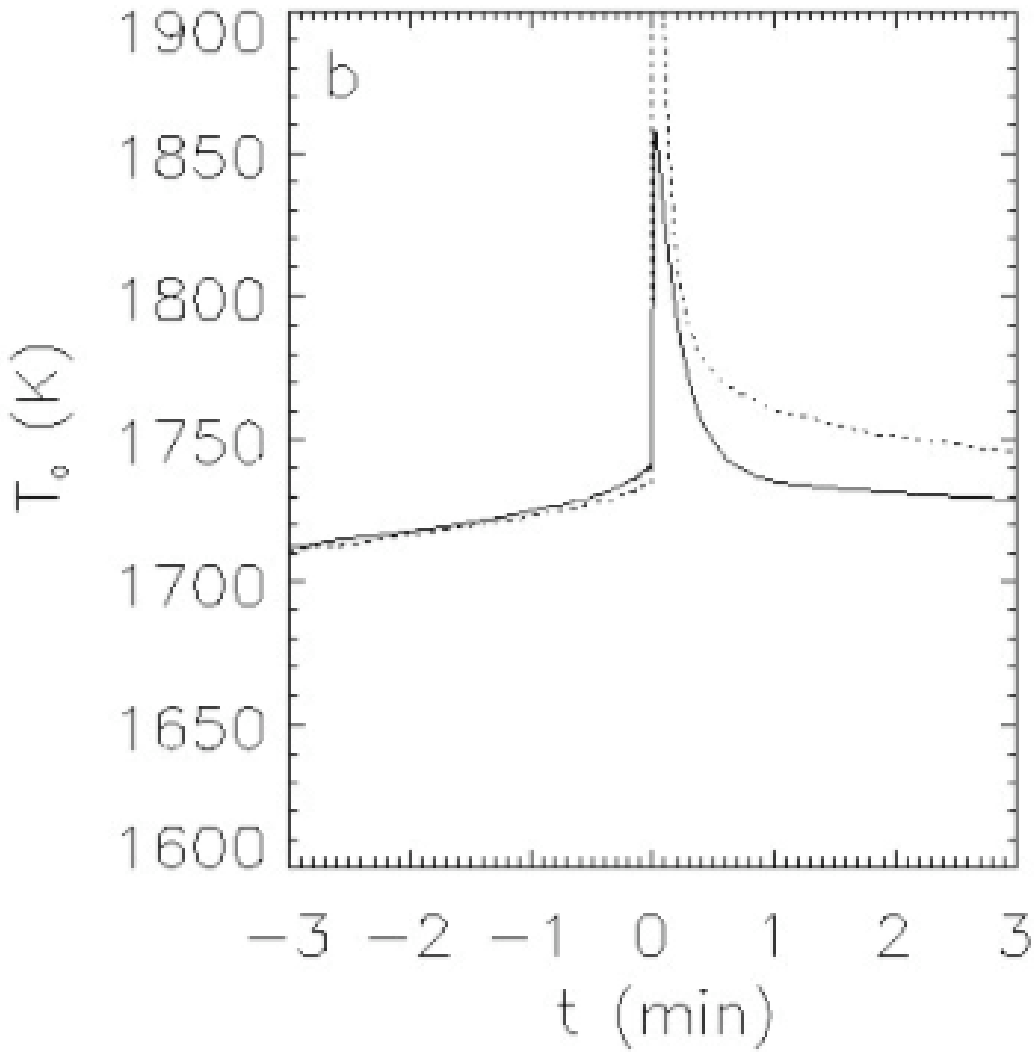
Desch & Connolly (2002)



Chondrules heated before reaching shock front.

Experience peak heating only in vicinity of shock front.

