Gas composition of the main volatile elements in protoplanetary discs and its implication for planet formation

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ABSTRACT

Context. Direct observations of gaseous exoplanets reveal that their gas envelope has a higher C/O ratio than that of the host star (e.g., Wasp 12-b). This has been explained by considering that the gas phase of the disc could be inhomogeneous, exceeding the stellar C/O ratio in regions where these planets formed; but few studies have considered the drift of the gas and planet migration.
Aims. We aim to derive the gas composition in planets through planet formation to evaluate if the formation of giant planets with an enriched C/O ratio is possible. The study focusses on the effects of different processes on the C/O ratio, such as the disc evolution, the drift of gas, and planet migration.
Methods. We used our previous models for computing the chemical composition, together with a planet formation model, to which we added the composition and drift of the gas phase of the disc, which is composed of the main volatile species H_2O, CO, CO_2, NH_3, N_2, CH_3OH, CH_4, and H_2S, H_2 and He. The study focusses on the region where ice lines are present and influence the C/O ratio of the planets.
Results. Modelling shows that the condensation of volatile species as a function of radial distance allows for C/O enrichment in specific parts of the protoplanetary disc of up to four times the solar value. This leads to the formation of planets that can be enriched in C/O in their envelope up to three times the solar value. Planet migration, gas phase evolution and disc irradiation enables the evolution of the initial C/O ratio that decreases in the outer part of the disc and increases in the inner part of the disc. The total C/O ratio of the planets is governed by the contribution of ices accreted, suggesting that high C/O ratios measured in planetary atmospheres are indicative of a lack of exchange of material between the core of a planet and its envelope or an observational bias. It also suggests that the observed C/O ratio is not representative of the total C/O ratio of the planet.

Key words. planets and satellites: atmospheres – planets and satellites: terrestrial planets – planets and satellites: formation – protoplanetary disks – planets and satellites: composition – planets and satellites: gaseous planets

Previous work

Passive disk, passive chemistry, stationary planet formation (Öberg+ 2011)

Passive disk, passive chemistry, migrating planets (Madhusudhan+ 2014)

Passive disk, diffusing gas, drifting solids, sublimating, condensation, passive chemistry (Ali-Dib+ 2014)

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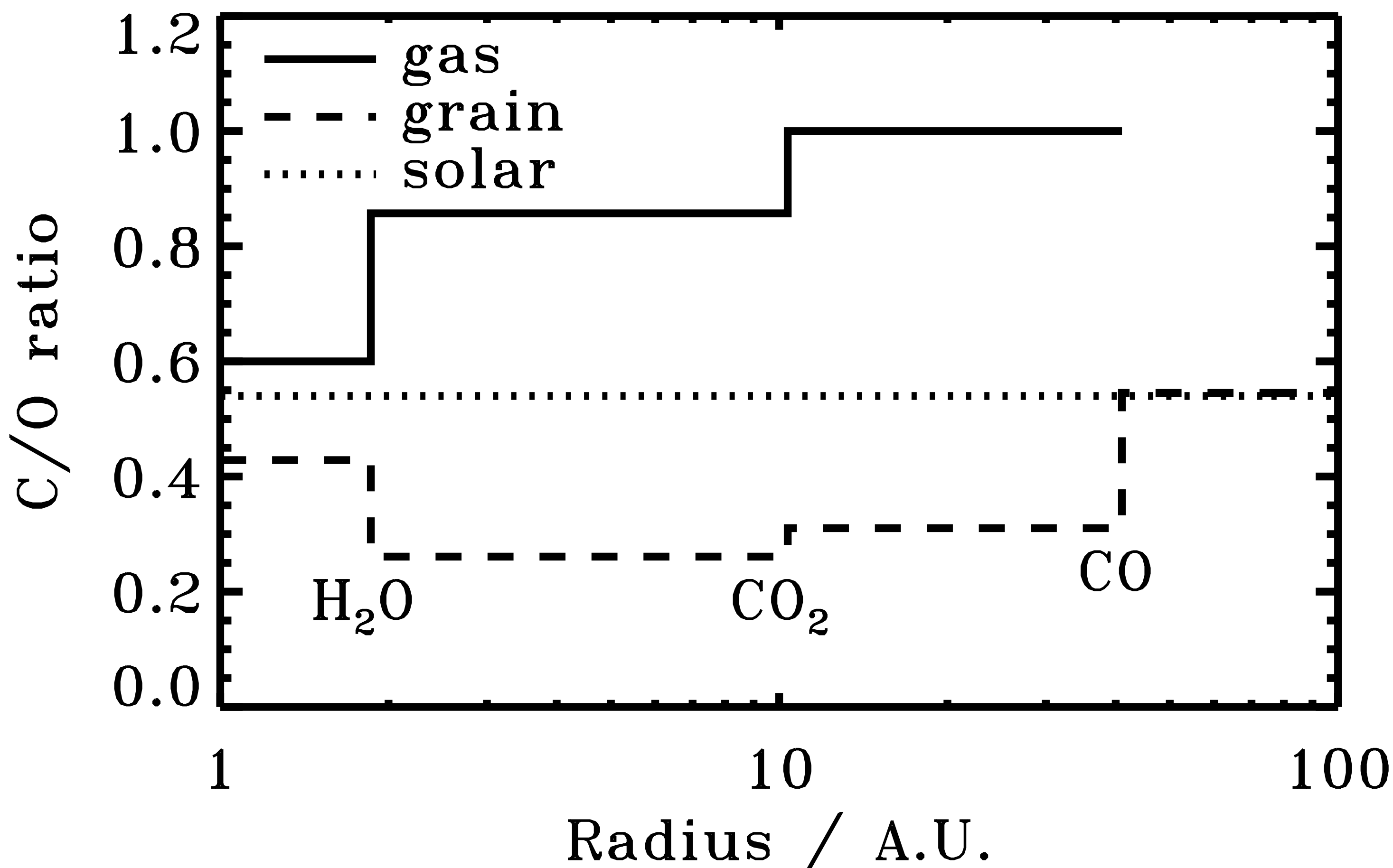

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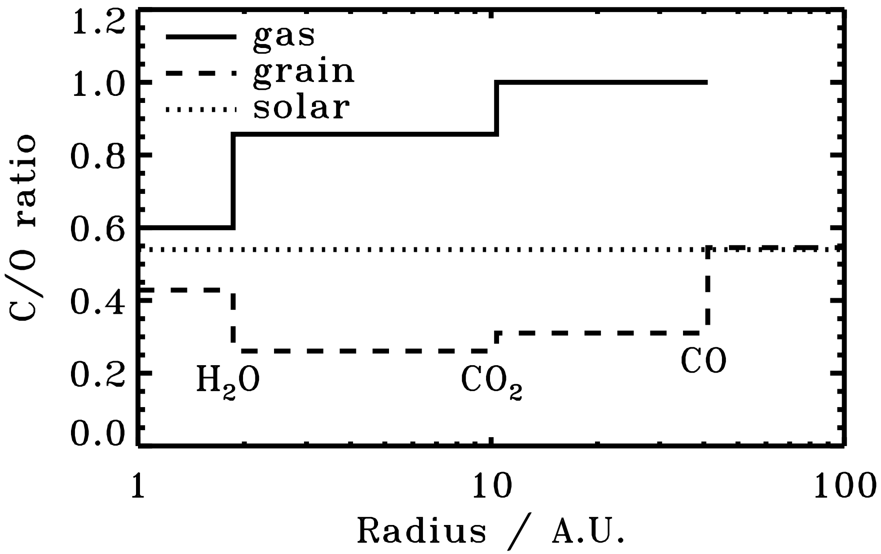

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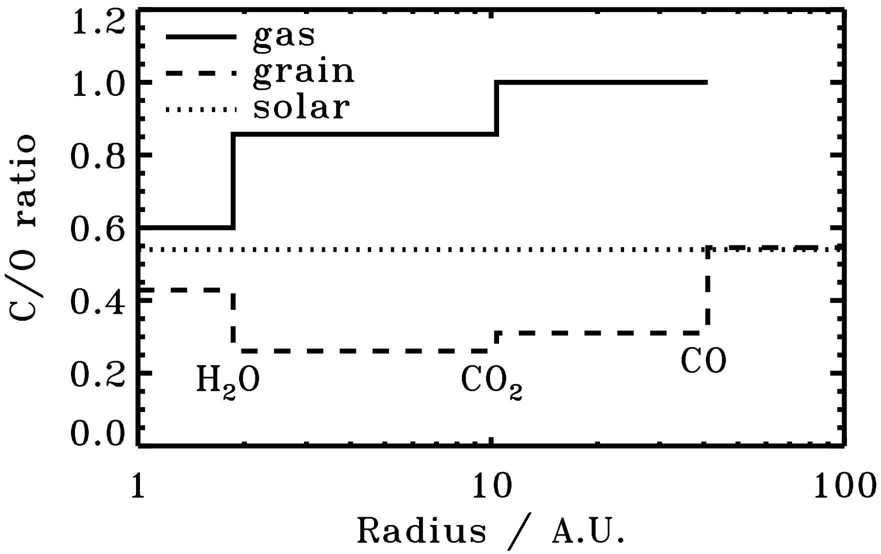

