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Recipes for forming a carbon-rich giant planet

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Abstract The exploration of carbon-to-oxygen ratios has yielded intriguing insights into the composition of close-in giant exoplanets, giving rise to a distinct classification: carbon-rich planets, characterized by a carbon-to-oxygen ratio ≥ 1 in their atmospheres, as opposed to giant planets exhibiting carbon-to-oxygen ratios close to the protosolar value. In contrast, despite numerous space missions dispatched to the outer solar system and the proximity of Jupiter, Saturn, Uranus, and Neptune, our understanding of the carbon-to-oxygen ratio in these giants remains notably deficient. Determining this ratio is crucial as it serves as a marker linking a planet's volatile composition directly to its formation region within the disk. This article provides an overview of the current understanding of the carbon-to-oxygen ratio in the four gas giants of our solar system and explores why there is yet no definitive dismissal of the possibility that Jupiter, Saturn, Uranus, or Neptune could be considered carbon-rich planets. Additionally, we delve into the three primary formation scenarios proposed in existing literature to account for a bulk carbon-to-oxygen ratio ≥ 1 in a giant planet. A significant challenge lies in accurately inferring the bulk carbon-to-oxygen ratio of our solar system's gas giants. Retrieval methods involve integrating in situ measurements from entry probes equipped with mass spectrometers and remote sensing observations conducted at microwave wavelengths by orbiters. However, these methods fall short of fully discerning the deep carbon-to-oxygen abundance in the gas giants due to their limited probing depth, typically within the 10–100 bar range. To complement these direct measurements, indirect determinations rely on understanding the vertical distribution of atmospheric carbon monoxide in conjunction with thermochemical models. These models aid in evaluating the deep oxygen abundance in the gas giants, providing valuable insights into their overall composition.

Keywords Giant planets · carbon-to-oxygen ratio · formation · protosolar nebula

1 Introduction

Along with hydrogen and helium, carbon (C) and oxygen (O) are the most abundant elements in the Universe, and their abundances are key to understanding the chemical evolution of protoplanetary disks and the structure of giant planets. The elemental C/O ratio is a potential tracer that relates the volatile composition of a planet atmosphere directly to the disk region in which it formed (Öberg et al, 2011; Mousis et al, 2012; Agüichine et al, 2022; Hobbs et al, 2022). The C/O ratio is estimated to be equal to ~ 0.55 in the protosolar nebula (PSN) (Lodders, 2021), and comparisons between this ratio and those inferred in the atmospheres of Jupiter, Saturn, Uranus, and

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Neptune are used to derive hints on their formation conditions (Mousis et al, 2012, 2020; Ali-Dib et al, 2014; Aguichine et al, 2022; Cavalié et al, 2023).

C/O ratios have also been estimated in a fairly large number of close-in giant exoplanets, giving birth to a new category of planets, namely the carbon-rich planets (CRPs), defined by a C/O ratio ≥ 1 in their atmospheres. The first carbon-rich atmosphere was inferred for the very hot Jupiter WASP-12b (Madhusudhan et al, 2011), and recent surveys of Hot-Jupiters suggest that many of them could display C/O ratios ≥ 1 (Howard et al, 2023). On the other hand, despite their proximity to Earth and the large number of space missions sent to the outer solar system, the status of the C/O ratio in Jupiter, Saturn, Uranus, and Neptune is still poorly defined. In the case of Jupiter, the microwave radiometer (MWR) on board the Juno spacecraft provided a measurement of the water abundance in its equatorial region, and found the deep oxygen abundance to be $2.2^{+3.9}_{-2.1}$ times the protosolar value, considering the 2σ uncertainties (Li et al, 2020). A recent reanalysis of the same data suggests a range of oxygen abundance between 1.4 to 8.3 times the solar value (Li et al, 2024). Furthermore, thermochemical and diffusion models derive a deep O abundance that is $0.3^{+0.5}_{-0.2}$ times the protosolar value, based on tropospheric CO observations and with assumptions regarding vertical mixing in the troposphere (Cavalié et al, 2023). This estimate, along with the lower bounds of the Juno oxygen measurements, hints at the possibility of Jupiter being a carbon-rich planet, particularly if the bulk carbon abundance aligns with the determination made by the Galileo probe (~ 3 – 5 times the protosolar value; Wong et al (2004)). The bulk O content in Saturn, Uranus, or Neptune is even more elusive, in absence of direct measurements. So far the only existing indirect determination of the deep O abundance in Saturn is the one provided by Cavalié et al. (2024, this issue) from thermochemical modelling and tropospheric CO observations. They find that the deep O abundance is 7–15 times the protosolar value (Lodders, 2021). With a C abundance measured to be ~ 9 times the protosolar value (Mousis et al, 2022), the resulting C/O ratio in Saturn could be then slightly supersolar. In the cases of Uranus and Neptune, the measurement of CO coupled with thermochemical models allowed the finding of an upper limit for the O abundance, set to 37 and 200 times the protosolar value, respectively (Venot et al, 2020), while the measured C abundance is ~ 70 – 100 times the protosolar value (Lodders, 2021) in the two planets (see Sec. 2.3). These considerations imply that, overall, the possibility that Jupiter, Saturn, Uranus or Neptune could belong to the family of CRPs remains open.

The aim of this paper is to describe the possible scenarios that could explain the formation of the four giants planets with bulk C/O ratios ≥ 1 in the protosolar nebula. Section 2 details the current status of knowledge about the C/O ratio in the four giants of the solar system. In Sec. 3, we review the three main types of formation scenarios that have been proposed in the literature to explain a bulk C/O ratio ≥ 1 in a giant planet. Sec. 4 is devoted to the measurement methods that could be used to derive the C/O ratio in the four giants of the solar system. Sec. 5 is dedicated to discussion and conclusions.

2 Clues about the existence of carbon-rich giant planets in the solar system

This section summarizes the current status of knowledge about the C/O ratio in the four giants of the solar system. It appears that a supersolar C/O ratio cannot be excluded in any of the four giants if one considers the current data.

2.1 Jupiter

The C/O ratio inside Jupiter is uncertain. The Galileo probe mass spectrometer provided what is generally regarded as a deep carbon-to-hydrogen ratio by measuring the CH₄ abundance at multiple levels to slightly more than 10 bars pressure. The most recent value by Wong et al (2004) takes into account a recalibration based on laboratory data, and ranges between 2.7 and 6 times solar, constant with depth within the error bars. In contrast, the oxygen abundance measured in water (H₂O) by the Galileo probe is always subsolar but increases with increasing depth down to the final measurement at around 22 bars. Such a depth is well below the theoretical base (5–10 bars) of the water cloud for the measured temperature profile, and has generally been assumed to reflect dynamics in the atmosphere rather than the deep abundance (Showman and Ingersoll, 1998; Atreya et al, 2020). The microwave radiometer on-board the Juno mission has mapped the brightness temperature of Jupiter over a range of latitudes, emission angles and wavelengths. The fluctuating presence of ammonia (NH₃) poses challenges in deducing the water abundance due to its significant contribution to microwave opacity. However, in the lowest northern latitudes, ammonia seems to maintain a relatively consistent depth abundance profile. In this region, the deep water abundance (down to 30 bars) has been initially determined to range between 0.1 to 7.5 times the solar value at the 2- σ confidence interval (Li et al, 2020). A recent reanalysis of these data, which operates under the assumption that Jupiter's equatorial region is super-adiabatic rather than adiabatic, suggests a range of oxygen abundance between 1.4 to 8.3 times the solar value, with the optimal estimate at about 4.9 solar (Li et al, 2024).

Indirect estimates of water abundance also come from the observations of convective eruptions in the planet in energetic moist convective events. Models of convective storms in the planet applied to these observations suggest lower limits of water abundance higher than 1.0 times solar. This abundance is required by the models to generate the expanding rate and high clouds observed on the upper troposphere in specific convective storms in the equatorial region (Stoker, 1986) and south latitudes (Iñurriagarro et al, 2022), with water abundance close to 2.0 times solar as the preferred value. The cloud tops of the most energetic storms observed in the north temperate belt, arriving to altitudes of 60 mbar, seem to require water abundances of 2–3 times solar (Sánchez-Lavega et al, 2008). However, Sankar and Palotai (2022) limit the water abundance in these storms to values lower than 2 times solar based on the occurrence rate of these convective outbreaks, with this value being compatible with most theoretical works on moist convective storms in the Jovian atmosphere. Interior models also provide some constraint to the water abundance because fits to the gravity field determined by Juno are sensitive to the tradeoff between the deep

temperature profile and the abundance of heavy elements in the bulk interior, provided one knows the equation-of-state of hydrogen and helium (Stevenson, 2020). The equation-of-state is, in fact, not well enough known to avoid a plethora of different interior models, but in general they severely limit the heavy element abundance to between one and two times solar (Helled et al, 2022; Howard et al, 2023), in disagreement with the Galileo carbon abundance and the Juno-derived NH_3 abundance in the presumably well-mixed low northern latitudes. This is puzzling and has led to serious consideration of the idea that the envelope abundance as measured by Galileo is a high-metallicity veneer with a different composition than the bulk interior (Shibata and Helled, 2022). This idea would be consistent with atmospheric models of moist convection that require abundances of atmospheric water with values near 1.0–2 times solar (Iñurriagarro et al, 2022; Sankar and Palotai, 2022).

