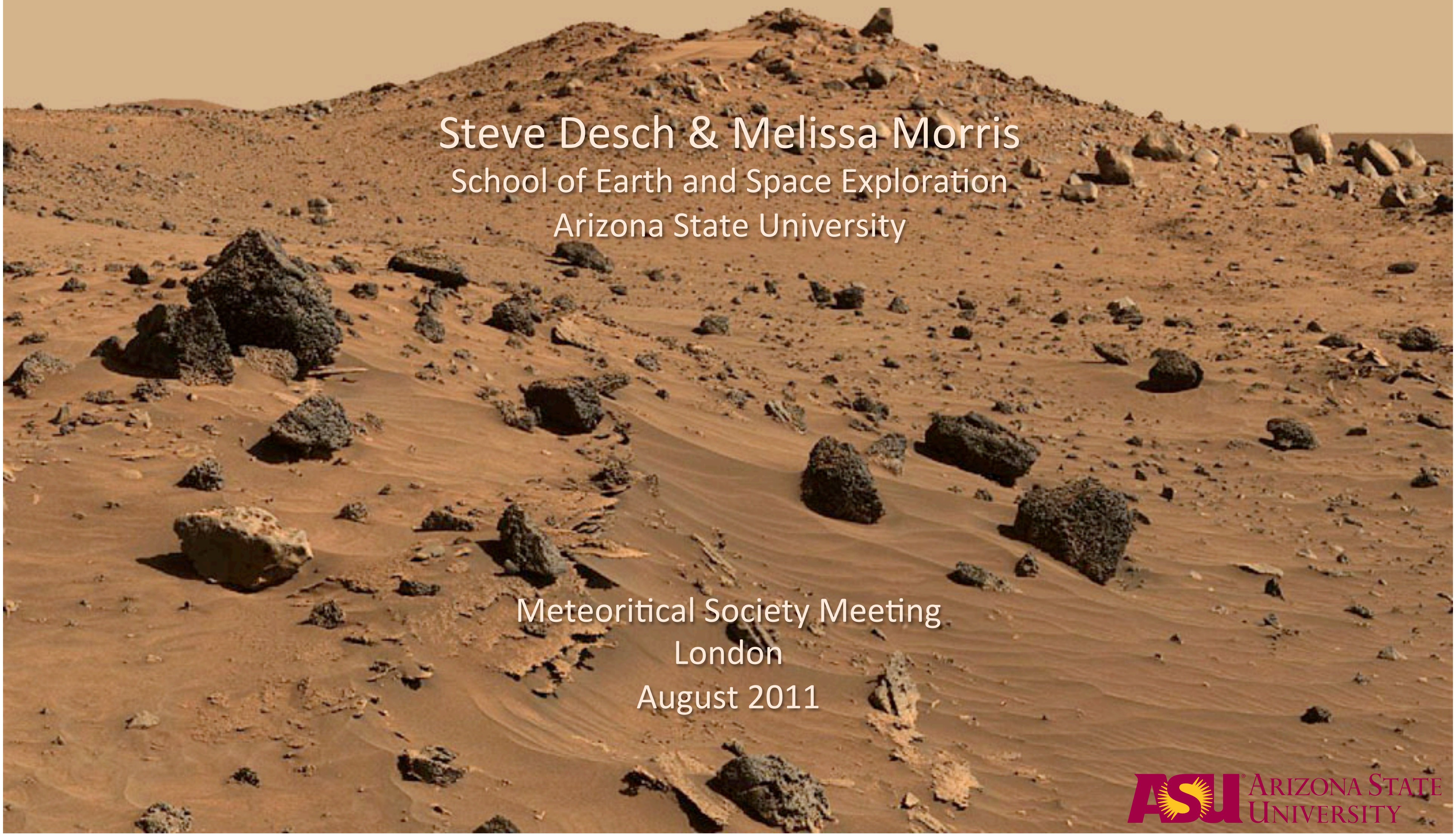
Did Mars Make Chondrules?



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Meteoritical Society Meeting

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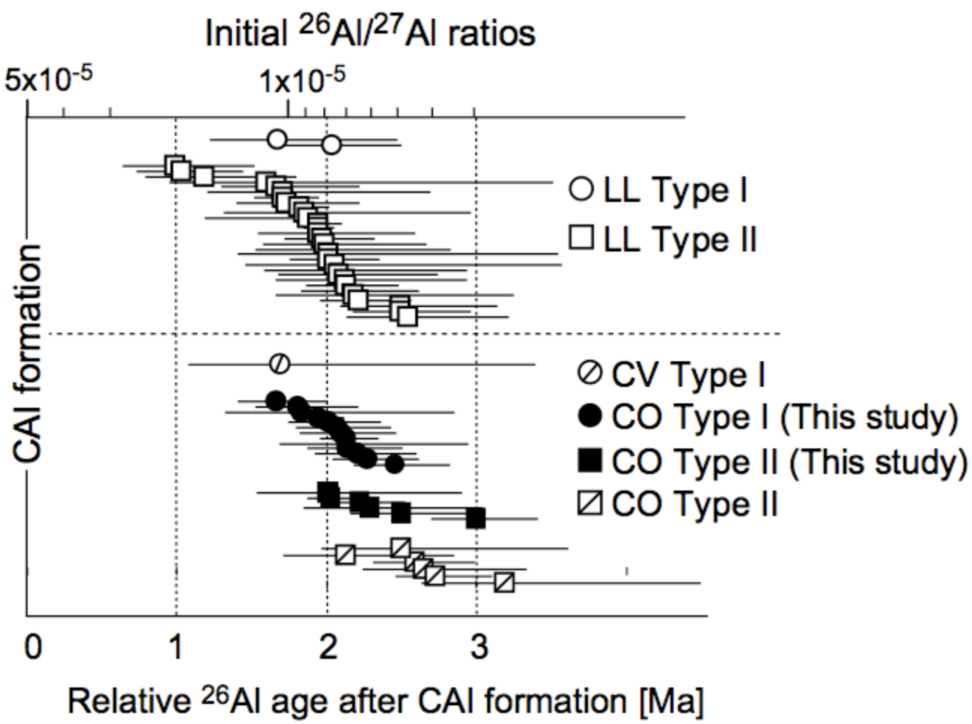
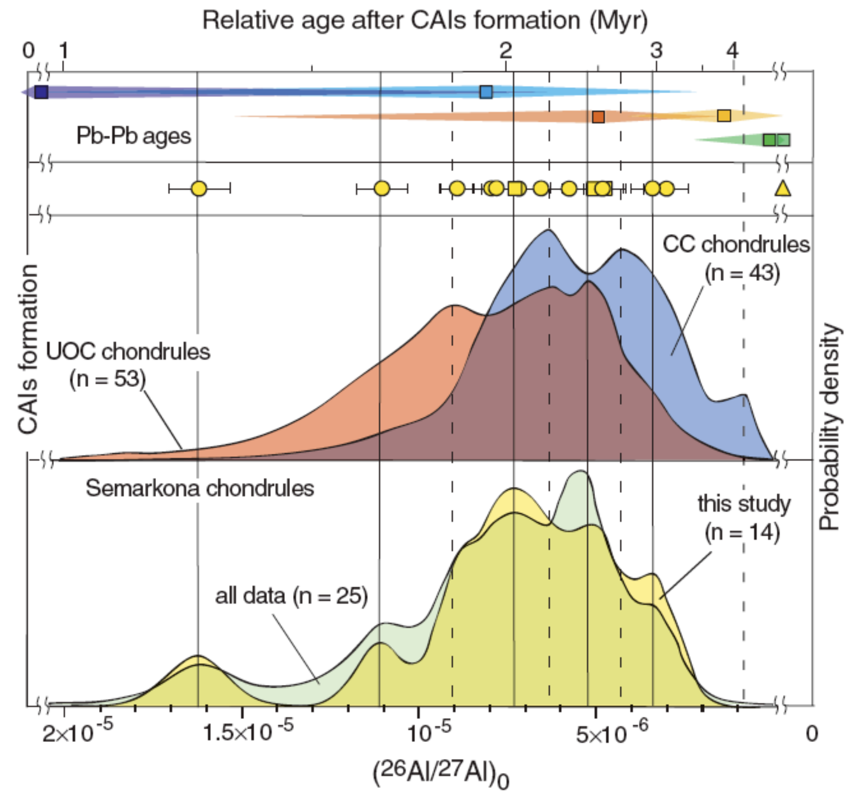
Outline