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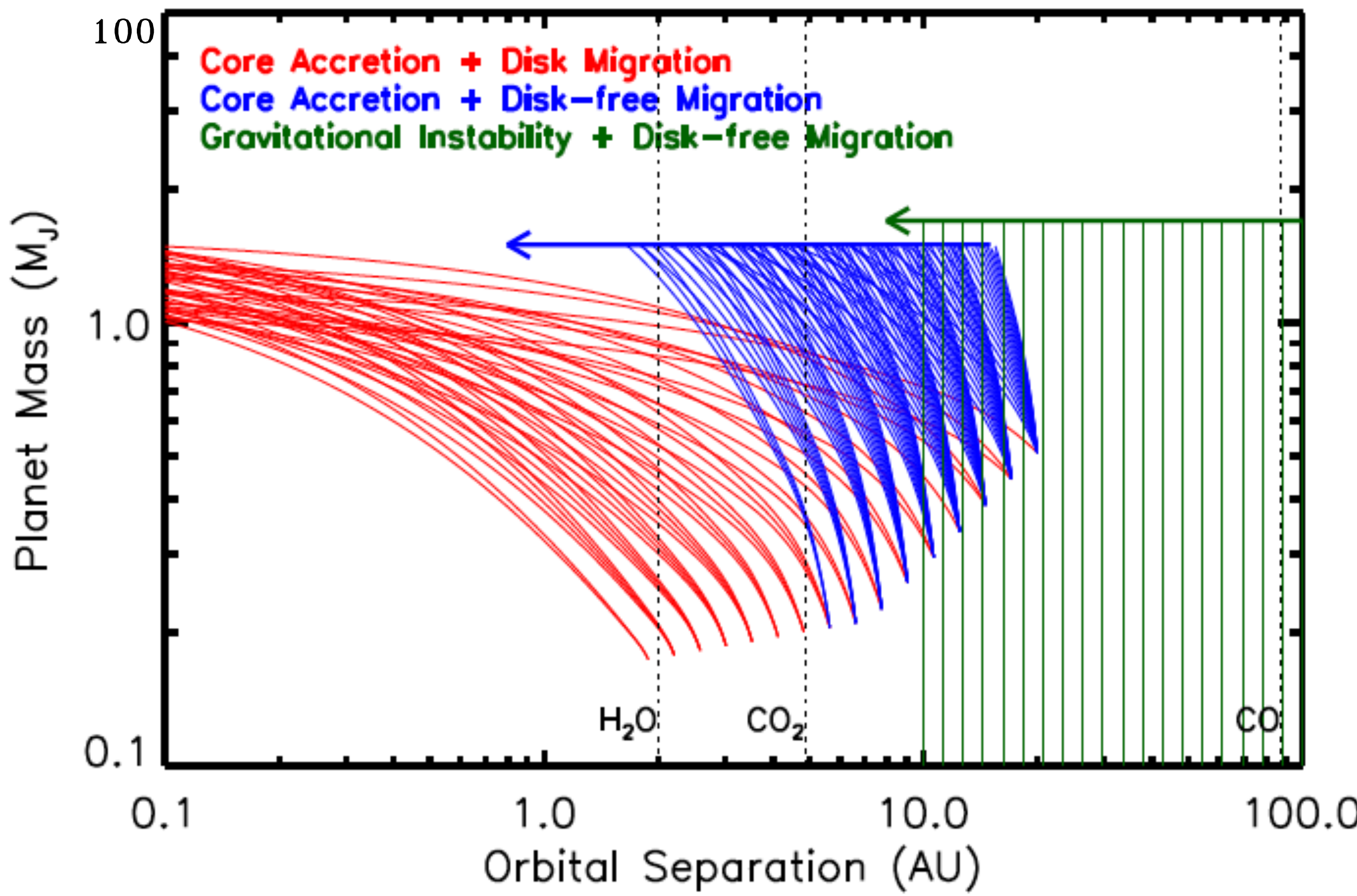

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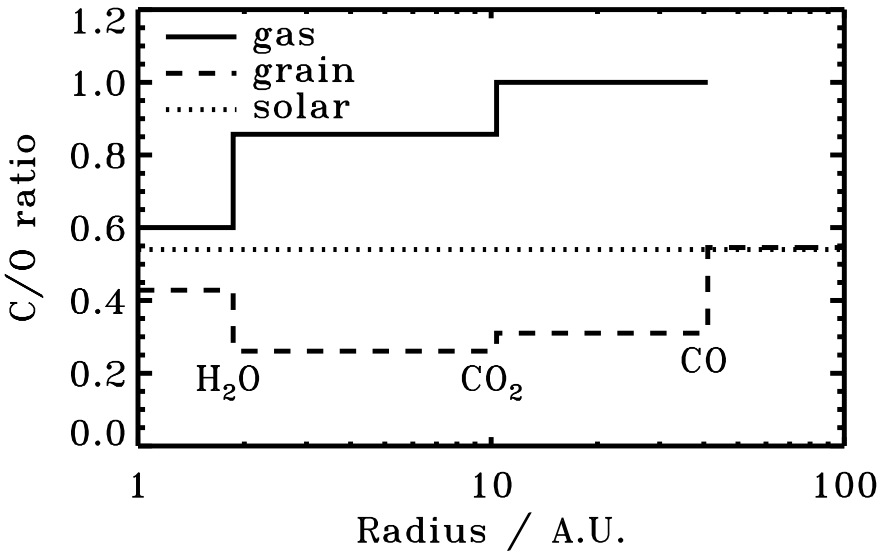

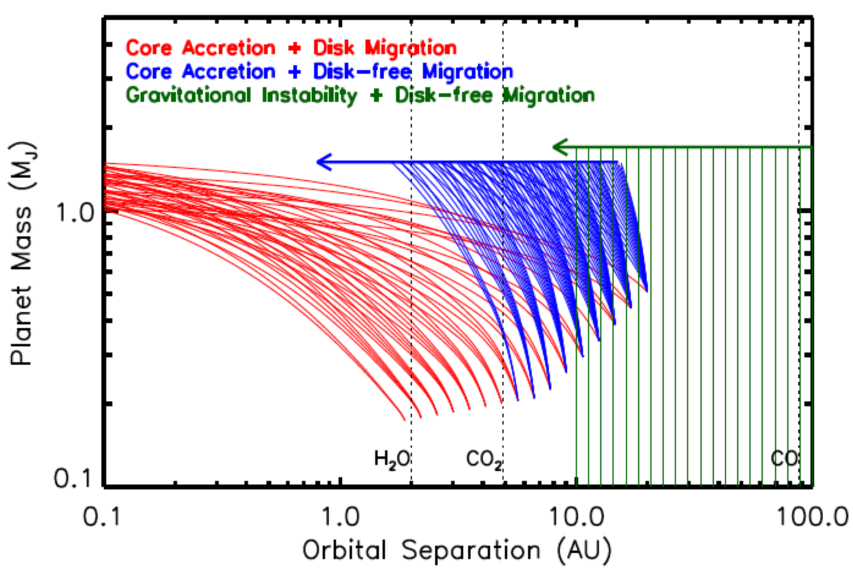

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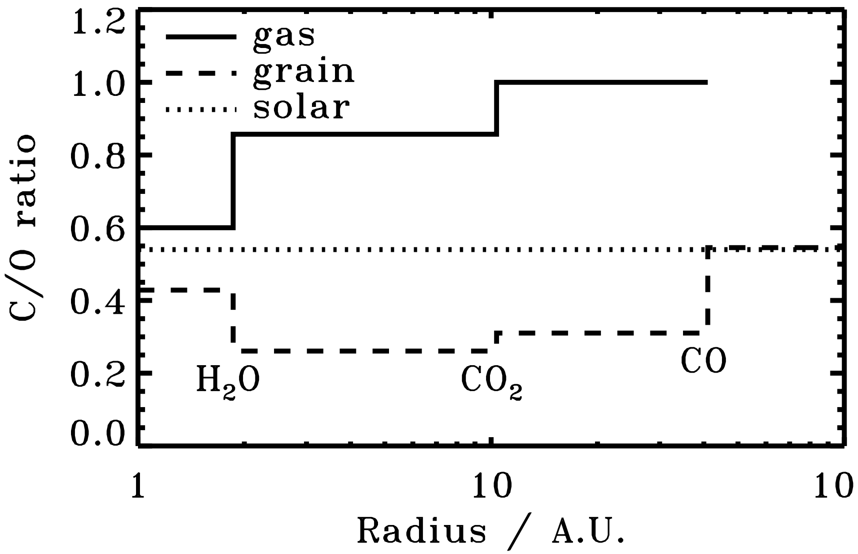