One way to resolve this dilemma is to determine the oxygen abundance at the kilobar level through measurements in the upper troposphere of disequilibrium species whose abundances are sensitive to the elemental C/O and vigor of vertical transport. For instance, Bézard et al (2002), Visscher et al (2010), and Wang et al (2015) found oxygen abundances that range from subsolar to supersolar values, the main differences arising from the use of different chemical schemes. Such modeling effort relies on the measurement of the abundances of the species that are involved in the chemical equilibrium occurring at the kilobar level. For the C/O ratio, the species involved are H_2O , CH_4 and CO , where H_2O is the unknown of the model. Cavalié et al (2023) adopted the upper tropospheric abundances of CH_4 and CO as measured by Galileo (Wong et al, 2004) and from ground-based observations (Bézard et al, 2002; Bjoraker et al, 2018), respectively. With a nominal vertical mixing coefficient of $10^8 \text{ cm}^2/\text{s}$ constant with altitude, their analysis yields O values that range from solar to subsolar, i.e. $0.3_{-0.2}^{+0.5}$ times the protosolar value of Lodders (2021), implying that C/O could be greater than unity ($\text{C/O} = 6_{-5}^{+10}$). Alternatively, Cavalié et al (2023) demonstrated that introducing a radiative layer around the CO quench level results in an oxygen abundance that is approximately consistent with the lower end of the new Li et al (2024) determination, while not violating the constraint on O from interior modeling.

To date, comprehensive analyses of the Juno data, alongside investigations into convective storms and thermochemical models of the envelope, consistently suggest that the oxygen abundance in Jupiter’s envelope might be half, or less, the abundance of carbon measured by the Galileo probe Wong et al (2004). This finding hints at the possibility of Jupiter conforming to the criterion of a C/O ratio ≥ 1 . Further details are discussed in Cavalié et al. (2024, this issue).

2.2 Saturn

Unlike Jupiter, only the abundances of a limited number of molecules have been measured in situ in Saturn. The main carbon carrier in the gas giant troposphere and stratosphere is methane. On Jupiter and Saturn, this molecule diffuses from the troposphere up to the stratosphere, where it can be photolyzed to produce a wealth of hydrocarbons (see, *e.g.*, Moses et al (2005); Moses and Greathouse (2005); Hue

et al (2015, 2018)). Saturn’s methane abundance has been measured from remote sensing observations using ground- and space-based observatories (*e.g.*, Karkoschka and Tomasko (1992); Buriez and de Bergh (1981); Kerola et al (1997); Courtin et al (1984); Flasar et al (2005)). Some of the more recent measurements were provided thanks to Cassini-CIRS, from which Fletcher et al (2009) derived a methane mole fraction of $(4.7 \pm 0.2) \times 10^{-3}$, which corresponds to a carbon enrichment of 10.9 ± 0.5 over the solar values, assuming protosolar abundances from Grevesse et al (2007).

As far as oxygen is concerned, water is the main oxygen carrier in Saturn’s atmosphere. Similarly to the methane situation on Uranus and Neptune, water is depleted near the cold tropopause trap. The detected stratospheric water on Saturn therefore results from external sources resulting from rings and satellites interaction (*e.g.*, Connerney and Waite (1984); Feuchtgruber et al (1997); Hartogh et al (2011); Cassidy and Johnson (2010); Cavalié et al (2019); Moses et al (2023); Moore et al (2015); O’Donoghue et al (2013)), the continuous supply of interplanetary dust particles (Landgraf et al, 2002; Poppe, 2016; Moses and Poppe, 2017), and/or possible cometary impacts (Cavalié et al, 2009, 2010). Tropospheric water was first detected in Saturn by the ISO spacecraft. Fits of the ISO-SWS spectra suggested a $[\text{H}_2\text{O}]/[\text{H}_2]$ ratio of $\sim 2 \times 10^{-7}$ below the 3-bar level (de Graauw et al, 1997). However, the amount of water measured at that pressure level was found to be undersaturated and therefore does not represent the planet’s bulk oxygen content. Similarly to Jupiter, observations of convective storms in Saturn suggest elevated values of the solar water abundance from 1–10 times solar to reconcile the observations of moist convective storms (Hueso and Sánchez-Lavega, 2004; Li and Ingersoll, 2015). As in Jupiter, the values required by models of storms could be representative of local enhancements of water, and not fully representative of a global average.

On the other hand, the deep O abundance is estimated by Cavalié et al. (2024, this issue) from thermochemical modelling and tropospheric CO observations. They find that the deep O abundance is 7–15 times the protosolar value of Lodders (2021). With a C abundance measured to be ~ 9 times the protosolar value (Mousis et al, 2022), the resulting C/O ratio in Saturn could be then slightly supersolar.

2.3 Uranus and Neptune

Spectroscopic compositional measurements at Uranus and Neptune remain difficult given their distance, cold tropopause temperatures, as well as small temperature gradient in the stratosphere of Uranus which limits spectral line intensities. Methane condenses in these atmospheres and direct observations in the thermal infrared only probe the depleted stratosphere (Lellouch et al, 2015). More complex techniques using reflective spectroscopy are then used to constrain the tropospheric CH_4 abundance. Surprisingly, both ice giants present equatorial regions with about 4% of CH_4 while their polar regions appear to be depleted by a factor of ~ 2 (Karkoschka and Tomasko, 2009, 2011; Sromovsky et al, 2014). These meridional variabilities are possibly caused by tropospheric circulation (*e.g.*, Fletcher et al (2020) and references therein). This was recently confirmed by Irwin et al (2021) for Neptune, though derived abundances were somewhat slightly higher, *i.e.*, 4–6% in the equatorial region

and 2–4% in the southern polar region. Error bars on the deep CH₄ abundance in both planets thus remain relatively large. Direct detection of tropospheric water in the atmospheres of Uranus and Neptune has remained elusive given their cold tropopause temperatures. Water vapor is locked below the water cloud level, which likely resides at pressures >100 bar (Cavalié et al, 2017; Atreya et al, 2020). Deriving the deep oxygen in the ice giants thus requires the use of indirect measurements and thermochemical modeling. From the detection of CO in the atmosphere of Neptune (Marten et al, 1993) and using estimates of the deep atmospheres vertical mixing, Lodders and Fegley (1994) found that Neptune could have a rather extreme oxygen enrichment factor of 400 times solar, difficult to explain with formation models (*e.g.*, Mousis et al (2018)). The lack of direct detection of CO in the atmosphere of Uranus resulted in the derivation of an O/H enrichment upper limit of 260 times solar (Lodders and Fegley, 1994).

Nearly 30 years later, the situation has slightly evolved. Improvements in the knowledge of the vertical distribution of CO in Uranus and Neptune (Lellouch et al, 2005; Teanby and Irwin, 2013; Cavalié et al, 2014; Teanby et al, 2019) coupled with better kinetics have led Venot et al (2020) to re-evaluate the deep oxygen abundances of the ice giants. They find O/H ratios of 200 and <37 times the protosolar value for Neptune and Uranus, respectively, when assuming the equatorial CH₄ abundances of Karkoschka and Tomasko (2009, 2011); Stromovsky et al (2014) and adopting the solar abundances of Lodders (2021). As a consequence, Uranus and Neptune present, at face value, a dichotomy regarding their C/O ratios. While Neptune is nominally more enriched in oxygen than in carbon, it is the reverse situation for Uranus, which could be more carbon-rich than oxygen-rich. However, and even if unlikely, CO observations are in principle compatible with very low tropospheric CO abundances (Teanby et al, 2019), which would result in a much lower deep oxygen abundance.

3 Formation scenarios

Three distinct formation scenarios have been proposed in literature to explain the occurrence of a C/O ratio greater than or equal to 1 in a giant planet. These scenarios include the formation of giant planets from tar, the sequestration of PSN oxygen in refractory matter, and the planetary growth along the ice lines of C-dominating volatiles. Each of these scenarios is discussed below and visually depicted in Fig. 1.

3.1 Tar planets

One possibility for how carbon-rich planets can form is the scenario where the core of a giant planet forms closer to the Sun or star than the water ice line, but beyond the “tar line”. This term designates the location where carbonaceous matter undergoes condensation or evaporation, characterized by temperatures ranging between approximately 350 and 530 K within a protoplanetary nebula. The relative locations of these lines in the protosolar nebula (PSN) are illustrated in Fig. 2. This scenario was initially proposed for Jupiter by Lodders (2004), based on the high C/O ratio measured

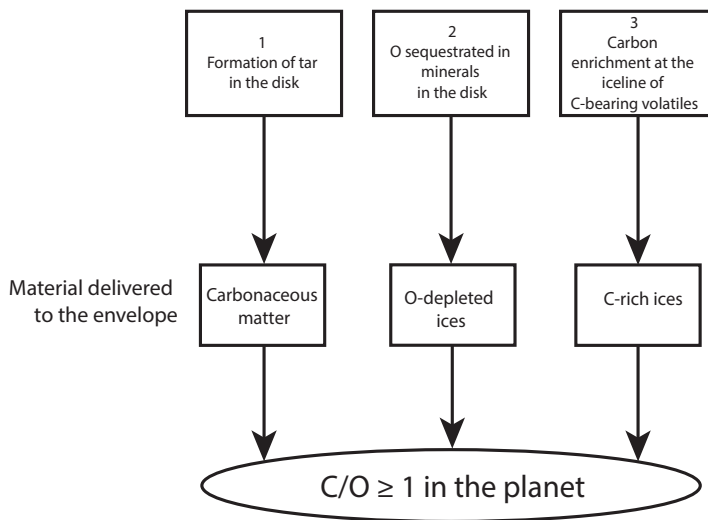


Fig. 1 A schematic summarizing the different formation scenarios of carbon-rich giant planets. Each scenario explores the accretion of solid matter with a bulk C/O ratio ≥ 1 by the forming giant planet under specific circumstances within the PSN (see text for details).

by the Galileo Probe Mass Spectrometer (Wong et al, 2004). In the region between the tar line and the water ice line, water is not able to condense, but carbonaceous material can either form by nonequilibrium processes or survive if it originates from the interstellar medium (ISM), thus constituting two possible sources of carbon-rich matter in this region of the PSN (Lodders, 2004). Solids quickly grow to large sizes because the solid organics in this region are stickier than at any other location in the disk (Kouchi et al, 2002). The presence of a “soot line” located at a somewhat imprecise ~ 1000 – 2000 K temperature range has also been argued to account for the high abundance of C_2H_2 observed in protoplanetary disks. The observed C_2H_2 would result from the thermal destruction of PAHs originating from ISM when they cross the soot line (Kress et al, 2010).

