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COULD JUPITER BE A CARBON-RICH PLANET?

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Abstract. Motivated by recent spectroscopic observations suggesting that atmospheres of some extrasolar giant-planets are carbon-rich, i.e. carbon/oxygen ratio (C/O) ≥ 1, we find that the whole set of compositional data for Jupiter is consistent with the hypothesis that it be a carbon-rich giant planet. We show that the formation of Jupiter in the cold outer part of an oxygen-depleted disk (C/O $\sim$1) reproduces the measured Jovian elemental abundances at least as well as the hitherto canonical model of Jupiter formed in a disk of solar composition (C/O = 0.54). The resulting O abundance in Jupiter's envelope is then moderately enriched by a factor of $\sim$2 × solar (instead of $\sim$7 × solar) and is found to be consistent with values predicted by thermochemical models of the atmosphere.

Keywords: planets and satellites: individual (Jupiter), formation, composition, atmospheres, protoplanetary discs

1 Introduction

Observations of extrasolar planets have revealed the possible existence of a new class of giant planets, the so-called carbon-rich planets (CRPs) (Madhusudhan et al. 2011a). A CRP is defined as a planet with a carbon-to-oxygen (C/O) ratio ≥ 1. Recently, we proposed that these planets arise from beyond the snow line in circumstellar disks with oxygen abundances lower than those inferred in their parent stars (Madhusudhan et al. 2011b). In the solar system, the C/O ratio remains poorly constrained in the giant planets because obtaining a measurement of the water abundance below the meteorologically-active layer is difficult (Taylor et al. 2004). Data returned by the Galileo probe mass spectrometer in 1995 around the one-bar pressure level in Jupiter's atmosphere has provided carbon, nitrogen, sulfur, argon, krypton and xenon abundances that are relatively well matched by formation scenarios based on solar nebula models assuming solar elemental composition (Owen & Encrenaz 2006; Mousis et al. 2009) – what we refer to here as "protosolar". Below expected water condensation level, the measured oxygen abundance was unexpectedly low, an effect typically attributed to the dynamics of the region within which the probe descended (Orton et al. 1998), but which we argue here could also partly reflect a bulk abundance lower than predicted by existing formation models.

Here we find that all the observed elemental abundances of Jupiter can be explained consistently within the standard core-accretion model of Jupiter's formation beyond the snow line by only changing the C/O ratio in the formation zone. The resulting O abundance in Jupiter's envelope then becomes moderately enriched compared to solar and is found to be consistent with values predicted by thermochemical models. To do so, we derived the elemental abundances in the envelope of Jupiter by tracking the chemical condensation and accretion of planetesimals through the planet's formation and evolution. We used a numerical model that relates the formation conditions of icy planetesimals accreted by Jupiter in the primitive nebula to the volatile abundances in its present atmosphere, the latter being determined from the amount of heavy elements accreted and dissolved in the planet's envelope during its growth.

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2 Modeling approach

Our model is based on a predefined initial gas phase composition in which all elemental abundances, except that of oxygen, reflect the bulk abundances of the Sun (Asplund et al. 2009) and describes the process by which volatiles are trapped in icy planetesimals formed in the protoplanetary disk. Oxygen, carbon, nitrogen, sulfur and phosphorus are postulated to exist only in the form of H_2O, CO, CO_2, CH_3OH, CH_4, N_2, NH_3, H_2S and PH_3. We fix $CO/CO_2/CH_3OH/CH_4 = 70/10/2/1$ in the gas phase of the disk, a set of values consistent with the Interstellar Medium (ISM) measurements made by the Infrared Space Observatory and at millimeter wavelengths from Earth considering the contributions of both gas and solid phases in the lines of sight. The dispersion of the ISM values is large and might reflect object-to-object variation as well as uncertainties of measurements but we stress that, among the possible molecular ratios, we selected those that are close to the cometary measurements (Bockelée-Morvan et al. 2004). Once the abundances of these molecules are fixed, the remaining oxygen gives the abundance of H_2O. Sulfur is assumed to exist in the form of H_2S, with an abundance fixed to half its protosolar value, and other refractory sulfide components (Pasek et al. 2005). We also consider $N_2/NH_3 = 10/1$ in the disk gas-phase, a value predicted by thermochemical models of the solar nebula (Lewis & Prinn 1980). The process of volatile trapping in planetesimals formed in the feeding zone of proto-Jupiter is calculated using the equilibrium curves of hydrates, clathrates and pure condensates, and the thermodynamic path detailing the evolution of temperature and pressure at 5 AU (i.e. the current location of Jupiter) in the protoplanetary disk.