- Review constraints on chondrule formation
  - Timing of formation
  - Thermal constraints
- Discuss formation mechanisms
  - Gravitational instability-driven shocks
  - Planetesimal bow shocks
- Large planetesimal – **Mars!**
  - Can Mars form chondrules?

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



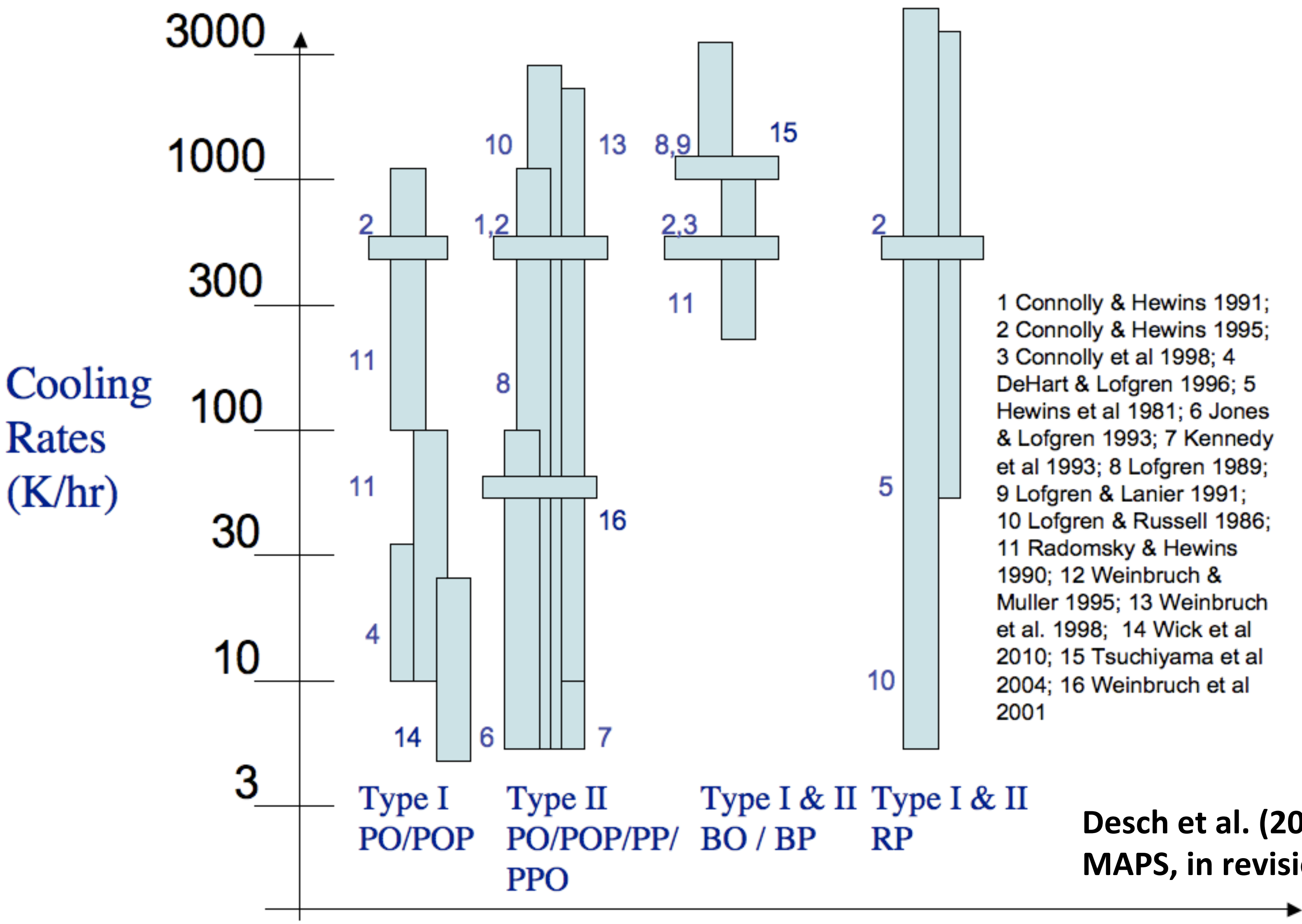
Kurahashi et al. (2008)



Villeneuve et al. (2009)

Vast majority of chondrules were heated and cooled in hours, at rates ~ 10-10^3 K/hr

> 80% of chondrules in ordinary chondrites are porphyritic (Gooding & Keil 1981), which cooled at rates < 10^3 K/hr. [Chemical zoning may favor low end ~ 10 K/hr (Jones & Lofgren 1993).]



Desch et al. (2011), MAPS, in revision

Chondrule formation in nebular shocks can satisfy these and all known constraints, especially thermal histories.

Large-scale shocks driven by gravitational instabilities match thermal histories.

Planetesimal bow shocks proposed (Hood 1998; Ciesla & Hood 2004; Hood et al. 2009; Hood & Weidenschilling 2011) but cooling rates *appear* to be too rapid (Ciesla & Hood 2004; Morris et al. 2010a, 2010b).

