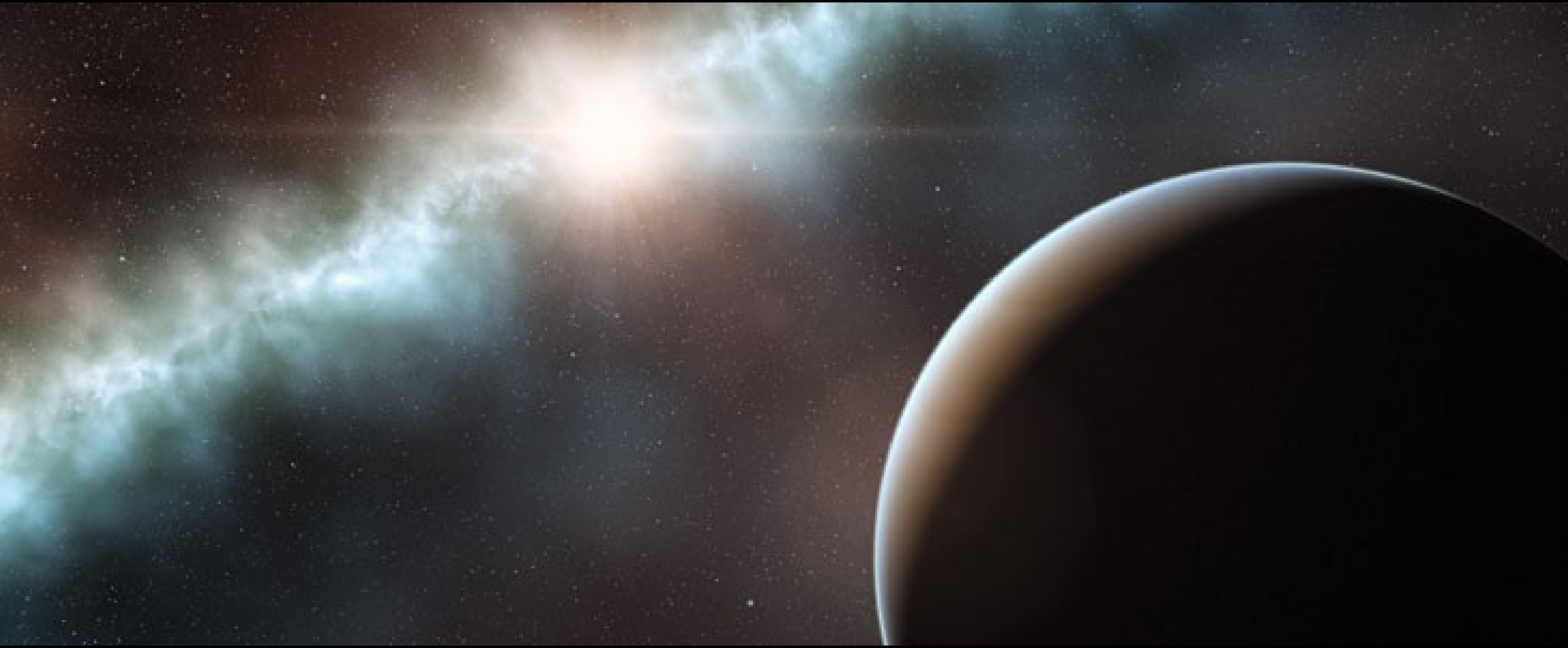
THE CHEMICAL ENVIRONMENT EXPERIENCED BY CHONDRULES FORMED IN PLANETARY EMBRYO BOW SHOCKS



