



Universiteit
Leiden
The Netherlands

Jupiter formed as a pebble pile around the N₂ ice line

Bosman, A.D.; Cridland, A.J.; Miguel, Y.

Citation

Bosman, A. D., Cridland, A. J., & Miguel, Y. (2019). Jupiter formed as a pebble pile around the N₂ ice line. *Astronomy And Astrophysics (0004-6361)*, 632, L11.
doi:10.1051/0004-6361/201936827

Version: Accepted Manuscript

License: [Leiden University Non-exclusive license](#)

Downloaded from: <https://hdl.handle.net/1887/84732>

Note: To cite this publication please use the final published version (if applicable).

LETTER TO THE EDITOR

Jupiter formed as a pebble pile around the N₂ ice line

A. D. Bosman^{1*}, A. J. Cridland¹, and Y. Miguel¹

Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands
e-mail: arbos@umich.edu

November 27, 2019

ABSTRACT

Context. The region around the H₂O ice line, due to its higher surface density, seems to be the ideal location to form planets. The core of Jupiter, as well as the cores of close in gas giants are thus thought to form in this region of the disk. Actually constraining the formation location of individual planets has proven to be difficult, however.

Aims. We aim to use the Nitrogen abundance in Jupiter, which is around 4 times solar, in combination with *Juno* constraints on the total mass of heavy elements in Jupiter, to narrow down its formation scenario.

Methods. Different pathways of enrichment of Jupiter's atmosphere, such as the accretion of enriched gas, pebbles or planetesimals are considered and their implications for the oxygen abundance of Jupiter is discussed.

Results. The super solar Nitrogen abundance in Jupiter necessitates the accretion of extra N₂ from the proto-solar nebula. The only location of the disk that this can happen is outside, or just inside the N₂ ice line. These constraints favor a pebble accretion origin of Jupiter, both from the composition as well as from a planet formation perspective. We predict that Jupiter's oxygen abundance is between 3.6 and 4.5 times solar.

Key words. Planets: formation – astrochemistry – Planets: Jupiter

1. Introduction

There are currently three theories dealing with the formation of gas giants in the solar system. The classical picture is the core accretion scenario, in which km-size planetesimals grow through mutual collisions. Eventually leading to a core of a few Earth masses which can start to efficiently capture a gaseous atmosphere. (Pollack et al. 1996; Kokubo & Ida 2002; Ida & Lin 2004). For planetesimal accretion to work on a reasonable timescale, within the few Myr lifetime of the gas disk, high surface densities of planetesimals are needed. As such planetesimal accretion is most efficient in forming giant planets at small radii. An increase in the surface density of planetesimals at the H₂O ice line at a few AU makes this the preferred location for the formation of Jupiter in this scenario (Stevenson & Lunine 1988; Ciesla & Cuzzi 2006; Schoonenberg & Ormel 2017). Further migration, due to interactions with the gas disk and resonances with Saturn would then put Jupiter at its current location (Walsh et al. 2011).

An alternative to the model of core accretion is the paradigm of pebble accretion, in which planetesimals grow by accreting millimeter and centimeter sized pebbles that flow radially through the disk. As the planet migrates as it is accreting its gas, the cores of these planets need to form at larger radii, outside of 15 AU, to end up at a few AU when the gas disk has dissipated (Bitsch et al. 2015, 2019, Cridland et al. *subm.*). Finally there is the possibility of forming giant planets through gravitational instabilities in the outer disk. In this scenario, Jupiter would form by direct gravitational collapse of a clump in the cold outer re-

gions of the solar nebula, before migrating in (Boss 1997, 2002; Boley et al. 2010).

This sets up a dichotomy of the origin of Jupiter, either formation around the water ice line, or formation at large radii. These different formation histories should leave an imprint on the composition of the planet, especially on the C/O ratio (Öberg et al. 2011). While a lot of effort has been put into constraining composition of Jupiter's atmosphere (Atreya et al. 2003, 2016; Bolton et al. 2017), there is a consensus that the oxygen abundance measurement by the *Galileo* mission is not representative for the bulk atmospheric abundance of oxygen in Jupiter, and thus the C/O ratio cannot be used (Niemann et al. 1998; Atreya et al. 2003). These studies have found however that both carbon and nitrogen are enhanced above solar levels (see Table 1, Asplund et al. 2009; Atreya et al. 2016). The enhancement of nitrogen is interesting, as nitrogen in the interstellar medium (ISM) is extremely volatile, since the main carrier, N₂, does not freeze-out until temperatures below ~ 20 K are reached (Bisschop et al. 2006). Furthermore, the next most abundant nitrogen carrier, NH₃, generally does not contain more than 10% of the total nitrogen budget (Lodders et al. 2009; Boogert et al. 2015; Cleeves et al. 2018; Pontoppidan et al. 2019; Altwegg et al. 2019). This potentially makes the nitrogen content of a planet a powerful probe of its formation location. In this letter we use recent insights in planet formation theory and new constraints from the *Juno* mission to put Jupiter in an astrochemical context. This approach brings forward a couple of formation scenarios for Jupiter that can explain the abundance of elemental N in its atmosphere.

