

Jupiter’s composition: sign of a (relatively) late formation in a chemically evolved protosolar disk

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DRAFT VERSION: 7 October 2005

ABSTRACT

It has been proposed that the enrichment in noble gases found by Galileo in Jupiter’s atmosphere can be explained by their delivery inside cold planetesimals. We propose instead that this is a sign that the planet formed in a chemically evolved disk and that noble gases were acquired mostly in gaseous form during the planet’s envelope capture phase.

We show that the combined settling of grains to the disk midplane in the cold outer layers, the condensation of noble gases onto these grains at temperatures below 20–30K, and the evaporation from high disk altitudes effectively lead to a progressive, moderate enrichment of the disk. The fact that noble gases are vaporized from the grains in the hot inner disk regions (e.g. Jupiter formation region) is not a concern because a negative temperature gradient prevents convection from carrying the species into the evaporating region. We show that the ~ 2 times solar enrichment of Ar, Kr, Xe in Jupiter is hence naturally explained by a continuous growth of the planet governed by viscous diffusion in the protosolar disk in conjunction with an evaporation of the disk and its progressive enrichment on a million years timescale.

Key words: Solar system: formation, planetary systems, planetary systems: formation, planetary systems: protoplanetary disks, accretion disks, planets: Jupiter

1 INTRODUCTION

Ten years have elapsed since the Galileo probe entered Jupiter’s atmosphere and allowed *in situ* measurements of its composition (e.g., Young et al. 1996; Owen et al. 1999). One of the key results of the mission is that, when compared to hydrogen, most measurable species appear to be enriched by a factor two to four compared to a solar composition.

Most surprisingly, the list of enriched species includes not only “ices” (i.e. species that condense at temperature ~ 100 K in the protosolar disk like methane, ammonia), but also the noble gases Ar, Kr, Xe (Mahaffy et al. 2000), which are enriched compared to the new solar abundances (e.g. Lodders 2003, for a review) by factors 2.2 ± 0.8 , 2.0 ± 0.7 , 2.0 ± 0.5 , respectively. This led Owen et al. (1999) to propose that Jupiter formed from very low-temperature planetesimals, at a temperature ~ 30 K allowing a direct condensation of noble gases onto amorphous ice. This explanation was challenged by Gautier et al. (2001) who proposed that noble gases would be incorporated into crystalline ice by clathration at slightly higher temperatures, and that they would thus be delivered into Jupiter by icy planetesimals. The large amount of cages available to trap noble gases implies that the ratio of oxygen to other species in Jupiter should be highly non-solar, but the

precise factor depends on the condensation sequence (Gautier et al. 2001; Hersant et al. 2004; Alibert et al. 2005).

In this letter, we propose instead that the present abundances of Jupiter indicate that the planet (and other giant planets as well) formed in an chemically evolved protoplanetary disk, in which part of the light gases (hydrogen, helium and maybe neon) had been lost by photoevaporation.

Except as otherwise noted, we will use the disk evolution model described by Hueso & Guillot (2005) with the following values of the parameters: $M_{\text{cd}} = 1 M_{\odot}$ (mass in the molecular cloud core), $M_0 = 0.4 M_{\odot}$ (seed mass for the protosun), $T_{\text{cd}} = 10$ K (ambient interstellar temperature), $\omega_{\text{cd}} = 10^{-14} \text{ s}^{-1}$ (assumed uniform rotation rate of the cloud core), $\alpha = 0.01$ (viscosity).