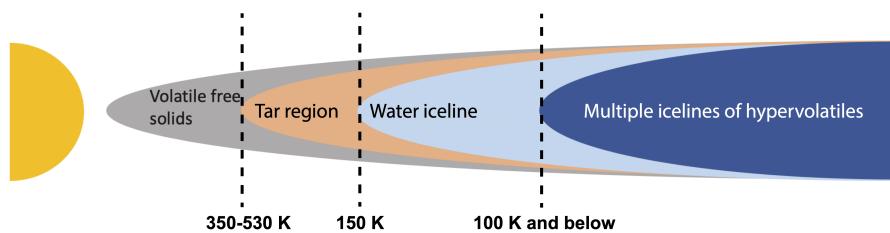


Fig. 2 A schematic of the relative locations of the different condensation lines in the PSN, with their corresponding temperatures. Carbonaceous material forms in the region between the tar line and the water ice line. Material accreted by giant planets and originating from this region of the PSN should be rich in organics.

Although this theory proposes what might be a physically plausible mechanism for the rapid growth of a planetary core that could result in the formation of a giant planet, the application to Jupiter’s core formation is not supported by the observations. For example, the heavy noble gases –Ar, Kr, and Xe– are all enhanced relative to H in Jupiter’s atmosphere to a similar degree compared to carbon. When using CI chondrites as an analog for the material that formed Jupiter’s core, the heavy noble gases should be depleted relative to solar values (Lodders, 2021). Furthermore, the nitrogen isotopes in Jupiter’s atmosphere (Owen et al, 2001) are the same as the solar value measured in the solar wind (Marty et al, 2011). This requires most of the nitrogen that formed Jupiter to have originated as N_2 in the PSN rather than nitrogen in organics that would have been enhanced in the heavy isotope (Mandt et al, 2014). Although it is possible that Jupiter captured gas that was enhanced in the heavy noble gasses, it would have also captured similar enhancements in nitrogen leading to a much higher N/C ratio than has been measured. Finally, the theoretical impetus for such a chemically-based particular mechanism, namely the need to accrete Jupiter’s core quickly, appears to have been solved by treating aerodynamic drag of “pebbles” in the cm-to-meter size range (Johansen and Lambrechts, 2017).

3.2 Oxygen depletion by sequestration in refractory species

In this scenario, the presence of a supersolar C/O ratio within the giant planet can be attributed to the devolatilization process of refractory materials within its envelope. Sequestration of oxygen in rock- and metal-forming species (those involving Mg, Si, Fe, Al, etc.) must be considered when the carbon-to-oxygen ratio exceeds the solar value of $C/O = 0.55$ in the PSN. Even here, the abundances of the rock forming elements are sufficient to depress the amount of oxygen available to form water by a noticeable amount if the dominant carbon-bearing molecule in the disk is CO. When the C/O ratio exceeds 0.8 in the initial gas phase of the PSN, the depletion of oxygen is severe, such that it is bound up in rock, metal oxides, CO and CO_2 to the exclusion of water (Pekmezci et al, 2019). The same is not true if the disk chemistry is reducing enough that CH_4 dominates (although the kinetics of maintaining a CH_4 -rich disk are difficult; see Prinn and Fegley (1989)). The presence of refractory organics also decreases the dependence of the water abundance on the C/O ratio (Wong et al, 2008). For our own solar system, recent work suggests that the presence of refractories in the protoplanetary disk could bias the apparent C/O ratios in the giant planets upward by as much as 1/3 (Fonte et al, 2023), but is still not enough to explain C/O values exceeding unity.

3.3 Role of icelines in the protosolar nebula

An iceline is defined as the distance where the surface density of vapor of a given volatile species is equal to that of its solid form in the PSN. Inside the snowline, water ice evaporates into water vapor. Outside the snowline, ice is present due to the condensation of vapor, though the motion of particles within the disk allows for

solids to exist in front of this line as well as some vapors to exist beyond, due to the kinetics of condensation/sublimation. These ice lines are locations where condensation/vaporization cycles can enhance their abundances in both solid and vapor forms, (Stevenson and Lunine, 1988; Cyr et al, 1998; Ali-Dib et al, 2014; Mousis et al, 2020, 2021; Aguichine et al, 2022; Schneeberger et al, 2023). When icy pebbles cross the iceline of a given species moving inward towards the Sun, its solid phase vaporizes and the released vapor diffuses both inward and outward, implying that a given fraction of the vapor crosses the iceline again. This fraction of vapor recondenses back onto icy grains which cross the iceline, and feed again its interior region with vapor. A key point is that the outward diffusion of vapor is shown to be faster than its replenishment inside the icelines by sublimating ices. This leads to depletion in vapors inside the icelines and a concentration of solids at the iceline positions. By doing so, this cycle produces an enrichment peak of the species at the iceline which can reach or exceed ~ 10 times the initial abundance in icy grains (Aguichine et al, 2022; Schneeberger et al, 2023). A schematic of this mechanism is shown in Fig. 3. This recycling process applies to all oxygen- and carbon-bearing volatile species, including H_2O , CO , CO_2 and CH_4 , and can shape the C/O ratio in the material accreted by gas and ice giants during their growth (Mousis et al, 2019, 2020, 2021; Aguichine et al, 2022; Cavalié et al, 2023).

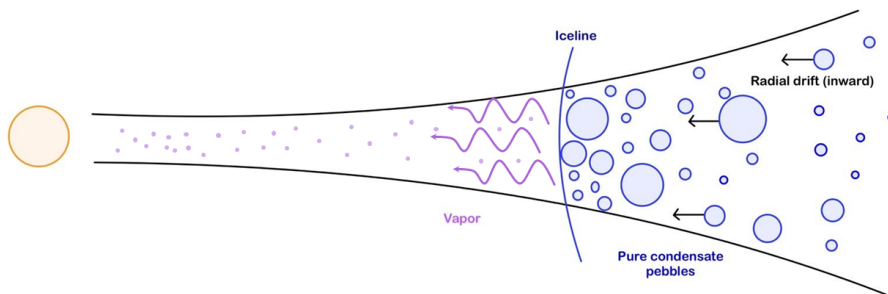


Fig. 3 A schematic of the overall system under consideration: the protosun surrounded by the PSN. The radial distribution of the volatile species under consideration is affected by the diffusion of its vapor out past the condensation front, where the vapor condenses into icy particles, and the radial drift back inward of those particles.

Pure condensates, and perhaps clathrates, are the two crystalline structures that can form during the cooling of the outer PSN (Schneeberger et al, 2023). Clathrates are believed to exist in large amounts in the crust of dwarf planets and the satellites of outer planets such as Titan and Pluto (Mousis et al, 2002; Tobie et al, 2006; Bouquet et al, 2019; Kamata et al, 2019). The potential presence of clathrates in the PSN depends on the local availability of crystalline water, as well as on their kinetics of formation at low-pressure and low-temperature conditions (Lunine and Stevenson, 1985; Gautier and Hersant, 2005; Mousis et al, 2010). The formation of Comet 67P/churyumov-Gerasimenko from a mixture of clathrates originating from the PSN has been invoked to explain the argon deficiency and the presence of ultravolatiles

observed in the interior of this body by the Rosetta spacecraft (Mousis et al, 2016; Luspay-Kuti et al, 2016).

Figure 4 illustrates the C/O abundance profile as a function of heliocentric distance in the PSN following 0, 0.1, 0.5, and 1.0 Myr of disk evolution, utilizing the methodology outlined in Schneeberger et al (2023). The model tracks the evolution of volatile species in both vapor and ice phases, including species trapped in clathrate hydrates. It incorporates the advection-diffusion of vapor species and considers the dynamics of dust and pebbles using the two-population model from Birnstiel et al (2012). Two scenarios are explored: the formation of pure condensates alone in the PSN and the concurrent formation of pure condensates and clathrates. In both scenarios, C and O are distributed among H₂O, CO, CO₂, and CH₄, with protosolar abundances drawn from Lodders et al (2009), resulting in a C/O ratio of approximately 0.46. The initial mixture assumes a volume ratio of CO:CO₂:CH₄ = 10:4:1 (see Schneeberger et al (2023) for details). Additionally, for comparison, the figure represents the C/O ratio (6_{-5}^{+10}) estimated by Cavalié et al (2023) within Jupiter’s interior.

Figure 4 demonstrates that both icelines and clathration lines of carbon-bearing compounds significantly enhance the C/O ratio, exceeding the protosolar value ($C/O \geq 1$) within the 5–15 AU region between different icelines. If Jupiter formed in this region during the first Myr of PSN evolution, it could have accreted C-rich solids, potentially resulting in a C/O ratio consistent with the estimate of Cavalié et al (2023). However, one should note that this study offers insight into the composition of the PSN before the formation of planetary cores, without modeling the formation of planetesimals and their subsequent evolution via pebble accretion and gas-runaway accretion (Helled et al, 2014; Bitsch et al, 2015).

We limit our modeling to 1 Myr of PSN evolution, as the disk thermodynamic profiles reach steady states after this period, with insignificant changes thereafter. Moreover, the timescale of planet formation, which remains a subject of debate, could be shorter than 1 Myr, according to Lambrechts and Johansen (2012); Helled et al (2014); Lambrechts and Johansen (2014).

