THERMAL HISTORIES OF CHONDRULES IN SOLAR NEBULA SHOCKS, INCLUDING THE EFFECT OF MOLECULAR LINE COOLING

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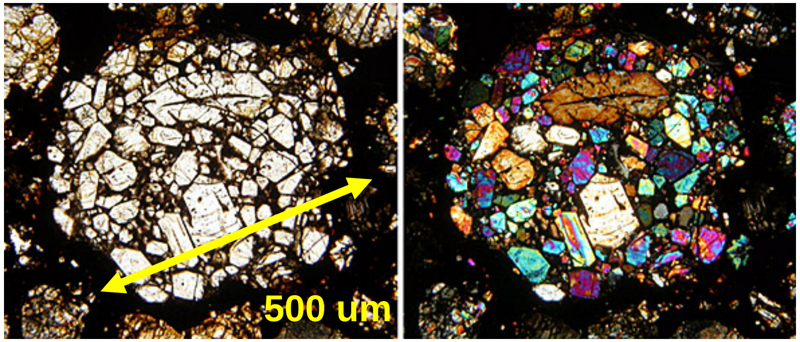
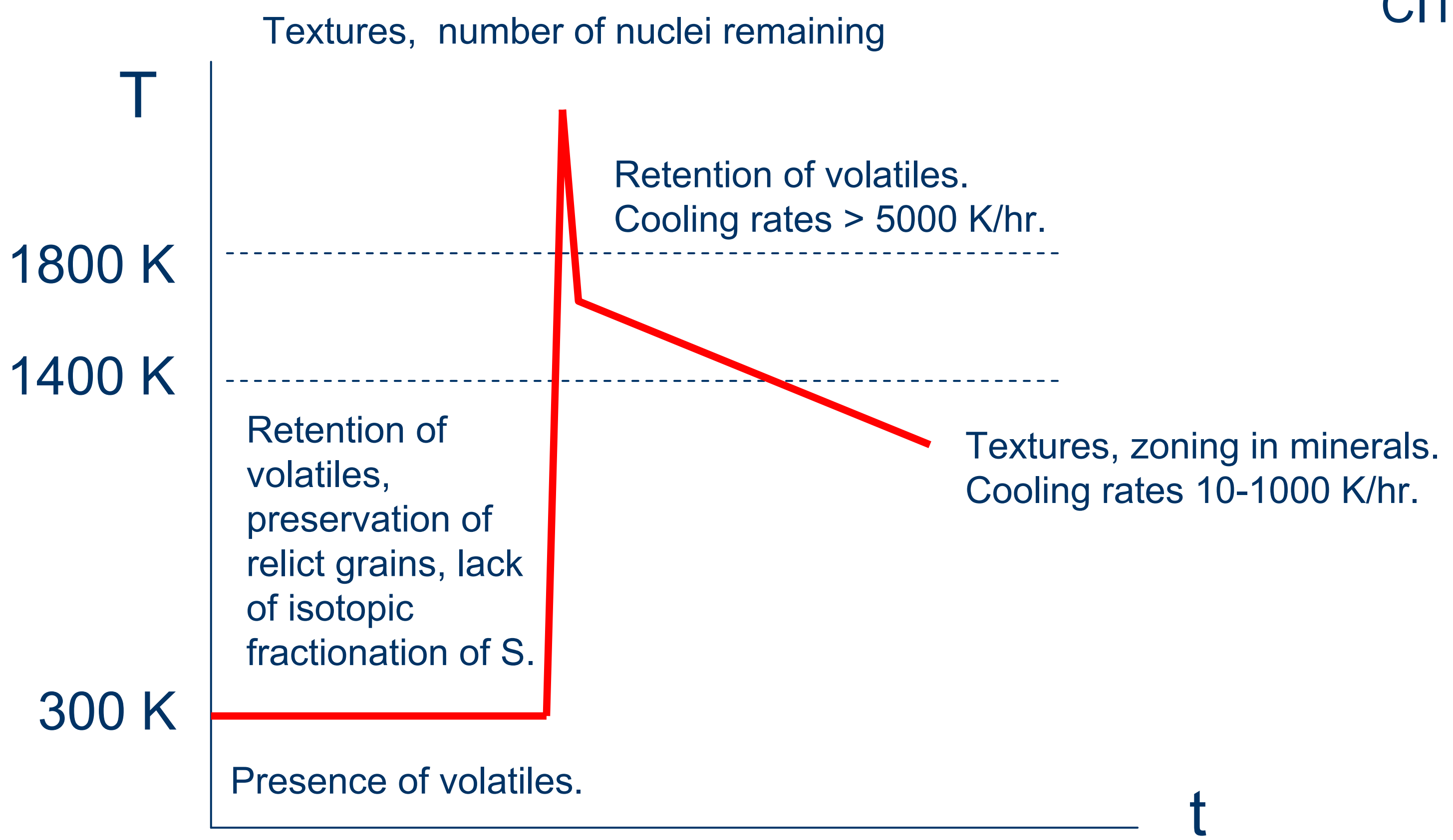
Chondrules



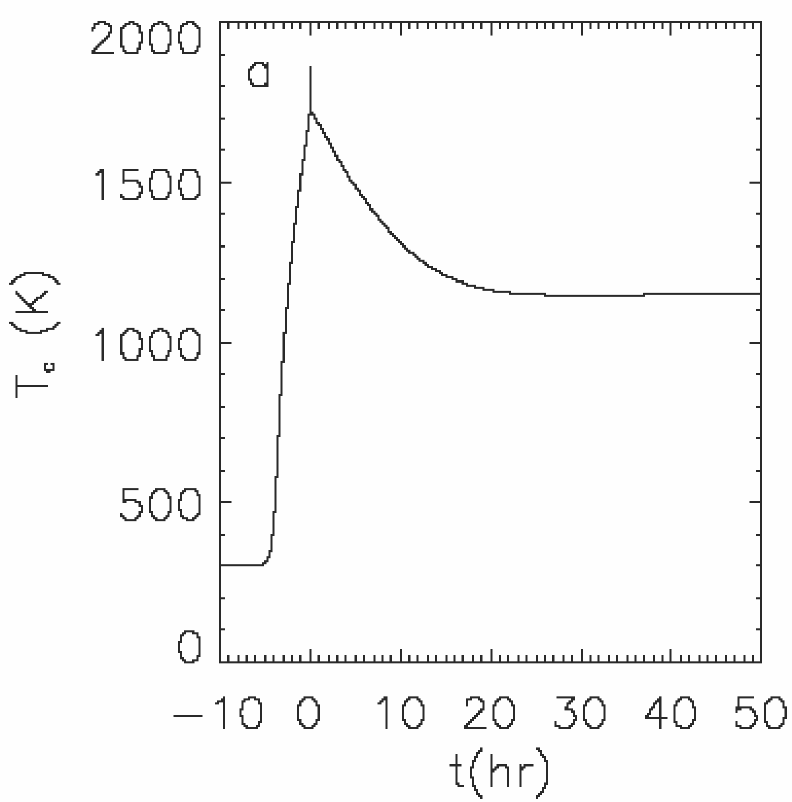
- Igneous textures
- What process could have melted ~ 10^{27} g of rock in the solar nebula?
- Constraints on thermal histories from
  - Retention of volatiles
  - Textures
  - Zoning in minerals
  - Etc.

