Carbon isotopes in the Solar System

Paul M Woods[1] & Karen Willacy[2]

Paul.Woods@manchester.ac.uk

The ratio of 12-carbon to 13-carbon throughout the Solar System shows homogeneity whether one looks at the centre, the Sun, or at the farthest components, comets. This homogeneity runs contrary to chemical models of carbon fractionation in the early Solar System, 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 molecular clouds in the interstellar medium (ISM) we see that fractionation varies with conditions and molecular species[1,2]. However, present-day Solar System values are very homogeneous, whether in warm regions or cold regions, and irrespective of molecular species (Figure 1.)
- What happened during the formation of the Solar System to effect this change?

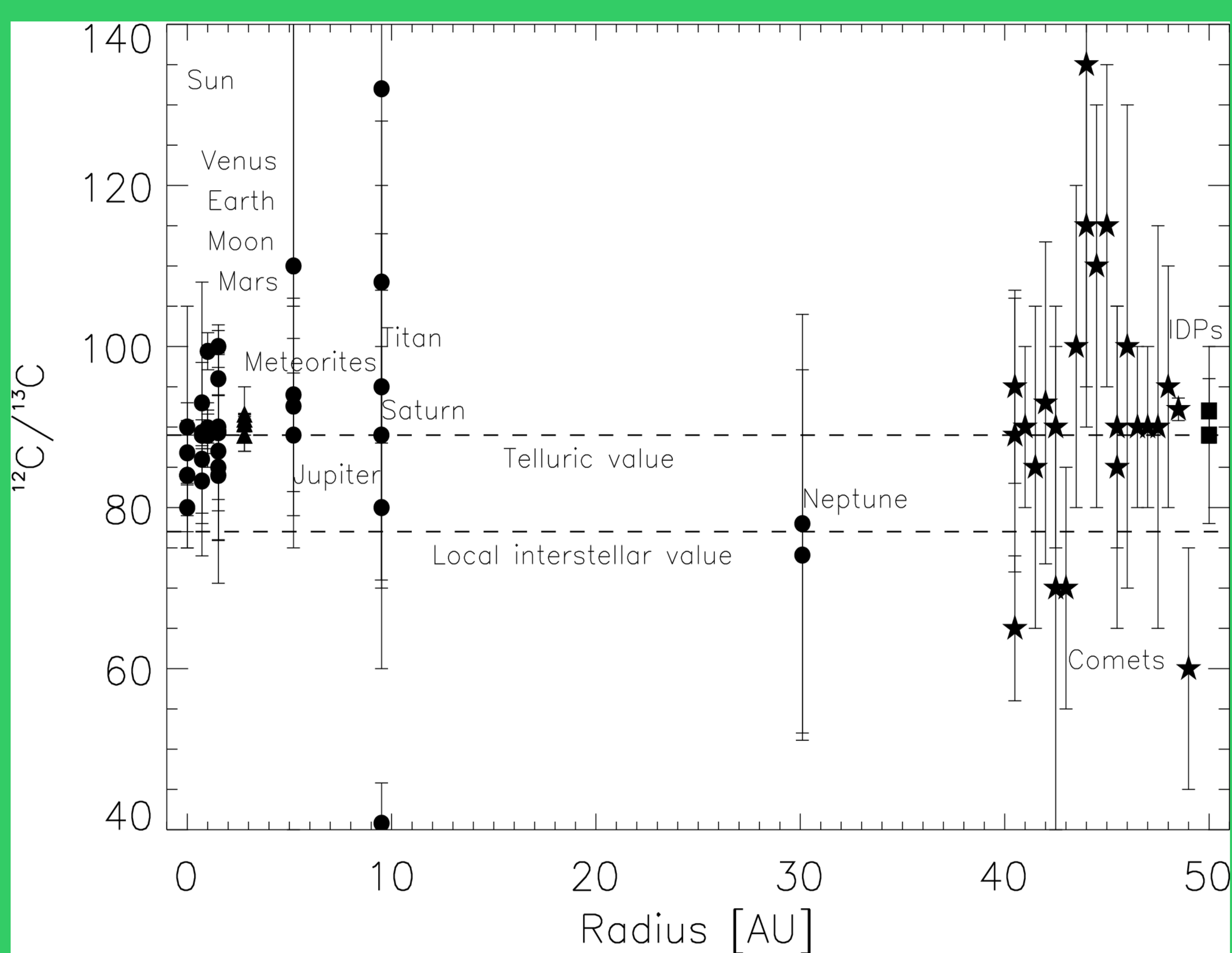
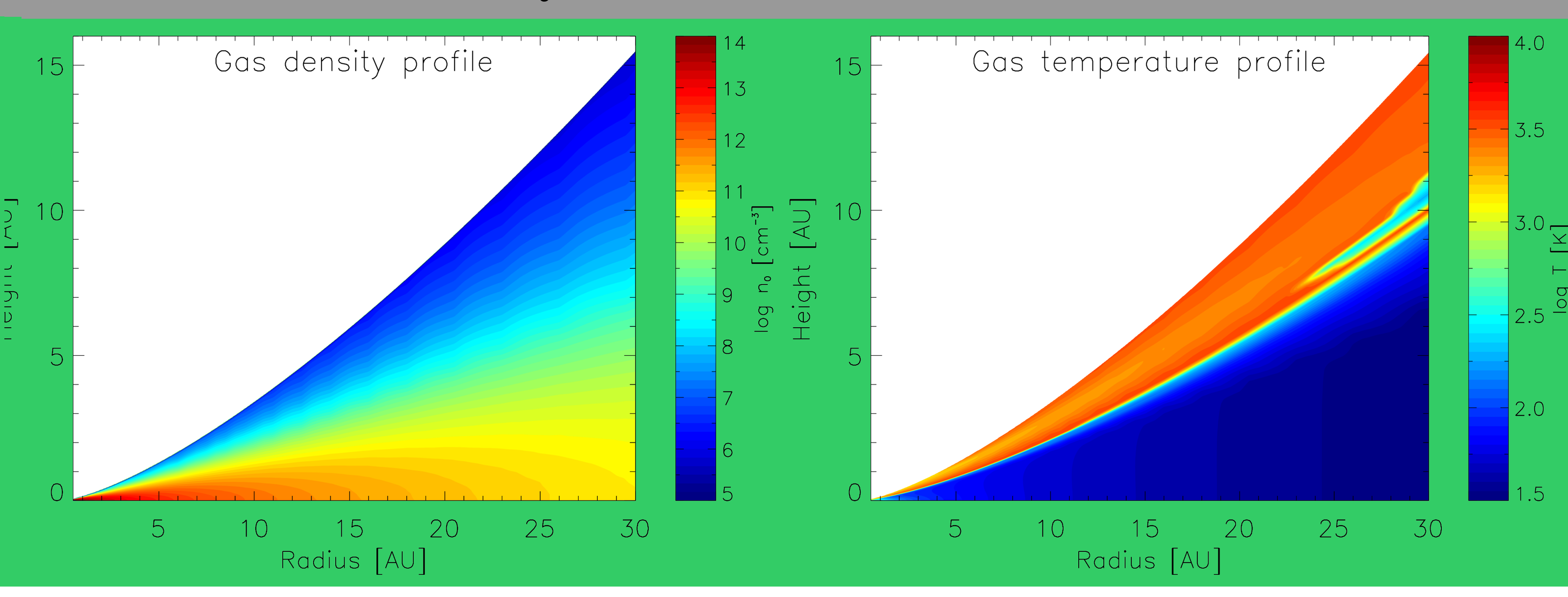