4 Measurements needed to assess the C/O status in giant planets

To determine the ratio of carbon-to-oxygen in the atmospheres of the giant planets requires measurements of the deep (well-mixed) abundances of both oxygen and carbon. Although carbon does not condense in the form of methane (CH₄) in the warmer atmospheres of Jupiter and Saturn and is therefore assumed to be well-mixed throughout the atmosphere of these planets, the situation is more complex at the ice giants where the much colder temperatures result in methane condensing into clouds in the upper troposphere. Oxygen is primarily contained within water which condenses into clouds in the troposphere of all the giant planets. According to equilibrium cloud condensation models (ECCMs) (Weidenschilling and Lewis, 1973; Atreya et al, 2020), the base of the water clouds is expected to be at about 5–8 bars at Jupiter depending on the abundance of oxygen and possible mixing with NH₃ and H₂S, at about 10–20

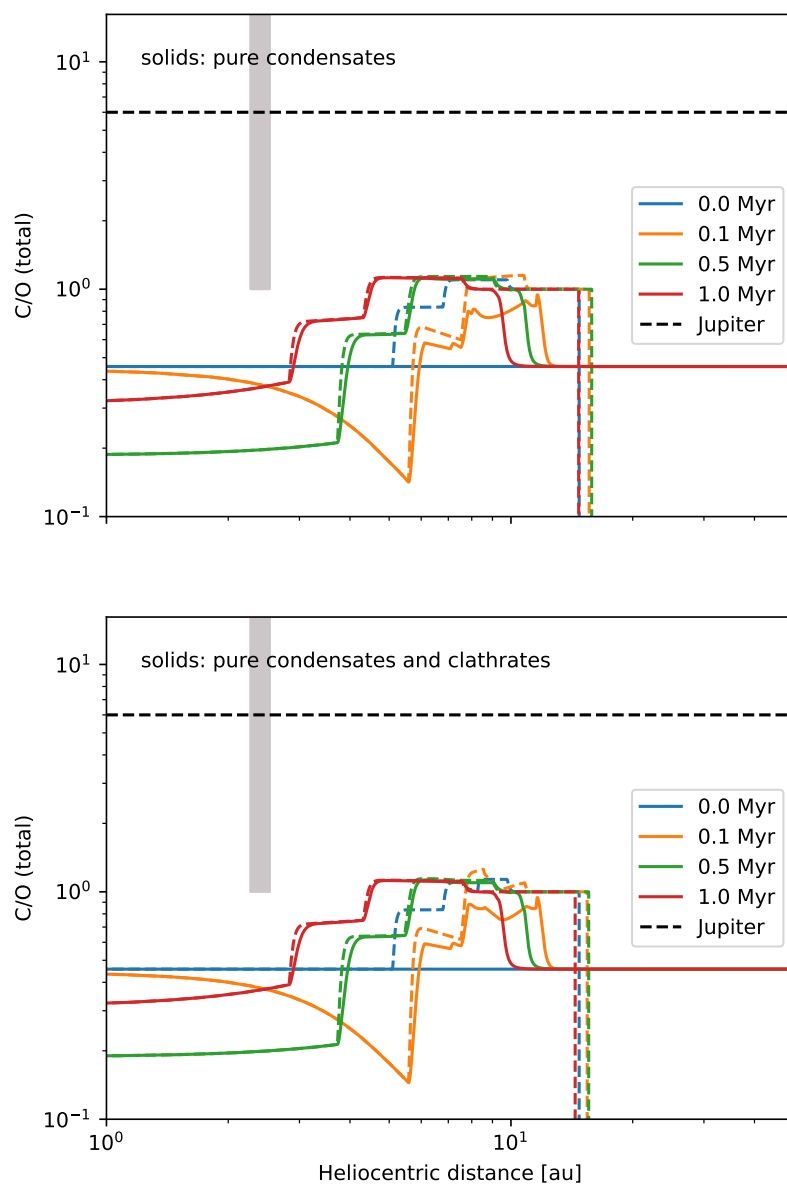


Fig. 4 C/O ratio in vapor phase (dashed lines) and in both vapor and solid phases (solid lines) as a function of heliocentric distance after 0, 0.1, 0.5, and 1 Myr of PSN evolution. Two scenarios are considered: solids composed of pure condensates (top panel) and of a mixture of pure condensates and clathrates (bottom panel). The vertical grey rectangle and the black dashed horizontal line correspond to the $1-\sigma$ error bar and the nominal value associated with the C/O ratio estimated in Jupiter, respectively (Cavalié et al, 2023). The blue horizontal line corresponds to the protosolar C/O ratio.

bars at Saturn, and much deeper at the ice giants, at pressures of 50–200 bars at Uranus and 40–500 bars at Neptune.

Obtaining in situ measurements to determine the global, deep, and well-mixed abundance of water presents considerable challenges. These challenges are due to the depth of water clouds based on the expected atmospheric temperature profiles and great range of potential water abundances, and ECCMs of the atmosphere. Achieving a representative measure of the giant planet's water abundance necessitates the deployment of a probe capable of descending well below the water cloud condensation level to access the well-mixed region of the atmosphere. Although the Galileo probe, despite returning data down to 22 bars on Jupiter, descended through a region devoid of clouds called a 5-micron hotspot and hence did not reach the well-mixed water region (Orton et al, 1998), the base of the 5-bar water cloud base predicted by ECCMs is well within the reach of descent probes. At Saturn, the temperature at a given pressure is lower than at Jupiter and the water cloud base is expected to be between 10–20 bars, still well within reach of an atmospheric descent probe mission. However, the ice giant water clouds are expected to be significantly deeper and far beyond the depth probes can reach with current technologies. To reach the well-mixed region beneath the water clouds at Uranus and Neptune would require a probe to survive and return data from levels potentially as deep as several 100's of bars. To ensure the survival of a descent probe at depths exceeding 100 bars where both pressure and temperatures will be extreme, several critical challenges must be addressed. These include developing power systems sufficient to sustain the probe throughout its descent and stay operational under such conditions. Moreover, crafting a robust telecommunications system capable of penetrating the dense and highly absorbing atmosphere above the probe will not be trivial. Meeting these challenges demands groundbreaking advancements in engineering and technology.

The only technique currently available by which measurements can be made of the deep abundances of water and other key constituents of the giant planets is by measurement of microwaves emitted by the deep atmosphere over a range of frequencies from UHF (~300MHz) to Ka-band (~30 GHz), corresponding to wavelengths of about 100 cm to 1 cm, respectively (de Pater et al, 2023). Microwave emissions from giant planet atmospheres originate from the tropopause and the lowest frequencies (longer wavelengths) emanate from the deepest atmosphere, possibly 1000 bars, much deeper than current probes are designed to operate. The microwave spectrum emitted by giant planet atmospheres depends on the temperature and composition of the atmosphere. Measurement of the microwave spectrum at multiple frequencies provides a means by which abundances of key microwave opacity sources can be determined. To accurately measure the abundance of key constituents in the deep atmosphere therefore requires an accurate model of the thermal structure of the atmosphere (Luszcz-Cook et al, 2013; Leconte et al, 2017).

Models of the thermal structure of the deep atmosphere are primarily based on physical principles, but can also be strongly constrained by measurements of temperatures at a single location in the upper atmosphere provided by in situ measurements from an atmospheric descent probe (Seiff et al, 1998). Although measurements of the microwave emissions from the giant planets can be made from Earth, there are limitations. First, synchrotron radiation due to extragalactic sources as well as from

Jupiter provide enough radio noise that Earth-based microwave measurements are either impossible, or at very low SNR (e.g. Courtin et al (2015) for Saturn). Additionally, due to the great distance to the outer solar system, the spatial resolution of outer planets possible at these wavelengths from Earth is quite poor. Although large baseline interferometers such as the Atacama Large Millimeter Array (ALMA), or the Very Large Array (VLA) can peer into the deep atmosphere of Uranus and Neptune resolving bands and deep structures (Tollefson et al, 2019; Molter et al, 2021), the deepest layers that can be sensed are about 50 bar, well above the layers where emissions from water should be observable. Therefore, the only reasonable means by which microwave measurements of the giant planets can be made is remote sensing from flyby or orbiting spacecraft. The Juno orbiter currently flies in a polar orbit that passed beneath Jupiter’s radiation belts to make microwave abundance measurements of H_2O and NH_3 to 100 bars or deeper, less contaminated by the noise from Jupiter’s intense synchrotron radiation (Bolton et al, 2017; Janssen et al, 2017; Li et al, 2020; Li et al, 2024).

To complete the measurement of the C/O ratio in giant planet atmospheres requires in situ measurements of atmospheric carbon by a mass spectrometer carried by an atmospheric descent probe. At the gas giants Jupiter and Saturn, carbon in the form of methane does not condense and is therefore well-mixed throughout the atmosphere. An atmospheric probe at any location on the gas giants would measure the well-mixed abundance of methane from which a value for the global inventory of carbon can be retrieved. The situation is more difficult at the ice giants Uranus and Neptune where temperatures are low enough that carbon condenses in the form of CH_4 clouds at levels of 1–2 bars (Mousis et al, 2022). If ECCMs are correct, a relatively shallow ice giant atmospheric entry probe would pass through the methane clouds into the region beneath the clouds where measurements of atmospheric methane by a probe mass spectrometer would provide the global atmospheric carbon content (Atkinson et al, 2020).

When the results of the measurements of NH_3 at Jupiter made by Juno are considered along with the fact that CH_4 condenses in ice giant atmospheres, it is questionable as to whether simple ECCMs and abundance measurements of CH_4 abundances made in situ by probes can truly reflect the composition of the bulk atmosphere. On the other hand, in the case of Juno at Jupiter, it is plausible that the observed NH_3 distribution is influenced by the presence of the water cloud, where moist convection establishes unexpected compositional gradients well below the cloud base (Sugiyama et al, 2014; Leconte et al, 2017). However, for the ice giants, CH_4 itself is abundant enough to inhibit convection (Guillot, 1995). Consequently, the vertical displacement between the well-mixed mixing ratio and the condensation level might be primarily governed by the inhibiting species (H_2O on Jupiter, CH_4 on Uranus), thereby influencing the distribution of trace species (NH_3 in Jupiter and CH_4 in Uranus). In this scenario, the depth difference of the well-mixed tracer layer in Uranus and Neptune may not be as significant. It should be also noted that, alongside CH_4 , a shallow probe outfitted with a sufficiently sensitive and high-resolution mass spectrometer could detect the abundance of CO (Cavalié et al, 2020).

Measurements of CO in thermochemical models would provide diagnostic assessments of the oxygen distribution in the deep atmospheres of the giant planets, complementing determinations made through microwave observations.

