Carbon isotopes in the Solar System

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The ratio of 12-carbon to 13-carbon throughout the Solar System shows homogeneity whether one looks at the Sun, or at the farthest components, comets. This homogeneity runs contrary to chemical models of carbon fractionation, where distinct regions of similar $^{12}C/^{13}C$ ratio arise due to the chemical and physical processes which are ongoing in those regions. Here we present such a chemical model and discuss how heterogeneity can become homogeneity, and the implications this has for the formation of the Solar System.

Introduction

⊙ Isotope fractionation (e.g., $^{12}C/^{13}C$) is a good tracer of the chemical and physical history of the Solar System.

⊙ The Solar System formed from a molecular cloud. In the ISM we see that fractionation varies with conditions and molecular species [2, 3]. However, Solar System values are very homogeneous (Figure 1.)

⊙ What happened during the formation of the Solar System to achieve this?

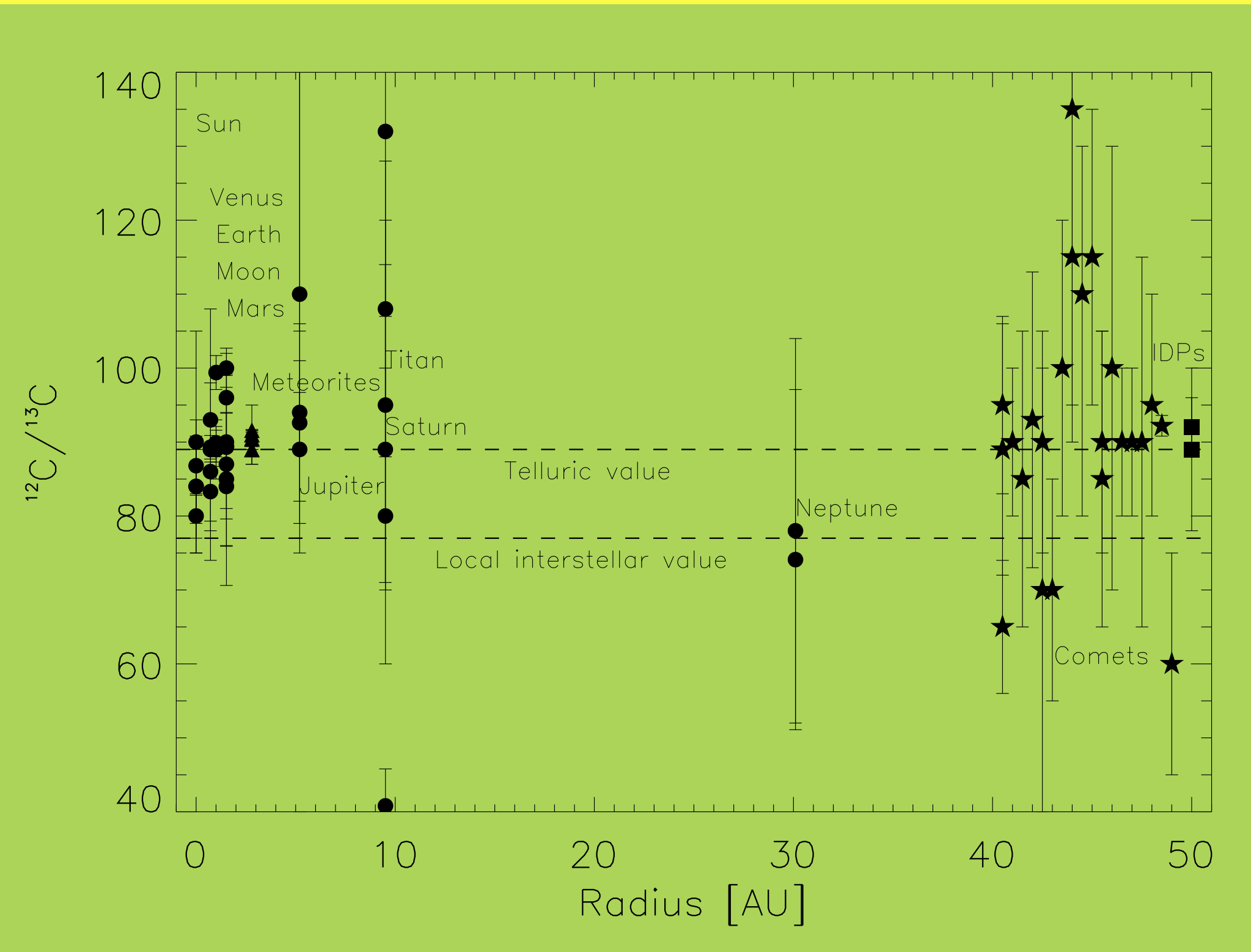

Figure 1. Measurements of the $^{12}C/^{13}C$ ratio in various objects of the Solar System. This ratio shows homogeneity whether one looks at the Sun, or whether one looks at the farthest components, comets. Data are consistent with the telluric value, $^{12}C/^{13}C=89$.

Model

⊕ We follow the chemical evolution of a molecular cloud for 1 Myr to get the initial abundances for a disk model.

⊕ We take the physical conditions in the disk (density, temperature, UV flux) from a 1+1D hydrodynamical model [1], using densities similar to that of the minimum mass solar nebula (Figure 2.)

⊕ In the disk, we follow the chemical evolution of parcels of gas as they advect inwards from 35.0 AU to 0.5 AU.

⊕ The outputs of the model are 2D molecular abundance and fractionation distributions (Figure 3.)

⊕ Using these, we can test the effects of assumptions about initial conditions, chemistry, densities, etc.