Constraints on Thermal Histories

CITE!



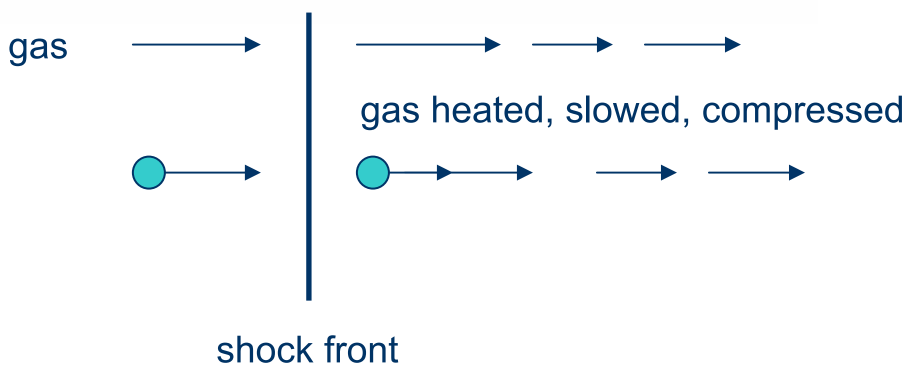
Chondrule Formation in Nebular Shocks



Chondrules heated before reaching shock front.

Experience peak heating only in vicinity of shock front.

Cooling rates consistent with constraints.



Desch & Connolly (2002)

Previous Shock Models – Problems

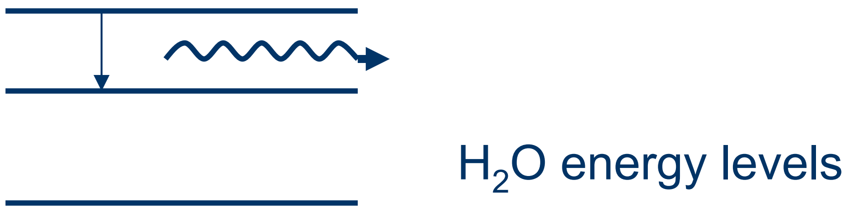
(identified by Desch, Ciesla, Hood, & Nakamoto; 2005)

- Post-shock boundary condition for the radiation field far from the shock.
- Opacity
  - Only Desch & Connolly (2002; hereafter DC02) considered micron-sized dust, but value too low.
- Evaporation of Dust
  - DC02 set dust evaporation temperature at 2000 K.
  - Dust evaporates over a range near 1500 K.

Previous Shock Models – Problems

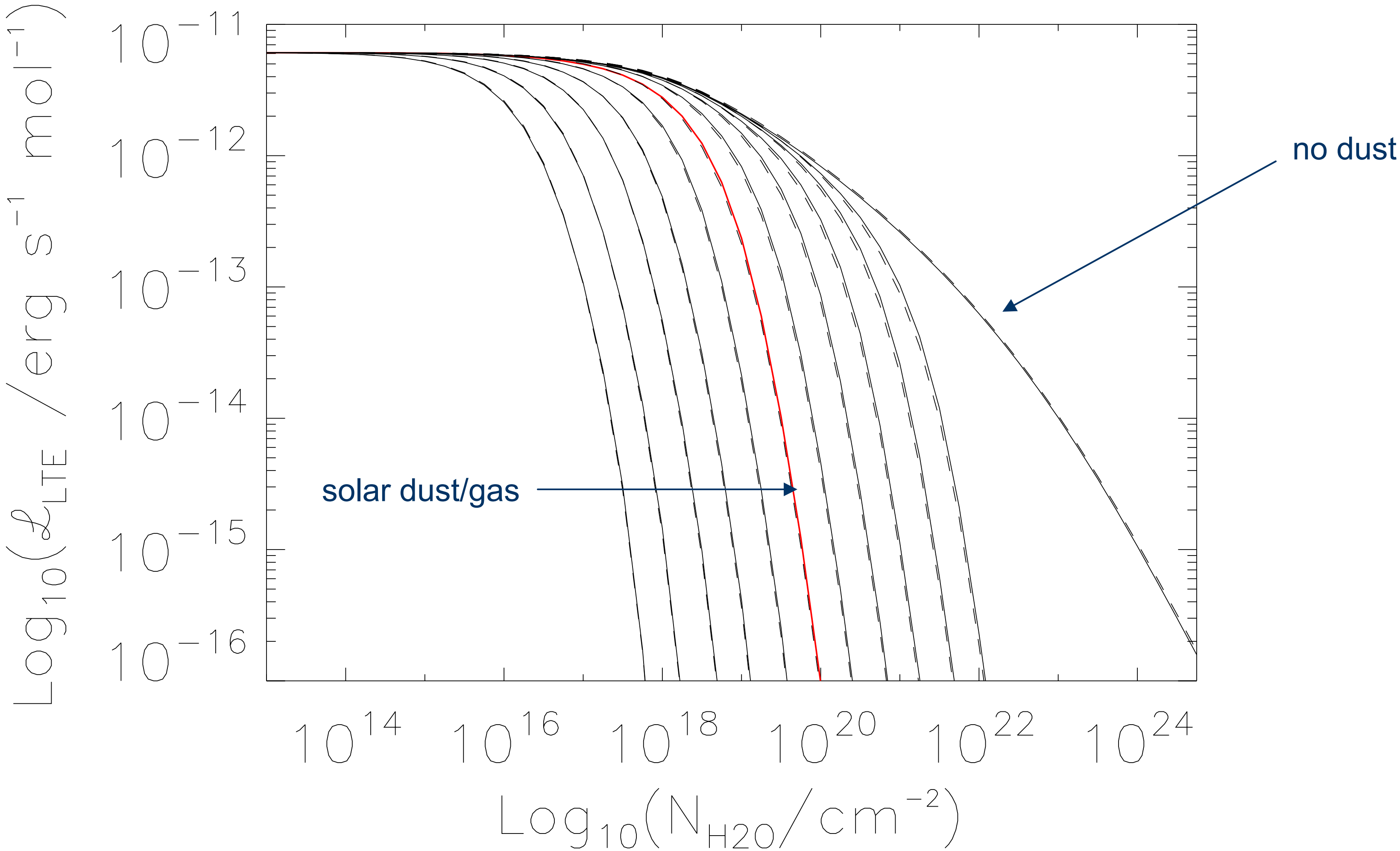
(identified by Desch, Ciesla, Hood, & Nakamoto; 2005)