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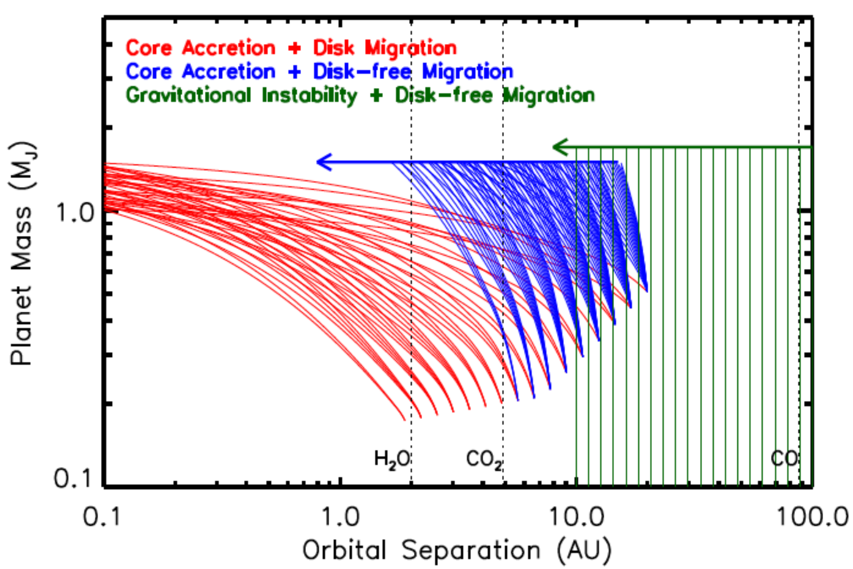
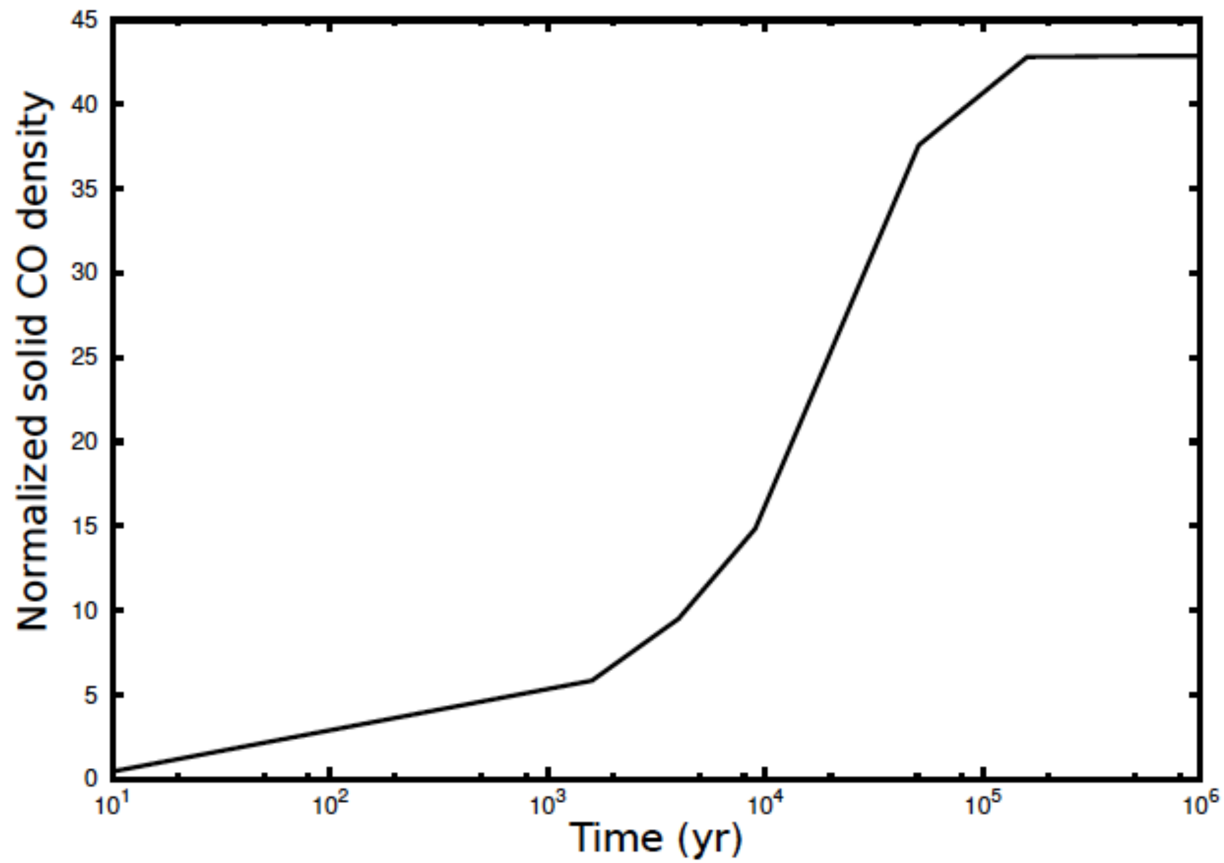




This work

Disk gas structure: non-irradiated accreting disk, i.e. gas diffusing toward star. Initial gas density profile set by self-similarity solution (power-law+exponential taper). Vertical structure set by hydrostatic equilibrium. Radial profile evolves with time:

$$\frac{\delta\Sigma}{\delta t} = \frac{3}{r}\frac{\delta}{\delta r}\left(r^{1/2}\frac{\delta}{\delta r}\left(\nu\Sigma r^{1/2}\right)\right) + Q_{\rm acc} + Q_{\rm ph},$$

$$T_{\rm s}^4 = T_{\rm s,noirr}^4 + T_{\rm s,irr}^4$$

$$T_{\rm s,irr} = T_* \left[\frac{2}{3\pi}\left(\frac{R_*}{r}\right)^3 + \frac{1}{2}\left(\frac{R_*}{r}\right)^2\left(\frac{H_{\rm P}}{r}\right)\left(\frac{{\rm d}\ln H_{\rm P}}{{\rm d}\ln r} - 1\right)\right]^{1/4}$$