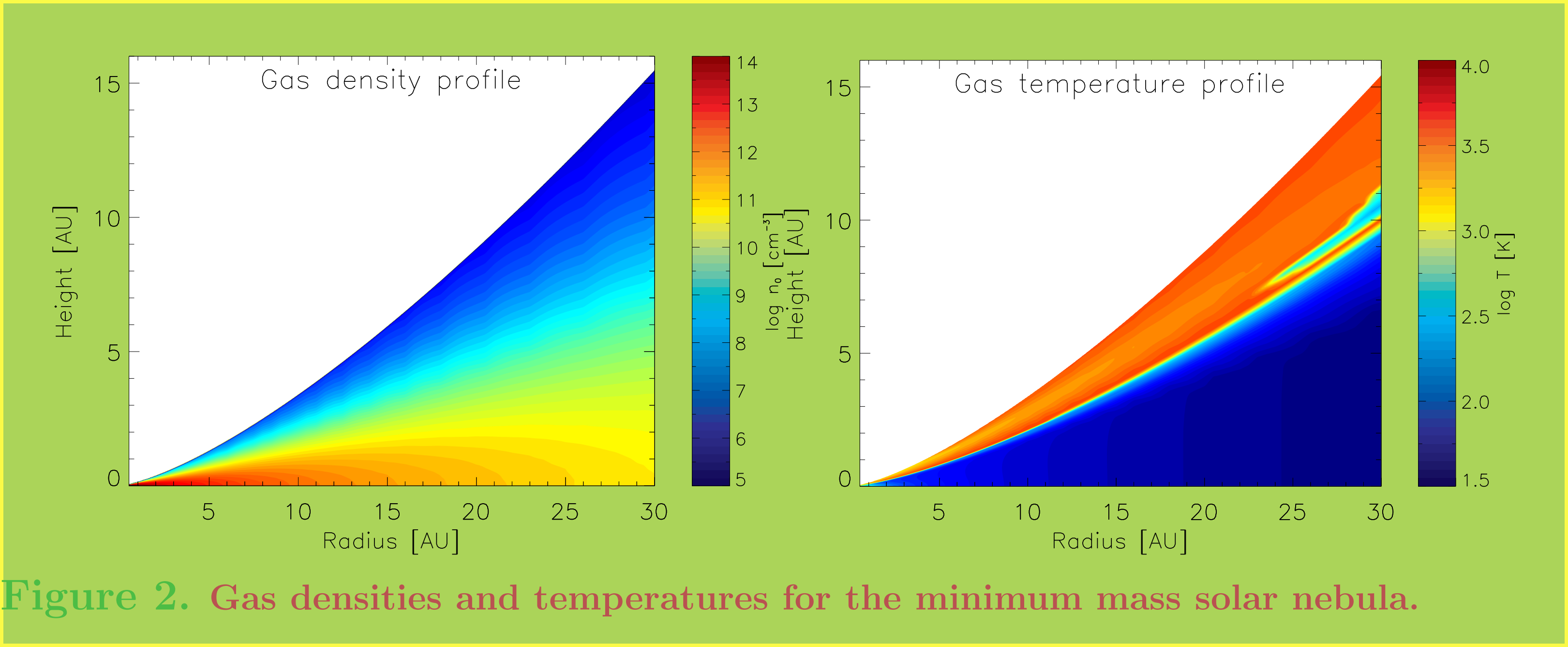

Figure 2. Gas densities and temperatures for the minimum mass solar nebula.

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Processes affecting fractionation

⊙ Exchange reactions: Species will exchange ^{12}C and ^{13}C at different rates due to differences in zero-point energy. e.g.,

$$^{13}C^+ + ^{12}CO \rightleftharpoons ^{13}CO \; + \; ^{12}C^+ + \Delta ZPE(=35\,K), \qquad (1)$$

$$k_{forward} = 3.3\times10^{-10}(T/300\,K)^{-0.448} \qquad k_{reverse} = k_{forward}\exp(-35\,K/T)$$

⊙ Photofractionation: ^{12}CO exhibits a greater degree of self-shielding to dissociating UV radiation than ^{13}CO. Thus ^{13}CO will be preferentially dissociated.