- Line cooling

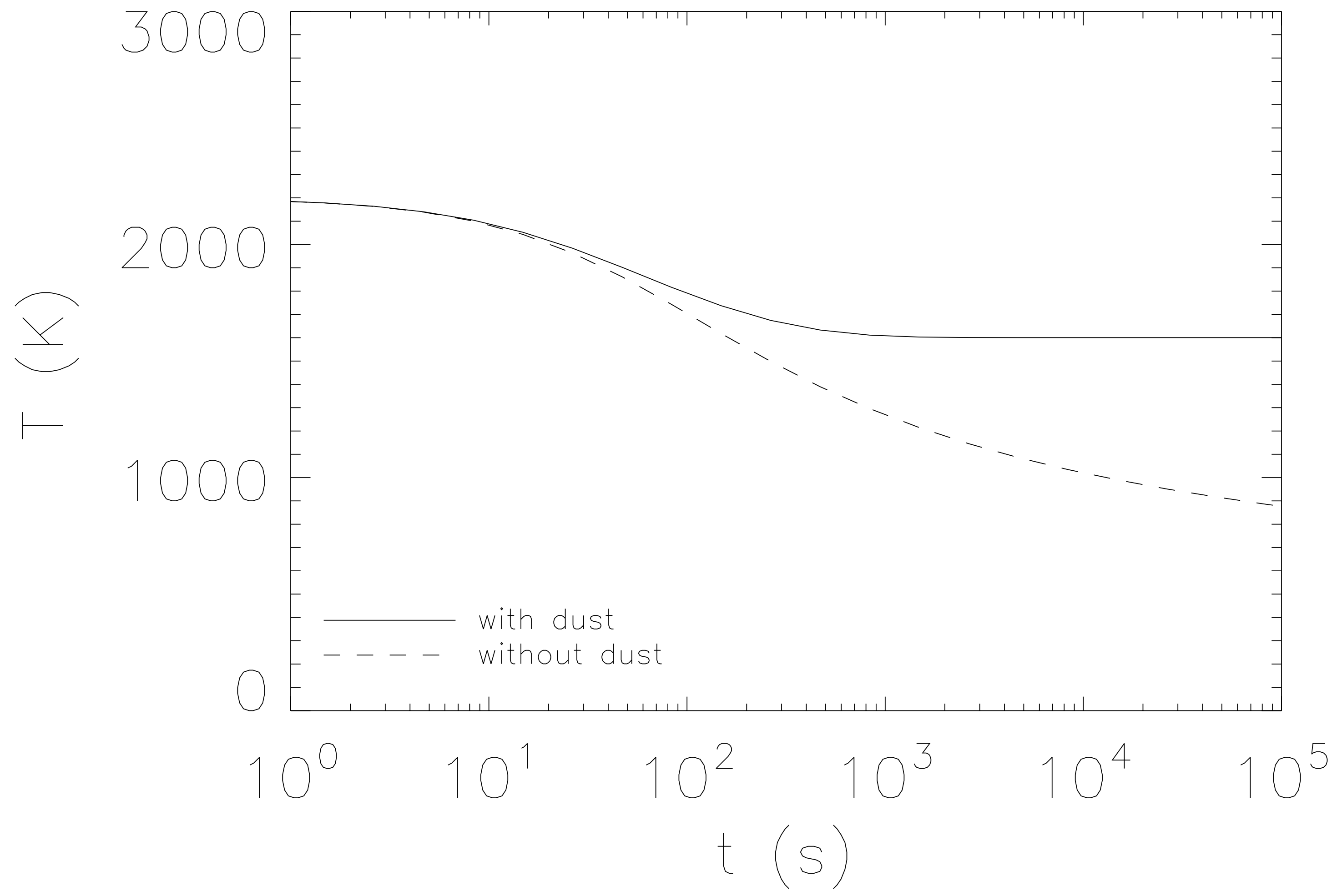


  - Iida et al. (2001) assume all line photons escape (optically thin limit).
  - DC02 and Ciesla & Hood (2002) neglect line cooling (optically thick limit).
  - MN06 include line cooling incompletely (no absorption by dust).

$$\frac{\Lambda ul}{n_{H_2O}} = S(T)\left(8\pi \frac{\nu^2}{c^2} kT \frac{h\nu/kT}{e^{-h\nu/kT}-1}\right) \rightarrow \mathcal{L}_{\mathrm{LTE}} = \sum \Lambda_{ul}\, P_{\mathrm{esc}}(\tau_{ul}, \tau_{\mathrm{d}})$$