Disk temperature structure

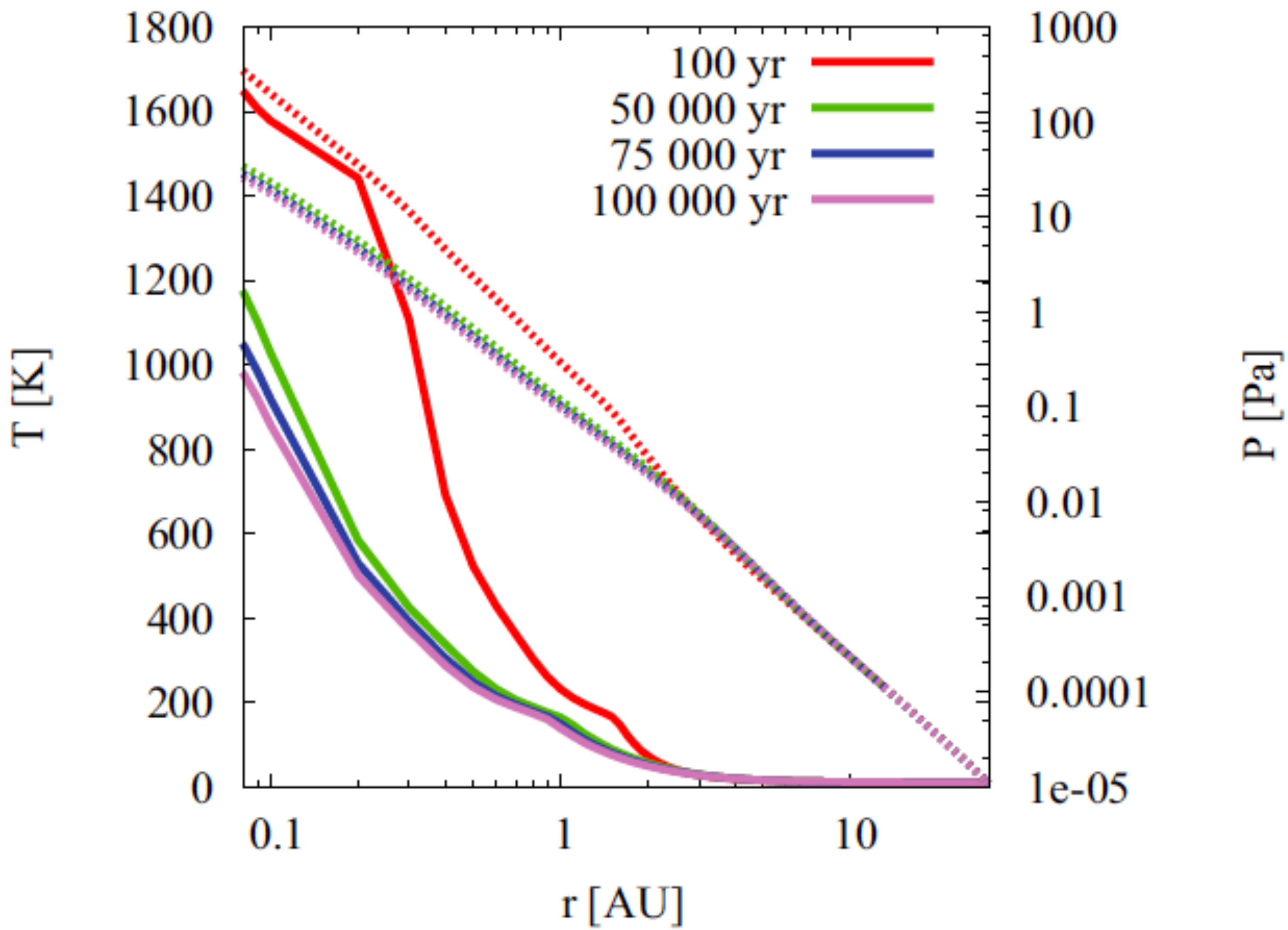
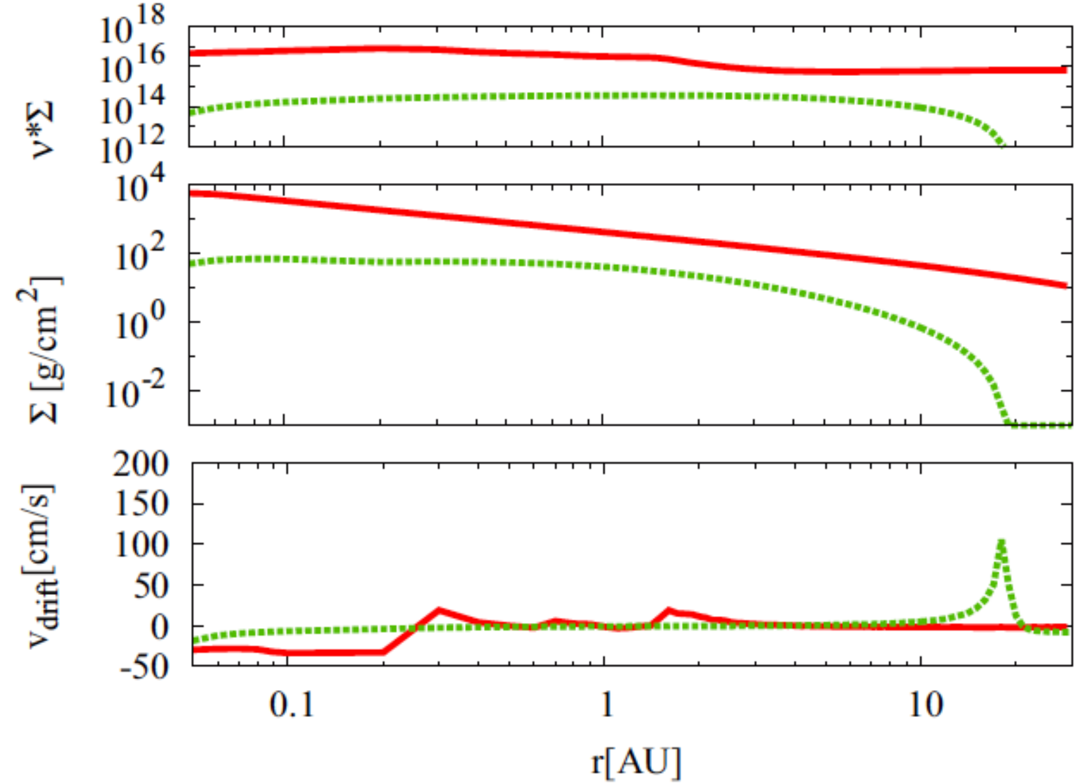
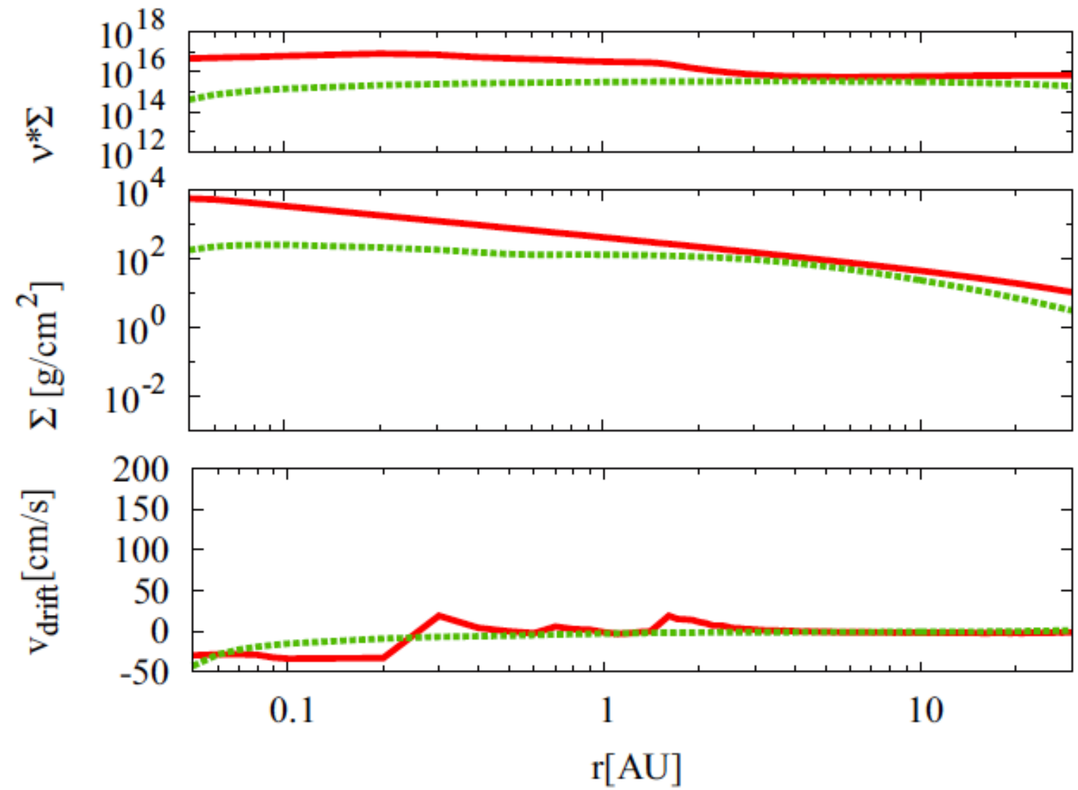


Fig. 1. Time evolution of the midplane temperature (solid lines) and pressure (dotted lines) of disc #1 ($\Sigma_0 = 95.8$ g cm^{-2}, $a_{core} = 46$ AU, $\gamma = 0.9$) in a case without irradiation.