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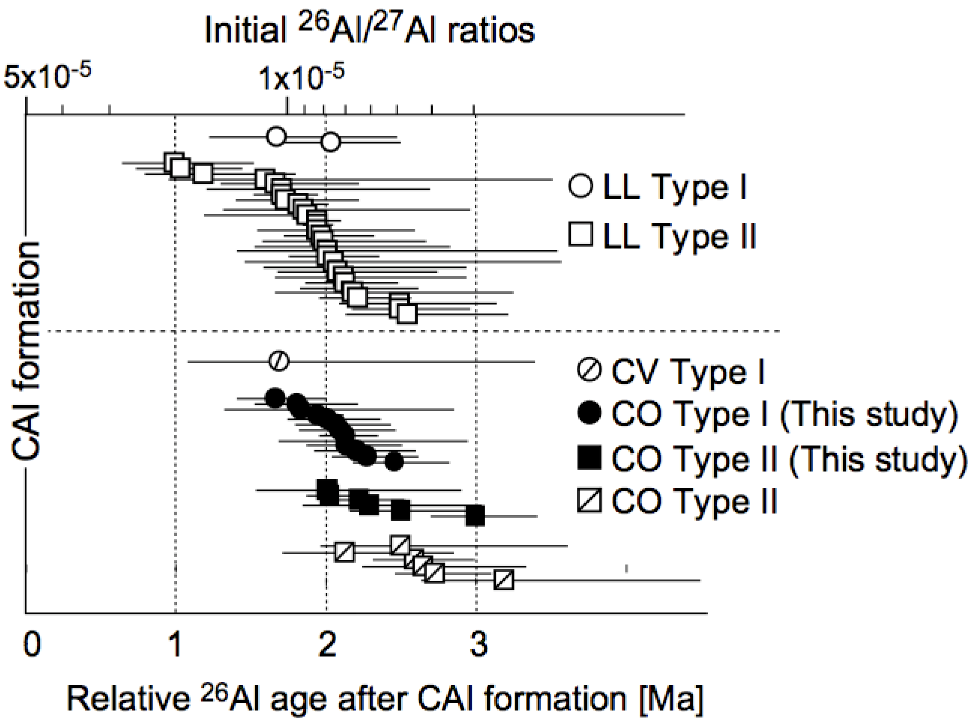
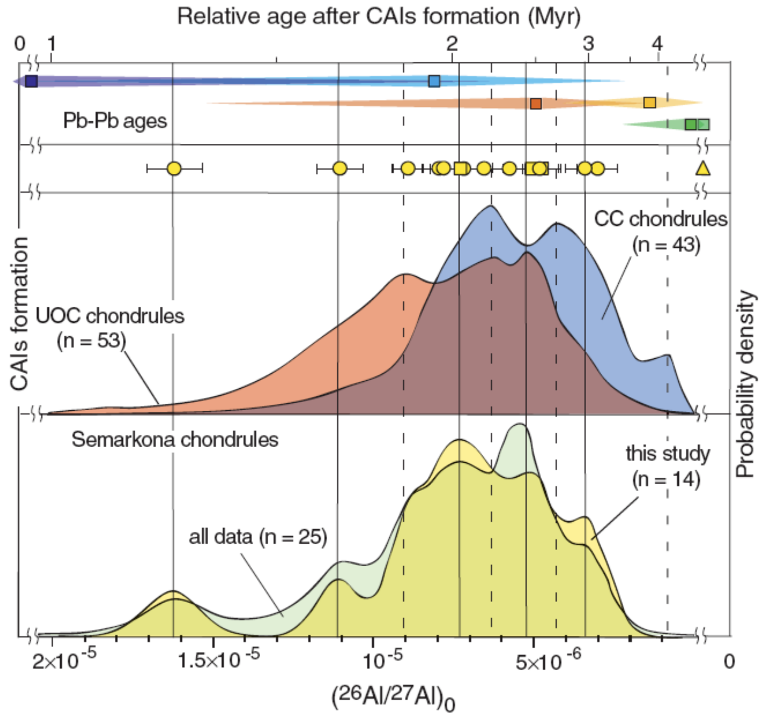
Outline

- Review constraints on chondrule formation
  - Timing of formation
  - Thermal constraints
- Discuss possible formation mechanisms
  - Gravitational instability-driven shocks
  - Planetesimal bow shocks
- Early formation of Mars
  - Embryos can form chondrules
  - Chemical environment of formation

Vast majority of chondrules formed ~ 2-3 Myr after CAIs



Kurahashi et al. (2008)



Villeneuve et al. (2009)