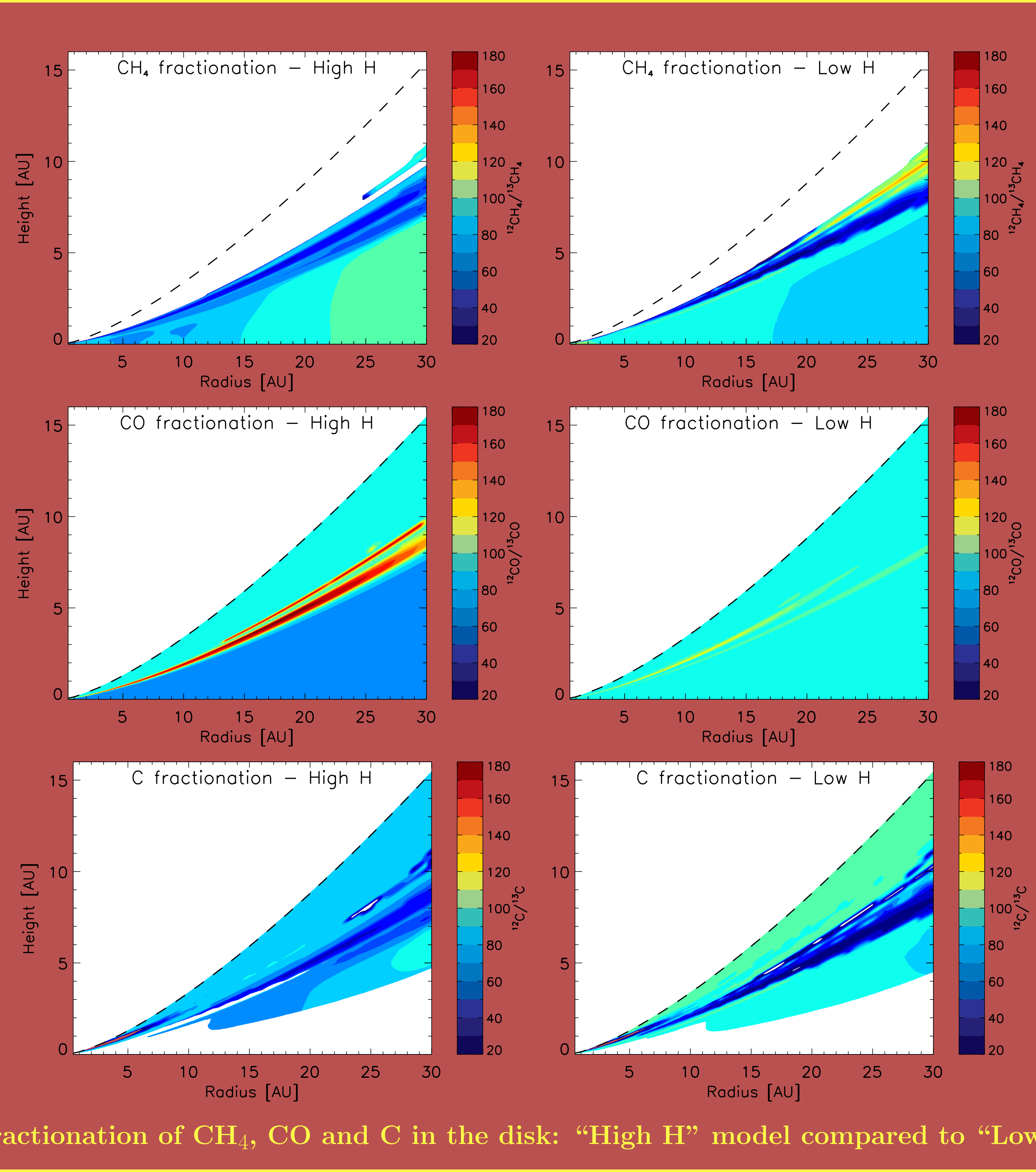

Figure 3. Fractionation of CH_4, CO and C in the disk: "High H" model compared to "Low H".

Key points

⊕ Disk chemistry produces differences in fractionation between species (e.g., CO vs. CH_4) and between layers of the disk (midplane vs. surface layers).

⊕ Fractionation is very dependent on input parameters, especially the H abundance. A high H abundance allows hydrocarbons to form in abundance, and hydrocarbons generally reflect the fractionation in C or C^+. A low H abundance means most of the carbon is locked in CO.

⊕ Species in the hot (>500 K) surface layers directly reflect total carbon fractionation ratio in the H-rich case.

Conclusions

⊙ The "High H" model cannot account for Solar System observations unless some other processing is involved, e.g.,

⊕ An exchange reaction which works in opposition to reaction (1).

⊕ A hot phase of the solar nebula, which normalises fractionation in a similar way to that in the disk surface.

⊕ Accretion shock – heating followed by freeze-out onto grains.

⊙ The "Low H" model is better at reproducing the observed fractionation. This suggests that the Solar System may have formed in a low-H environment.