Disk gas evolution





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Disk solids: all in km boulders — no drift

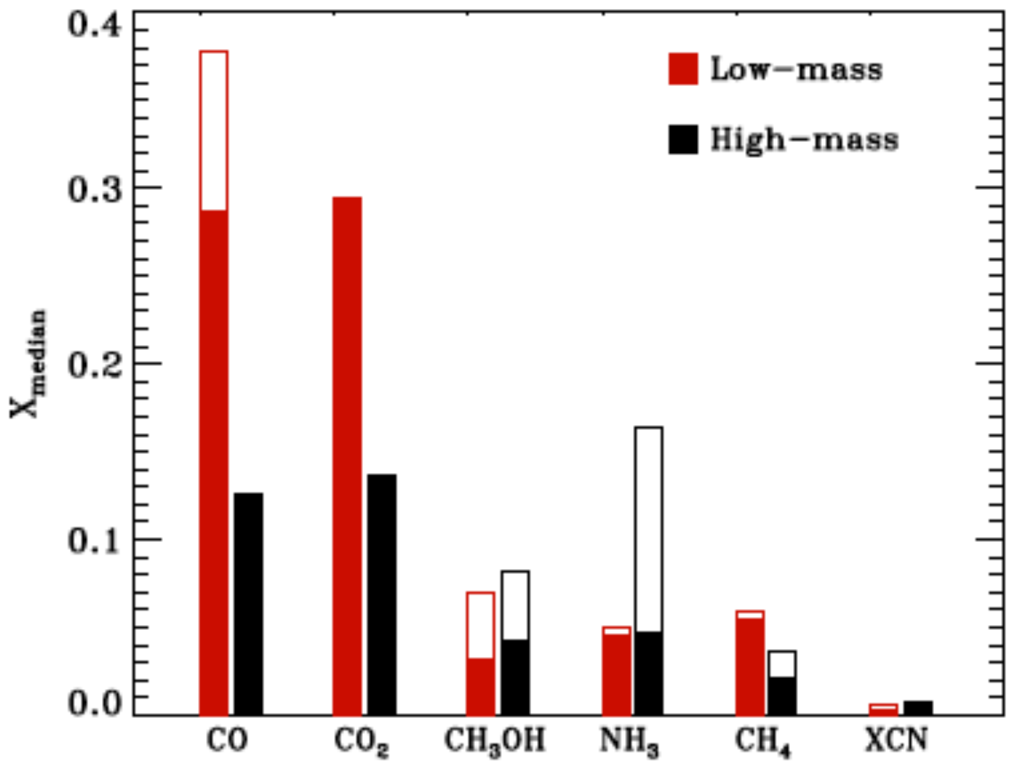
Chemistry: No chemical evolution. Explores two different molecular compositions.

Chemistry

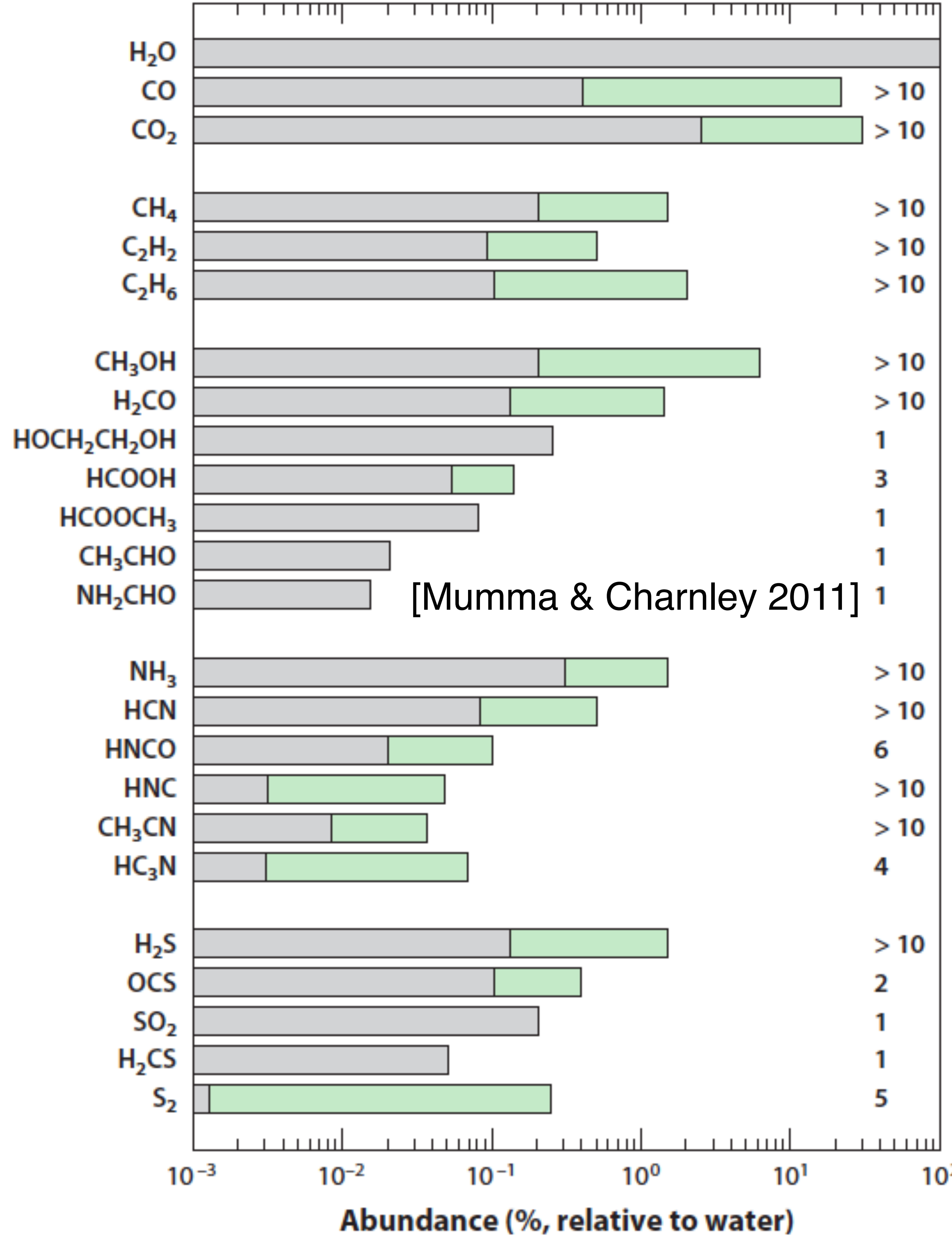
Table 2. Condensation temperatures and nebulae abundances of volatile species in the model.

Specie	T_{cond} (K)	Nebulae abundance (mass/H_2)	
		CO:H_2O = 0.2	CO:H_2O = 1
H_2O	152–173	8.16×10^{-3}	5.62×10^{-3}
CH_3OH	127–143	2.17×10^{-3}	1.5×10^{-3}
NH_3	88–99	5.39×10^{-4}	3.72×10^{-4}
CO_2	77–86	3.99×10^{-3}	2.75×10^{-3}
H_2S	67–75	3.09×10^{-4}	2.13×10^{-4}
CH_4	31–60	4.35×10^{-4}	3.00×10^{-4}
CO	28–60	2.54×10^{-3}	8.75×10^{-3}
N_2	23–60	8.89×10^{-4}	6.12×10^{-4}