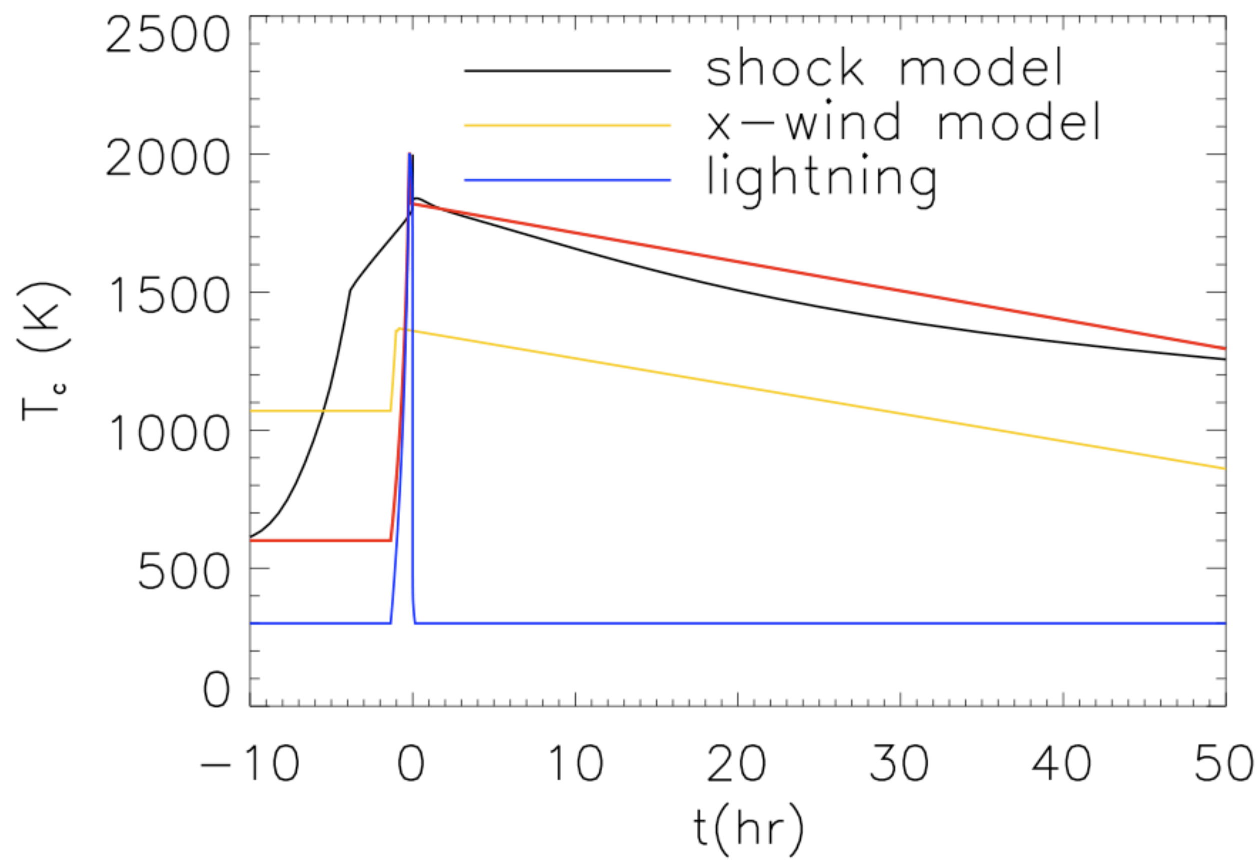


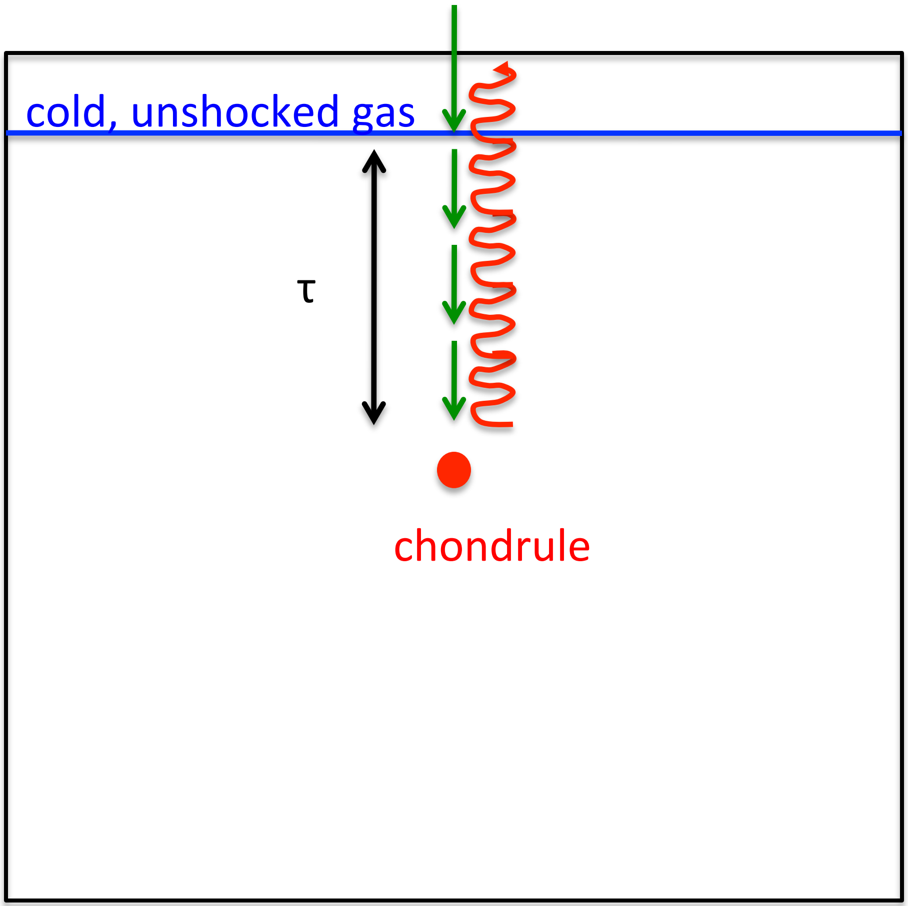
Table 1. Non-Thermal Constraints on Chondrule Formation

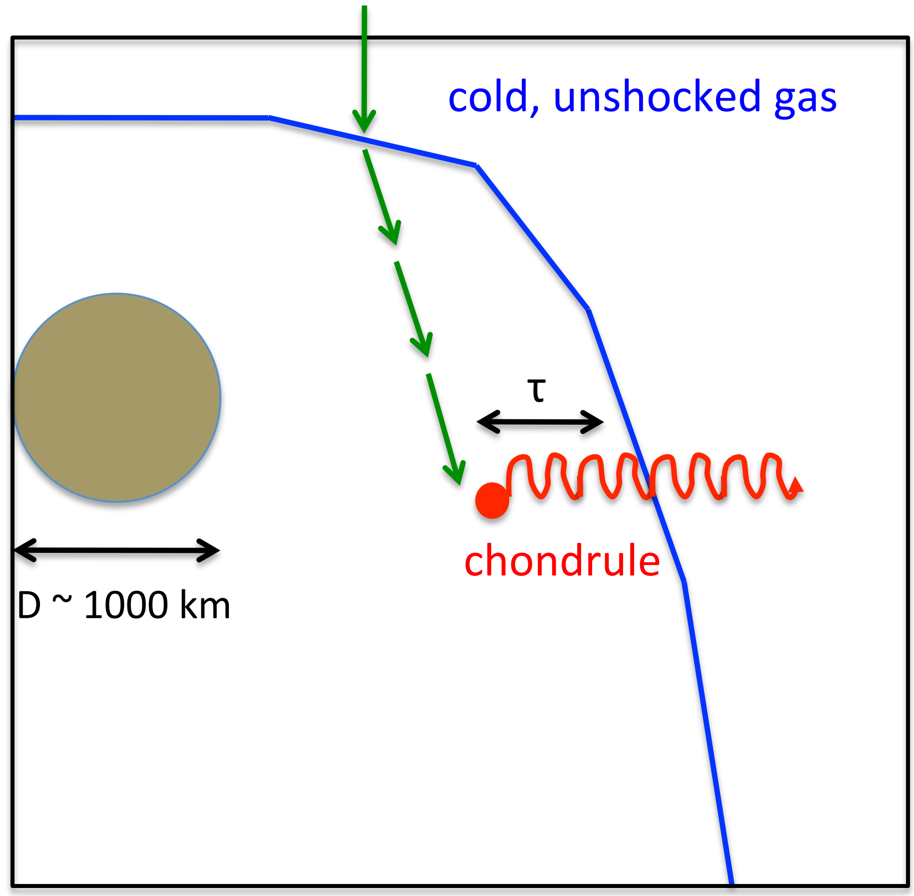
Constraint	X-wind	Lightning	Bow Shocks	GI shocks
$L \gg 10^3$ km	✓	X	?	✓
$n_c \sim 10\,\mathrm{m}^{-3}$	✓	?	?	?
$P > 10^{-3}$ atm	✓	X	✓	✓
fO_2 variable, oxidizing	?	?	?	?
Chondrules, matrix cogenetic	X	✓	✓	✓
Form $\approx 1.6 - 3$ Myr after CAIs	X	✓	✓	✓