2 SOLIDS AS CARRIERS OF THE NOBLE GASES?

Explaining the efficient delivery of noble gases into Jupiter’s atmosphere by embedding them into solids (either through a direct condensation at ~ 30 K, or through clathration at slightly higher temperature) is difficult: As shown by Fig. 1, the disk should always remain warmer due to stellar irradiation up to 10 AU from the central star, i.e. where Jupiter and Saturn should have formed. A possibility could be that the disk self-shadows this region (e.g., Dullemond et al. 2001), but it remains to be proved that this effect occurs at the right time and distances, and that it is able to maintain

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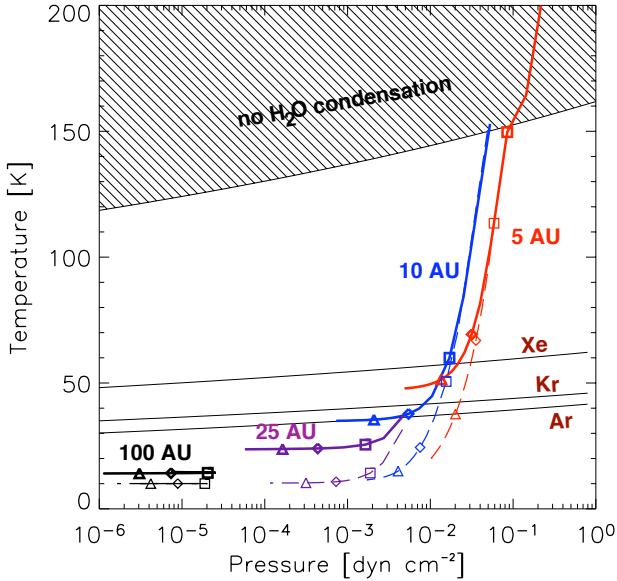


Figure 1. Temperature pressure diagram showing the region of condensation of H_2O , and the clathration lines for Xe, Kr and Ar into crystalline ice, assuming a solar composition. The coloured lines are evolution tracks in the protosolar disk at distances of 5, 10, 25 and 100 AU, respectively, for irradiated disks (plain) or without including stellar irradiation (dashed). The symbols corresponds to ages of 1 (squares), 2.5 (diamonds) and 5 Ma (triangles), respectively. The disk evolution models are calculated without evaporation.

sufficiently low temperatures. Similarly, Jupiter could have formed further from the Sun and migrated inward (Alibert, Mousis & Benz 2005), but it is yet unclear why Jupiter would have accreted its gas in the > 10 AU region, sufficiently late for the disk to have cooled, and then not in the 5 – 10 AU region when its migration there imposes that a massive disk was still present.

Furthermore, the clathration model requires a large number of available cages to trap a significant fraction of the argon. This implies that the ratio of H_2O to all other clathrated species has to be large to provide as many cages as possible, and yet it is constrained by interior models of Jupiter that imply that the total mass of heavy elements in Jupiter, including the core and including rocks, is smaller than $40 M_{\oplus}$ (Guillot 2005). Alibert et al. require the accretion of $\sim 20 M_{\oplus}$ of clathrated ices, assuming a 100% clathration efficiency. An efficiency of 50% or less would rule out the clathration hypothesis as it stands. Finally, this overabundance of H_2O has to be postulated but is not consistently calculated.

In summary, although it appears very likely that chemical species including noble gases were at some point trapped into solid planetesimals, explaining Jupiter’s composition through that mechanism only seems to require an unlikely combination of factors.

3 GIANT PLANET FORMATION IN A CHEMICALLY EVOLVED DISK

We now assess the possibility that the giant planets were formed in a chemically evolved protoplanetary disk and that noble gases were delivered to the planets mostly in *gaseous* form. In our model, the noble gases are trapped into the solids at low temperatures in the outer disk, but most of them are released in gaseous form in

the giant planet formation region. We postulate that this trapping is almost complete because of the low (~ 20 K) temperatures there (see Nomesco & Bar-Nun 2005).

For simplicity, we consider that our protoplanetary disk is made of 2 components: a dominant one that includes hydrogen, helium and neon (species that remain gaseous at all temperatures), of abundance $x_{\text{H}} \sim 1$; and a minor one (e.g. argon, krypton or xenon) of abundance $x_{\text{Z}} \equiv x \ll 1$ that is carried with the grains to the midplane of the disk and radially inward.