During the development of this work, Öberg & Wordsworth (2019) published a similar line of argument as discussed here. We share their conclusion, that Jupiter must have formed outside of the N₂ iceline. Enrichment of Jupiter's atmosphere by

* *Present address:* Department of Astronomy, University of Michigan, 311 West Hall, 1085 S. University Avenue, Ann Arbor, MI 48109, USA

Table 1. Elemental abundances relative to H

Element	Protosolar	Jupiter	Enhancement
C	2.95×10^{-4}	$1.19 \pm 0.29 \times 10^{-3}$	4.02 ± 0.98
N	7.41×10^{-5}	$3.32 \pm 1.27 \times 10^{-4}$	4.48 ± 1.71
O	5.37×10^{-4}	$2.45 \pm 0.80 \times 10^{-4}$ *	0.46 ± 0.15 *

Notes. Proto-solar abundances from Asplund et al. (2009), Jupiter abundances from Atreya et al. (2016)

*Oxygen measurement in a hot spot and probably does not represent bulk oxygen abundance of the atmosphere.

N_2 is critical in both works, but whereas Öberg & Wordsworth (2019) use the relative enrichment pattern of volatile species to constrain the composition and formation temperature of the enriching bodies, we use the total heavy element mass to constrain Jupiter’s most likely formation location.

2. Enriching Jupiter with Nitrogen

Generally speaking there are three methods to enrich the atmosphere of a gas giant planet in a specific element: through the accretion of enriched gas, through the accretion of solids during core or atmosphere formation, or through the late accretion of solids after the planet has accreted its atmosphere (see Fig. 1). Recently there have been multiple studies that have looked at the effect of disk evolution, especially the growth and drift of icy grains, at the effect this has on the gas-phase elemental abundances (Ciesla & Cuzzi 2006; Booth et al. 2017; Stammerl et al. 2017; Bosman et al. 2018; Krijt et al. 2018; Booth & Ilee 2019). In general, it is found that enrichments above solar abundances in a certain element can happen just inside an ice line if radial drift is efficient and the ice line corresponds to a species that is an abundant ($\geq 10\%$) carrier of that element.

In the case of nitrogen, Booth & Ilee (2019) find an enrichment of elemental nitrogen up to a factor of 2 above solar both within the NH_3 ice line and in an annulus just within the N_2 ice line. The high elemental nitrogen abundances within the NH_3 ice line are strongly dependent on the initial NH_3 abundance. Booth & Ilee (2019) put 50% of elemental nitrogen in NH_3 . Such high NH_3 abundances have not been seen in observations of the cold ISM (Boogert et al. 2015), proto-planetary disks (Cleeves et al. 2018; Pontoppidan et al. 2019) or solar system objects (Lodders et al. 2009; Altwegg et al. 2019), indicating that in all these environments N_2 is the dominant carrier, containing $\sim 90\%$ of the elemental nitrogen. As such a super-solar nitrogen abundance due to the sublimation of NH_3 is unlikely. This means that if Jupiter’s atmospheric enrichments are due to the accretion of enriched gas (Fig. 1, scenario A), it must have accreted most of its mass just within the N_2 ice line.

The second and third scenario depend on the enrichment by solids that deposit nitrogen in the atmosphere. For simplicity, we assume that Jupiter accreted a solar N/H ratio from the gas, and that all of the extra nitrogen is brought in by solids. We furthermore assume that the solids that are accreted onto Jupiter deposited their full nitrogen reservoir into the atmosphere. With these assumption it is possible to calculate the mass of refractories (silicates and metals) that Jupiter needs to accrete as a function of the nitrogen to refractory mass ratio for the accreting solid bodies.