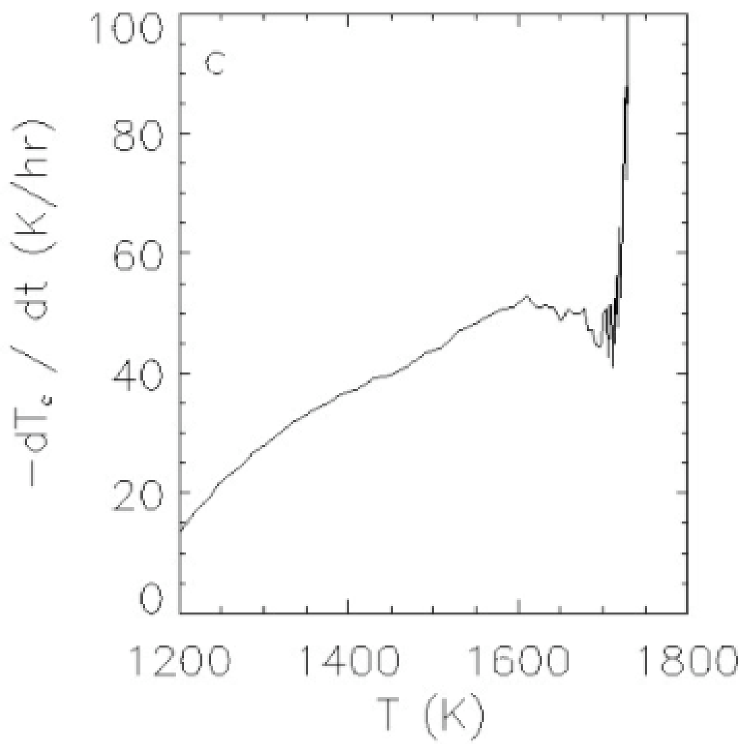
Desch & Connolly (2002)

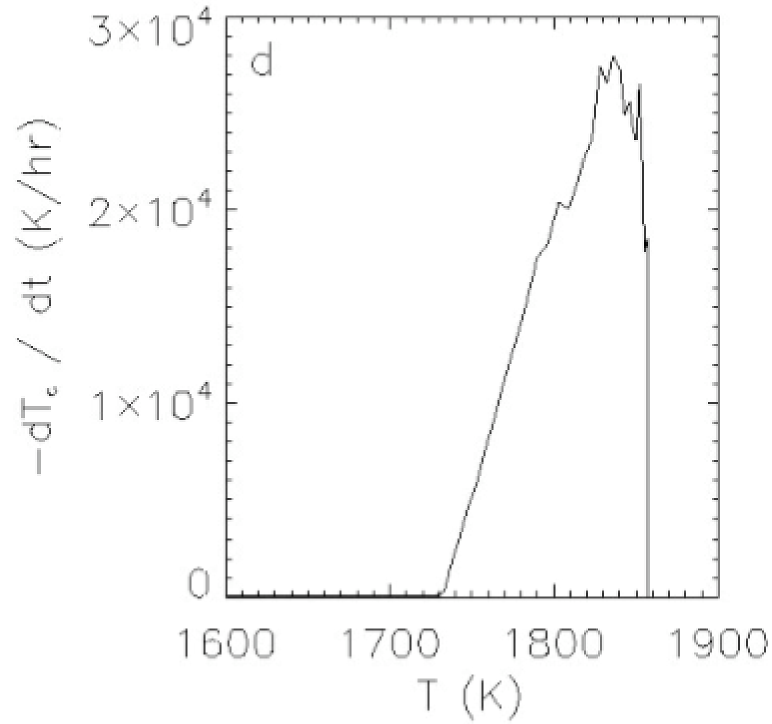


Chondrules heated by gas drag (in first minute past shock), exchange with hot, compressed gas, and radiation emitted by other solids.

Chondrules experience peak heating only in vicinity of shock front.

Desch & Connolly (2002)