3.1 Enrichment by an inward radial migration of grains?

The inward radial migration of grains of $\sim \text{cm}$ size has been postulated to be a key ingredient in the problem of the formation of planetesimals (e.g. Cuzzi & Zahnle 2004). Since these grains should have captured noble gases in the cold outer regions of the disk, this could potentially also lead to an enrichment of the inner disk in noble gases. We find however that this scenario is unlikely to yield noble gases abundances that are compatible with the measured values in Jupiter. This is due to two reasons:

(i) Given that we expect a fast mixing of the inner regions, the local enrichment of a given species should be proportional to the disk mass inside its vaporization radius. Now, this factor is very dependent on the vaporization temperature: Compared to a species with a 20 K vaporization temperature, species that would be released at 30, 40 or 50 K should be more enriched by factors ~ 3 , 5 and 10, respectively. Given the relatively uniform enrichment of Jupiter’s atmosphere in Ar, Kr, Xe, and given that Ar is much more volatile than Xe, it is difficult to imagine that this scenario can work.

(ii) An efficient transport of noble gases into the disk’s inner region also implies a rapid loss by accretion onto the star, and a global *depletion* of these elements. Solving the problem then requires a careful balance between inward transport and loss of the depleted outer disk (which otherwise will be accreted onto the giant planets).

Preliminary mass balance calculations indicate that the inward transport of noble gases had to be very limited, and is unlikely to have had an important role: we choose to neglect it in what follows. We will assume that it may have occurred early on, but led to the loss of only a minor fraction of the noble gases in the disk.

3.2 Evaporation from the disk

3.2.1 Main characteristics

It is relatively natural to invoke evaporation of disk material in order to explain the loss of light hydrogen and helium while retaining heavier elements. The fact that disks evaporate has been observed in the relatively extreme situations of *proplyds* under the intense irradiation of O-B stars, but is also commonly invoked to account for the fast disappearance of disks around young stars.

The temperature in the disk atmosphere controls the evaporation, and defines the critical radius, when the sound speed is equal to the orbital velocity (e.g. Shu et al. 1993):

$$R_g = \frac{GM_*\mu}{kT}, \quad (1)$$

where G and k are the gravitational and Boltzmann constants, M_* is the mass of the central star, and μ the mean molecular mass. For a solar-type star and atomic hydrogen, R_g is of order of 10, 100 and

Table 1. Average characteristics of the evaporation flow estimated at the disk’s mid-life

		Distance [AU]	n_{midplane} [cm ⁻³]	n_{esc} [cm ⁻³]	T_{esc} [K]	$m_{\text{crit}}/m_{\text{H}}$ []	λ_{esc}/H_P []	$\dot{\Sigma}_{\text{esc}}$ [g cm ⁻² s ⁻¹]	\dot{M}_{esc} [M _⊙ a ⁻¹]
EUV	$\Phi = 10^{41} \text{ s}^{-1}$	~ 10	~ 10 ¹¹	~ 10 ⁴	10000	~ 3000	~ 10 ⁻²	~ 10 ⁻¹⁴	~ 4 × 10 ⁻¹⁰
	$\Phi = 10^{43} \text{ s}^{-1}$						~ 10 ⁻³	~ 10 ⁻¹³	~ 4 × 10 ⁻⁹
FUV / thermal	$T_{\text{esc}} = 100 \text{ K}$	outer disk	~ 10 ¹⁰	~ 10 ⁵	100	~ 4 × 10 ⁴	~ 3 × 10 ⁻³	~ 10 ⁻¹⁴	~ 3 × 10 ⁻⁸
	$T_{\text{esc}} = 200 \text{ K}$				200	~ 3 × 10 ⁵	~ 4 × 10 ⁻⁴	~ 6 × 10 ⁻¹⁴	~ 7 × 10 ⁻⁸
	$T_{\text{esc}} = 600 \text{ K}$				600	~ 10 ⁶	~ 5 × 10 ⁻⁵	~ 3 × 10 ⁻¹³	~ 2 × 10 ⁻⁷