5 Conclusions

In this review, we provide an overview of the ongoing debate surrounding the carbon-to-oxygen (C/O) ratio in the bulk interiors of the four gas giants in our solar system, suggesting the possibility that some may indeed be carbon-rich. Various formation mechanisms have been proposed in the literature to explain this potential scenario. For instance, carbon-rich giant planets could have originated if their cores formed closer to the host star, within the region bounded by the tar line and the water ice line (Lodders, 2004). However, this hypothesis doesn't apply to Jupiter, as the supersolar abundances of noble gases observed in its atmosphere are inconsistent with the notion that they were delivered alongside carbon-rich refractory matter. As of now, no compelling mechanism has been put forward to explain the supersolar abundances of the heavy noble gases within the framework of this hypothesis. Another scenario suggests that a significant portion of oxygen was sequestered in rock- and metal-forming species within the protosolar nebula, rather than forming water (Fonte et al, 2023; Pekmezci et al, 2019). However, this would necessitate assuming an initial C/O ratio in the protosolar nebula gas much higher than the solar value (0.55) before the formation of the first solids. Intriguingly, this hypothesis finds support in measurements of the density and moment of inertia of icy moons and dwarf planets, which indicate accretion from low-density carbonaceous components in their rocky cores (Reynard and Sotin, 2023), suggesting that condensed organic carbon could be a significant constituent of outer solar system planetary bodies. Another proposed mechanism involves the growth of gas giants near the icelines of key carbon-bearing volatiles (such as CH₄, CO, CO₂, etc.) (Stevenson and Lunine, 1988; Cyr et al, 1998; Ali-Dib et al, 2014; Mousis et al, 2020, 2021; Aguichine et al, 2022; Schneeberger et al, 2023). In these regions, giant planets could have naturally accreted a mixture of ices and vapors with C/O ratios equal to or greater than 1.

Despite encountering challenges in the case of Jupiter, the notion of giant planet formation from tar requires consideration. Moreover, it is worth highlighting that both of the latter scenarios may coexist within the PSN. The constitution of Jupiter's envelope could plausibly emerge from the devolatilization of carbonaceous material, alongside the vaporization of ices that formed in proximity to the CO and CO₂ icelines, among other possibilities. In the absence of observational constraints indicating challenges akin to those observed in Jupiter, the three scenarios under discussion could conceivably operate simultaneously in other planetary systems to explain the existence of carbon-rich giant planets. If planetary embryo migration spans a broad distance range within a protoplanetary disk, each forming giant planet could accrete material formed through each of the three distinct scenarios. These scenarios would operate at various distance ranges within the disk, allowing for the accumulation of diverse solid materials.

The primary challenge persists in accurately determining the bulk carbon-to-oxygen (C/O) ratio of the gas giants in our solar system. Current retrieval methods involve a combination of in-situ measurements with mass spectrometers aboard entry probes and remote sensing observations using microwave wavelengths from orbiters. However, these retrieval methods do not guarantee the precise derivation of the deep C/O abundance within the giant planets, as they are constrained by probing depth limitations, typically within the range of 10 to 100 bars. Thus far, only indirect determinations, reliant on understanding the vertical distribution of CO in the giant planets alongside enhanced thermochemical models, can aid in assessing the deep oxygen abundances. This underscores the critical necessity for probe mass spectrometers and/or tunable laser spectrometers to possess sensitivity not only sufficient to measure elemental main carriers (e.g., CH₄, H₂O, NH₃, etc.) but also various less abundant species (Cavalié et al, 2020; Webster et al, 2023).

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References

- Aguichine A, Mousis O, Lunine JI (2022) The Possible Formation of Jupiter from Supersolar Gas. *Planet. Sci. J.* 3(6):141, DOI 10.3847/PSJ/ac6bf1, 2204.14102
- Ali-Dib M, Mousis O, Petit JM, Lunine JI (2014) Carbon-rich Planet Formation in a Solar Composition Disk. *Astrophys. J.* 785(2):125, DOI 10.1088/0004-637X/785/2/125, 1402.5182
- Atkinson DH, Mousis O, Spilker TR, Ferri F (2020) Reference Model Payload for Ice Giant Entry Probe Missions. *Space Sci. Rev.* 216(8):120, DOI 10.1007/s11214-020-00738-y
- Atreya SK, Hofstadter MH, In JH, Mousis O, Reh K, Wong MH (2020) Deep Atmosphere Composition, Structure, Origin, and Exploration, with Particular Focus on Critical in situ Science at the Icy Giants. *Space Science Reviews* 216(1):18, DOI 10.1007/s11214-020-0640-8, 2006.13869
- Bézard B, Lellouch E, Strobel D, Maillard JP, Drossart P (2002) Carbon Monoxide on Jupiter: Evidence for Both Internal and External Sources. *Icarus* 159(1):95–111, DOI 10.1006/icar.2002.6917
- Birnstiel T, Klahr H, Ercolano B (2012) A simple model for the evolution of the dust population in protoplanetary disks. *Astron. Astrophys.* 539:A148, DOI 10.1051/0004-6361/201118136, 1201.5781

- Bitsch B, Lambrechts M, Johansen A (2015) The growth of planets by pebble accretion in evolving protoplanetary discs 582:A112, DOI 10.1051/0004-6361/201526463
- Bjoraker GL, Wong MH, de Pater I, Hewagama T, Ádámkóvics M, Orton GS (2018) The Gas Composition and Deep Cloud Structure of Jupiter's Great Red Spot. *Astron. J.* 156(3):101, DOI 10.3847/1538-3881/aad186, 1808.01402
- Bolton SJ, Adriani A, Adumitroaie V, Allison M, Anderson J, Atreya S, Bloxham J, Brown S, Connerney JEP, DeJong E, Folkner W, Gautier D, Grassi D, Gulkis S, Guillot T, Hansen C, Hubbard WB, Iess L, Ingersoll A, Janssen M, Jorgensen J, Kaspi Y, Levin SM, Li C, Lunine J, Miguel Y, Mura A, Orton G, Owen T, Ravine M, Smith E, Steffes P, Stone E, Stevenson D, Thorne R, Waite J, Durante D, Ebert RW, Greathouse TK, Hue V, Parisi M, Szalay JR, Wilson R (2017) Jupiter's interior and deep atmosphere: The initial pole-to-pole passes with the Juno spacecraft. *Science* 356(6340):821–825, DOI 10.1126/science.aal2108
- Bouquet A, Mousis O, Glein CR, Danger G, Waite JH (2019) The Role of Clathrate Formation in Europa's Ocean Composition. *Astrophys. J.* 885(1):14, DOI 10.3847/1538-4357/ab40b0
- Buriez JC, de Bergh C (1981) A study of the atmosphere of Saturn based on methane line profiles near 1.1 microns. *Astron. Astrophys.* 94(2):382–390
- Cassidy TA, Johnson RE (2010) Collisional spreading of Enceladus' neutral cloud. *Icarus* 209(2):696–703, DOI 10.1016/j.icarus.2010.04.010
- Cavalié T, Billebaud F, Dobrijevic M, Fouchet T, Lellouch E, Encrenaz T, Brillet J, Moriarty-Schieven GH, Wouterloot JGA, Hartogh P (2009) First observation of CO at 345 GHz in the atmosphere of Saturn with the JCMT: New constraints on its origin. *Icarus* 203(2):531–540, DOI 10.1016/j.icarus.2009.05.024
- Cavalié T, Hartogh P, Billebaud F, Dobrijevic M, Fouchet T, Lellouch E, Encrenaz T, Brillet J, Moriarty-Schieven GH (2010) A cometary origin for CO in the stratosphere of Saturn? *Astron. Astrophys.* 510:A88, DOI 10.1051/0004-6361/200912909
- Cavalié T, Moreno R, Lellouch E, Hartogh P, Venot O, Orton GS, Jarchow C, Encrenaz T, Selsis F, Hersant F, Fletcher LN (2014) The first submillimeter observation of CO in the stratosphere of Uranus. *Astronomy and Astrophysics* 562:A33, DOI 10.1051/0004-6361/201322297, 1311.2458
- Cavalié T, Venot O, Selsis F, Hersant F, Hartogh P, Leconte J (2017) Thermochemistry and vertical mixing in the tropospheres of Uranus and Neptune: How convection inhibition can affect the derivation of deep oxygen abundances. *Icarus* 291:1–16, DOI 10.1016/j.icarus.2017.03.015, 1703.04358
- Cavalié T, Hue V, Hartogh P, Moreno R, Lellouch E, Feuchtgruber H, Jarchow C, Cassidy T, Fletcher LN, Billebaud F, Dobrijevic M, Rezac L, Orton GS, Rengel M, Fouchet T, Guerlet S (2019) Herschel map of Saturn's stratospheric water, delivered by the plumes of Enceladus. *Astron. Astrophys.* 630:A87, DOI 10.1051/0004-6361/201935954, 1908.07399
- Cavalié T, Venot O, Miguel Y, Fletcher LN, Wurz P, Mousis O, Bounaceur R, Hue V, Leconte J, Dobrijevic M (2020) The Deep Composition of Uranus and Neptune from In Situ Exploration and Thermochemical Modeling. *Space Science Reviews* 216(4):58, DOI 10.1007/s11214-020-00677-8, 2004.13987