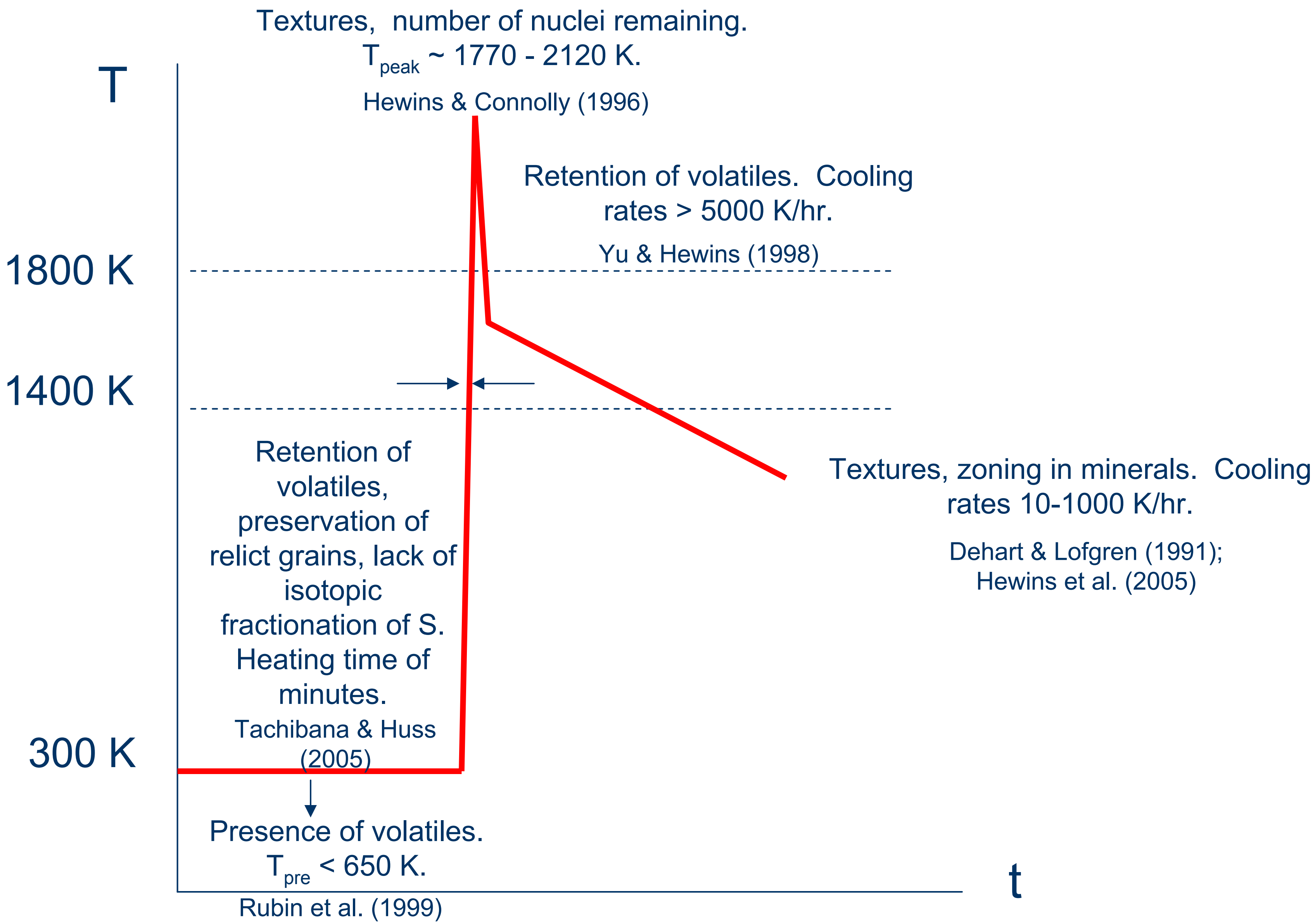




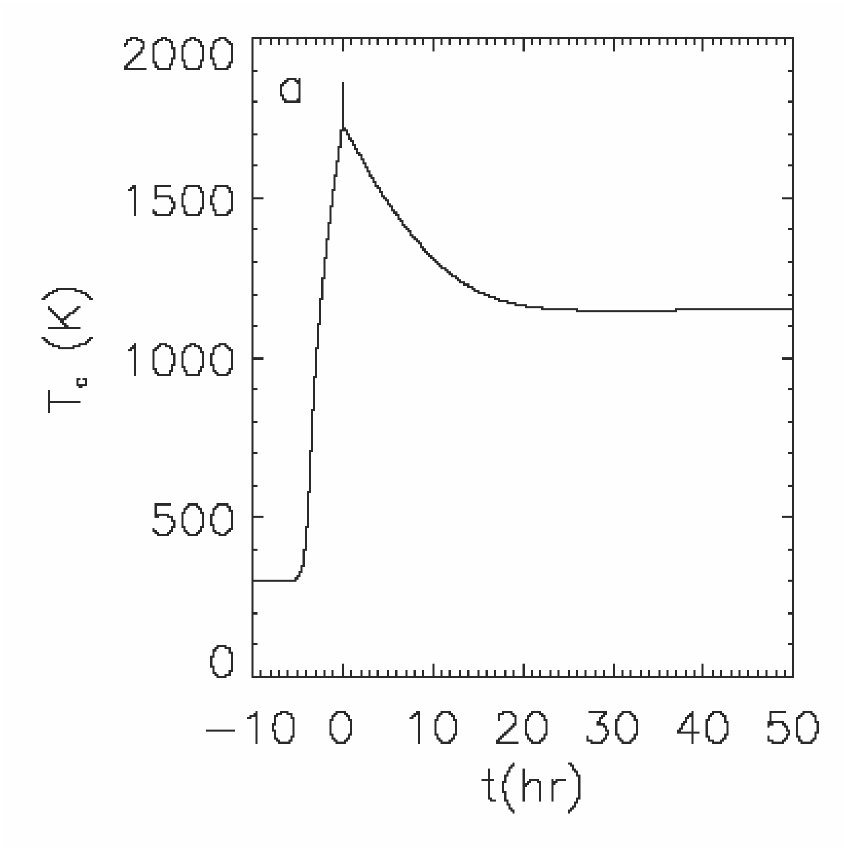
Cool > 10^4 K/hr above liquidus, < 100 K/hr through crystallization range.