300 AU, for atmospheric temperatures of 10000, 1000 and 350 K respectively.

It is generally thought that only disks that are supercritical (i.e. $r > R_g$ somewhere in the disk) evaporate (Shu et al. 1993; Hollenbach et al. 2000; Clarke et al. 2001), but Adams et al. (2004) show that an efficient evaporation is also possible in subcritical disks. In all cases, this requires that a disk atmosphere is superheated significantly compared to the midplane. High temperatures (~ 10⁴ K) in the inner disk (~ 10 AU) can be due to extreme UV radiation from the central star (Shu et al. 1993); Moderate temperatures (~ 100 – 600 K) in the outer disk can be maintained by the far UV ambient radiation from a stellar cluster (Adams et al. 2004) or by disequilibrium heating of the gas in the presence of some dust particles (Jonkheid et al. 2004; Kamp & Dullemond 2004). (Far more violent evaporation effects can occur near massive stars, but for simplicity, we choose not to discuss this possibility).

Table 1 depicts the global characteristics of the evaporation flow. A crucial point is that the evaporation is *hydrodynamical*, i.e. it occurs at levels where the mean free path λ_{esc} is significantly smaller than the pressure scale height H_P . Because of the very low gravity, the evaporation also occurs without any separation of the chemical elements, as shown by the high value of the critical mass (Hunten et al. 1987):

$$m_c/m_{\text{H}} = 1 + \frac{kT\dot{\Sigma}_e}{bgX_{\text{H}}m_{\text{H}}^2}, \quad (2)$$

where b is a diffusion coefficient (we use $b \approx 10^{20} \text{ cm}^{-1} \text{ s}^{-1}$), g is the gravity.

In all cases, the levels at which evaporation takes place correspond to relatively high altitudes in the disk, much higher than the estimated thickness of the dust subdisk (Dubrulle et al. 1995; Dullemond & Dominik 2005; Tanaka et al. 2005; Throop & Bally 2005). This implies that species that condense onto grains and are transported towards the midplane will generally not be lost from the disk. Furthermore, because a negative vertical temperature gradient prevails (e.g. Malbet & Bertout 1991; Chiang & Goldreich 1997), even species that are captured by grains at low temperatures but later vaporize when subject to higher temperatures will not be transported by convection back up to the levels where they would hydrodynamically escape. This implies that the disk can become progressively enriched in species that condense onto grains at low temperatures down to ~ 15 – 30 K.

3.2.2 The model

Let us consider the evolution of a viscous accretion disk of surface density $\Sigma(r, t)$, subject to an evaporation rate $\dot{\Sigma}_{\text{esc}}$. Its evolution is governed by the following equation (e.g. Clarke et al. 2001; Hueso & Guillot 2005):

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r} \frac{\partial}{\partial r} \left[r^{1/2} \frac{\partial}{\partial r} (\nu \Sigma r^{1/2}) \right] - \dot{\Sigma}_{\text{esc}}, \quad (3)$$

and the escape rate is limited to a layer of temperature T_{esc} , mean molecular mass m_{esc} , corresponding sound speed c_{esc} , and number density n_{esc} :

$$\dot{\Sigma}_{\text{esc}} = m_{\text{esc}} c_{\text{esc}} n_{\text{esc}}. \quad (4)$$

Let us now consider that a second minor component of surface density $c\Sigma$ is present (with $c \ll 1$) and obeys the same diffusion equation as for Σ , with the exception that for the reasons discussed previously, its escape rate is very small. (Obviously, this is a simplification because one should include backreactions between the 2 species). Within this framework, the evolution of the concentration c , or equivalently of the enrichment $\mathcal{E} \equiv c/c_{\odot}$ (where c_{\odot} is the protosolar concentration of that element) can be shown to obey the following equations:

$$\frac{\partial \mathcal{E}}{\partial t} = 3\nu \left[\left(2 \frac{\partial \ln(\nu \Sigma)}{\partial \ln r} + \frac{3}{2} \right) \frac{1}{r} \frac{\partial \mathcal{E}}{\partial r} + \frac{\partial^2 \mathcal{E}}{\partial r^2} \right] + \dot{\mathcal{E}}_{\text{esc}} \quad (5)$$

$$\dot{\mathcal{E}}_{\text{esc}} = \left(1 - \frac{\mathcal{E}}{\mathcal{E}_{\text{max}}} \right) \mathcal{E} \frac{\dot{\Sigma}_{\text{esc}}}{\Sigma} \quad (6)$$