In Fig. 2 we show this relation along with mass constraints based on the known properties of Jupiter and the solar system. The relative solid nitrogen mass and refractory mass is based on the nitrogen-to-refractory mass ratio, assuming that the volatile

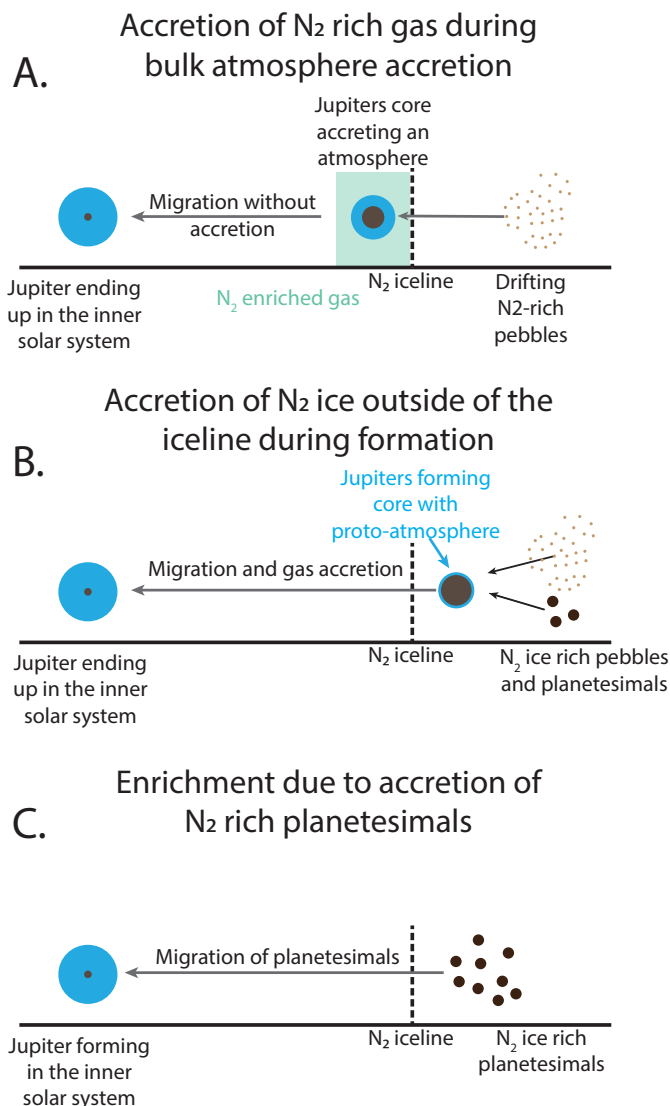


Fig. 1. Different scenarios for the origin of nitrogen in Jupiter’s atmosphere. In scenario A (*top*), the nitrogen is accreted during the bulk of the atmosphere accretion from the part of the disk that is rich in N_2 gas close to the N_2 ice line. The gas is enriched by rapidly drifting pebbles from outside the N_2 ice line. In scenario B (*middle*), nitrogen is brought in with the solid material that accretes onto Jupiter while it is in the cold outer disk. This limits core formation to outside the N_2 ice line, leaving the location of gas accretion unconstrained. In scenario C (*bottom*), Jupiter forms somewhere inside the N_2 ice line, as far in as the H_2O ice line, the classical location of Jupiter formation. N_2 then has to be brought in on planetesimals that originate outside of the N_2 ice line and migrate towards the location of the forming Jupiter. This scenario leaves almost no room for other solids than the N_2 rich solids to be accreted by Jupiter after the initial core has formed. Scenario B seems to be the most reasonable scenario.

and refractory elemental abundances add up to the proto-solar abundance of Asplund et al. (2009). We assume that the refractories contain all of the sulfur, iron, magnesium and silicon available of the ISM. Furthermore, we assume that the silicon is in equal parts enstatite and forsterite (e.g. Meeus et al. 2009), resulting in an average of 3.5 oxygen atoms per silicon in the refractories. Finally we follow Pontoppidan et al. (2014) and Bergin et al. (2015) and place 25% of the total carbon in the refractory phase. This leads to a gas-to-refractory mass ratio of