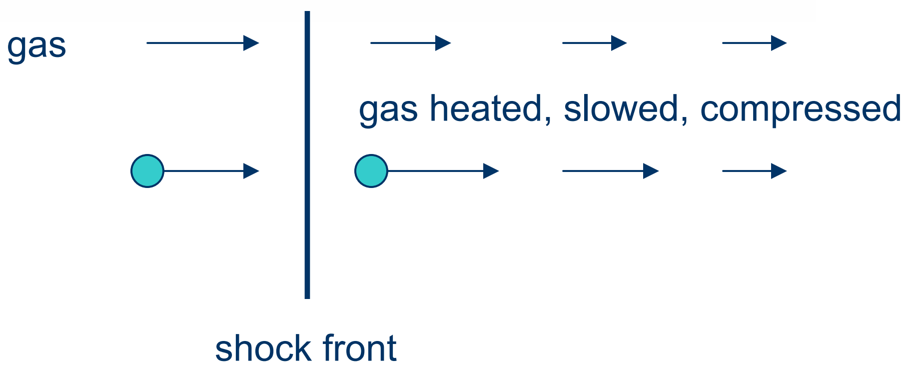
Desch & Connolly (2002)

Constraints on Thermal Histories



Chondrule Formation in Nebular Shocks





Chondrules heated by radiation before reaching shock front.

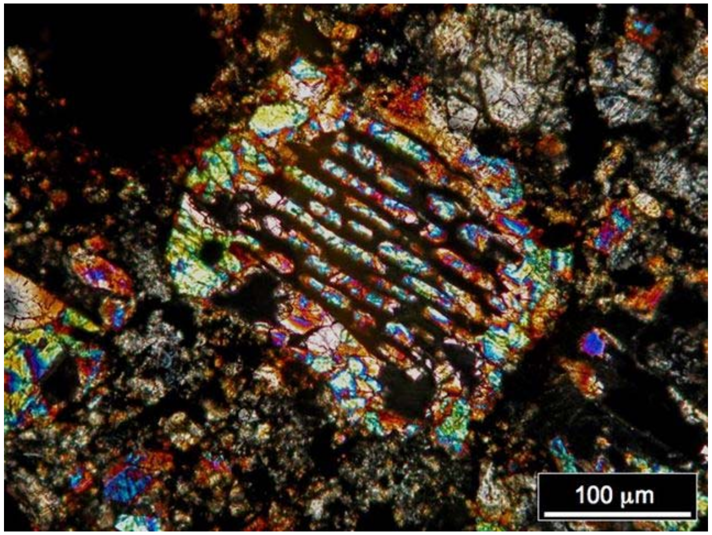
Chondrules heated by friction (peak heating) only in first few minutes past the shock front.