Here, we assume that the enrichment can be at most \mathcal{E}_{max} , after which both the major and the minor species escape. This maximal enrichment is difficult to estimate, but it should mostly depend on the ratio of the mass of a slab of the disk to the mass of the same slab in the dust subdisk. We thus expect that $\mathcal{E}_{\text{max}} \approx 10 - 100$. Note that equation 5 contains both a diffusion term and an advection term. The latter accounts for the fact that both near the inner and outer boundaries, matter is essentially advected as it is either accreted by the star or lost from the system, respectively. Basically, the problem to be studied is one in which the disk becomes progressively enriched in heavy elements as it loses hydrogen and helium, but at a rate that is limited by the diffusion of these heavy elements in the disk, with a timescale $\sim R^2/\nu$.

We further assume that the accretion of the envelopes of Jupiter and Saturn is limited by the viscous diffusion in the disk so that the planets’ growth is (see Lecar & Sasselov 2003):

$$\dot{M}_{\text{planet}}(t) \equiv e_{\text{planet}} \dot{M}_{\text{disk}}(r_{\text{planet}}, t), \quad (7)$$

where $\dot{M}_{\text{disk}}(r_{\text{planet}}, t)$ is the mass flux in the disk that crosses the annulus of radius r_{planet} at time t . The parameter e_{planet} is the ratio of the flux accreted by the planet to the total flux that viscously diffuses inward. It is mostly unknown, and certainly very dependent on the mass of the planet and its cooling. Based on numerical simulations for Jupiter, we choose $e_{\text{planet}} \sim 0.3$ (F. Masset, pers. communication).

3.2.3 *Inner disk evaporation*

We first follow the approach of Clarke et al. (2001) by assuming that the young T-Tauri Sun emits extreme UV photons at a rate Φ , and expecting that $\Phi \approx 10^{41} \text{ s}^{-1}$. In that case, given that the photons heat the upper layers of the disk to $\sim 10,000 \text{ K}$, the evaporation mostly takes place at a critical radius $R_g \sim 10 \text{ AU}$ (Shu et al. 1993). The escape flux is defined by eq. (4) with $T_{\text{esc}} \approx 10^4 \text{ K}$ and by

$$\begin{cases} n_{\text{esc}} = n_0 \Phi_{41}^{1/2} R_{g14}^{-3/2} \left(\frac{r}{R_g} \right)^{-5/2}, & \text{for } r \geq R_g \\ n_{\text{esc}} = 0 & \text{otherwise} \end{cases} \quad (8)$$

where $n_0 = 5.7 \times 10^4 \text{ cm}^{-3}$, $\Phi_{41} \equiv \Phi/10^{41} \text{ s}^{-1}$ and $R_{g14} \equiv R_g/10^{14} \text{ cm}$. The fact that viscous diffusion is much faster close to the Sun leads to an inside-out removal of disk material (Clarke et al. 2001).

Figure 2 shows the resulting evolution of the disk mass and disk enrichment, the growth of Jupiter and Saturn as derived from the disk properties and eq. (7) and the consequent enrichment of their envelopes, assuming that they are fully mixed by convection. The effect of evaporation becomes apparent only when mass of the disk decreases to a point when the mass flux in the disk becomes comparable to the evaporation mass flux. Because the evaporation proceeds from inside out, inner regions ($\lesssim 10 \text{ AU}$) are depleted rapidly and the corresponding local enrichment (2nd panel in fig. 2) can become very large. When this occurs, the mass flux across these radii has become tiny, so that Jupiter's enrichment is always found to be moderate and close to the observed values.