The top panel of Fig. 1 corresponds to the case where the gas phase abundances of various elements are solar, with the afore-mentioned gas phase molecular ratios. For each ice considered in this panel, the domain of stability is the region located below its corresponding equilibrium curve. The clathration process stops when no more crystalline water ice is available to trap the volatile species. In this case, the icy part of planetesimals is essentially made of a mix of pure condensates and clathrates. The bottom panel of Fig. 1 corresponds to the case of a disk composition similar to the one used in the top panel, except for the oxygen abundance that is set half the solar value. The subsolar O abundance adopted in the gas phase allows us to retrieve a composition of planetesimals that matches the value $C/O = 1$ in planetesimals formed in Jupiter's feeding zone. In this case, because the oxygen abundance is strongly depleted compared to previous case, this element is only distributed between carbon bearing species and the remaining water becomes zero in the initial gas phase of the protoplanetary disk. This implies that the icy part of planetesimals formed in such conditions in the protoplanetary disk is only made of pure condensates.

Finally, the intersection of the thermodynamic paths with the equilibrium curves of the different ices allows determination of the amount of volatiles that are condensed or trapped in clathrates at these locations in the disk following the approach depicted in Mousis et al. (2009) and Madhusudhan et al. (2011b). This method permits computation of the composition of the volatile phase present in the planetesimals formed in Jupiter's feeding zone. The precise adjustment of the mass of these ices accreted by Jupiter and vaporized into its envelope allows us to reproduce the observed volatile enrichments. The fitting strategy is to match the maximum number of observed volatile enrichments and to determine the uncertainty range corresponding to this matching.

3 Results

Once the composition of planetesimals has been calculated in the two cases, we adjusted the mass of heavy elements located in Jupiter's envelope to fit the maximum number of volatile abundances measured by the Galileo probe. Figure 2 represents the superimposition of the two fits with the measured volatile abundances. The figure shows that the same number of elements (carbon, nitrogen, sulfur and argon) is fitted in the two cases. However, the oxygen abundance predicted in Jupiter for an oxygen-depleted nebula is much closer to the measured abundance than the value predicted for a protosolar oxygen abundance. If the former case is correct, this supports the argument that the oxygen abundance in Jupiter derived from Galileo Probe water measurements reflects a bulk interior depletion of O relative to C, and is much less affected by atmospheric dynamical or meteorological processes than in the standard model. Neither calculation matches the observed phosphorus abundance, which is however only expected to provide lower bounds on the bulk abundance (Fletcher et al. 2009). The same remark applies for the observed krypton and xenon abundances but their relatively low values suggest the possibility of systematic error in their determination (Owen & Encrenaz 2006).

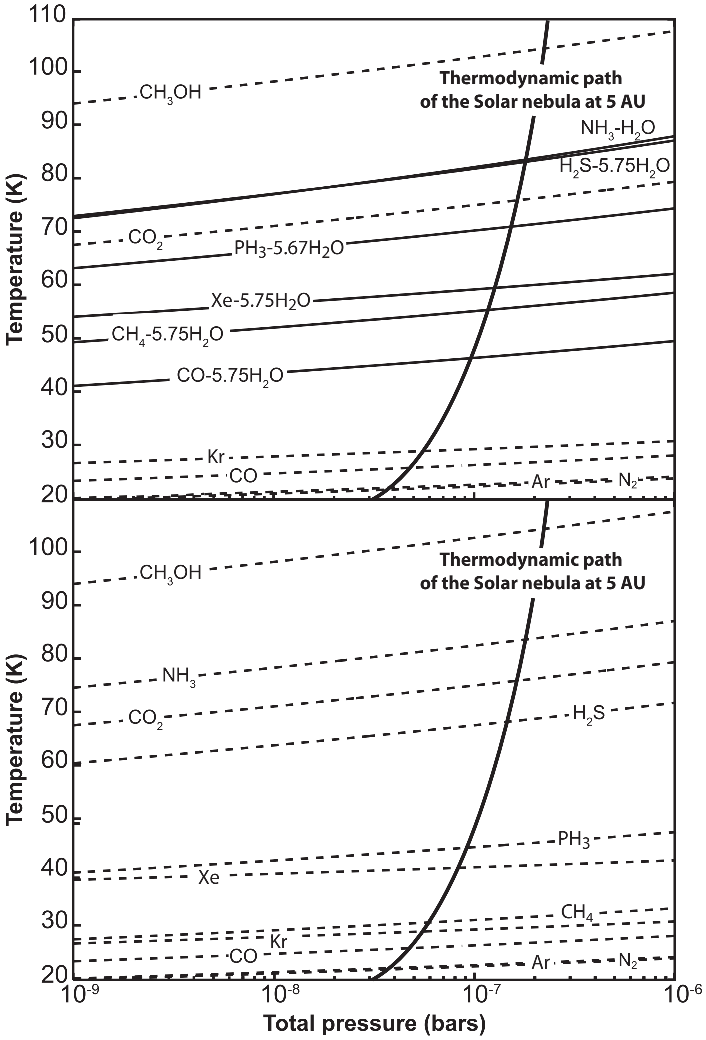

Fig. 1. Formation conditions of icy planetesimals in the solar nebula. Top panel: equilibrium curves of hydrate (NH_3-H_2O), clathrates (X-5.75H_2O or X-5.67H_2O) (solid lines), and pure condensates (dotted lines), and cooling curve of the solar nebula at 5 AU, assuming a full efficiency of clathration. Bottom panel: same as top panel but with an oxygen abundance that is half the solar value. In this case, water does not exist in the disk and only pure condensates form.