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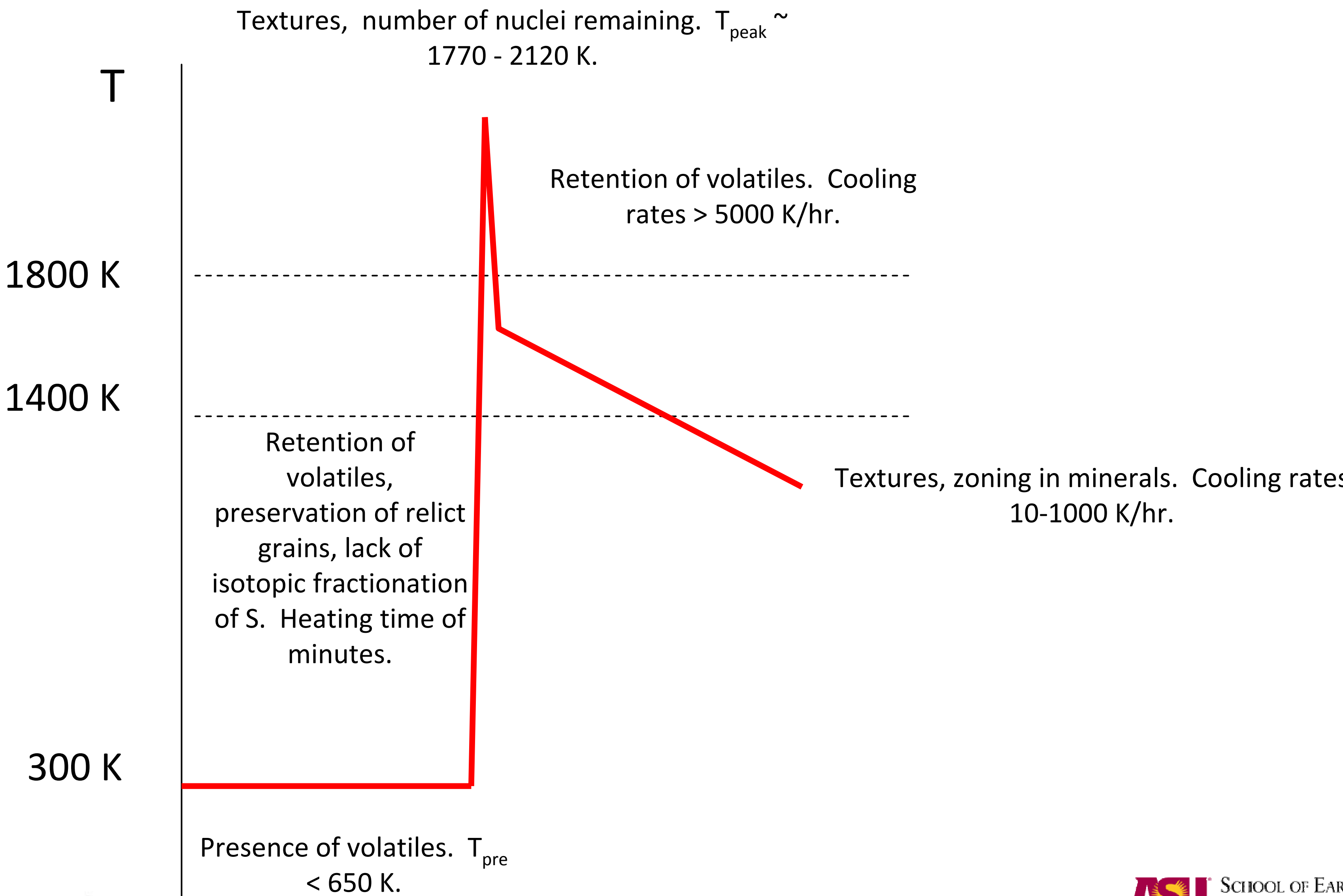
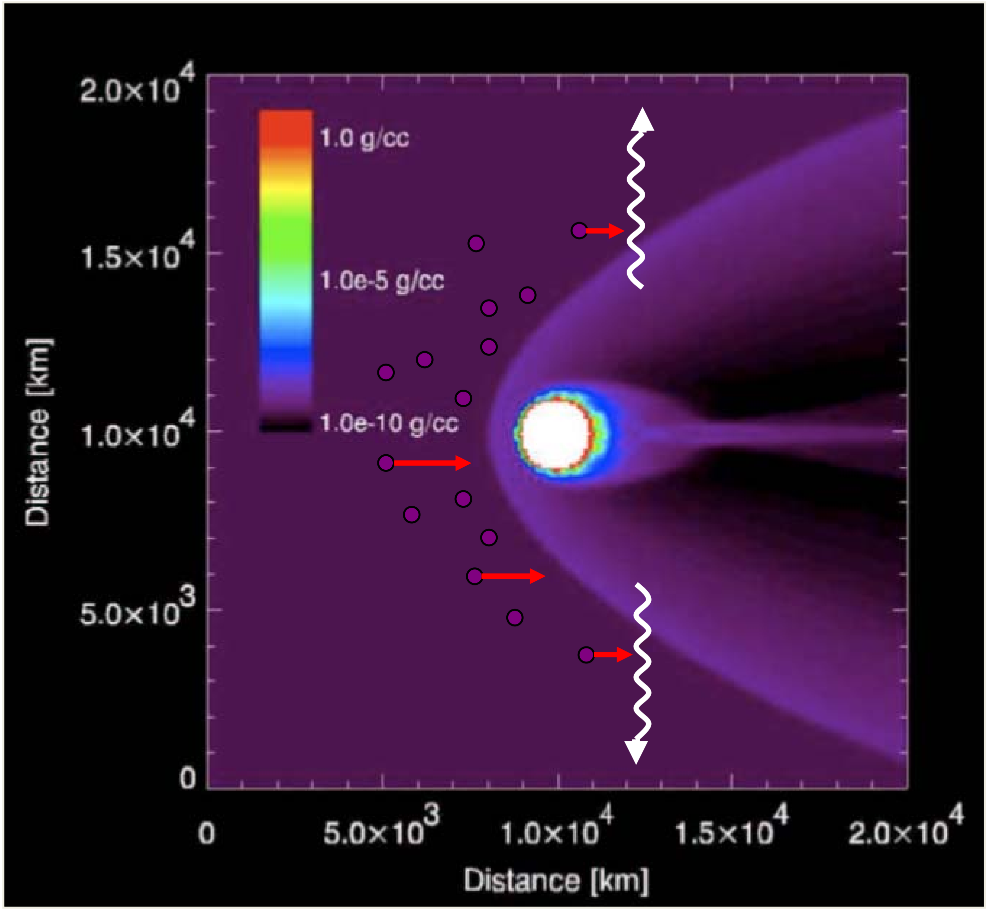
Constraints on thermal histories



Planetesimal Bow Shocks



Ciesla et al. (2004) (Chondrules not to scale)

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.