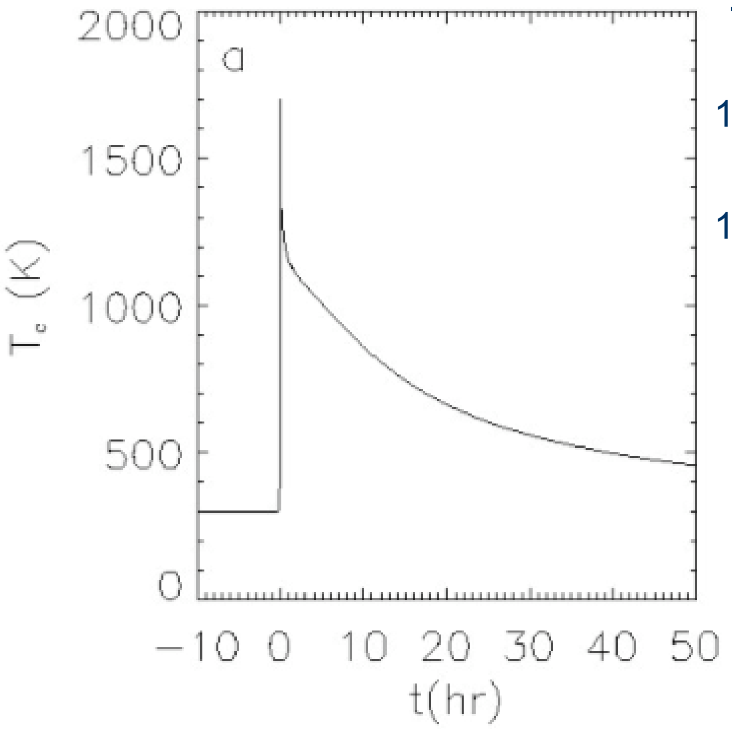
Chondrules heated minimally by thermal exchange.

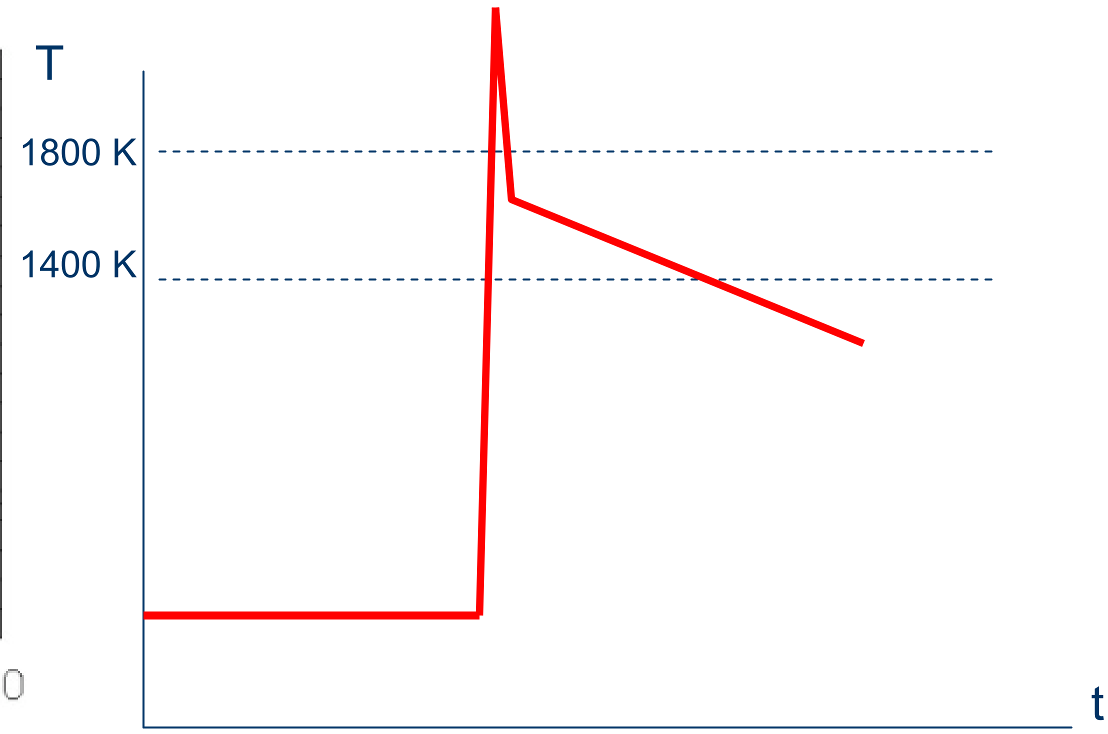
Cool only when they move many optical depths past the shock front. Cooling rates consistent with constraints.