Table 2. Constraints on Chondrule Thermal Histories

Constraint	X-wind	Lightning	Bow Shocks	GI shocks
Ambient $T < 650$ K	X	✓	✓	✓
Heating Duration < 10 minutes	X	✓	✓	?
Peak $T \gtrsim 2000$ K	X	?	✓	✓
Cooling rate from peak $\sim 10^3 - 10^4\,\mathrm{K\,hr^{-1}}$	X	?	✓	✓
Crystallization cooling rate $\sim 10 - 10^3\,\mathrm{K\,hr^{-1}}$ (porphyritic)	✓	X	?	✓
Crystallization cooling rate $\sim 10^2 - 10^3\,\mathrm{K\,hr^{-1}}$ (barred)	X	X	?	✓
Cooling rate correlates with chondrule density	X	X	?	✓

Desch et al. (2011; MAPS, in revision)





Chondrules / gas heated by large-scale ($> 10^5$ km) shocks (e.g., due to gravitational instabilities) necessarily see τ ~ a few to cold gas.

Cooling rates are naturally 10 – 100 K/hr, depending on chondrule density (Desch and Connolly 2002; Ciesla & Hood 2002; Morris and Desch 2010).

Chondrules / gas heated by planetesimal bow shocks radiate into cold, unshocked gas. Typically τ << 1 so they cool like optically thin gas at rates >> 10^4 K/hr (Ciesla et al. 2004).

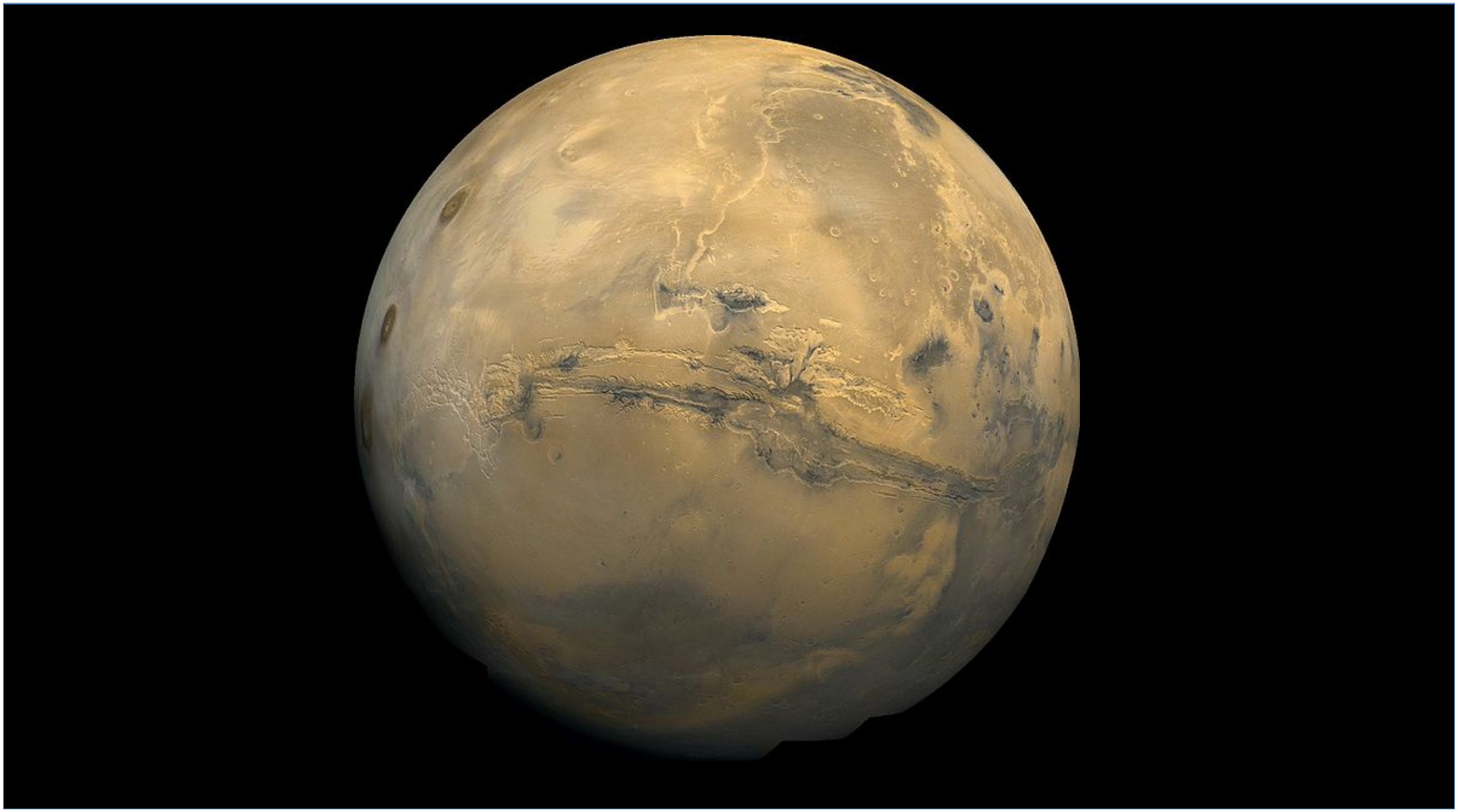
Buffering by H_2 recombinations and increase in optical depth τ can slow cooling rate to ~ 10^3 K/hr (Morris et al. 2010a,2010b).

Buffering of cooling by H_2 recombination reduces cooling rates by an order of magnitude (Morris et al. 2009 LPSC), but to produce slowly cooling chondrules, the planetesimal bow shock model really needs ***larger planetesimals***.

We consider the largest planetesimal of all:

Buffering of cooling by H_2 recombination reduces cooling rates by an order of magnitude (Morris et al. 2009 LPSC), but to produce slowly cooling chondrules, the planetesimal bow shock model really needs ***larger planetesimals***.

We consider the largest planetesimal of all: **MARS!**



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).