See also Thomson 1985; Hood et al. 1998; Weidenschilling et al. 1998; Hood et al. 2009.

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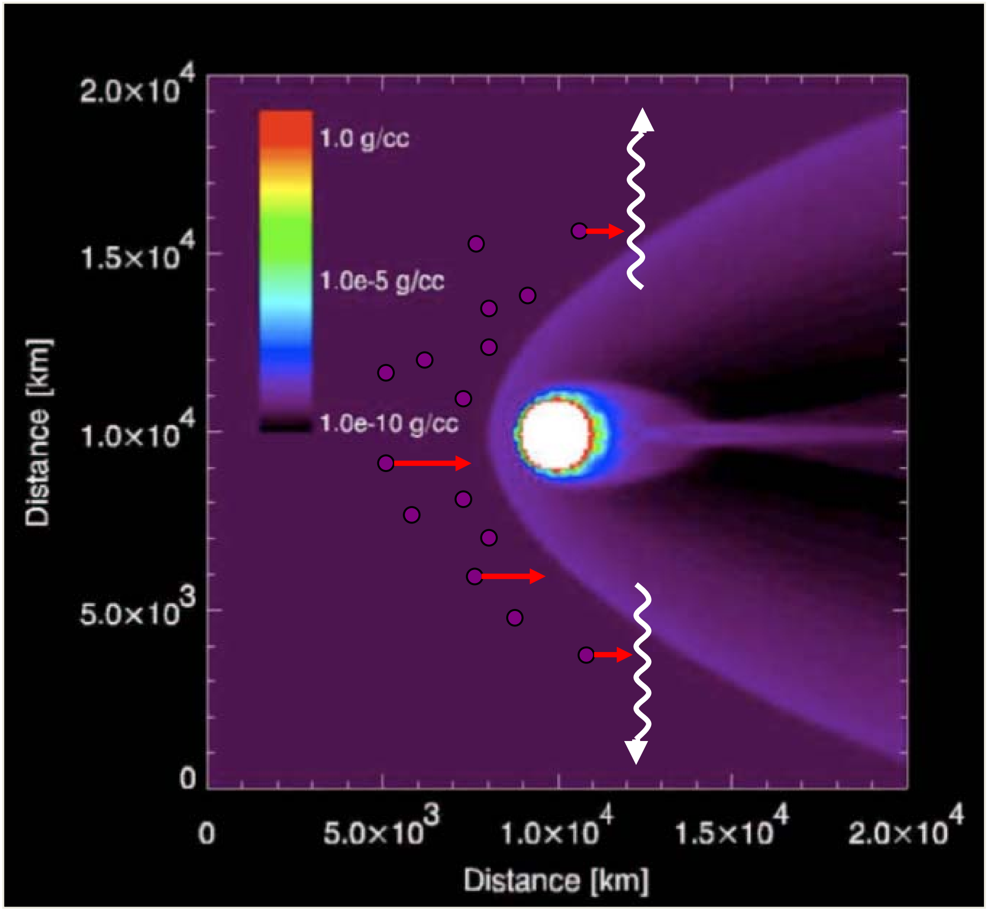
Planetesimal Bow Shocks



Ciesla et al. (2004) (Chondrules not to scale)

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

Morris et al. (2010a,b) have shown that for chondrule formation in a bow shock you need:

- large planetesimals
  - (D > 1000 km)
- high chondrule concentration
  - (30-200 x "solar")
- 100s of large planetesimals