- Cavalié T, Lunine J, Mousis O (2023) A subsolar oxygen abundance or a radiative region deep in Jupiter revealed by thermochemical modelling. *Nature Astronomy* DOI 10.1038/s41550-023-01928-8
- Connerney JEP, Waite JH (1984) New model of Saturn's ionosphere with an influx of water from the rings. *Nature* 312(5990):136–138, DOI 10.1038/312136a0
- Courtin R, Gautier D, Marten A, Bezard B, Hanel R (1984) The composition of Saturn's atmosphere at northern temperate latitudes from Voyager IRIS spectra - NH₃, PH₃, C₂H₂, C₂H₆, CH₃D, CH₄, and the Saturnian D/H isotopic ratio. *Astrophys. J.* 287:899–916, DOI 10.1086/162748
- Courtin R, Pandey-Pommier M, Gautier D, Zarka P, Hofstadter M, Hersant F, Girard J (2015) Metric Observations of Saturn with the Giant Metrewave Radio Telescope. In: SF2A-2015: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics, pp 241–245
- Cyr KE, Sears WD, Lunine JI (1998) Distribution and Evolution of Water Ice in the Solar Nebula: Implications for Solar System Body Formation. *Icarus* 135(2):537–548, DOI 10.1006/icar.1998.5959
- de Graauw T, Feuchtgruber H, Bezard B, Drossart P, Encrenaz T, Beintema DA, Griffin M, Heras A, Kessler M, Leech K, Lellouch E, Morris P, Roelfsema PR, Roos-Serote M, Salama A, Vandenbussche B, Valentijn EA, Davis GR, Naylor DA (1997) First results of ISO-SWS observations of Saturn: detection of CO₂, CH₃C₂H, C₄H₂ and tropospheric H₂O. *Astron. Astrophys.* 321:L13–L16
- de Pater I, Molter EM, Moeckel CM (2023) A Review of Radio Observations of the Giant Planets: Probing the Composition, Structure, and Dynamics of Their Deep Atmospheres. *Remote Sensing* 15(5):1313, DOI 10.3390/rs15051313
- Feuchtgruber H, Lellouch E, de Graauw T, Bézard B, Encrenaz T, Griffin M (1997) External supply of oxygen to the atmospheres of the giant planets. *Nature* 389(6647):159–162, DOI 10.1038/38236
- Flasar FM, Achterberg RK, Conrath BJ, Gierasch PJ, Kunde VG, Nixon CA, Bjoraker GL, Jennings DE, Romani PN, Simon-Miller AA, Bézard B, Coustenis A, Irwin PGJ, Teanby NA, Brasunas J, Pearl JC, Segura ME, Carlson RC, Mamoutkine A, Schinder PJ, Barucci A, Courtin R, Fouchet T, Gautier D, Lellouch E, Marten A, Prangé R, Vinatier S, Strobel DF, Calcutt SB, Read PL, Taylor FW, Bowles N, Samuelson RE, Orton GS, Spilker LJ, Owen TC, Spencer JR, Showalter MR, Ferrari C, Abbas MM, Raulin F, Edgington S, Ade P, Wishnow EH (2005) Titan's Atmospheric Temperatures, Winds, and Composition. *Science* 308(5724):975–978, DOI 10.1126/science.1111150
- Fletcher LN, Orton GS, Teanby NA, Irwin PGJ, Bjoraker GL (2009) Methane and its isotopologues on Saturn from Cassini/CIRS observations. *Icarus* 199(2):351–367, DOI 10.1016/j.icarus.2008.09.019
- Fletcher LN, de Pater I, Orton GS, Hofstadter MD, Irwin PGJ, Roman MT, Toledo D (2020) Ice Giant Circulation Patterns: Implications for Atmospheric Probes. *Space Science Reviews* 216(2):21, DOI 10.1007/s11214-020-00646-1, 1907.02901
- Fonte S, Turrini D, Pacetti E, Schisano E, Molinari S, Polychroni D, Politi R, Changeat Q (2023) Oxygen depletion in giant planets with different formation histories. *Mon. Not. R. Astron. Soc.* 520(3):4683–4695, DOI 10.1093/mnras/stad245,

2301.08616

- Gautier D, Hersant F (2005) Formation and Composition of Planetesimals: Trapping Volatiles by Clathration. *Space Science Reviews* 116(1-2):25–52, DOI 10.1007/s11214-005-1946-2
- Grevesse N, Asplund M, Sauval AJ (2007) The Solar Chemical Composition. *Space Sci. Rev.* 130(1-4):105–114, DOI 10.1007/s11214-007-9173-7
- Guillot T (1995) Condensation of Methane, Ammonia, and Water and the Inhibition of Convection in Giant Planets. *Science* 269(5231):1697–1699, DOI 10.1126/science.7569896
- Hartogh P, Lellouch E, Moreno R, Bockelée-Morvan D, Biver N, Cassidy T, Rengel M, Jarchow C, Cavalié T, Crovisier J, Helmich FP, Kidger M (2011) Direct detection of the Enceladus water torus with Herschel. *Astron. Astrophys.* 532:L2, DOI 10.1051/0004-6361/201117377
- Helled R, Bodenheimer P, Podolak M, Boley A, Meru F, Nayakshin S, Fortney JJ, Mayer L, Alibert Y, Boss AP (2014) Giant Planet Formation, Evolution, and Internal Structure. DOI 10.2458/azu_uapress_9780816531240-ch028, 1311.1142
- Helled R, Stevenson DJ, Lunine JJ, Bolton SJ, Nettelmann N, Atreya S, Guillot T, Militzer B, Miguel Y, Hubbard WB (2022) Revelations on Jupiter’s formation, evolution and interior: Challenges from Juno results. *Icarus* 378:114937, DOI 10.1016/j.icarus.2022.114937, 2202.10041
- Hobbs R, Shorttle O, Madhusudhan N (2022) Molecular tracers of planet formation in the atmospheres of hot Jupiters. *Mon. Not. R. Astron. Soc.* 516(1):1032–1046, DOI 10.1093/mnras/stac2106, 2112.04930
- Howard S, Guillot T, Bazot M, Miguel Y, Stevenson DJ, Galanti E, Kaspi Y, Hubbard WB, Militzer B, Helled R, Nettelmann N, Idini B, Bolton S (2023) Jupiter’s interior from Juno: Equation-of-state uncertainties and dilute core extent. *Astron. Astrophys.* 672:A33, DOI 10.1051/0004-6361/202245625, 2302.09082
- Hue V, Cavalié T, Dobrijevic M, Hersant F, Greathouse TK (2015) 2D photochemical modeling of Saturn’s stratosphere. Part I: Seasonal variation of atmospheric composition without meridional transport. *Icarus* 257:163–184, DOI 10.1016/j.icarus.2015.04.001, 1504.02326
- Hue V, Hersant F, Cavalié T, Dobrijevic M, Sinclair JA (2018) Photochemistry, mixing and transport in Jupiter’s stratosphere constrained by Cassini. *Icarus* 307:106–123, DOI 10.1016/j.icarus.2018.02.018, 1802.08697
- Hueso R, Sánchez-Lavega A (2004) A three-dimensional model of moist convection for the giant planets II: Saturn’s water and ammonia moist convective storms. *Icarus* 172(1):255–271, DOI 10.1016/j.icarus.2004.06.010
- Iñurrigarro P, Hueso R, Sánchez-Lavega A, Legarreta J (2022) Convective storms in closed cyclones in Jupiter: (II) numerical modeling. *Icarus* 386:115169, DOI 10.1016/j.icarus.2022.115169
- Irwin PGJ, Dobinson J, James A, Toledo D, Teanby NA, Fletcher LN, Orton GS, Pérez-Hoyos S (2021) Latitudinal variation of methane mole fraction above clouds in Neptune’s atmosphere from VLT/MUSE-NFM: Limb-darkening reanalysis. *Icarus* 357:114277, DOI 10.1016/j.icarus.2020.114277, 2101.01063
- Janssen MA, Oswald JE, Brown ST, Gulkis S, Levin SM, Bolton SJ, Allison MD, Atreya SK, Gautier D, Ingersoll AP, Lunine JJ, Orton GS, Owen TC, Steffes PG,

- Adumitroaie V, Bellotti A, Jewell LA, Li C, Li L, Misra S, Oyafuso FA, Santos-Costa D, Sarkissian E, Williamson R, Arballo JK, Kitiyakara A, Ulloa-Severino A, Chen JC, Maiwald FW, Sahakian AS, Pingree PJ, Lee KA, Mazer AS, Redick R, Hodges RE, Hughes RC, Bedrosian G, Dawson DE, Hatch WA, Russell DS, Chamberlain NF, Zawadski MS, Khayatian B, Franklin BR, Conley HA, Kempenaar JG, Loo MS, Sunada ET, Vorperion V, Wang CC (2017) MWR: Microwave Radiometer for the Juno Mission to Jupiter. *Space Sci. Rev.* 213(1-4):139–185, DOI 10.1007/s11214-017-0349-5
- Johansen A, Lambrechts M (2017) Forming Planets via Pebble Accretion. *Annual Review of Earth and Planetary Sciences* 45(1):359–387, DOI 10.1146/annurev-earth-063016-020226
- Kamata S, Nimmo F, Sekine Y, Kuramoto K, Noguchi N, Kimura J, Tani A (2019) Pluto’s ocean is capped and insulated by gas hydrates. *Nature Geoscience* 12(6):407–410, DOI 10.1038/s41561-019-0369-8
- Karkoschka E, Tomasko M (2009) The haze and methane distributions on Uranus from HST-STIS spectroscopy. *Icarus* 202(1):287–309, DOI 10.1016/j.icarus.2009.02.010
- Karkoschka E, Tomasko MG (1992) Saturn’s upper troposphere 1986–1989. *Icarus* 97(2):161–181, DOI 10.1016/0019-1035(92)90125-Q
- Karkoschka E, Tomasko MG (2011) The haze and methane distributions on Neptune from HST-STIS spectroscopy. *Icarus* 211(1):780–797, DOI 10.1016/j.icarus.2010.08.013
- Kerola DX, Larson HP, Tomasko MG (1997) Analysis of the Near-IR Spectrum of Saturn: A Comprehensive Radiative Transfer Model of Its Middle and Upper Troposphere. *Icarus* 127(1):190–212, DOI 10.1006/icar.1997.5688
- Kouchi A, Kudo T, Nakano H, Arakawa M, Watanabe N, Sirono Si, Higa M, Maeno N (2002) Rapid Growth of Asteroids Owing to Very Sticky Interstellar Organic Grains. *Astrophys. J. Lett.* 566(2):L121–L124, DOI 10.1086/339618
- Kress ME, Tielens AGGM, Frenklach M (2010) The ‘soot line’: Destruction of presolar polycyclic aromatic hydrocarbons in the terrestrial planet-forming region of disks. *Advances in Space Research* 46(1):44–49, DOI 10.1016/j.asr.2010.02.004
- Lambrechts M, Johansen A (2012) Rapid growth of gas-giant cores by pebble accretion. *Astron. Astrophys.* 544:A32, DOI 10.1051/0004-6361/201219127, 1205.3030
- Lambrechts M, Johansen A (2014) Forming the cores of giant planets from the radial pebble flux in protoplanetary discs. *Astron. Astrophys.* 572:A107, DOI 10.1051/0004-6361/201424343, 1408.6094
- Landgraf M, Liou JC, Zook HA, Grün E (2002) Origins of Solar System Dust beyond Jupiter. *Astron. J.* 123(5):2857–2861, DOI 10.1086/339704, astro-ph/0201291
- Leconte J, Selsis F, Hersant F, Guillot T (2017) Condensation-inhibited convection in hydrogen-rich atmospheres. Stability against double-diffusive processes and thermal profiles for Jupiter, Saturn, Uranus, and Neptune. *Astron. Astrophys.* 598:A98, DOI 10.1051/0004-6361/201629140, 1610.05506
- Lellouch E, Moreno R, Paubert G (2005) A dual origin for Neptune’s carbon monoxide? *Astronomy and Astrophysics* 430:L37–L40, DOI 10.1051/0004-6361:200400127