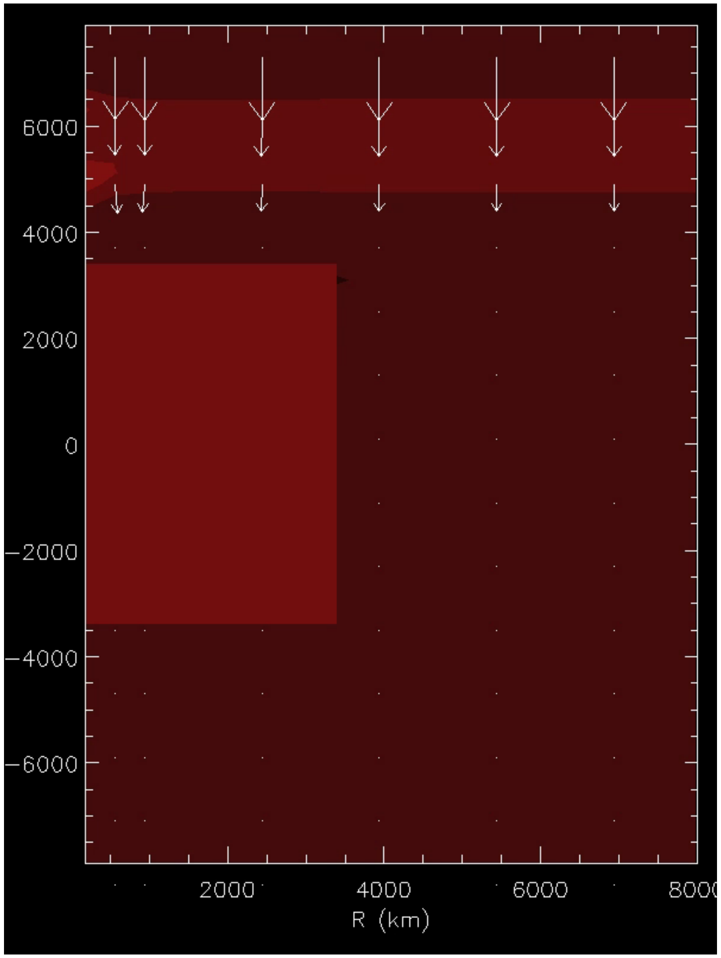
Hf-W ages suggest Mars formed in 1-10 Myr (Nimmo & Kleine 2007).
Dauphas et al. (2011) find Mars accreted 50% of its mass in 2 Myr, 90% by 4 Myr.
Mars formed in presence of nebular gas!
Chondrule formation took place while Mars existed!

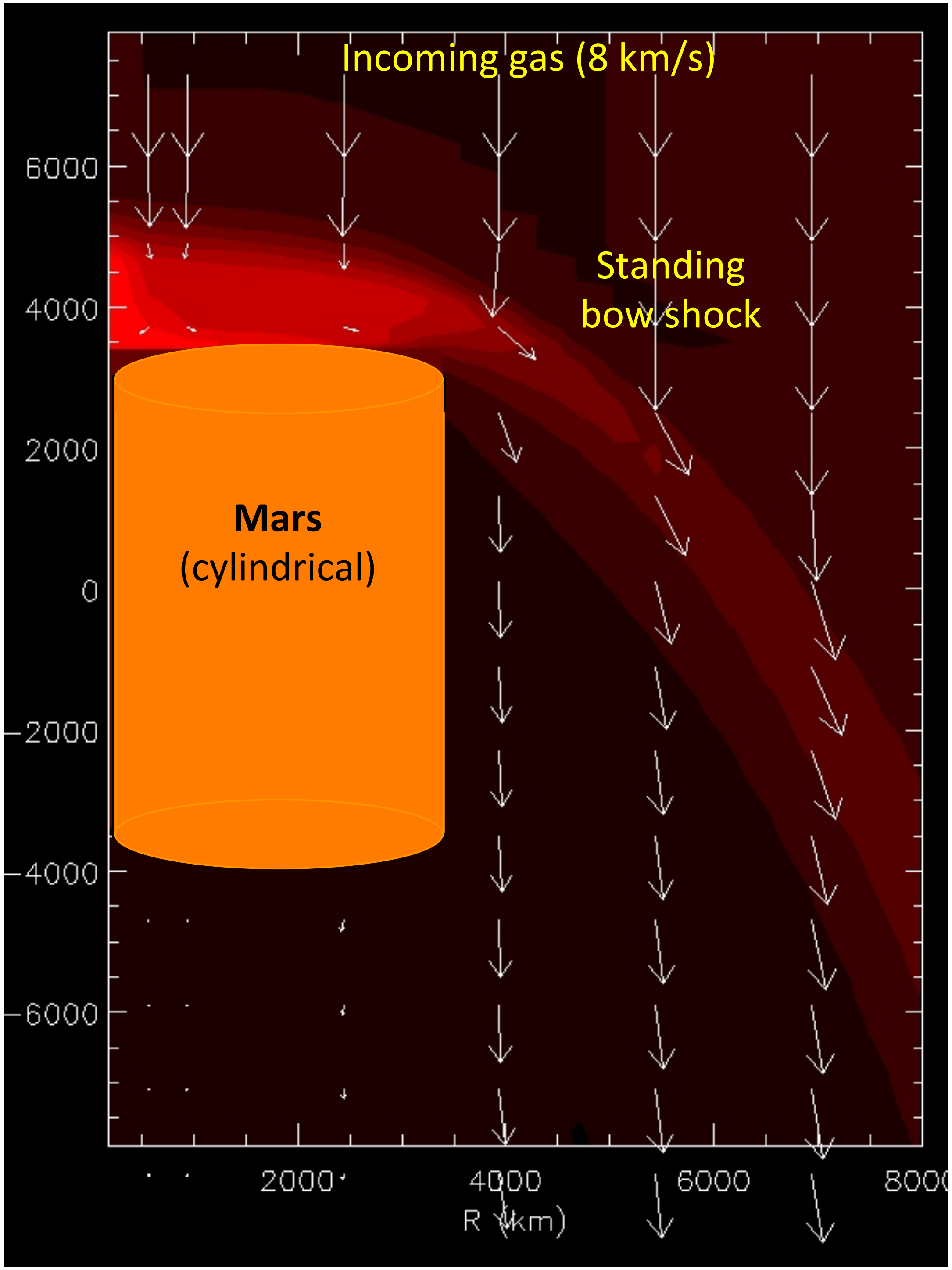
Recent simulations by Hansen (2009) conjecture that all the terrestrial planets formed in an annulus 0.7 – 1.0 AU. Model explains low mass of Mars. Mars is ejected from annulus very early (at a few Myr), potentially at 2 Myr.

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 Mars's bow shock?