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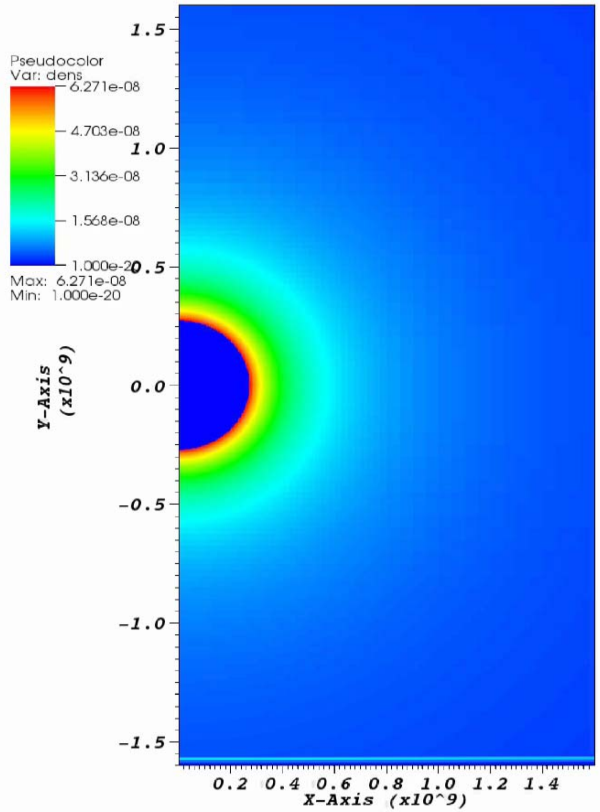
Planetary Embryos

- Mars has long been proposed to be a "starved planetary embryo" (Chambers & Wetherill 1998)
- Accretion models indicate planetary embryos could have formed in a few Myr (Wetherill & Stewart 1993; Weidenschilling et al. 1997).
- Hf-W ages suggest Mars formed in 1-10 Myr (Nimmo & Kleine 2007).
- Mars accreted 50% of its mass in 2 Myr, 90% by 4 Myr (Dauphas et al. 2011) .

Mars formed in presence of nebular gas!
Chondrule formation took place while Mars existed!

- Recent simulations conjecture that all the terrestrial planets formed in an annulus 0.7 – 1.0 AU. Model explains low mass of Mars. Mars is ejected from annulus very early (at a few Myr), potentially at 2 Myr (Hansen 2009; Walsh 2011) .
- Perihelion at 1.0 AU and aphelion at 1.5 AU imply a=1.25 AU and e=0.2. Typical inclinations 0° – 20°. Implies relative velocity 2.6 – 8.5 km/s as Mars crosses disk.
- **What are the thermal histories of chondrules passing through a planetary embryo bow shock?**
- **What is the chemical environment these chondrules are exposed to?**

Bow Shock Simulation
- used to determine structure

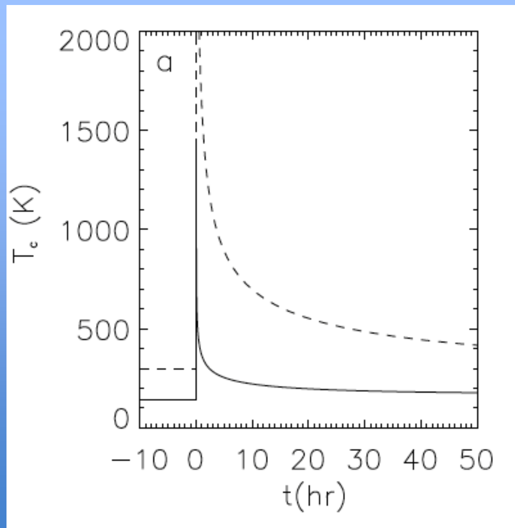


$R_p = 0.8\ R_{Mars} = 2720$ km

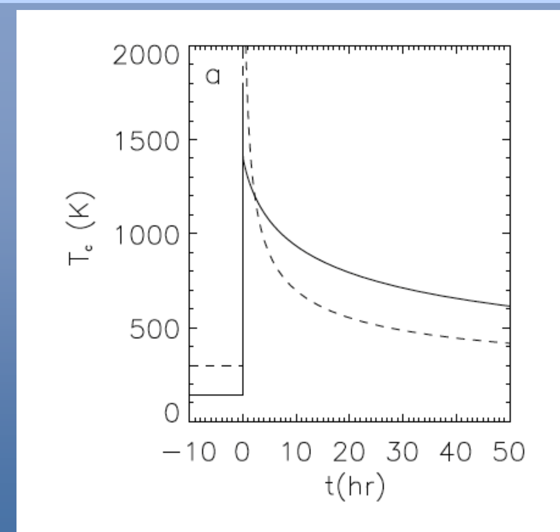
$V_s = 8$ km/s

Morris et al. (2012, *ApJ*, in revision)

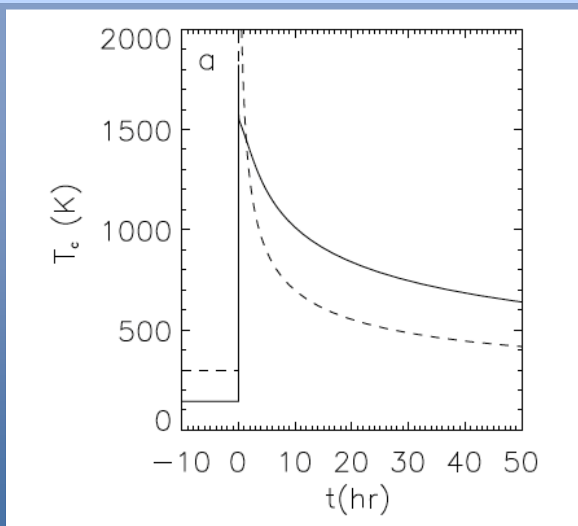
We have run 1-D code with effective optical depth τ to unshocked region: local radiation field J reduced, replaced by $B(T_{CH})+1/2\ [B(T_{BG})-B(T_{CH})]E_2(\tau)$, chondrules / gas mass ratio = 0.4%, gas 1×10^{-9} g cm^{-3} assumed.