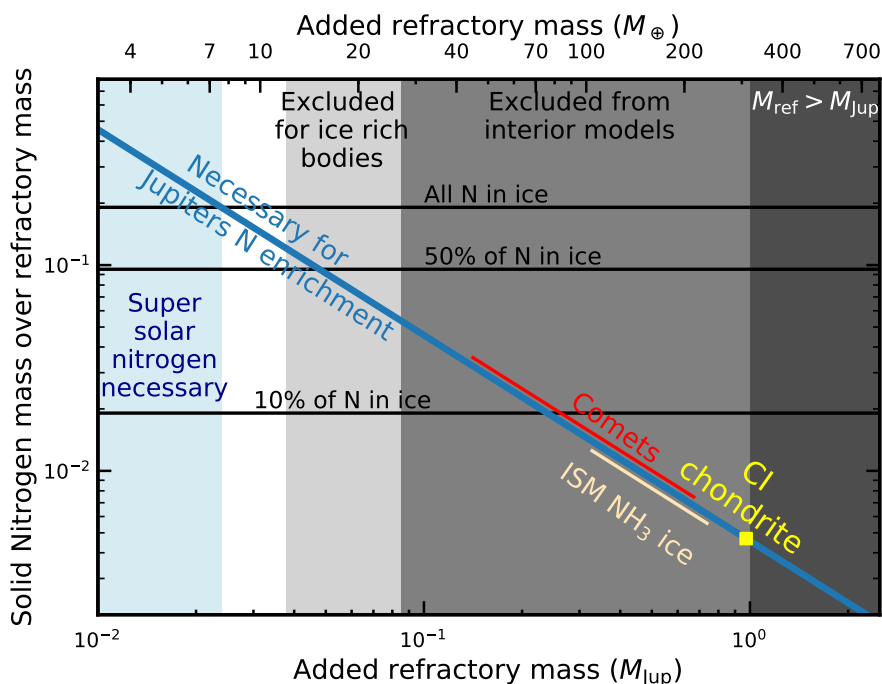


Fig. 2. Nitrogen to refractory mass ratio of enriching solids necessary to reach Jupiter’s Nitrogen content as a function of total refractory mass added to Jupiter. It is assumed that Jupiter has accreted solar composition gas and that the excess nitrogen was brought in frozen on solids. The upper limit to the total heavy element mass is taken to be $27 M_{\oplus}$ (Wahl et al. 2017). This can be in the form of ice poor or ice rich bodies, for ice poor bodies the refractory mass is assumed to be the total mass of heavy elements, for ice rich bodies, assuming H₂O and CO are frozen out, as would be expected for a very N₂ rich body, the heavy element mass is around two times the refractory mass, meaning that only $\sim 12 M_{\oplus}$ plus of refractories can be accreted. The nitrogen to refractory mass ratio of ISM grains without N₂ ice (Boogert et al. 2015), comets (Altwegg et al. 2019) and CI chondrites (Lodders et al. 2009) have been added for comparison. None of these have a high enough nitrogen fraction to enhance Jupiter’s atmosphere.

186 and a nitrogen-to-refractory mass ratio of 0.2, the effective upper limit to the amount of nitrogen that can be added to the solid-phase. Above this mass ratio, the outer disk would have had to be more enhanced in nitrogen than seen in the solar photosphere, a scenario we find unlikely. In the outer parts in the disk, where all non-noble elements heavier than hydrogen are in the solids, the total gas-to-solid ratio drops to 77, so the total solid mass in these regions is about twice the available refractory mass.

The gravitational moments measured by *Juno* (Bolton et al. 2017; Folkner et al. 2017; Iess et al. 2018) limit the total mass of heavy elements in the planet to be between 24 and 27 Earth masses (Wahl et al. 2017). Hence we can immediately neglect any refractory source that would need to accrete masses $\geq 27 M_{\oplus}$. Furthermore, assuming that Jupiter accretes near the N₂ snowline, the pebbles that are incorporated into the planet will also carry a significant portion of H₂O and CO ice.

The combination of the accreted heavy element mass and the available nitrogen strongly limit the amount and composition of the solids that have enriched Jupiter’s atmosphere. In the case of ice-free bodies this requires bodies that $> 25\%$ of the available nitrogen budget is incorporated in these bodies. However, for ice-rich bodies, the total heavy element mass (which includes the ice) is about twice the refractory mass, which further rules out the enrichment of Jupiter by nitrogen poor bodies and moves the minimum solid nitrogen fraction required to more than $\sim 75\%$ of the total available nitrogen. Comets and Meteorites are strongly ruled out as carriers of the nitrogen enhancement of Jupiter’s atmosphere, as they contain far too little nitrogen (Lodders et al. 2009; Altwegg et al. 2019). Since we require at least 75% of the proto-solar nitrogen budget to be in the solid phase, to explain the N-enrichment of Jupiter’s atmosphere, it must have accreted this mass in the form of N₂ ice.