- Lellouch E, Moreno R, Orton GS, Feuchtgruber H, Cavalié T, Moses JI, Hartogh P, Jarchow C, Sagawa H (2015) New constraints on the CH₄ vertical profile in Uranus and Neptune from Herschel observations. *Astronomy and Astrophysics* 579:A121, DOI 10.1051/0004-6361/201526518
- Li C, Ingersoll AP (2015) Moist convection in hydrogen atmospheres and the frequency of Saturn's giant storms. *Nature Geoscience* 8(5):398–403, DOI 10.1038/ngeo2405
- Li C, Ingersoll A, Bolton S, Levin S, Janssen M, Atreya S, Lunine J, Steffes P, Brown S, Guillot T, Allison M, Arballo J, Bellotti A, Adumitroaie V, Gulkis S, Hodges A, Li L, Misra S, Orton G, Oyafuso F, Santos-Costa D, Waite H, Zhang Z (2020) The water abundance in Jupiter's equatorial zone. *Nature Astronomy* 4:609–616, DOI 10.1038/s41550-020-1009-3, 2020. 10305
- Li C, Allison M, Atreya S, Brueshaber S, Fletcher LN, Guillot T, Li L, Lunine J, Miguel Y, Orton G, Steffes P, Waite JH, Wong MH, Levin S, Bolton S (2024) Super-adiabatic temperature gradient at Jupiter's equatorial zone and implications for the water abundance. *Icarus* p 116028, DOI <https://doi.org/10.1016/j.icarus.2024.116028>, URL <https://www.sciencedirect.com/science/article/pii/S0019103524000873>
- Lodders K (2004) Jupiter Formed with More Tar than Ice. *Astrophys. J.* 611(1):587–597, DOI 10.1086/421970
- Lodders K (2021) Relative Atomic Solar System Abundances, Mass Fractions, and Atomic Masses of the Elements and Their Isotopes, Composition of the Solar Photosphere, and Compositions of the Major Chondritic Meteorite Groups. *Space Science Reviews* 217(3):44, DOI 10.1007/s11214-021-00825-8
- Lodders K, Fegley J B (1994) The Origin of Carbon Monoxide in Neptune's Atmosphere. *Icarus* 112(2):368–375, DOI 10.1006/icar.1994.1190
- Lodders K, Palme H, Gail HP (2009) Abundances of the Elements in the Solar System. *Landolt-Börnstein* 4B:712, DOI 10.1007/978-3-540-88055-4_34, 0901. 1149
- Lunine JI, Stevenson DJ (1985) Thermodynamics of clathrate hydrate at low and high pressures with application to the outer solar system. *The Astrophysical Journal Supplement Series* 58:493, DOI 10.1086/191050
- Luspay-Kuti A, Mousis O, Hässig M, Fuselier SA, Lunine JI, Marty B, Mandt KE, Wurz P, Rubin M (2016) The presence of clathrates in comet 67P/Churyumov-Gerasimenko. *Science Advances* 2(4):1501781, DOI 10.1126/sciadv.1501781
- Luszcz-Cook SH, de Pater I, Wright M (2013) Spatially-resolved millimeter-wavelength maps of Neptune. *Icarus* 226(1):437–454, DOI 10.1016/j.icarus.2013.05.019, 1306. 2654
- Madhusudhan N, Harrington J, Stevenson KB, Nymeyer S, Campo CJ, Wheatley PJ, Deming D, Blečić J, Hardy RA, Lust NB, Anderson DR, Collier-Cameron A, Britt CBT, Bowman WC, Hebb L, Hellier C, Maxted PFL, Pollacco D, West RG (2011) A high C/O ratio and weak thermal inversion in the atmosphere of exoplanet WASP-12b. *Nature* 469(7328):64–67, DOI 10.1038/nature09602, 1012. 1603
- Mandt KE, Mousis O, Lunine J, Gautier D (2014) Protosolar Ammonia as the Unique Source of Titan's nitrogen. *Astrophys. J. Lett.* 788(2):L24, DOI 10.1088/2041-8205/788/2/L24

- Marten A, Gautier D, Owen T, Sanders DB, Matthews HE, Atreya SK, Tilanus RPJ, Deane JR (1993) First Observations of CO and HCN on Neptune and Uranus at Millimeter Wavelengths and Their Implications for Atmospheric Chemistry. *Astrophysical Journal* 406:285, DOI 10.1086/172440
- Marty B, Chaussidon M, Wiens RC, Jurewicz AJG, Burnett DS (2011) A ^{15}N -Poor Isotopic Composition for the Solar System As Shown by Genesis Solar Wind Samples. *Science* 332(6037):1533, DOI 10.1126/science.1204656
- Molter EM, de Pater I, Luszcz-Cook S, Tollefson J, Sault RJ, Butler B, de Boer D (2021) Tropospheric Composition and Circulation of Uranus with ALMA and the VLA. *Planet. Sci. J.* 2(1):3, DOI 10.3847/PSJ/abc48a, 2010.11154
- Moore L, O'Donoghue J, Müller-Wodarg I, Galand M, Mendillo M (2015) Saturn ring rain: Model estimates of water influx into Saturn's atmosphere. *Icarus* 245:355–366, DOI 10.1016/j.icarus.2014.08.041
- Moses JI, Greathouse TK (2005) Latitudinal and seasonal models of stratospheric photochemistry on Saturn: Comparison with infrared data from IRTF/TEXES. *Journal of Geophysical Research (Planets)* 110:E09007, DOI 10.1029/2005JE002450
- Moses JI, Poppe AR (2017) Dust ablation on the giant planets: Consequences for stratospheric photochemistry. *Icarus* 297:33–58, DOI 10.1016/j.icarus.2017.06.002, 1706.04686
- Moses JI, Fouchet T, Bézard B, Gladstone GR, Lellouch E, Feuchtgruber H (2005) Photochemistry and diffusion in Jupiter's stratosphere: Constraints from ISO observations and comparisons with other giant planets. *Journal of Geophysical Research (Planets)* 110:E08001, DOI 10.1029/2005JE002411
- Moses JI, Brown ZL, Koskinen TT, Fletcher LN, Serigano J, Guerlet S, Moore L, Waite JH, Ben-Jaffel L, Galand M, Chadney JM, Hörst SM, Sinclair JA, Vuitton V, Müller-Wodarg I (2023) Saturn's atmospheric response to the large influx of ring material inferred from Cassini INMS measurements. *Icarus* 391:115328, DOI 10.1016/j.icarus.2022.115328, 2211.05253
- Mouis O, Gautier D, Coustenis A (2002) The D/H Ratio in Methane in Titan: Origin and History. *Icarus* 159(1):156–165, DOI 10.1006/icar.2002.6930
- Mouis O, Lunine JI, Picaud S, Cordier D (2010) Volatile inventories in clathrate hydrates formed in the primordial nebula. *Faraday Discussions* 147:509, DOI 10.1039/c003658g, 1011.4171
- Mouis O, Lunine JI, Madhusudhan N, Johnson TV (2012) Nebular Water Depletion as the Cause of Jupiter's Low Oxygen Abundance. *Astrophys. J. Lett.* 751(1):L7, DOI 10.1088/2041-8205/751/1/L7, 1204.3887
- Mouis O, Lunine JI, Luspay-Kuti A, Guillot T, Marty B, Ali-Dib M, Wurz P, Altwegg K, Bieler A, Hässig M, Rubin M, Vernazza P, Waite JH (2016) A Protosolar Nebula Origin for the Ices Agglomerated by Comet 67P/Churyumov-Gerasimenko. *Astrophys. J. Lett.* 819(2):L33, DOI 10.3847/2041-8205/819/2/L33, 1604.08827
- Mouis O, Atkinson DH, Cavalié T, Fletcher LN, Amato MJ, Aslam S, Ferri F, Renard JB, Spilker T, Venkatapathy E, Wurz P, Aplin K, Coustenis A, Deleuil M, Dobrijevic M, Fouchet T, Guillot T, Hartogh P, Hewagama T, Hofstadter MD, Hue V, Hueso R, Lebreton JP, Lellouch E, Moses J, Orton GS, Pearl JC, Sánchez-Lavega