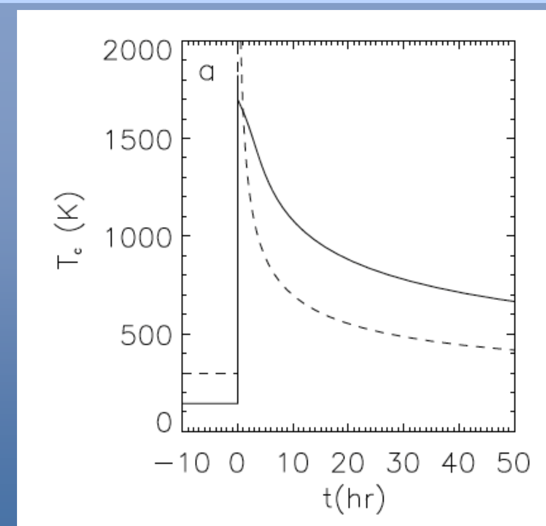
T(t) thermal history for Vs = 5 km/s – cooling rates much too rapid



T(t) thermal history for Vs = 6 km/s – cooling rates slightly too rapid *



T(t) thermal history for Vs = 7 km/s – cooling rates < 100 K/hr



T(t) thermal history for Vs = 8 km/s – cooling rates < 100 K/hr

Chondrules will reach peak temperatures ~ 2000 K, cooling rates < 100 K/hr, in shocks with V_s ~ 6-8 km/s.

a(AU)	e	i(degrees)	v_s (km/s)	$M_s(M_\oplus)$	Duration (yr)
1	0.1	0	3.0	-	-
1	0.2	0	6.1	8.3(-7)	1 000
1	0.3	0	9.4	7.4(-5)	21 000
1	0.4	0	13	1.1(-4)	29 000
1	0.1	7	4.8	-	-
1	0.2	7	7.2	2.5(-5)	12 000
1	0.3	7	10.2	6.5(-5)	24 000
1	0.4	7	13.7	7.4(-5)	22 000
1	0.1	15	8.4	4.6(-5)	43 000
1	0.2	15	10.1	3.7(-5)	31 000
1	0.3	15	12.5	3.6(-5)	25 000
1	0.4	15	15.6	4.3(-5)	22 000
1.5	0.1	0	2.5	-	-
1.5	0.2	0	5.0	-	-
1.5	0.3	0	7.7	3.7(-5)	32 000
1.5	0.4	0	11	8.9(-5)	64 000
1.5	0.1	7	3.9	-	-
1.5	0.2	7	5.9	-	-
1.5	0.3	7	8.3	5.1(-5)	55 000
1.5	0.4	7	11	6.5(-5)	56 000
1.5	0.1	15	6.9	1.3(-5)	37 000
1.5	0.2	15	8.2	2.7(-5)	68 000
1.5	0.3	15	10	2.9(-5)	63 000
1.5	0.4	15	13	3.6(-5)	58 000