Protostellar abundances



Comet abundances



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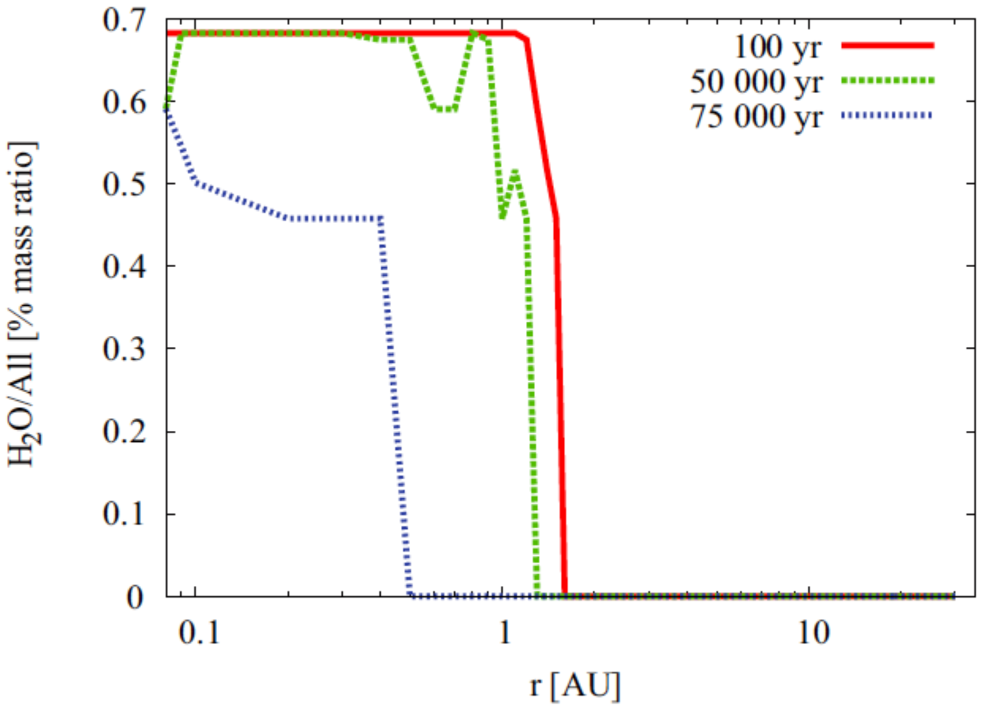
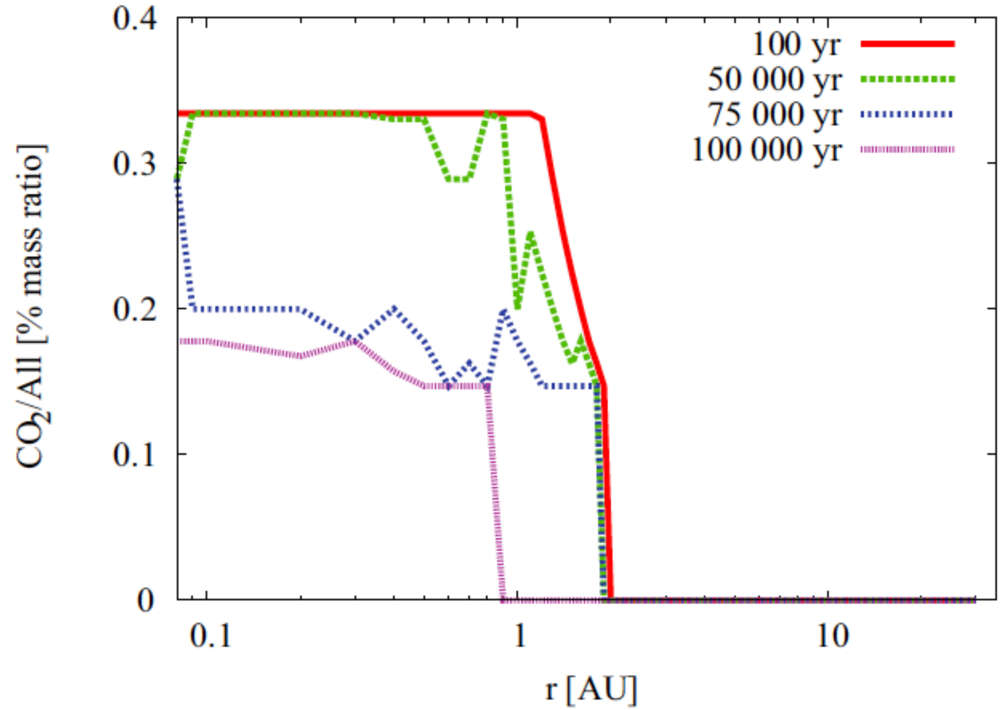
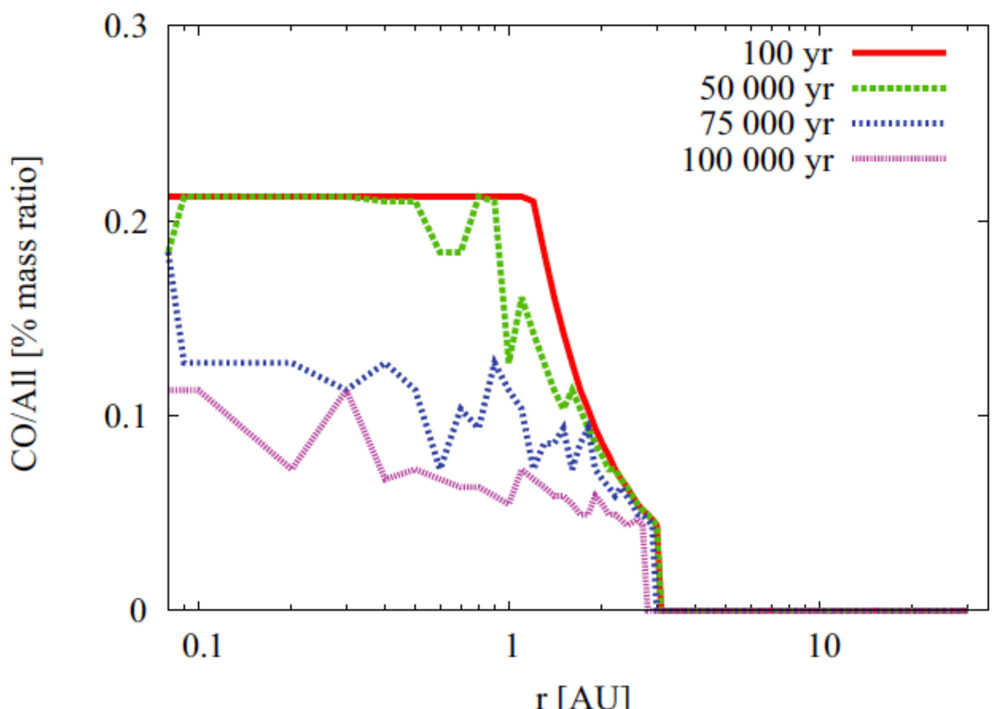
Gas-grain partition: calculate equilibrium pressure and if partial pressure is higher than equilibrium pressure, all of the species at that radius becomes vapor