This low temperature origin of the building blocks of Jupiter was also proposed by Owen et al. (1999); Owen & Encrenaz (2006). However, as new observations have constrained the total amount of enriching solids, we need the majority of the N₂ to

be in the ice, and thus temperatures below 20 K (Bisschop et al. 2007), instead of a smaller fraction of trapped N₂ in a water-rich ice, in which case N₂ can be trapped in the ice up to temperatures of 40 K (Lunine & Stevenson 1985; Collings et al. 2004).

3. Implications of Jupiter’s Nitrogen enrichment

3.1. Enrichment during formation

The high nitrogen abundance in Jupiter necessitates the accretion of N₂ rich gas or solids. Enriching Jupiter during its formation means that the nitrogen was from a local source. The accretion of very nitrogen enriched gas can only happen just inside the N₂ ice line, at 60 AU (Fig. 1, A). At the same time, enrichment of the atmosphere by accretion of small bodies necessitates N₂ ice to be present, which similarly requires early atmosphere growth outside of the N₂ ice line (Fig. 1, B). Finally nitrogen outgassing from the core would necessitate a N₂ rich core and thus core formation outside of the N₂ ice line. The exact location of the N₂ ice line in the early solar system is hard to constrain and estimates of the N₂ ice line in protoplanetary disks around solar mass stars vary greatly, ranging between 20 and 80 AU (Huang et al. 2016; van Terwisga et al. 2019; Qi et al. 2019).

Forming Jupiter’s core of around 10 Earth masses (e.g. Lambrechts & Lega 2017), at these radii is very hard to do by planetesimal accretion (Bitsch et al. 2015) and would point at a pebble accretion or gravitational instability origin for Jupiter.

Pebble accretion seems especially promising as building a core from pebbles would leave the N₂ on the pebbles until it is captured within the gravitational influence. Models by Bitsch et al. (2019) show that, as long as the pebble flux is high enough in the outer disk, it is possible to form a cold Jupiter starting core growth as far out as 50 AU. Taking an optimistic estimate for both the pebble accretion efficiency (10% Ormel & Liu 2018) and the total mass of pebble accreted onto the proto-Jupiter ($7.5 M_{\oplus}$), indicates a pebble reservoir of $75 M_{\oplus}$ of refractories, or equivalently $0.05 M_{\odot}$ of gas, outside the N₂ iceline. This trans-

lates in to disks with radii between 30 and 100 AU, assuming a surface density power law slope between -1 and -0.5 (Tazzari et al. 2016). The total amount of dust necessary to form these pebble in the model is even larger (Bitsch et al. 2019), indicating an even larger and more massive disks would be necessary. This puts the proto-solar nebula among the largest and most massive disks currently observed (Tazzari et al. 2016; van Terwisga et al. 2019).

In the case of formation by a gravitational instability of the gas disk, the energy released by the collapse of gas would locally heat the disk and evaporate the N_2 ice off the grains, making accretion of N-enhanced material difficult (Ilee et al. 2017). The large transport rates in a gravitational unstable disk would quickly smooth any pre-existing overdensities in the gas or dust, making it difficult to build a nitrogen enriched object (Kratzer & Lodato 2016). In all of the cases discussed above, N_2 needs to be frozen out in the part of the disk where Jupiter is forming. This indicates that the disk needs to be large and cold, and thus likely to be in either the late class I or early class II stage, as the younger, still embedded disks are too warm to have CO, and thus N_2 frozen out (van 't Hoff et al. 2018).

3.2. Enrichment after formation

It could also be possible to enrich Jupiter's atmosphere after it formed and has accreted the majority of its atmosphere. At this point we require the N-enriched bodies to be formed at large radii, while Jupiter is formed at smaller radii, for example the water ice line. The enriching bodies in this case need to be large, roughly kilometres in size, as they need to be able to hold-on to their N_2 while traveling to Jupiter. If enrichment happens in the disk stage, these bodies need to be big enough not to be trapped in the pressure maximum caused by Jupiter, but not too big. As N_2 is very volatile, and any internal heating by large impacts, or though radioactive decay (e.g. Prialnik et al. 1987) will lead to lower N_2 abundances in the solids.