$dM_c/dt = \sigma V_{rel} f C \rho_0$

$\sigma = \pi(4300 \text{ km})^2$

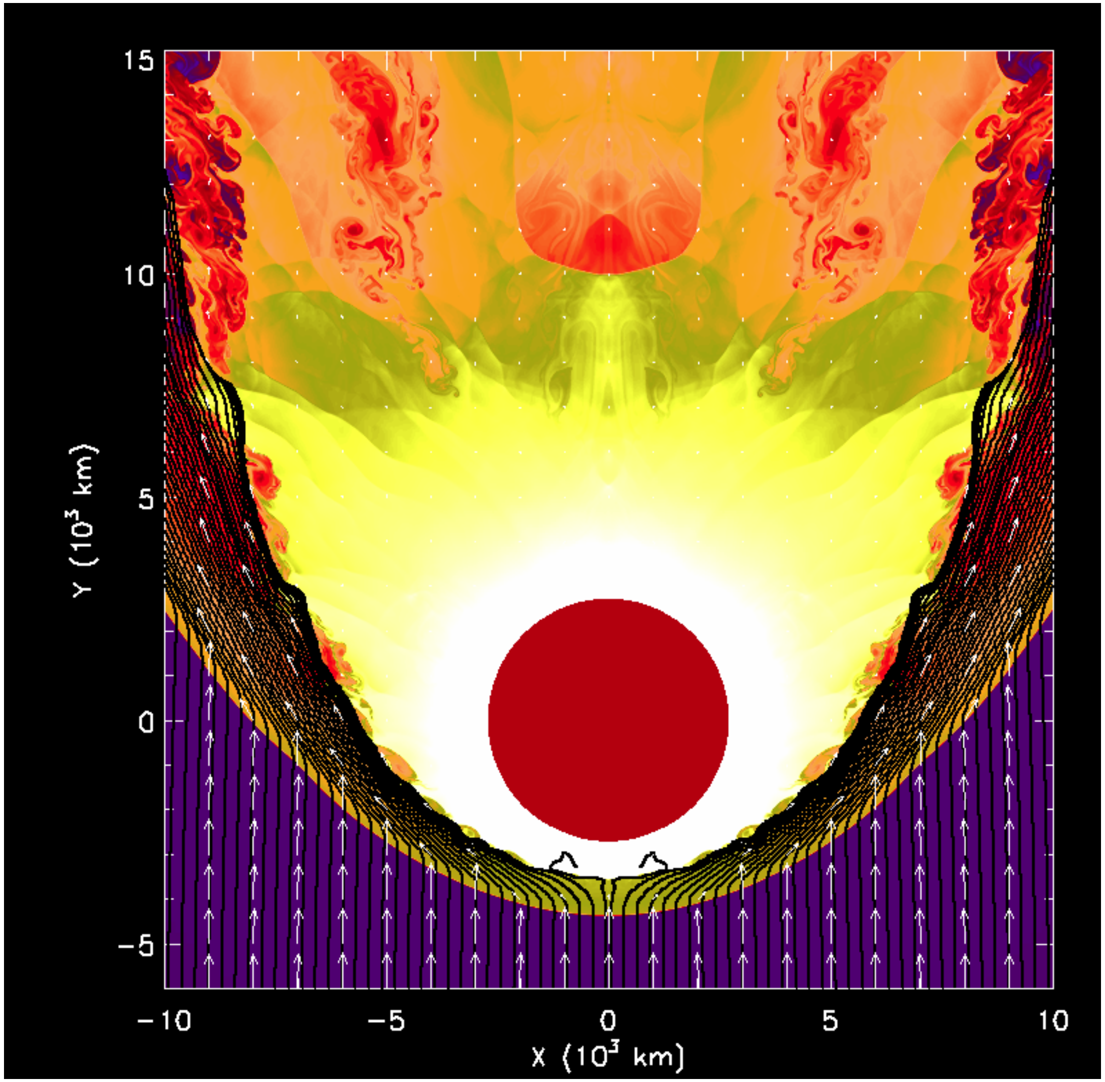
$V_s = 6 – 8$ km/s

$f = 3.75 \times 10^{-3}$

$C = 1$

Morris et al. (2012, *ApJ*, in revision)

Planetary Embryo, *r* = 2720 km



Standoff distance ~ 2000 km.

Chondrules move ~ 300 km
Before being recoupled to gas, so majority of chondrules are *NOT* accreted!

Chondrules are concentrated by factors of ~ 2-3.

Chondrules interact and sometimes are embedded in atmosphere.

Outgassing replenishes stripping CO_2, $H_2 0$, Na, & K for >> 10^5 yr.

Chondrules exposed to Na partial pressures orders of magnitude above "ambient".