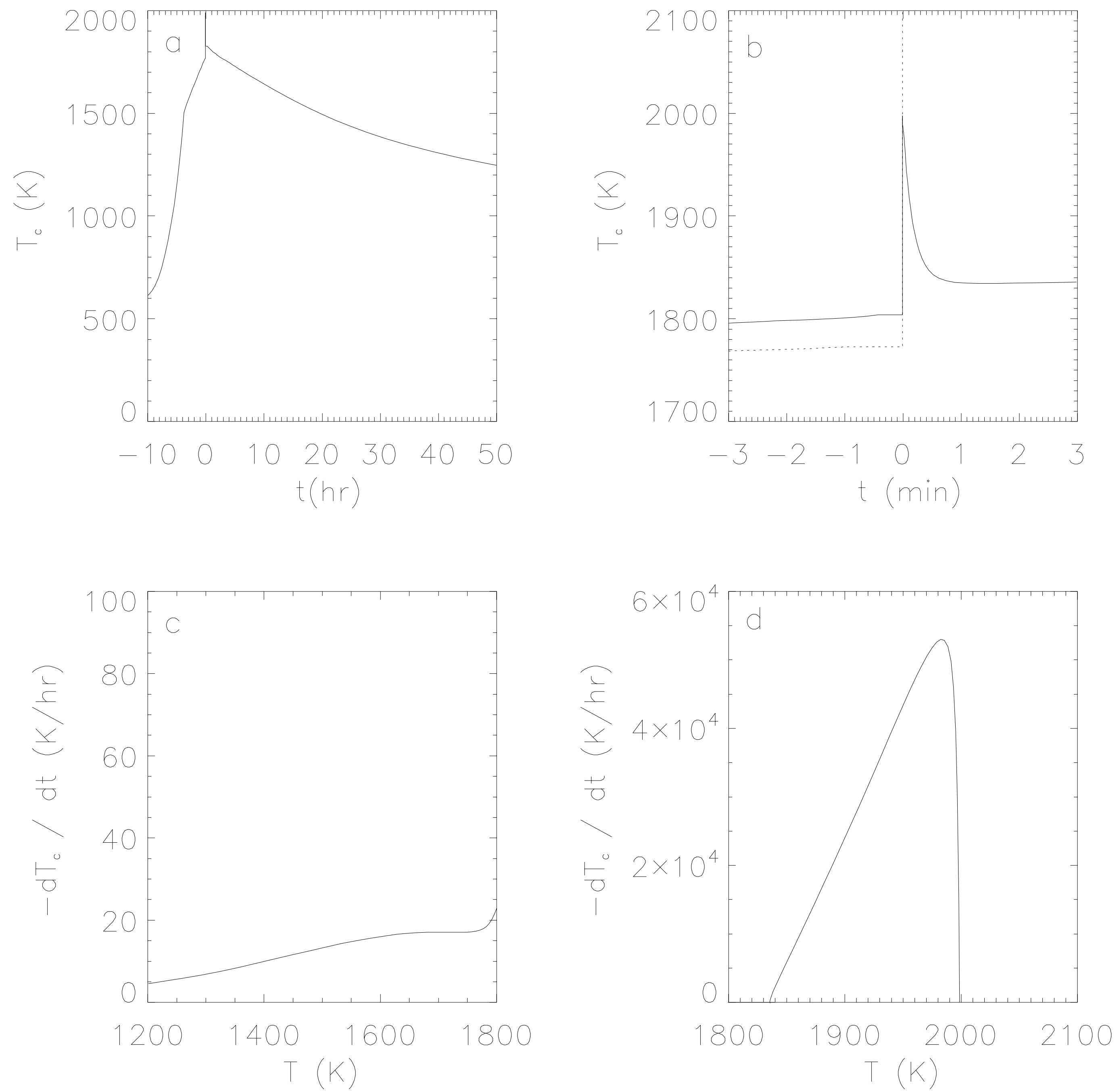
Desch & Connolly (2002)

Modeling of chondrule formation (Desch & Connolly 2002; Morris & Desch 2010) supports transient heating of chondrules in place by nebular shocks.