We find that Saturn should be about 50% more enriched according to this scenario. However, this crucially depends on the assumption that Saturn and Jupiter stole the same constant part of the disk mass flux to build their envelopes (i.e. $e_{\text{Jup}} = e_{\text{Sat}} = 0.3$). If Saturn has been less efficient at that, then it may be as enriched in noble gases as Jupiter.

3.2.4 *Outer disk evaporation*

There are two problems with the EUV evaporation scenario: (i) The timescale for the loss of the circumstellar disk is uncomfortably long compared to observations, even in the extreme case of $\Phi = 10^{43} \text{ s}^{-1}$; (ii) It requires a high, constant value of EUV photons production from an unidentified mechanism not powered by the accretion flow (Matsuyama et al. 2003).

Adams et al. (2004) hence proposed a scenario based on a moderate heating of the disks atmosphere by ambient FUV radiation and a subcritical evaporation. We use a simplified version of their evaporation rates (see their appendix) to obtain an evaporation that is controlled by the temperature of the escaping disk atmosphere:

$$\begin{cases} n_{\text{esc}} = \frac{\sigma_{\text{FUV}}^{-1}}{r}, & \text{for } r \geq R_g \\ n_{\text{esc}} = \frac{\sigma_{\text{FUV}}^{-1}}{r} \left(\frac{R_g}{r} \right)^{1/2} e^{-(R_g/r-1)/2} & \text{otherwise,} \end{cases} \quad (9)$$

where $\sigma_{\text{FUV}} \approx 10^{-21} \text{ cm}^2$ is the FUV dust cross section. These escape rates correspond to the evaporation from the disk surface. The mass lost in the *radial* direction is to be considered and is even dominant for subcritical disks, and we hence remove the mass to the last radial layer R_d of the disk:

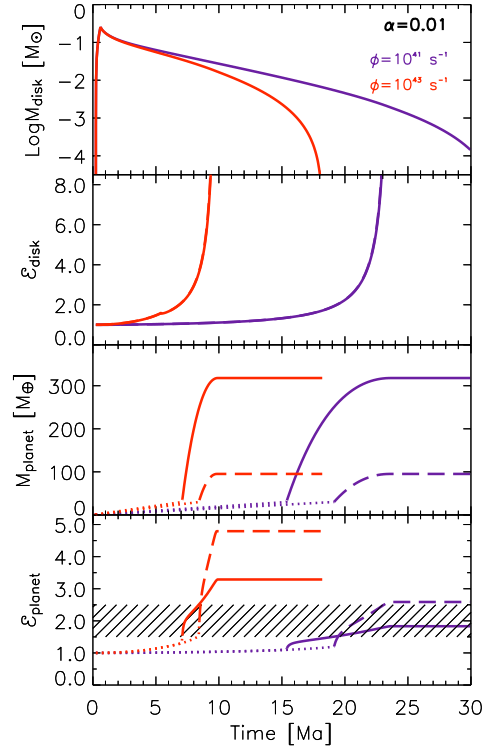


Figure 2. Time evolution of the mass of the protosolar disk M_{disk} , of its local (5 AU) enrichment $\mathcal{E}_{\text{disk}}$, of the masses M_{planet} and enrichments $\mathcal{E}_{\text{planet}}$ of Jupiter (plain) and Saturn (dashed). The calculations are made for a EUV evaporation flux of 10^{41} (blue) and 10^{43} s^{-1} (red), respectively. The dashed area in the bottom panel indicates the enrichments in Ar, Kr and Xe inferred for Jupiter from the Galileo probe data.

$$\begin{cases} \dot{M}_{\text{rad}} = m_{\text{esc}} c_{\text{esc}} \sigma_{\text{FUV}}^{-1} R_d, & \text{for } R_d \geq R_g \\ \dot{M}_{\text{rad}} = m_{\text{esc}} c_{\text{esc}} \sigma_{\text{FUV}}^{-1} R_d \left(\frac{R_g}{R_d} \right)^2 e^{-(R_g/R_d-1)/2} & \text{otherwise} \end{cases} \quad (10)$$

Figure 3 shows the evolutions of the disk and planets resulting from the combination of early supercritical and later subcritical evaporation, as the disk progressively shrinks. As radial evaporation does not lead to an increase in \mathcal{E} , the enrichment is always self-limited, and mostly controlled by the value of T_{esc} (i.e. by the global ratio of the vertical to radial evaporation). Once again, we find that for a quite wide range of values of the different parameters, the resulting enrichment for Jupiter agrees with the measured enrichment in noble gases. In this scenario, because the enrichment in the disk is very progressive, it is expected that Jupiter and Saturn should have about the same enrichment in noble gases.