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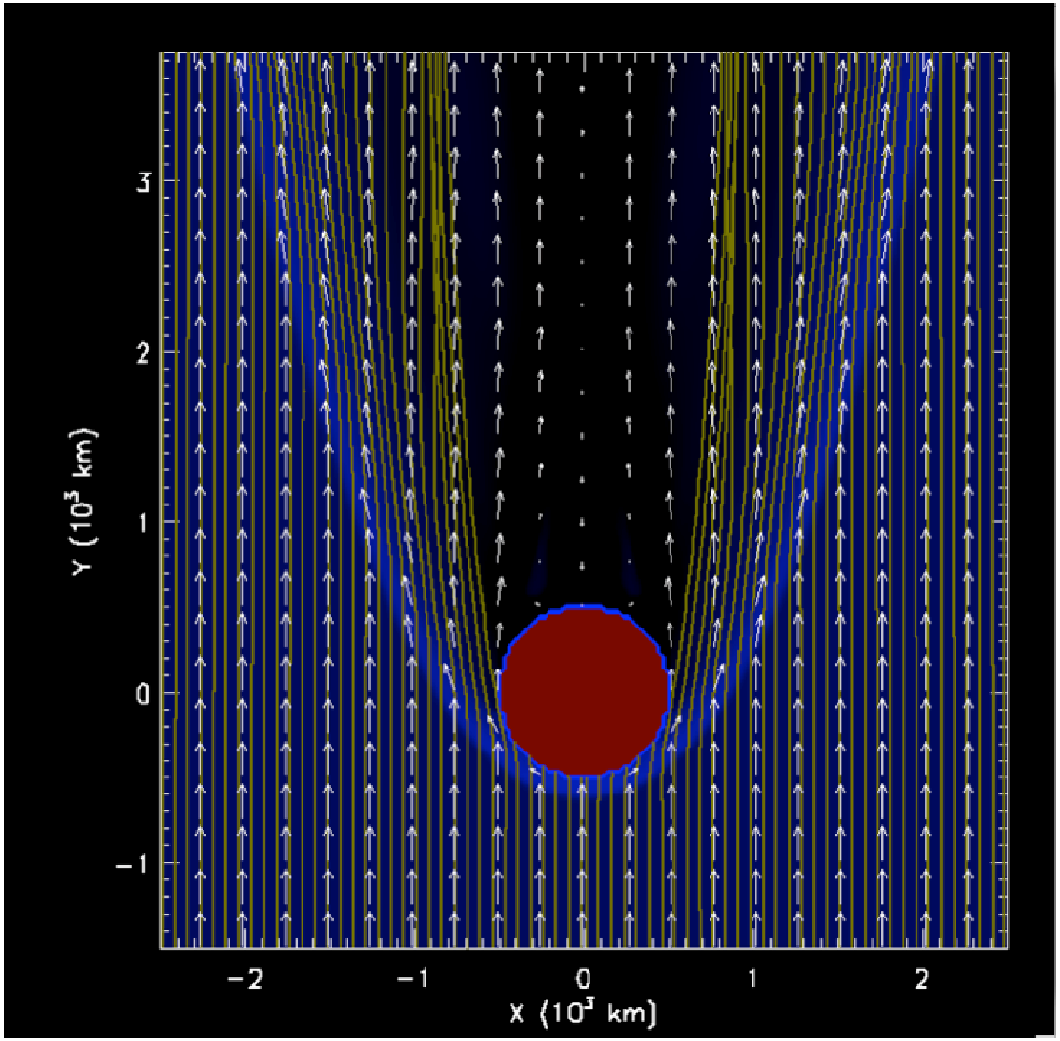
Planetesimal, *r* = 500 km



Standoff distance ~ 110 km.

Chondrules still move ~ 300 km
Before being recoupled to gas, so
all chondrules *ARE* accreted!

Chondrules *WILL NOT* survive in
bow shocks around planetesimals!

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Chemical Environment of Chondrule Formation

•High Na

- High mass fractions of Na_2O in olivine phenocrysts of chondrules (Alexander et al. 2008)
- Implies Na in melt through crystallization
- Implies high partial pressures of Na vapor ≈ 2×10^{-5} bar
- Implies chondrule concentrations 10^6 times solar

•High FeO (Fedkin & Grossman 2006; et al., Grossman et al. 2008,2011; Fedkin et al, 2011)

- Implies oxygen fugacities 5-6 log units above solar
- Implies water enrichments 240-820 over solar
- Implies water vapor pressures ≈ 4×10^{-5} bar

•Calculated partial pressures of volatiles in chemical equilibrium with magma ocean

- Assume mass fraction x_{H20} = 0.2 wt% (representative of Mars; e.g. Craddock & Greely 2009)
- Calculate outgassing of Na following formulation of van Limpt (2006)
- Partial pressure at surface: $P_{H20} \approx 3.3$ bar, $P_{Na} \approx 2 \times 10^{-3}$ bar
- Use 1% of calculated surface values (altitude ~ 800 km above planet)
  - ➔ $P_{H20} \approx 3 \times 10^{-2}$
  - ➔ $P_{NaOH} \approx 2 \times 10^{-5}$

Conclusions

•Chondrules can form in bow shocks around large planetesimals only in areas with extremely high chondrule concentrations. Even if they do, they are accreted to the body, therefore do not survive for later incorporation into chondrite parent bodies.

•Planetary embryos appear to have been present during the epoch of chondrule formation.

•For a range of plausible inclinations and eccentricities, protoplanets produce bow shocks with speeds necessary for chondrule formation.

•Chondrules are not accreted and are concentrated to levels consistent with compound chondrules and lack of volatile loss.

•Spatial environment around planetary embryos may be rich in species outgassed from the protoplanet itself, perhaps explaining elevated oxygen fugacities and partial pressures of Na.

•Apparent ~ 2 Myr time gap between CAIs and chondrules naturally explained.

•A small number of planetary embryos/scattering events (≤ 10) can produce the observed mass of chondrules, consistent with meteoritic constraints.

•Multiple planetary embryos could explain the diversity of chondrule sizes, compositions, and textural types.