Bow Shock Simulation

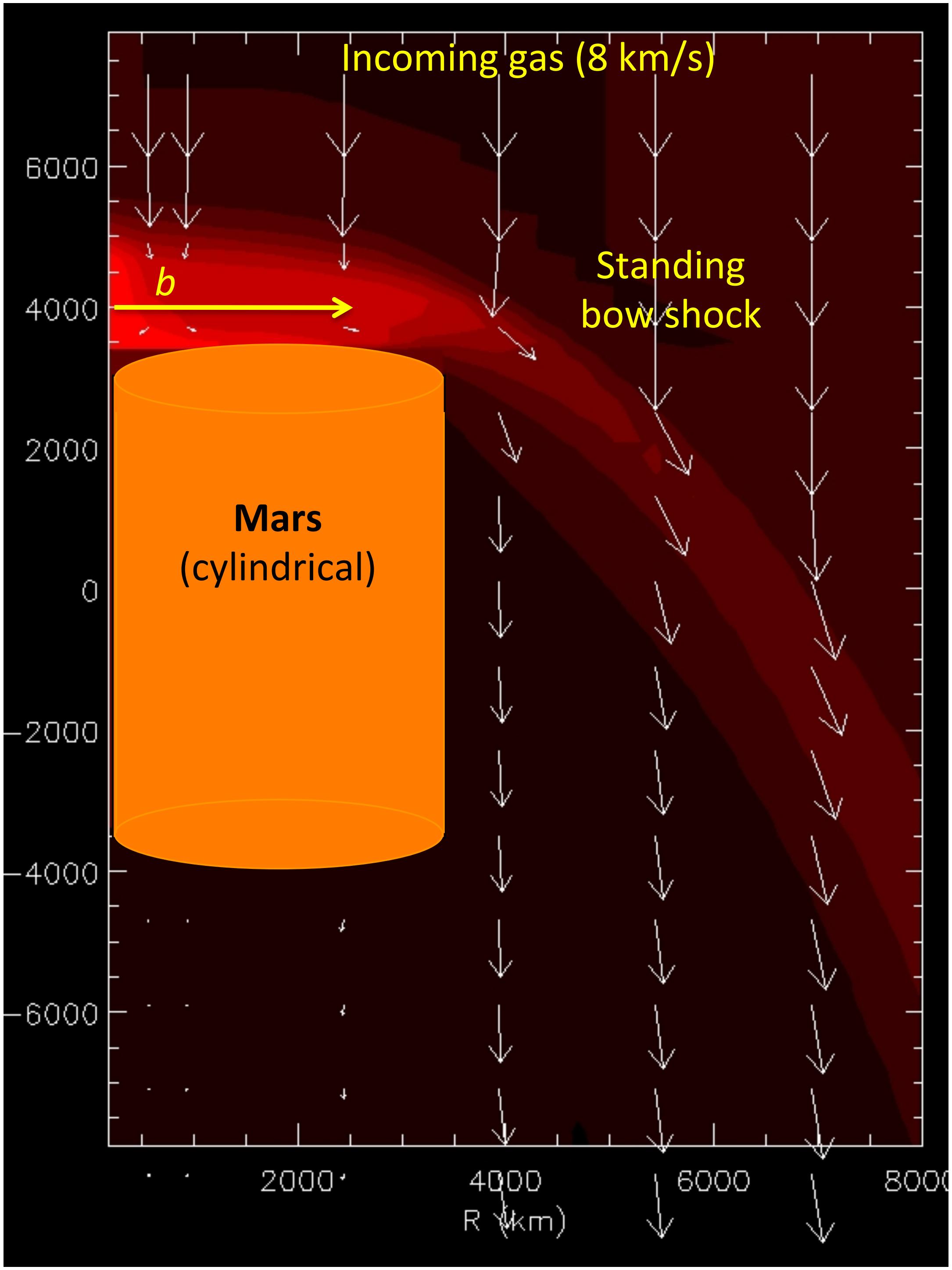




Hydro code:
We are currently developing a 2-D hydrodynamics code including internal boundary conditions and radiative transfer in cylindrical geometry.

Based on code of Ouellette et al. (2007, 2010), in turn based on Zeus-2D (Stone & Norman 1992).

Progress to date:
- Simple internal boundary conditions (soda can) added so far, but more complicated (spherical) BCs need testing.
- Radiative transfer module written, but not yet incorporated into hydro code.
- Able to determine shock structure



<u>Dust dynamics</u>:

Chondrules entrained in gas on stopping time $t_{stop} = \rho_s\, a / \rho_g\, C = 50$ s

$\rho_s = 3$ g cm^{-3} = silicate density

$a = 300$ µm = chondrule radius

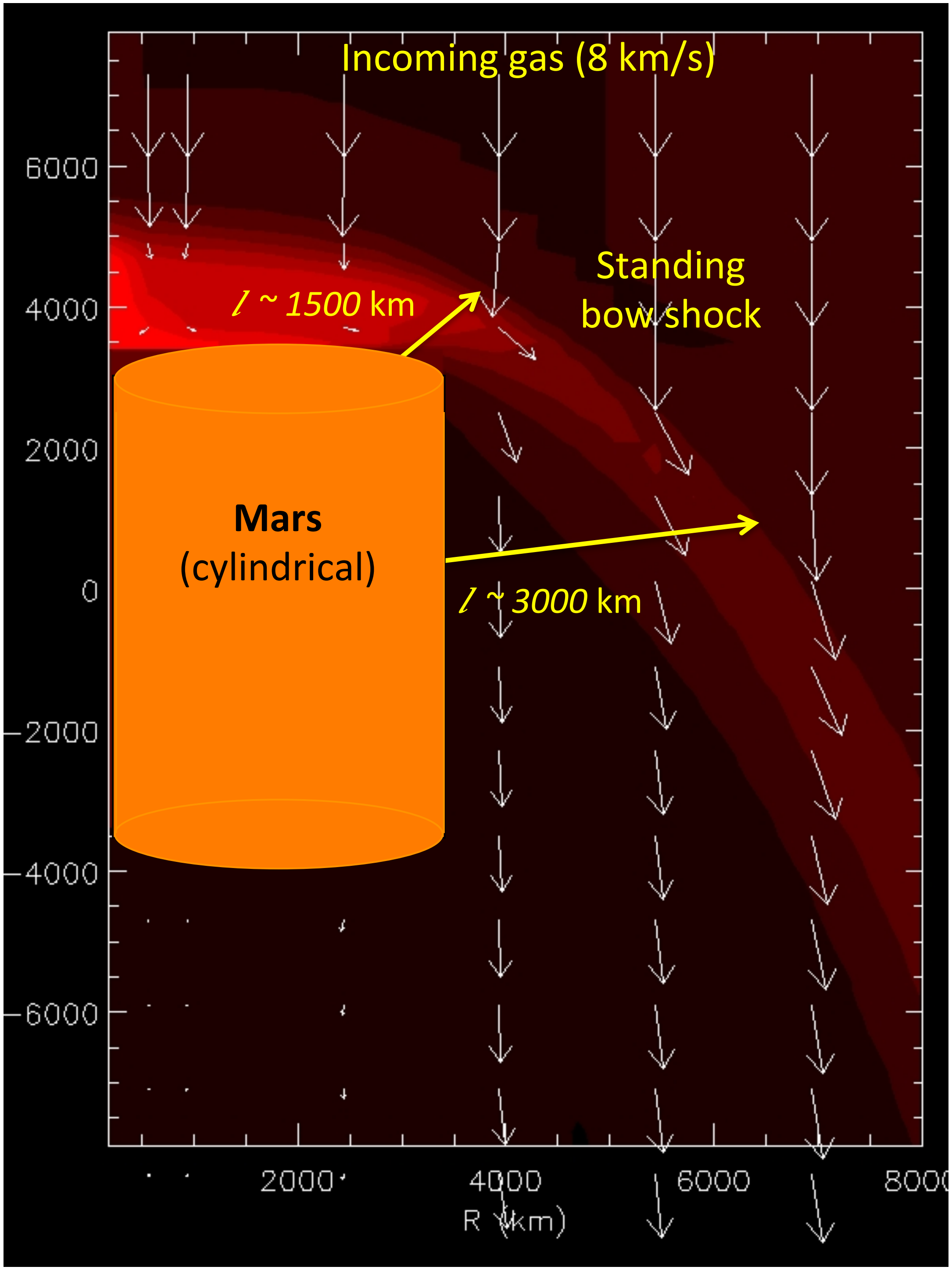
$\rho_g = 6 \times 10^{-9}$ g cm^{-3} = post-shock density

$C_s = 3$ km/s = post-shock sound speed

Chondrules move ~ (8 km/s) (50 s) ~ 400 km past shock front before being entrained in gas.