This scenario requires a very strict set of circumstances: assuming a core of around $10 M_{\oplus}$ is needed to start gas accretion (Lambrechts & Lega 2017), then this leaves at most $15 M_{\oplus}$ of heavy elements, that is ice and refractories, that can be added. The minimal amount of refractories needed, assuming it manages to capture all the available N_2 is $7.5 M_{\oplus}$. If Jupiter formed at the water ice line, there is a part of the disk (~ 15 AU wide) that does not contribute to the enrichment in Jupiter's atmosphere, while a significant amount of mass from the outer disk (≥ 20 AU) makes it to Jupiter with its volatile component intact. This seems highly unlikely - which further argues for a young Jupiter forming very close, or even beyond the N_2 ice line.

4. Discussion

4.1. Nitrogen rich bodies in the solar system

Up until now, there is little evidence of bodies incorporating the bulk of the proto-solar N_2 as ice in the solar system (Glein & Waite 2018). Pluto might have incorporated a significant amount of N_2 ice at its formation, but without a measurement of the nitrogen isotopic ratio its origin is open to speculation (Mandt et al. 2017). Finding bodies that incorporated and still contain a significant fraction of the primordial nitrogen would point to the possible reservoir of Jupiter enriching bodies, and their current orbits could be indicative of the formation location of Jupiter. Both the very CH_3OH rich 2014 MU₆₉ (Stern et al. 2019) and the comet C/2016 R2, which has a high N_2/CO ratio measured

(Opitom et al. 2019) could be one of these bodies. This indicates that bodies rich in N_2 exist outside the orbit of Neptune.

The $^{14}N/^{15}N$ nitrogen isotopic ratio can be used to look at the origin of nitrogen in other bodies as well. There is a large discrepancy between the solar nitrogen isotopic ratio and the isotopic ratio found in many comet (e.g. Mumma & Charnley 2011). This is most likely due to fractionation processes either in the ISM or in the proto-planetary disk enriching HCN and NH_3 and derivatives in ^{15}N (Terzieva & Herbst 2000; Visser et al. 2018). As these species are less volatile than N_2 , ices above the sublimation temperature of N_2 can easily be enriched in ^{15}N .

The nitrogen isotopic ratio in Jupiter is the same as the one measured in the solar wind, implying that Jupiter's nitrogen is indeed coming from the bulk nitrogen reservoir of the proto-solar nebula (Fletcher et al. 2014). Saturn has a similar nitrogen isotopic ratio to Jupiter as well as a similar overabundance of total nitrogen over the sun, indicating that Saturn likely inherited its nitrogen from the same source as Jupiter (Fletcher et al. 2014; Atreya et al. 2016). Other bodies which have measured isotopic ratios are up to a factor three lower than the solar value (Niemann et al. 2010; Mandt et al. 2014; Bockelée-Morvan et al. 2015; Mandt et al. 2017), which includes, meteorites, comets and Titan. Indicating that these bodies did not accrete their nitrogen from the bulk N_2 reservoir.

4.2. Carbon and oxygen in Jupiter

Working with the assumption that Jupiter did not accrete a significant amount of solids after accreting most of its gas, it is possible to use the different formation scenarios and measured carbon content in the planet, to predict the oxygen content of Jupiter. These prediction depend critically on what is assumed to happen with the refractory carbon (here 25% of total carbon Pontoppidan et al. 2014; Bergin et al. 2015) and oxygen contained in refractories. Assuming silicates are in a 50–50 mix of SiO_3 and SiO_4 ions and iron not in the form of iron oxides, about 23% of the oxygen is refractory (Costantini et al. 2005; Meeus et al. 2009). For simplicity we assume that all available volatile carbon is in CO, which then contains 40% of the total oxygen and the remaining 37% of the oxygen in H_2O , representative of gas in the inner regions of disks (Pontoppidan et al. 2014). As such we are ignoring the few to tens of percent of carbon that can be contained within CO_2 in the ice (Pontoppidan et al. 2014; Boogert et al. 2015; Le Roy et al. 2015).

Table 2 shows the oxygen and carbon abundances in Jupiter as predicted from different enrichment scenarios. In the case that N_2 is accreted from N_2 enriched gas, we assume that that gas is also enriched in CO by the same factor, which leads to an enrichment in both oxygen and carbon. The extra carbon cannot explain the full carbon enrichment observed in Jupiter's atmosphere and thus additional carbon from the refractory reservoir is necessary. Here one can assume that only the water ice on these grains enriches the atmosphere in oxygen, or that both the water ice and the silicates deposit oxygen in the atmosphere. In all cases a super solar C/O ratio is found.