Morris et al. 2009



Morris et al. 2009

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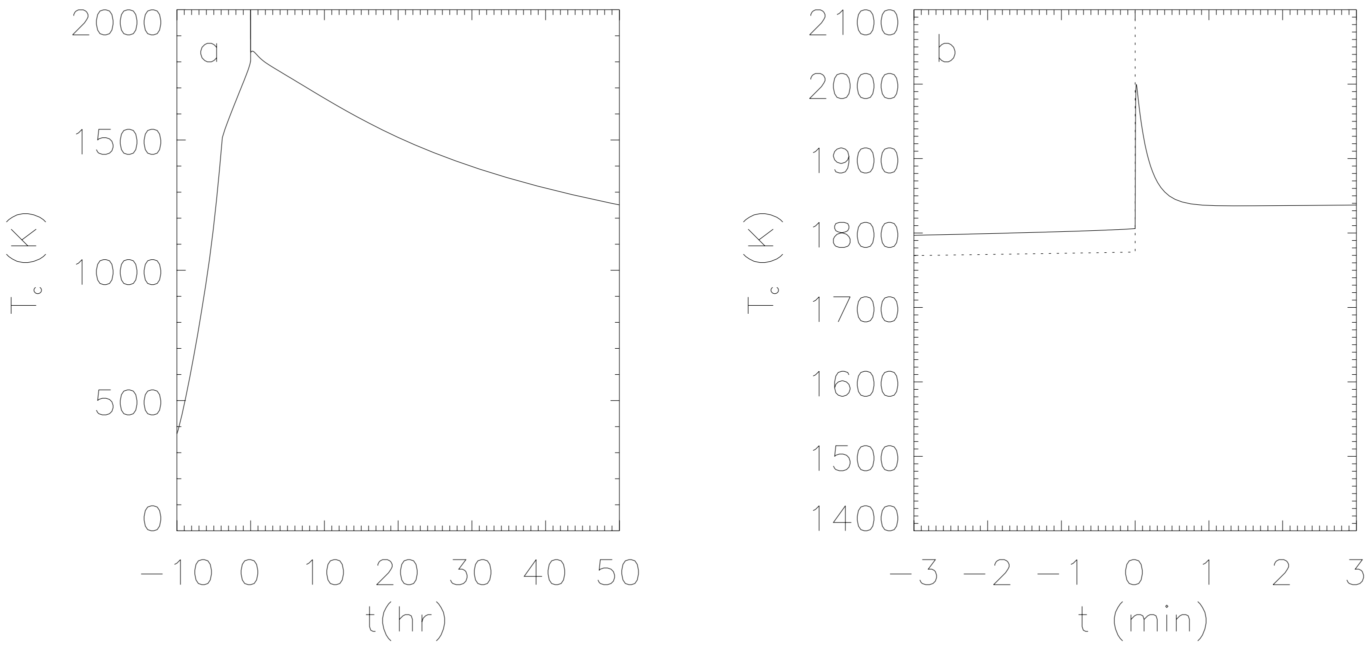


New results

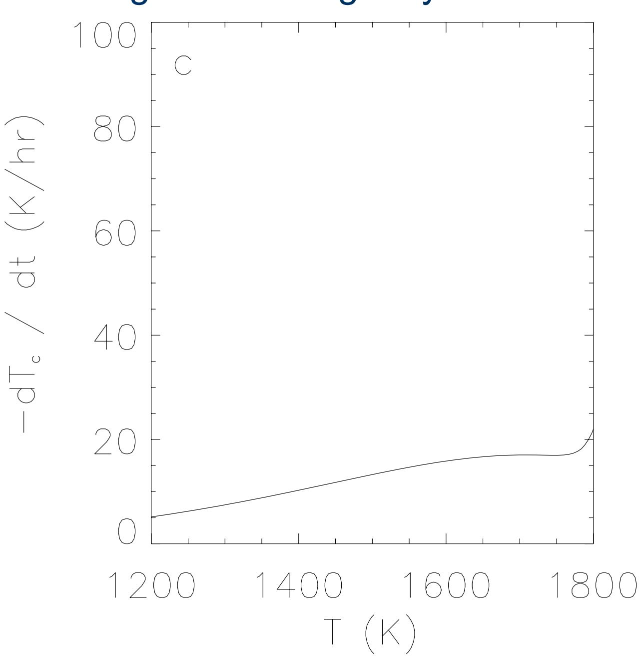
V_s = 8 km s^{-1}

ρ_0 = 10^{-9} g cm^{-3}

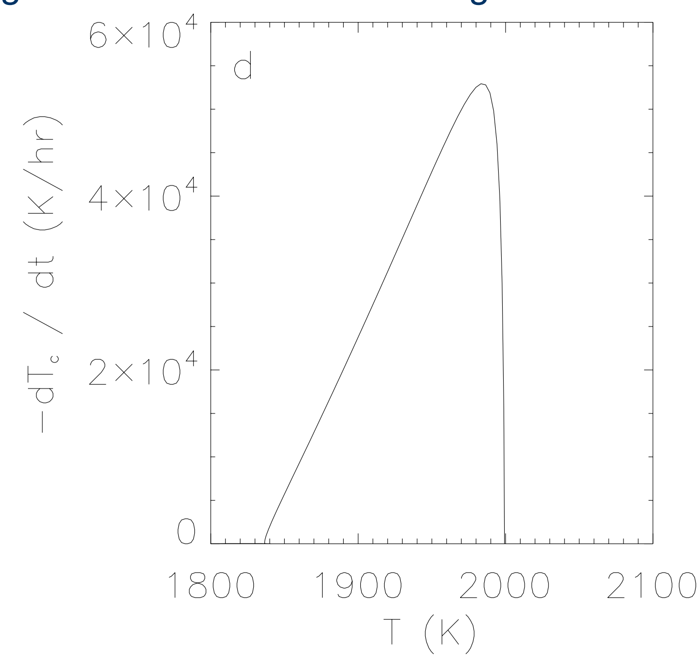
ρ_s/ρ_g = 5 x 10^{-2}

(10 x solar)

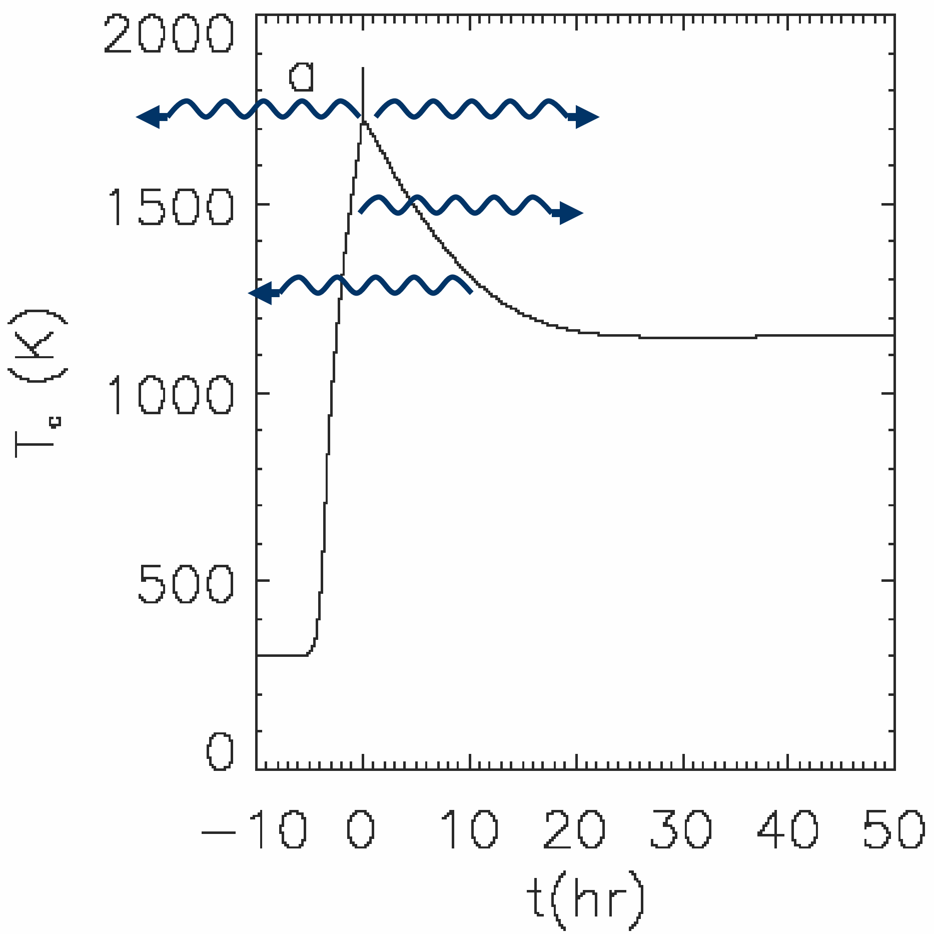
Cooling rates through crystallization range