Figure 1. Measurements of the $^{12}C/^{13}C$ ratio in various objects of the Solar System. This ratio shows homogeneity whether one looks at the Sun, or whether one looks at planets or comets. Data are consistent with the telluric value, $^{12}C/^{13}C$=89.

Model[4]

- We follow the chemical evolution of a molecular cloud for 1 Myr to get initial abundances for a protoplanetary disk model.
- We take the physical conditions in the disk (density, temperature, UV flux) from a 1+1D hydrodynamical model[3], using surface 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.



Processes affecting fractionation

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

$$^{13}C^+ + {}^{12}CO \longleftrightarrow {}^{13}CO + {}^{12}C^+ + \Delta ZPE(=35K)$$

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

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

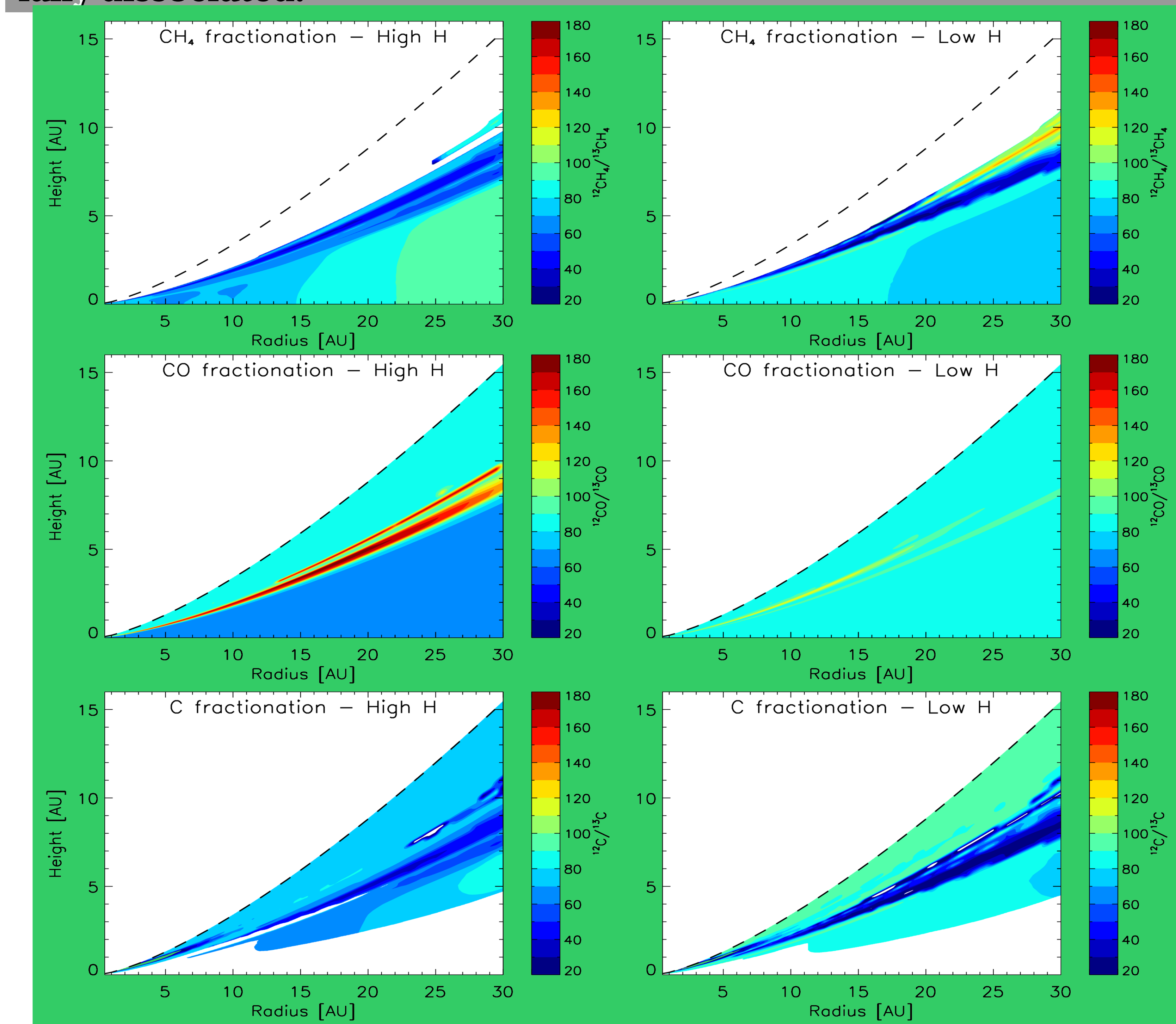


Figure 3. Fractionation of CH_4, CO and C in the disk: "High H" model (2% H/H_2) compared to "Low H" (0.002% H/H_2).

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.
- Some species in the hot (>500K) surface layers directly reflect total carbon fractionation ratio.

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 that above.
- A hot phase of the solar nebula, which normalises fractionation in a similar way to that in the disk surface.
- An accretion shock -- transient heating followed by freeze-out onto dust 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"		"Low H model"	
	Cloud	Disk	Cloud	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. $^{12}C/^{13}C$ ratios output from a 1 Myr-old interstellar cloud, and at the midplane at 10 AU from a model of a protoplanetary disk.

[1]Jodrell Bank Centre for Astrophysics, The University of Manchester
[2]Jet Propulsion Laboratory, Pasadena, CA 91109, USA

[1]Langer, W.D. & Penzias, A.A. 1993, Astrophysical Journal, 408, 539
[2]Langer, W.D., Graedel, T.E., et al. 1984, Astrophysical Journal, 277, 581
[3]D'Alessio, P., Calvet, N. & Hartmann, L. 2001, Astrophysical Journal, 553, 321
[4]Woods, P.M. & Willacy, K. 2007, Astrophysical Journal, 655, L49