In the case that excess N_2 was accreted as solid N_2 on top of a $1 M_{Jup}$ solar composition atmosphere, it is safe to assume that all of the ices on the grains would also enrich the atmosphere. Again this does not match the carbon enrichment in the atmosphere and an additional carbon source is necessary. However, including all of the refractory carbon that is brought in by these grains would raise the carbon abundance in Jupiter to a value higher than the nominal measured value, but still within the range of observations. Finally adding enrichment by the full release of

Table 2. Carbon and oxygen abundances relative to solar predicted for Jupiter's atmosphere assuming different contributing sources.

Incorporated species	[O/H]/[O/H] _★	[C/H]/[C/H] _★	C/O
Accretion of N ₂ enriched gas			
1: Gaseous N ₂ and CO	1.8	3.6	1.1
2: 1 + refr. C and H ₂ O ice	2.7	4.0*	0.8
3: 2 + silicates	3.3	4.0*	0.66
Accretion of N ₂ rich pebbles			
1: N ₂ , CO and H ₂ O ice	3.6	3.6	0.55
2: 1 + refractory carbon	3.6	4.5	0.7
3: 2 + silicates	4.5	4.5	0.55

Notes. *Set to match Jupiter's carbon abundance.

oxygen from the silicates brings the oxygen enhancement up to 4.5 times solar and the C/O ratio back to solar. Hence a solar or slightly super solar C/O ratio is predicted for Jupiter.

5. Conclusions

The nitrogen enrichment in Jupiter's atmosphere makes it likely that Jupiter formed at much larger radii than it is observed now. At these radii, core formation due to pebble accretion onto a planetesimal seems to be the most likely scenario as it would naturally bring in a lot of nitrogen rich ice. This would however, necessitate a cold, massive and large disk to have a massive enough N₂ ice reservoir to enrich Jupiter and enough pebbles flowing in these cold regions to be able to form Jupiter. The proto-solar nebula should thus have looked like the most massive and largest proto-planetary disks that are currently observed.

This formation scenario necessitates the formation of Jupiter's core at a time that the disk was cool enough to have N₂ as an ice. Furthermore, the mass of pebbles necessary to enrich Jupiter's atmosphere imply that formation of Jupiter in a large, massive disk. Implying that the proto-solar disk was analogous to the largest proto-planetary disks currently observed. Jupiter's atmosphere should be enriched in oxygen, in this case, with a O/H below 4.5 times solar, with the preferred models predicting O/H between 3.6 and 4.5 times solar.

Acknowledgements. The authors thank the referee for a constructive report that improved the quality of the paper. Astrochemistry in Leiden is supported by the Netherlands Research School for Astronomy (NOVA). This project has made use Matplotlib (Hunter 2007).

References

Altwegg, K., Balsiger, H., & Fuselier, S. A. 2019, *ARA&A*, 57, 113
 Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, *ARA&A*, 47, 481
 Atreya, S. K., Crida, A., Guillot, T., et al. 2016, arXiv e-prints, arXiv:1606.04510
 Atreya, S. K., Mahaffy, P. R., Niemann, H. B., Wong, M. H., & Owen, T. C. 2003, *Planet. Space Sci.*, 51, 105
 Bergin, E. A., Blake, G. A., Ciesla, F., Hirschmann, M. M., & Li, J. 2015, *Proceedings of the National Academy of Science*, 112, 8965
 Bisschop, S. E., Fraser, H. J., Öberg, K. I., van Dishoeck, E. F., & Schlemmer, S. 2006, *A&A*, 449, 1297
 Bisschop, S. E., Fuchs, G. W., van Dishoeck, E. F., & Linnartz, H. 2007, *A&A*, 474, 1061
 Bitsch, B., Izidoro, A., Johansen, A., et al. 2019, *A&A*, 623, A88
 Bitsch, B., Lambrechts, M., & Johansen, A. 2015, *A&A*, 582, A112
 Bockelée-Morvan, D., Calmonte, U., Charnley, S., et al. 2015, *Space Sci. Rev.*, 197, 47
 Boley, A. C., Hayfield, T., Mayer, L., & Durisen, R. H. 2010, *Icarus*, 207, 509
 Bolton, S. J., Adriani, A., Adumitroaie, V., et al. 2017, *Science*, 356, 821
 Boogert, A. C. A., Gerakines, P. A., & Whittet, D. C. B. 2015, *ARA&A*, 53, 541
 Booth, R. A., Clarke, C. J., Madhusudhan, N., & Ilee, J. D. 2017, *MNRAS*, 469, 3994