New results

V_s = 8 km s^{-1}

$\rho_0 = 10^{-9}$ g cm^{-3}

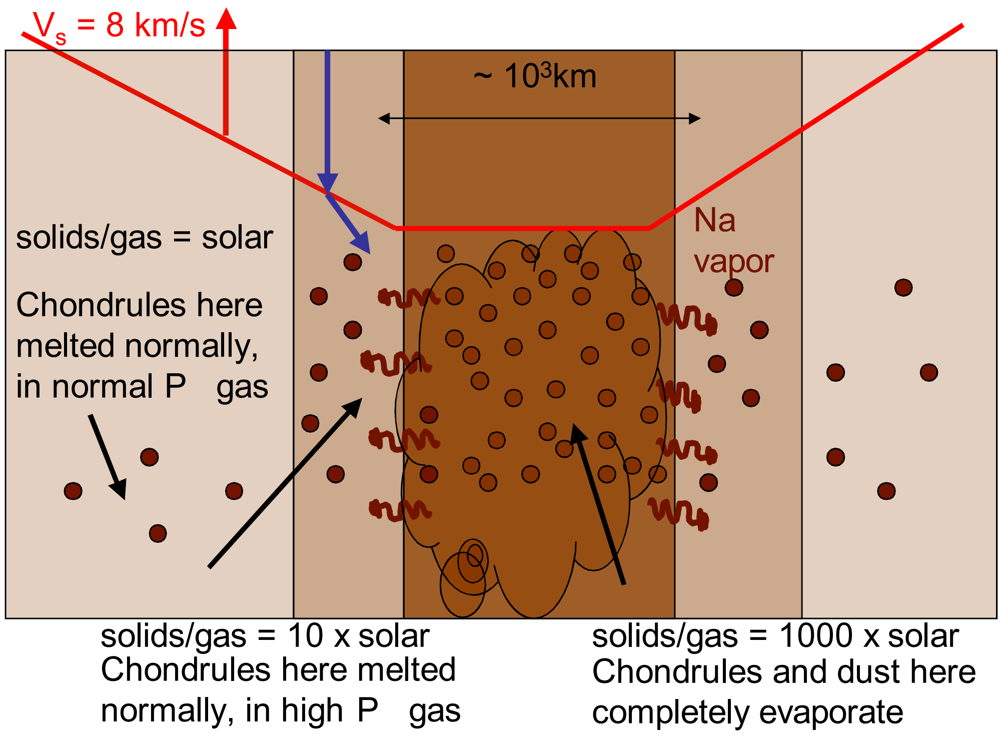
$\rho_s/\rho_g = 5 \times 10^{-2}$

(10 x solar)

Morris & Desch (2010)

Remaining Problems

- Heating too long in pre-shock region
  - No way to avoid – Marshak wave
  - 2-D model?
- Primary Na in olivine phenocrysts (Alexander et al. 2008)
  - Requires high partial pressure of Na vapor
  - “Supracanonical” chondrule densities?