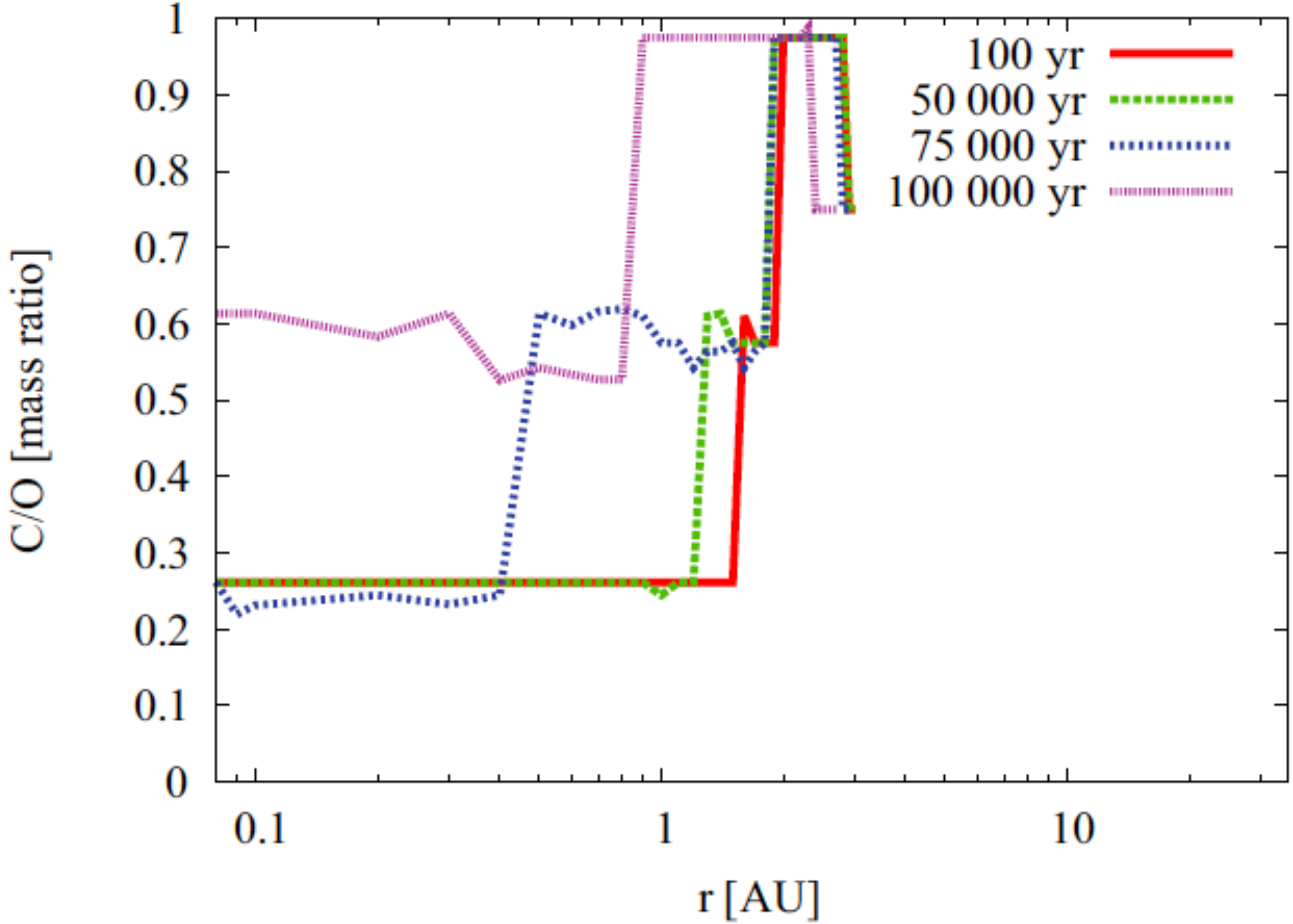
Volatile evolution







C/O mass ratio



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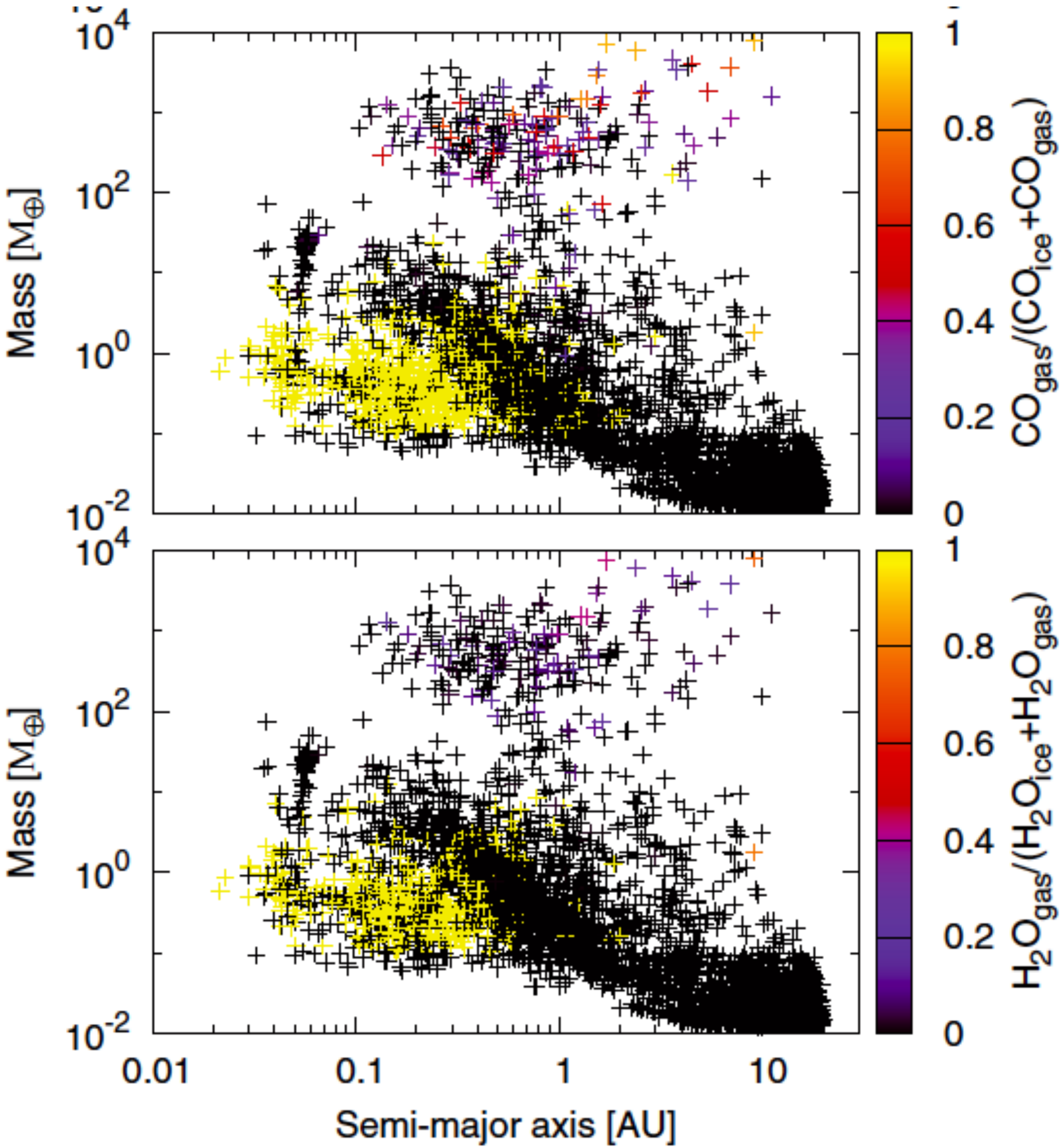
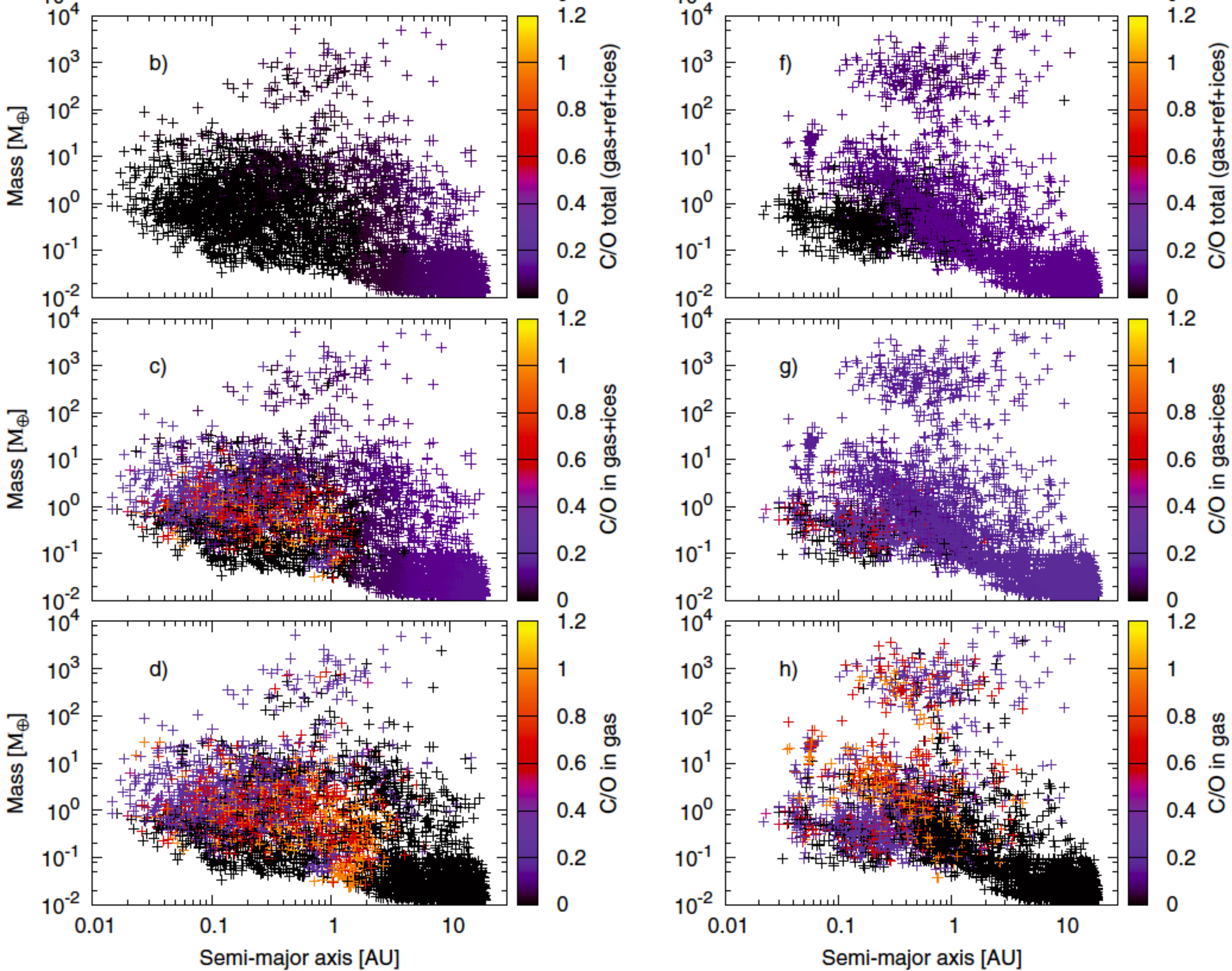
Planet formation: core accretion with migration