4 Discussion

Our results, as discussed above, imply that a carbon-rich Jupiter provides a better explanation for the measured elemental abundances than the canonical case based on a protosolar oxygen abundance in the nebula. Our prediction of 2 × solar enhancement of oxygen in a carbon-rich Jupiter also agrees extremely well with recent constraints on the Jovian water abundance (∼0.5–2.6 × solar) derived from tropospheric CO mixing ratios using thermochemical kinetics and diffusion models (Visscher & Moses 2011). On the other hand, our model for the protosolar case predicts 7 × solar enhancement of oxygen in Jupiter which is ruled out by the thermochemical models (Visscher & Moses 2011). The important difference between the oxygen abundances in the two cases is a consequence of the presence or not of water ice in the giant planet's feeding zone. In the case of a solar oxygen abundance, water ice is the main O-bearing volatile present in the disk and accreted by Jupiter. The oxygen enhancement in the Jovian atmosphere is also amplified by the fact that, at the formation epoch of planetesimals, water condenses at much higher disk temperature and surface density compared to the other volatiles, thus increasing its mass fraction in solids. When the oxygen abundance becomes half solar in the nebula, the water abundance tends towards zero and the main O-bearing species supplied to the protoplanet

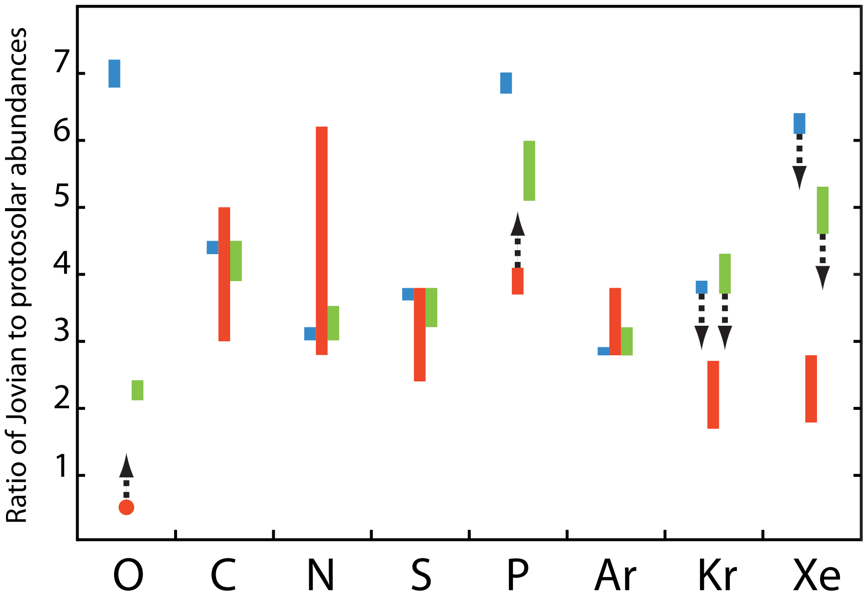

Fig. 2. Ratio of Jovian to protosolar abundances. Red bars and red dot correspond to observations. Green and blue bars correspond to calculations based on an oxygen abundance that is 0.5 and 1 times the protosolar value in the disk, giving C/O = 1 and 0.35 in Jupiter, respectively. The oxygen abundance is predicted to be 2.1–2.4 and 6.8–7.2 times protosolar in the cases of C/O = 1 and 0.35 in Jupiter, respectively. Arrows up correspond to the possibility that the measured oxygen and phosphorus abundances are lower than their bulk abundances and arrows down to the possibility that planetesimals could be impoverished in krypton and xenon.

atmosphere become CO and CO_2. These species condense at much lower disk surface density than water does and this effect increases the oxygen impoverishement in planetesimals accreted by proto-Jupiter.

A key observational test is the measurement of oxygen as water below the meteorological layer within Jupiter. A value of water about 2 × solar deep below the water clouds would confirm that Jupiter is carbon-rich. The Microwave Radiometer aboard the recently launched Juno spacecraft will probe the deep atmosphere of Jupiter at radio wavelengths ranging from 1.3 cm to 50 cm to measure the planet's thermal emissions. This instrument will obtain measurements of water at pressures down to 100 bars deep in the Jovian atmosphere (Janssen et al. 2005), thereby constraining Jupiter's O/H and C/O ratios.

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