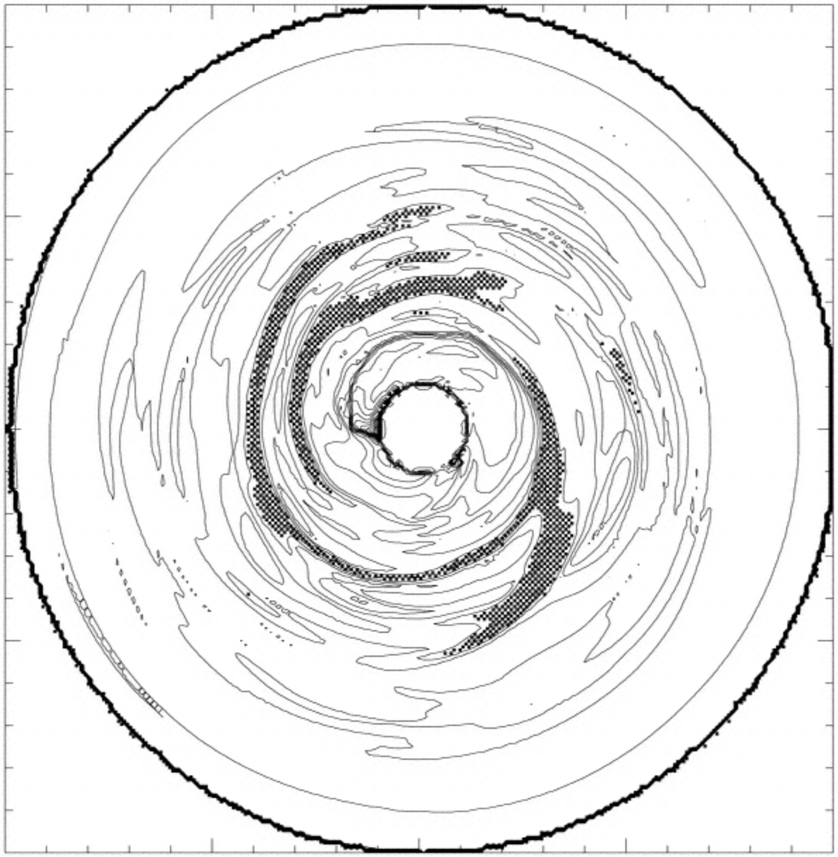


- Shock propagates more slowly through the clump than the surrounding gas .
- The trajectories of chondrules entering the shock refracted.
- Chondrules focused into the clump (after clump has experienced peak heating).
- Some fraction of chondrules should experience otherwise normal thermal histories indicative of moderate chondrule concentrations, but in the presence of very high pressures of chondrule vapor that can only arise from regions of higher chondrule concentration.

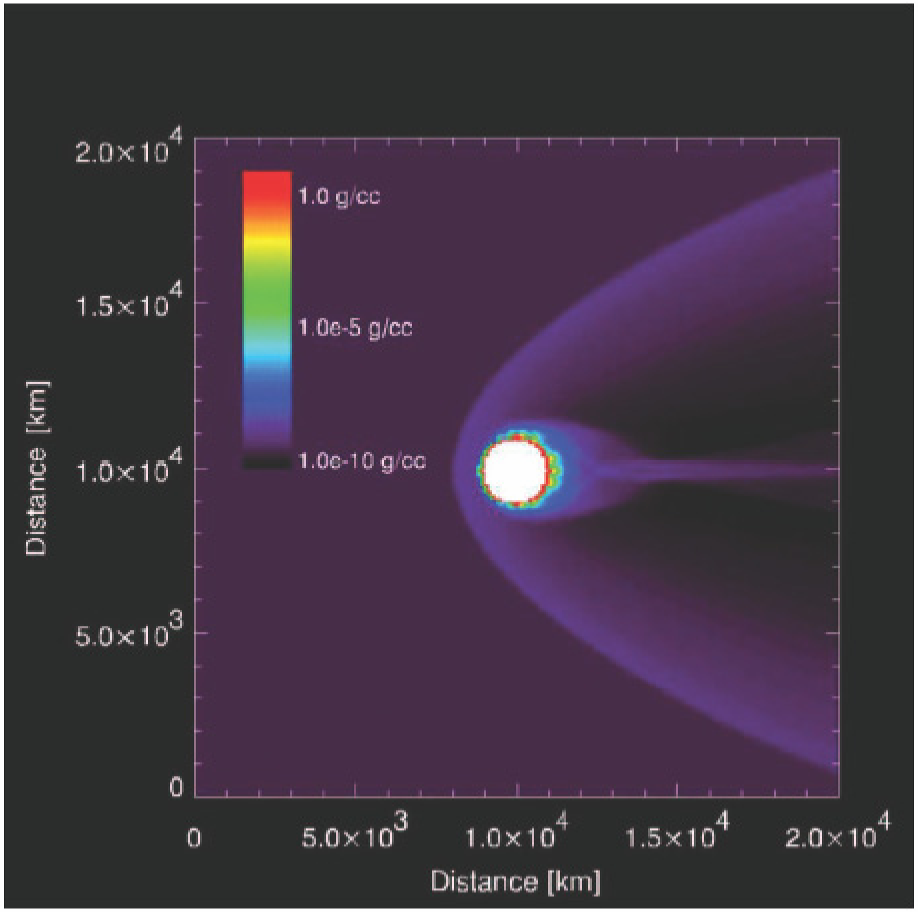
Requires 2-D Modeling

Summary

Our disk likely experienced frequent nebular shocks, driven by gravitational instabilities, in the inner nebula…OR



Planetesimal Bow Shocks?



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

Preliminary assessment indicates formation in bow shocks possible if:

large planetesimal AND
high chondrule concentrations

Requires 2-D modeling

Further Progress Requires:

2-D Hydrodynamic Modeling!