Initial cooling rates

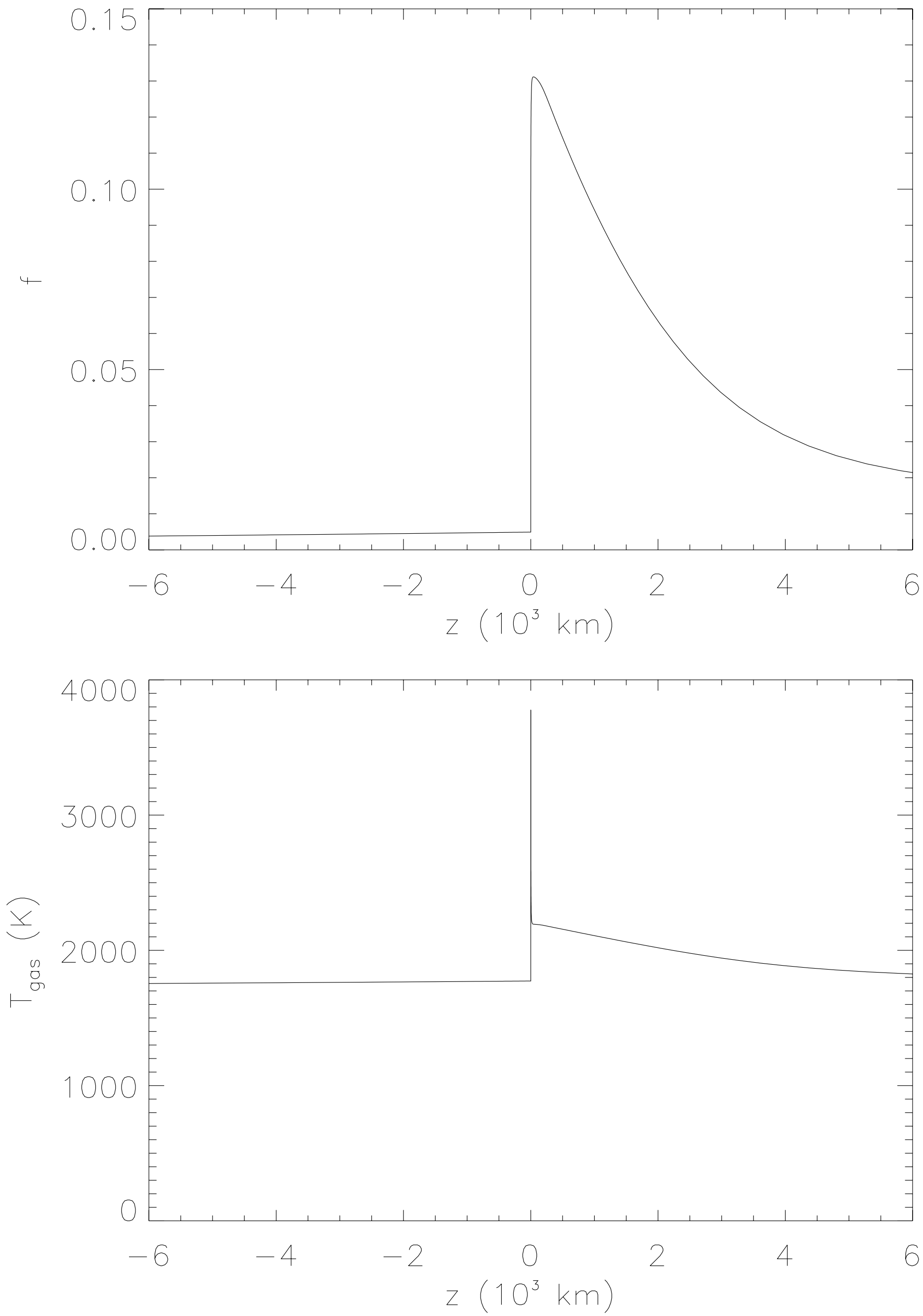


Backwarming



Reduces cooling rates by factor of 3

Desch & Connolly (2002)



Scott et al. (1996) hypothesized that hydrogen dissociation would buffer the peak temperature of chondrules.