Chondrules with impact parameter *b* > 1700 km will miss planet

Chondrules with impact parameter *b* < 1700 km *might* strike planet



Optical depths:
Melted chondrules typically lie
ℓ ~ 1500-3500 km from unshocked gas.

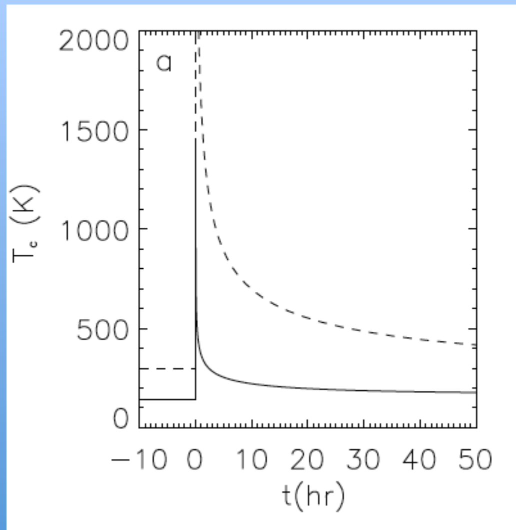
Optical depths
$\tau \sim \rho\, \kappa\, \ell \sim$
$(6 \times 10^{-9}\ \mathrm{g\ cm^{-3}})(.65\ \mathrm{cm^2\ g^{-1}})10^{8}(b/1000\ \mathrm{km})$
$\sim 0.19(1 + C/10)(b/1000\ \mathrm{km})$
~ **0.6 – 1.7** for $C = 10$

Much higher optical depths for $C > 10$
(settling to midplane)

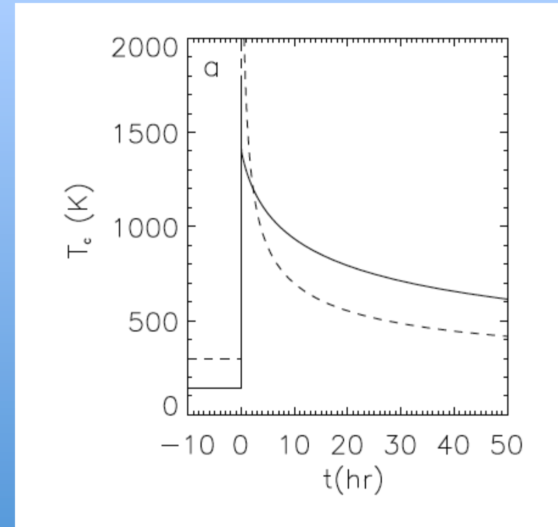
Optical depths higher (> 1) than those encountered in previous planetesimal bow shock scenarios.

Optically thick post-shock region may justify use of 1-D code (this will be tested upon 2-D code's completion!)

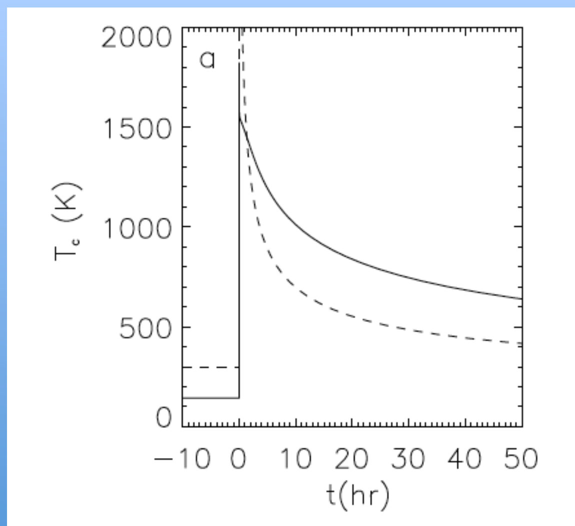
We have run 1-D code with effective optical depth to unshocked region, τ: local radiation field J reduced, replaced by B(T) [1 - exp(-τ)], chondrules / gas mass ratio = 0.4%, gas = 1 x 10^{-9} g cm^{-3} assumed.



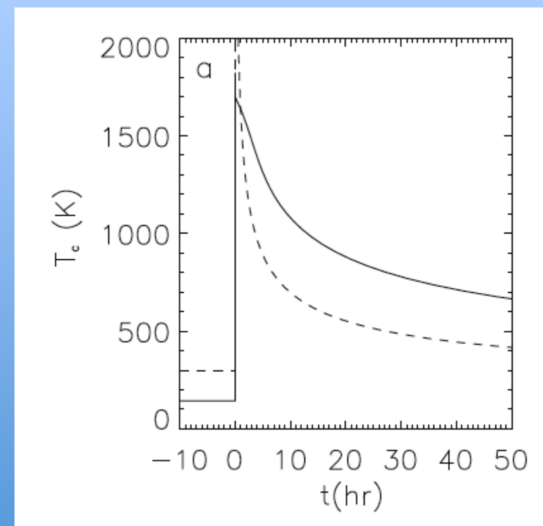
T(t) thermal history for Vs = 5 km/s – cooling rates much too rapid