Even though the details of the photoevaporation have been greatly simplified, we stress that this model does provide an explanation for the Ma timescales for the removal of circumstellar disks, with viscous diffusion playing a key role in spreading the disk outward to regions where it can evaporate more efficiently.

3.2.5 *Sensitivity to input parameters*

We have shown that different scenarios of the evaporation of disks lead to similar results in terms of final enrichments of the giant planets. We briefly describe how the most important parameters affect the results:

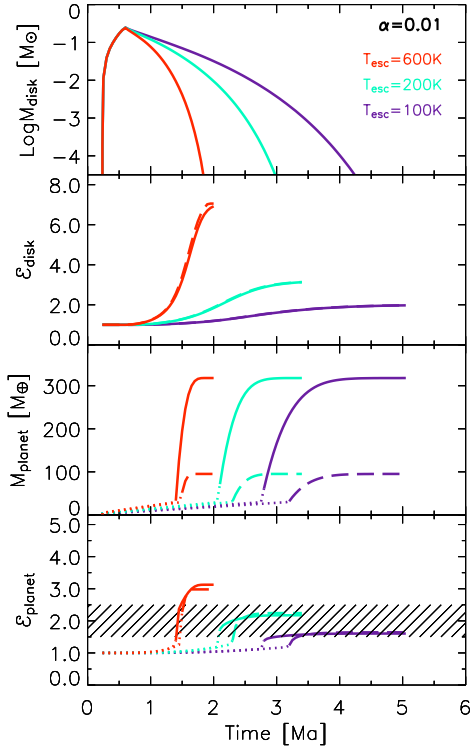


Figure 3. Same as fig. 2, but in the case of an evaporation of the outer disk for three temperatures of the escaping disk atmosphere: 100, 200 and 600 K.

Viscosity (α): It affects the global evolution timescale (proportional to α in the outer-disk evaporation scenario), but very marginally the final values of the enrichment.

Initial angular momentum (ω_{cd}): The maximum disk mass is directly related to the amount of angular momentum of the molecular cloud core from which the disk is born. We find that except for low values of this parameter, the final \mathcal{E}_{planet} remains quite similar.

Maximal enrichment (\mathcal{E}_{max}): Our model rests on the assumption that the local enrichment in the disk can be relatively large; the conclusions of the article remain qualitatively valid and quantitatively similar as long as $\mathcal{E}_{max} \gtrsim 5$. For smaller values we expect the final planet enrichment to be smaller than calculated here and incompatible with the observations.

Planet growth factor (e_{planet}): This parameter governs the growth of our model planets. Because the enrichment in the disk rapidly increases, larger values of this factor yields larger \mathcal{E}_{planet} . However, the dependance is only moderate because of the rapid decline in the disk (and planet) accretion rate. We tested that changes are smaller than the error bars on the noble gas compositions for values of e between 0.1 and 1.

4 CONCLUSIONS

We have shown that the observed enrichment of Jupiter in noble gases can be explained by a progressive, moderate evaporation of the protosolar disk. Provided disk atmospheres can be heated to temperatures of 100 K or more, the model that we propose further qualitatively explains the disparition of disks in Ma timescales, and the final masses of Jupiter and Saturn as resulting from a competition between limited viscous accretion and disk evaporation. We

further predict that the enrichments in Ar, Kr, Xe in Saturn should be similar to that in Jupiter.

These results show the importance of noble gases for tracing back events that occurred in the early Solar System and stress the need for an accurate determination of the compositions of all giant planets.

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