Species	"High H" model Cloud	"High H" model Disk	"Low H" model Cloud	"Low H" model Disk
$^{12}CH_4/^{13}CH_4$	108	80	68	81
$H^{12}CN/H^{13}CN$	107	79	50	84
$^{12}CN/^{13}CN$	105	82	68	85
$^{12}CH/^{13}CH$	105	71	73	80
$^{12}CH_3/^{13}CH_3$	105	76	70	81
$H_2{}^{12}CO/H_2{}^{13}CO$	105	76	70	81
$^{12}C/^{13}C$	95	71	77	80
$^{12}CO/^{13}CO$	67	69	83	83
$^{12}CO_2/^{13}CO_2$	65	58	82	81
$H^{12}CO^+/\ H^{13}CO^+$	60	58	71	70

Table 1. $^{12}C/^{13}C$ isotope ratios output from a 1 Myr interstellar cloud, and at the midplane at 10 AU from model of the protoplanetary disk. $^{12}C_{total}/^{13}C_{total}=89$. "High H" signifies 1% of total hydrogen is atomic initially, "Low H", 0.001%.

References

[1] D'Alessio, P., Calvet, N., et al. 2006, ApJ, 638, 314
[2] Langer, W. D., & Penzias, A. A. 1993, ApJ, 408, 539
[3] Langer, W. D., Graedel, T. E., et al. 1984, ApJ, 277, 581

For more information on the modelling, please see:
Woods, P. M., & Willacy, K. 2007, ApJ, 655, L49
Woods, P. M., & Willacy, K. 2007, in prep.

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