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

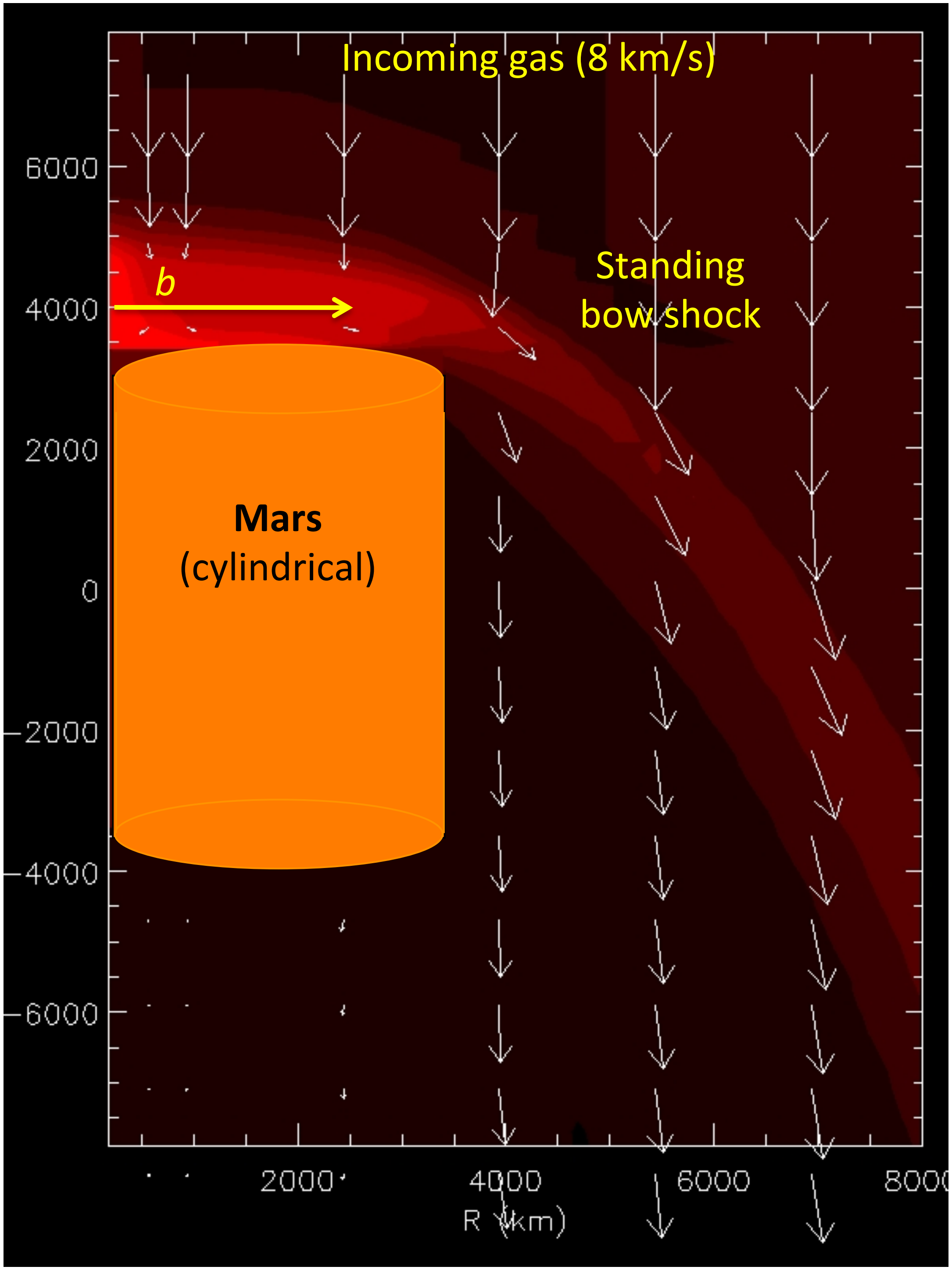


T(t) thermal history for Vs = 7 km/s – cooling rates < 100 K/hr



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 > 7 km/s.



<u>Shock speeds</u>:

Normal shock speeds depend on *b*:

b = 0 km, V = 8.00 km/s

b = 2000 km, V = 7.91 km/s

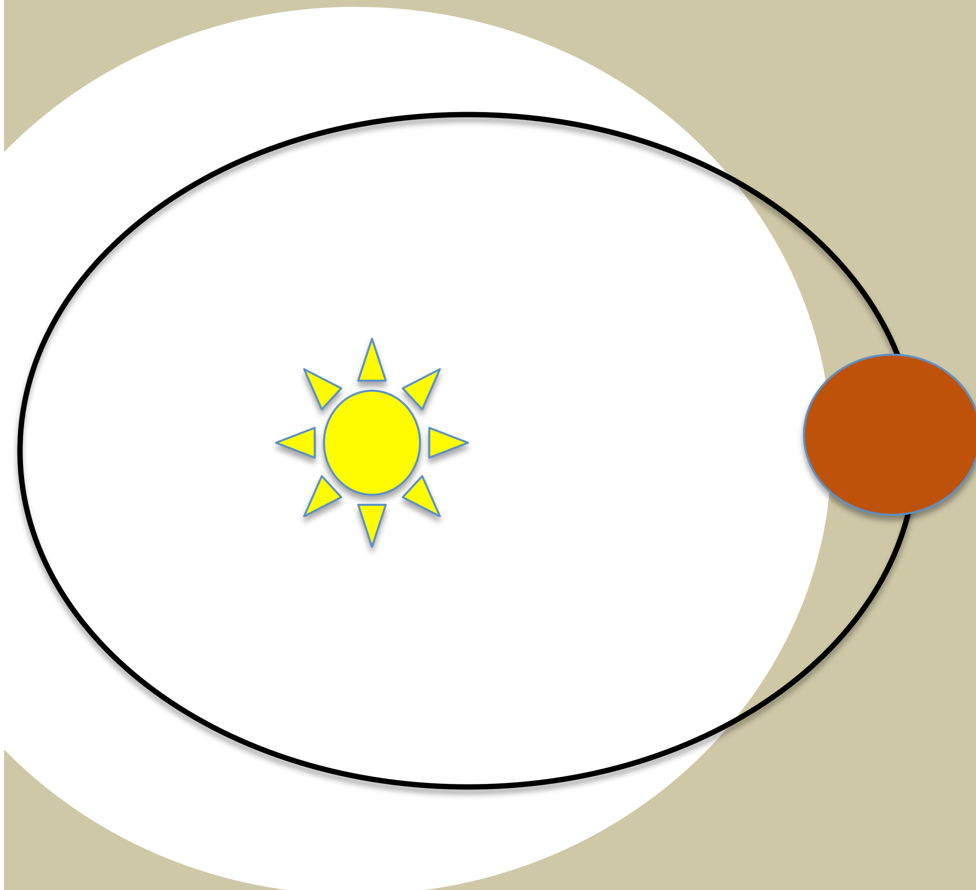
b = 4000 km, V = 7.66 km/s

b = 6000 km, V = 5.18 km/s

b = 8000 km, V = 3.50 km/s

Chondrules with impact parameter b < 4500 km see V > 7 km/s, are melted

$\boldsymbol{\sigma = 5.7 – 6.4 \times 10^{17}\ \mathrm{cm}^2}$



Every passage through the disk shocks a mass of chondrules
$M = \Sigma_c \, \sigma / \sin i$
$\sim (10 \text{ g cm}^{-2}) \, (6 \times 10^{17} \text{ cm}^2) / \sin 20°$
$\sim 1.5 \times 10^{19} \text{ g} / (1.4 \text{ yr})$
$\sim 10^{25} \text{ g} / \text{Myr}$

Mars can shock several asteroid belts' worth of chondrules in 1 Myr (until its orbit circularizes).

Mars may continue to accrete mass in disk at 1.5 AU, possibly explaining its higher oxidation.

Conclusions

Mars appears to have largely formed by 2 Myr (Dauphas et al. 2011).

Current models favor growth in annulus 0.7 – 1.0 AU, followed by scattering event to 1.5 AU (Hansen 2009).

A Mars formed and scattered at 2 Myr would create shocks up to 8 km/s at 1.5 AU, near the time and place associated with chondrule formation.

A planetesimal bow shock around an object as large as Mars appears capable of providing low cooling rates associated with porphyritic chondrules, and potentially can process the observed mass of chondrules.

Spatial environment around Mars may be rich in species outgassed from the planet itself, perhaps explaining high partial pressure of Na inferred for chondrules (Alexander 2008).

Chondrule formation by Mars---or just similarly large planetary embryos---is worth exploring.

A 2-D hydro code with radiative transfer is being developed now to address these questions.