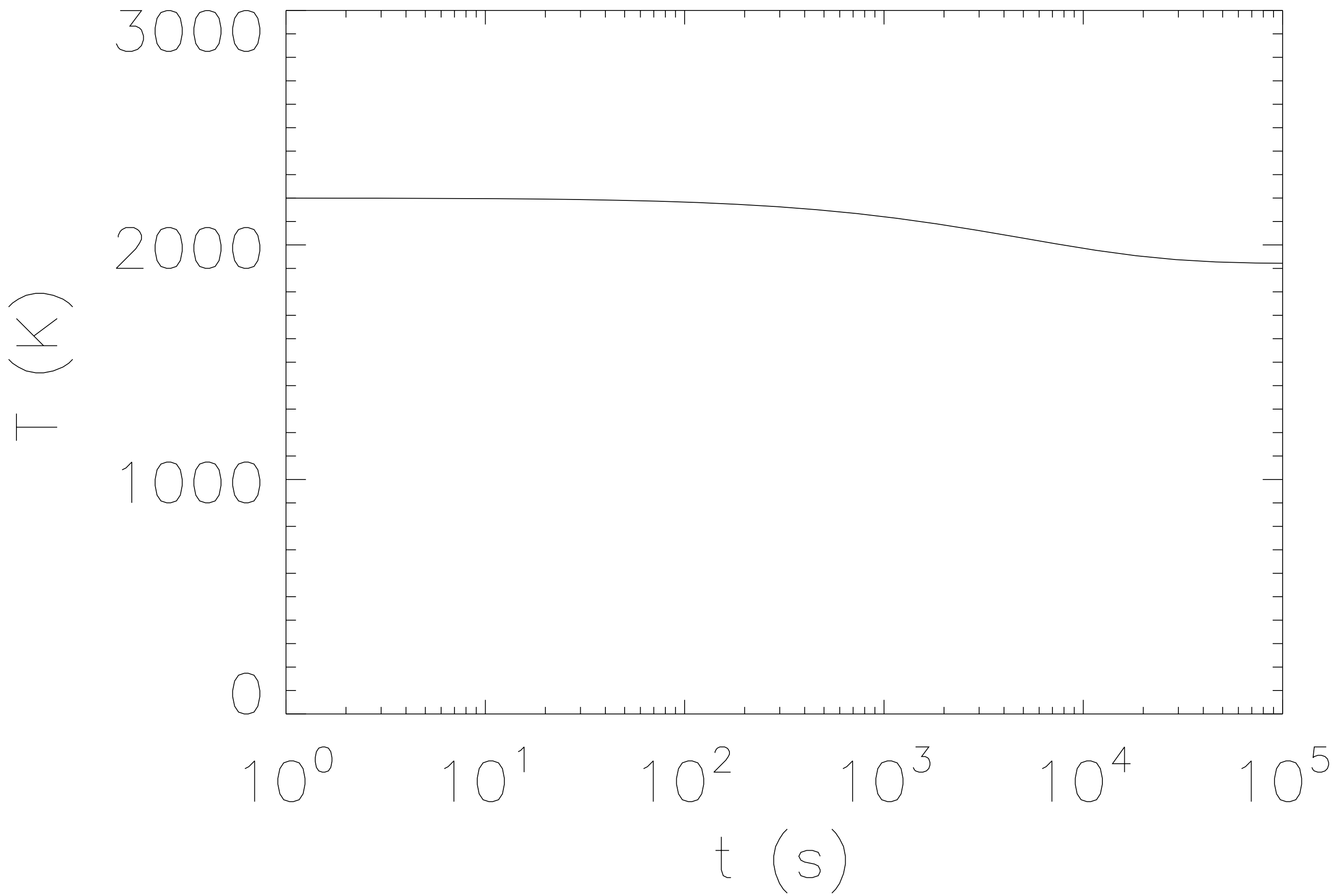
Recombination of Hydrogen

- Recombination of hydrogen adds energy to gas, slowing cooling rates.
- Fraction of hydrogen that is atomic: $$f = \frac{n_{\rm H}}{n_{\rm H} + 2n_{\rm H_2}}$$
- Heating rate per recombination: $$\Gamma \cong \frac{df}{dT}\frac{dT}{dt} n_{\rm H_{TOT}} \left(\frac{\epsilon}{2}\right)$$
- New cooling rate: $$\left(\frac{dT}{dt}\right) = \left(\frac{dT}{dt}\right)_{\rm f=0} \left[(1-f) + \left(\frac{\epsilon}{k} - T\right)\frac{df}{dT}\right]^{-1}$$

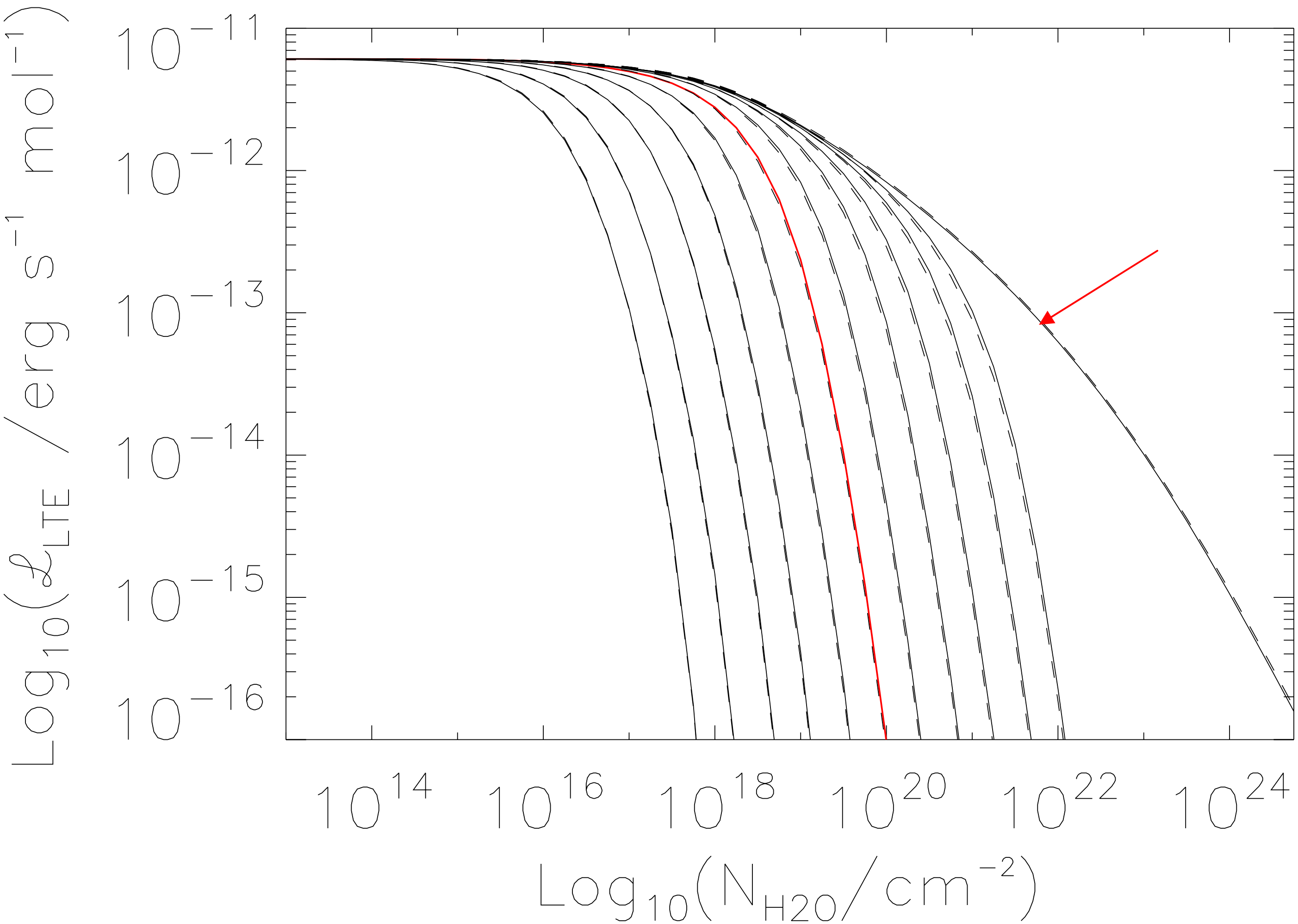
Backwarming: reduces cooling rates by factor of ~ 3

Hydrogen recombination: reduces cooling rates by factor of ~ 25

Cooling rates reduced by 2 orders of magnitude!