- A, Simon A, Venot O, Waite JH, Achterberg RK, Atreya S, Billebaud F, Blanc M, Borget F, Brugger B, Charnoz S, Chiavassa T, Cottini V, d'Hendecourt L, Danger G, Encrenaz T, Gorius NJP, Jorda L, Marty B, Moreno R, Morse A, Nixon C, Reh K, Ronnet T, Schmider FX, Sheridan S, Sotin C, Vernazza P, Villanueva GL (2018) Scientific rationale for Uranus and Neptune in situ explorations. *Planetary and Space Science* 155:12–40, DOI 10.1016/j.pss.2017.10.005, 1708.00235
- Mousis O, Ronnet T, Lunine JI (2019) Jupiter's Formation in the Vicinity of the Amorphous Ice Snowline. *Astrophys. J.* 875(1):9, DOI 10.3847/1538-4357/ab0a72, 1902.08924
- Mousis O, Aguichine A, Helled R, Irwin PGJ, Lunine JI (2020) The role of ice lines in the formation of Uranus and Neptune. *Philosophical Transactions of the Royal Society of London Series A* 378(2187):20200107, DOI 10.1098/rsta.2020.0107
- Mousis O, Aguichine A, Bouquet A, Lunine JI, Danger G, Mandt KE, Luspay-Kuti A (2021) Cold Traps of Hypervolatiles in the Protosolar Nebula at the Origin of the Peculiar Composition of Comet C/2016 R2 (PanSTARRS). *Planet. Sci. J.* 2(2):72, DOI 10.3847/PSJ/abeaa7
- Mousis O, Atkinson DH, Ambrosi R, Atreya S, Banfield D, Barabash S, Blanc M, Cavalié T, Coustenis A, Deleuil M, Durry G, Ferri F, Fletcher LN, Fouchet T, Guillot T, Hartogh P, Hueso R, Hofstadter M, Lebreton JP, Mandt KE, Rauer H, Rannou P, Renard JB, Sánchez-Lavega A, Sayanagi KM, Simon AA, Spilker T, Venkatapathy E, Waite JH, Wurz P (2022) In Situ exploration of the giant planets. *Experimental Astronomy* 54(2-3):975–1013, DOI 10.1007/s10686-021-09775-z
- Öberg KI, Murray-Clay R, Bergin EA (2011) The Effects of Snowlines on C/O in Planetary Atmospheres. *Astrophys. J. Lett.* 743(1):L16, DOI 10.1088/2041-8205/743/1/L16, 1110.5567
- O'Donoghue J, Stallard TS, Melin H, Jones GH, Cowley SWH, Miller S, Baines KH, Blake JSD (2013) The domination of Saturn's low-latitude ionosphere by ring 'rain'. *Nature* 496(7444):193–195, DOI 10.1038/nature12049, 1310.7293
- Orton GS, Fisher BM, Baines KH, Stewart ST, Friedson AJ, Ortiz JL, Marinova M, Ressler M, Dayal A, Hoffmann W, Hora J, Hinkley S, Krishnan V, Masanovic M, Tesic J, Tziolas A, Parija KC (1998) Characteristics of the Galileo probe entry site from Earth-based remote sensing observations. *J. Geophys. Res.* 103(E10):22,791–22,814, DOI 10.1029/98JE02380
- Owen T, Mahaffy PR, Niemann HB, Atreya S, Wong M (2001) Protosolar Nitrogen. *Astrophys. J. Lett.* 553(1):L77–L79, DOI 10.1086/320501
- Pekmezci GS, Johnson TV, Lunine JI, Mousis O (2019) A Statistical Approach to Planetary Condensate Composition beyond the Snowline Based on the Carbon-to-oxygen Ratio. *Astrophys. J.* 887(1):3, DOI 10.3847/1538-4357/ab4c4a
- Pöppe AR (2016) An improved model for interplanetary dust fluxes in the outer Solar System. *Icarus* 264:369–386, DOI 10.1016/j.icarus.2015.10.001
- Prinn RGP, Fegley J B (1989) Solar nebula chemistry: origins of planetary, satellite and cometary volatiles. In: Atreya SK, Pollack JB, Matthews MS (eds) *Origin and Evolution of Planetary and Satellite Atmospheres*, pp 78–136
- Reynard B, Sotin C (2023) Carbon-rich icy moons and dwarf planets. *Earth and Planetary Science Letters* 612:118172, DOI 10.1016/j.epsl.2023.118172

- Sánchez-Lavega A, Orton GS, Hueso R, García-Melendo E, Pérez-Hoyos S, Simon-Miller A, Rojas JF, Gómez JM, Yanamandra-Fisher P, Fletcher L, Joels J, Kemerer J, Hora J, Karkoschka E, de Pater I, Wong MH, Marcus PS, Pinilla-Alonso N, Carvalho F, Go C, Parker D, Salway M, Valimberti M, Wesley A, Pujic Z (2008) Depth of a strong jovian jet from a planetary-scale disturbance driven by storms. *Nature* 451(7177):437–440, DOI 10.1038/nature06533
- Sankar R, Palotai C (2022) A new convective parameterization applied to Jupiter: Implications for water abundance near the 24°N region. *Icarus* 380:114973, DOI 10.1016/j.icarus.2022.114973, 2202.13543
- Schneeberger A, Mousis O, Aguichine A, Lunine JI (2023) Evolution of the reservoirs of volatiles in the protosolar nebula. *Astronomy & Astrophysics* DOI 10.1051/0004-6361/202244670
- Seiff A, Kirk DB, Knight TCD, Young RE, Mihalov JD, Young LA, Milos FS, Schubert G, Blanchard RC, Atkinson D (1998) Thermal structure of Jupiter's atmosphere near the edge of a 5- μ m hot spot in the north equatorial belt. *J. Geophys. Res.* 103(E10):22,857–22,890, DOI 10.1029/98JE01766
- Shibata S, Helled R (2022) Enrichment of Jupiter's Atmosphere by Late Planetary Bombardment. *Astrophys. J. Lett.* 926(2):L37, DOI 10.3847/2041-8213/ac54b1, 2202.06847
- Showman AP, Ingersoll AP (1998) Interpretation of Galileo Probe Data and Implications for Jupiter's Dry Downdrafts. *Icarus* 132(2):205–220, DOI 10.1006/icar.1998.5898
- Sromovsky LA, Karkoschka E, Fry PM, Hammel HB, de Pater I, Rages K (2014) Methane depletion in both polar regions of Uranus inferred from HST/STIS and Keck/NIRC2 observations. *Icarus* 238:137–155, DOI 10.1016/j.icarus.2014.05.016, 1502.06480
- Stevenson DJ (2020) Jupiter's Interior as Revealed by Juno. *Annual Review of Earth and Planetary Sciences* 48:465–489, DOI 10.1146/annurev-earth-081619-052855
- Stevenson DJ, Lunine JI (1988) Rapid formation of Jupiter by diffusive redistribution of water vapor in the solar nebula. *Icarus* 75(1):146–155, DOI 10.1016/0019-1035(88)90133-9
- Stoker CR (1986) Moist convection: A mechanism for producing the vertical structure of the Jovian Equatorial Plumes. *Icarus* 67(1):106–125, DOI 10.1016/0019-1035(86)90179-X
- Sugiyama K, Nakajima K, Odaka M, Kuramoto K, Hayashi YY (2014) Numerical simulations of Jupiter's moist convection layer: Structure and dynamics in statistically steady states. *Icarus* 229:71–91, DOI 10.1016/j.icarus.2013.10.016
- Teanby NA, Irwin PGJ (2013) An External Origin for Carbon Monoxide on Uranus from Herschel/SPIRE? *Astrophysical Journal Letters* 775(2):L49, DOI 10.1088/2041-8205/775/2/L49
- Teanby NA, Irwin PGJ, Moses JI (2019) Neptune's carbon monoxide profile and phosphine upper limits from Herschel/SPIRE: Implications for interior structure and formation. *Icarus* 319:86–98, DOI 10.1016/j.icarus.2018.09.014
- Tobie G, Lunine JI, Sotin C (2006) Episodic outgassing as the origin of atmospheric methane on Titan. *Nature* 440(7080):61–64, DOI 10.1038/nature04497

-
- Tollefson J, de Pater I, Luszcz-Cook S, DeBoer D (2019) Neptune's Latitudinal Variations as Viewed with ALMA. *Astron. J.* 157(6):251, DOI 10.3847/1538-3881/ab1fdf, 1905.03384
- Venot O, Cavalié T, Bounaceur R, Tremblin P, Brouillard L, Lhoussaine Ben Brahim R (2020) New chemical scheme for giant planet thermochemistry. Update of the methanol chemistry and new reduced chemical scheme. *Astronomy and Astrophysics* 634:A78, DOI 10.1051/0004-6361/201936697, 1912.07246
- Visscher C, Moses JI, Saslow SA (2010) The deep water abundance on Jupiter: New constraints from thermochemical kinetics and diffusion modeling. *Icarus* 209(2):602–615, DOI 10.1016/j.icarus.2010.03.029, 1003.6077
- Wang D, Gierasch PJ, Lunine JI, Mousis O (2015) New insights on Jupiter's deep water abundance from disequilibrium species. *Icarus* 250:154–164, DOI 10.1016/j.icarus.2014.11.026, 1412.0690
- Webster CR, Hofmann AE, Mahaffy PR, Atreya SK, House CH, Simon AA, Garvin JB (2023) Tunable Laser Spectrometers for Planetary Science. *Space Sci. Rev.* 219(8):78, DOI 10.1007/s11214-023-01023-4
- Weidenschilling SJ, Lewis JS (1973) Atmospheric and cloud structures of the Jovian planets. *Icarus* 20(4):465–476, DOI 10.1016/0019-1035(73)90019-5
- Wong MH, Mahaffy PR, Atreya SK, Niemann HB, Owen TC (2004) Updated Galileo probe mass spectrometer measurements of carbon, oxygen, nitrogen, and sulfur on Jupiter. *Icarus* 171(1):153–170, DOI 10.1016/j.icarus.2004.04.010
- Wong MH, Lunine JI, Atreya SK, Johnson T, Mahaffy PR, Owen TC, Encrenaz T (2008) Oxygen and Other Volatiles in the Giant Planets and their Satellites. *Reviews in Mineralogy and Geochemistry* 68(1):219–246, DOI 10.2138/rmg.2008.68.10