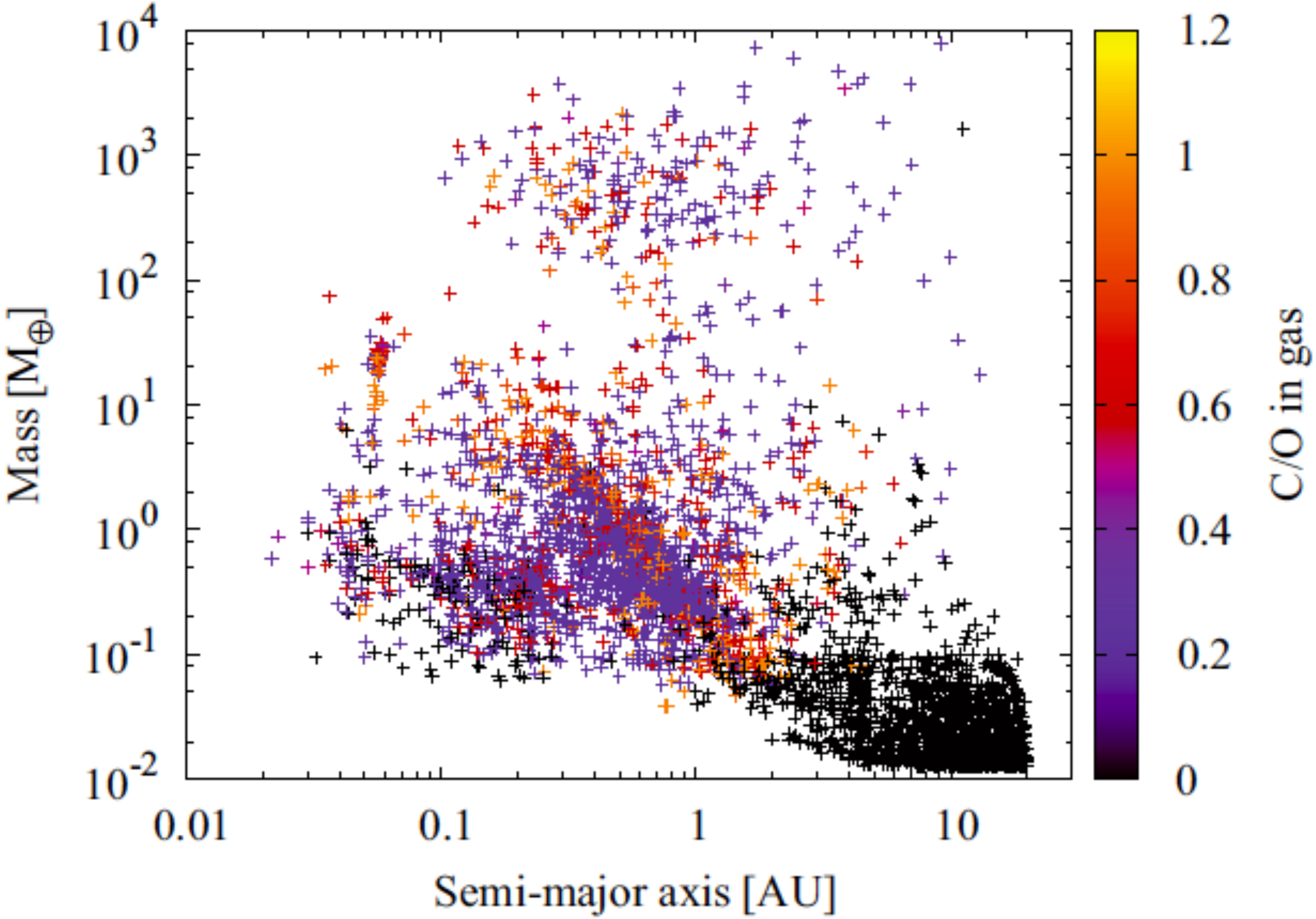


Volatile gas fractions

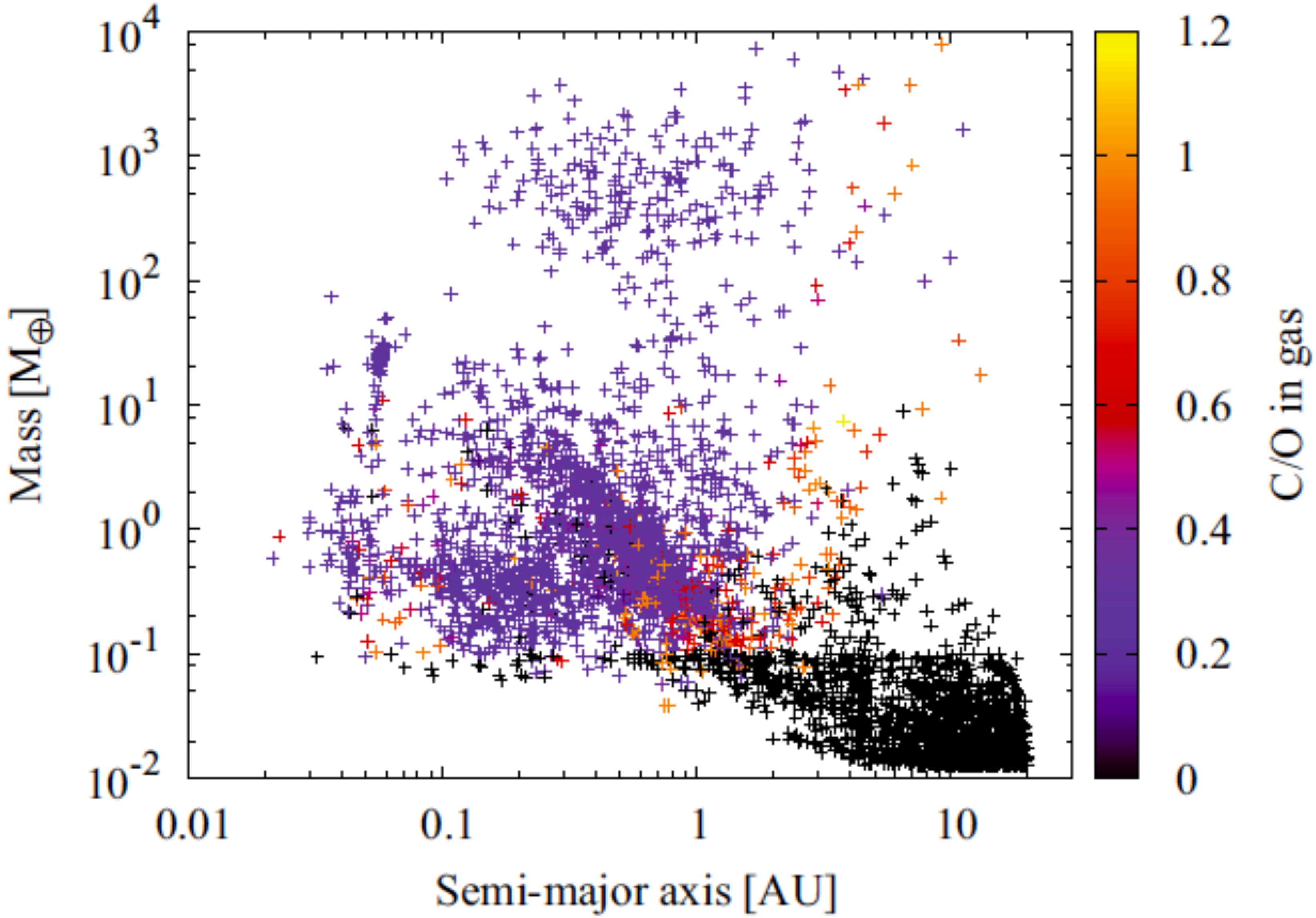


b)
c)
d)
f)
g)
h)
Mass [M⊕]
Semi-major axis [AU]
C/O total (gas+ref+ices)
C/O in gas+ices
C/O in gas

C/O in planets without migration



C/O in planets in a passive disk



Summary: Things that matter for planetary C/O ratios

- The position of the protoplanet when it starts accreting gas, which gives the planet its initial C/O.
- The gas phase evolution, which depletes or enhances specific regions in volatile compounds and thus increases or decreases the initial C/O ratio. If the gas phase does not evolve (as in Öberg et al. 2011), only a few planets are able to obtain a C/O ratio higher than that of the host star.
- The time of accretion. The time evolution of the gas phase shows that removing species from the gas phase such as H_2O can increase the C/O ratio in the gas phase of the disc in the inner regions.
- The migration path of the protoplanet. The C/O ratio in in situ formed planets is slightly different for rocky and giant planets, but the effect is strong for planets located between 0.4 and 1 AU whith a mass of between 0.1 and 10 $M_\oplus$. However, the migration path of the protoplanet can increase or decrease its initial C/O ratio, depending on the gas phase evolution.
- The irradiation. Irradiation pushes the position of the ice line outwards (see T14; M14a), meaning that the volatile molecules can be present at positions farther outside than in evolving planetary systems without irradiation. This leads to a possible enrichment of the C/O ratio in the envelope of low-mass planets around 1 AU.