In 10^5 s gas has moved to $N_{H20} \sim 10^{22}$ cm^{-2}

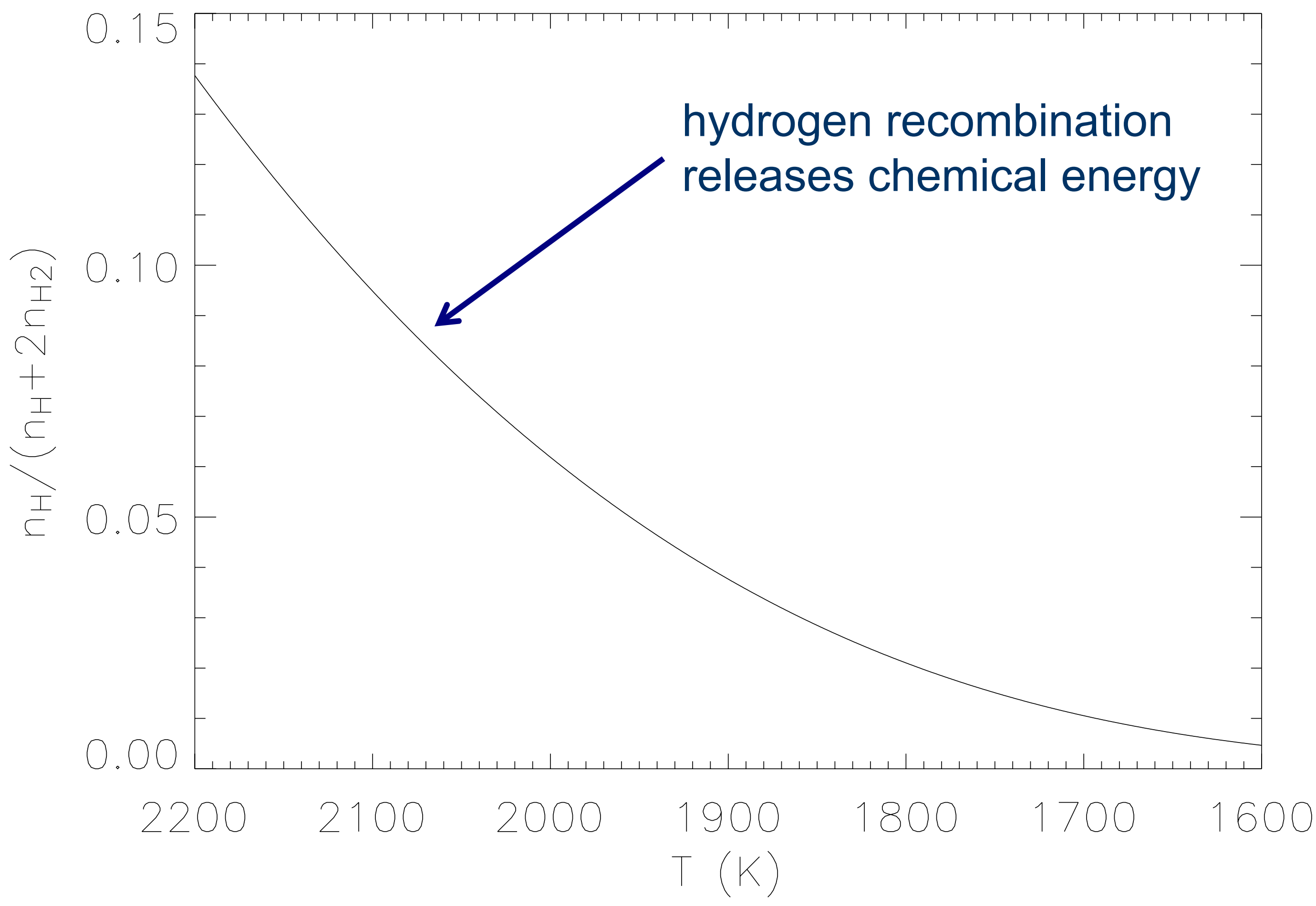


Morris et al. 2009

Conclusion

- Hydrogen buffers the gas until it's optically thick to line radiation.
  - Reduces line cooling to ~ 200 K/hr.
- Chondrules
  - Thermal exchange with gas ~ 5%
- Effect of line cooling on cooling rates of chondrules:

at most ~ 10 K/hr = <u>negligible</u>



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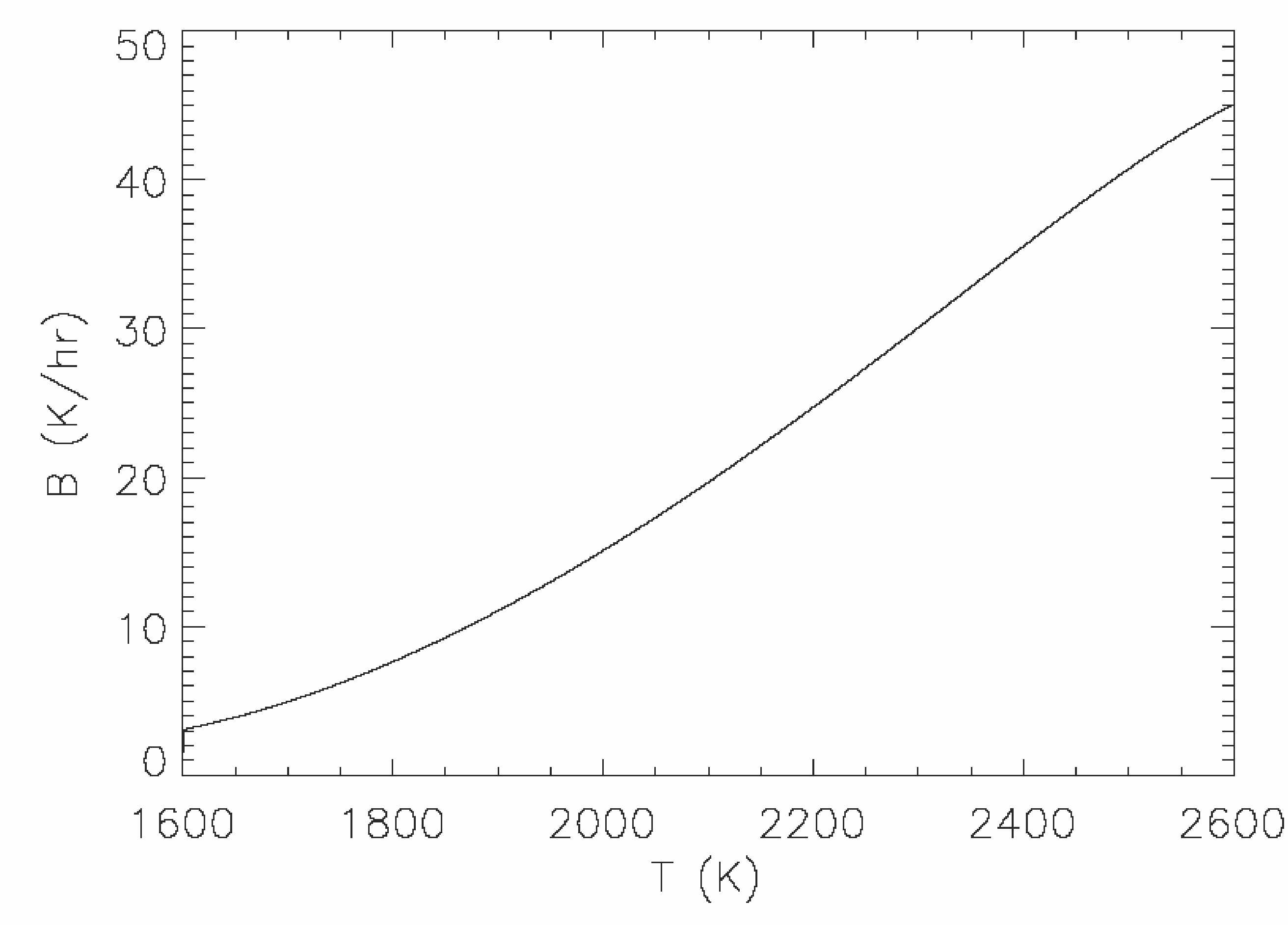
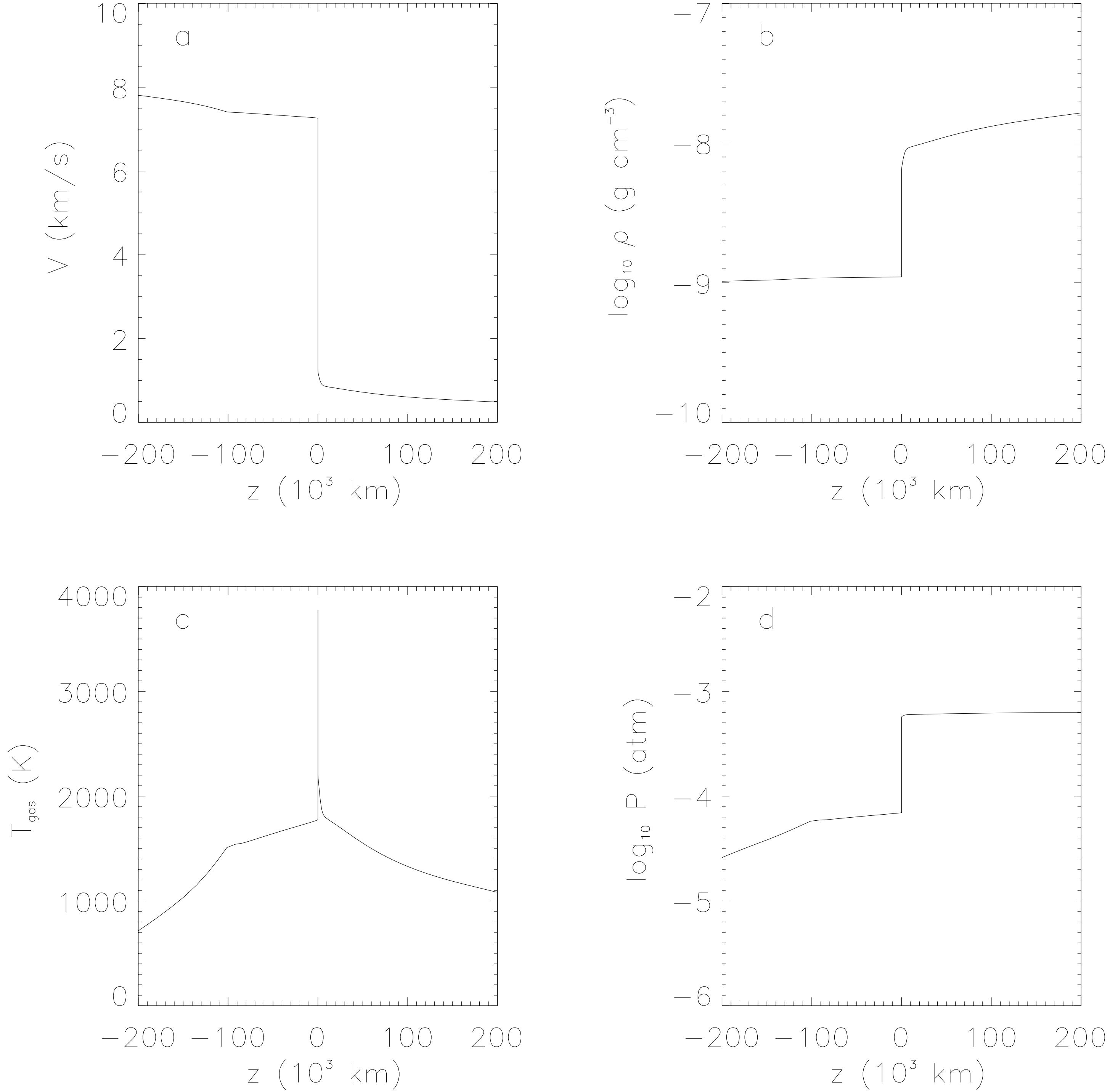
Recombination of hydrogen adds energy to gas, slowing cooling rates.



The reduction of cooling rates, $B \equiv [(1 - f) + (\varepsilon/k - T_g)\, df/dT_g]$, due to hydrogen recombination

Nebular Shock Model

- Nebular shock model consistent with:
  - size of chondrule-forming region
  - chondrule-matrix complementarity
  - frequency of compound chondrules
  - maximum size of chondrules, etc. etc.
- Nebular shock model predicts:
  - higher chondrule density correlates with higher T_{peak}, faster cooling, and compound chondrule frequency → compound chondrules should include more barred olivines.
  - NB: non-compound chondrules are < 15% barred olivines; compound chondrules are > 70% barred olivines



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