Booth, R. A. & Ilee, J. D. 2019, *MNRAS*, 487, 3998
 Bosman, A. D., Tielens, A. G. G. M., & van Dishoeck, E. F. 2018, *A&A*, 611, A80
 Boss, A. P. 1997, *Science*, 276, 1836
 Boss, A. P. 2002, *Earth and Planetary Science Letters*, 202, 513
 Ciesla, F. J. & Cuzzi, J. N. 2006, *Icarus*, 181, 178
 Cleaves, L. I., Öberg, K. I., Wilner, D. J., et al. 2018, *ApJ*, 865, 155
 Collings, M. P., Anderson, M. A., Chen, R., et al. 2004, *MNRAS*, 354, 1133
 Costantini, E., Freyberg, M. J., & Predehl, P. 2005, *A&A*, 444, 187
 Fletcher, L. N., Greathouse, T. K., Orton, G. S., et al. 2014, *Icarus*, 238, 170
 Folkner, W. M., Iess, L., Anderson, J. D., et al. 2017, *Geophys. Res. Lett.*, 44, 4694
 Glein, C. R. & Waite, J. H. 2018, *Icarus*, 313, 79
 Huang, J., Öberg, K. I., & Andrews, S. M. 2016, *ApJ*, 823, L18
 Hunter, J. D. 2007, *Computing in Science & Engineering*, 9, 90
 Ida, S. & Lin, D. N. C. 2004, *ApJ*, 604, 388
 Iess, L., Folkner, W. M., Durante, D., et al. 2018, *Nature*, 555, 220
 Ilee, J. D., Forgan, D. H., Evans, M. G., et al. 2017, *MNRAS*, 472, 189
 Kokubo, E. & Ida, S. 2002, *ApJ*, 581, 666
 Kratter, K. & Lodato, G. 2016, *ARA&A*, 54, 271
 Krijt, S., Schwarz, K. R., Bergin, E. A., & Ciesla, F. J. 2018, *ApJ*, 864, 78
 Lambrechts, M. & Lega, E. 2017, *A&A*, 606, A146
 Le Roy, L., Altwegg, K., Balsiger, H., et al. 2015, *A&A*, 583, A1
 Lodders, K., Palme, H., & Gail, H. P. 2009, *Landolt Börstein*, 4B, 712
 Lunine, J. I. & Stevenson, D. J. 1985, *ApJS*, 58, 493
 Mandt, K., Luszpay-Kuti, A., Hamel, M., et al. 2017, *MNRAS*, 472, 118
 Mandt, K. E., Mousis, O., Lunine, J., & Gautier, D. 2014, *ApJ*, 788, L24
 Meeus, G., Juhász, A., Henning, T., et al. 2009, *A&A*, 497, 379
 Mumma, M. J. & Charnley, S. B. 2011, *ARA&A*, 49, 471
 Niemann, H. B., Atreya, S. K., Carignan, G. R., et al. 1998, *J. Geophys. Res.*, 103, 22831
 Niemann, H. B., Atreya, S. K., Demick, J. E., et al. 2010, *Journal of Geophysical Research (Planets)*, 115, E12006
 Öberg, K. I., Boogert, A. C. A., Pontoppidan, K. M., et al. 2011, *ApJ*, 740, 109
 Öberg, K. I. & Wordsworth, R. 2019, arXiv e-prints, arXiv:1909.11246
 Opitom, C., Hutsemékers, D., Jehin, E., et al. 2019, *A&A*, 624, A64
 Ormel, C. W. & Liu, B. 2018, *A&A*, 615, A178
 Owen, T. & Encrenaz, T. 2006, *Planet. Space Sci.*, 54, 1188
 Owen, T., Mahaffy, P., Niemann, H. B., et al. 1999, *Nature*, 402, 269
 Pollack, J. B., Hubickyj, O., Bodenheimer, P., et al. 1996, *Icarus*, 124, 62
 Pontoppidan, K. M., Salyk, C., Banzatti, A., et al. 2019, *ApJ*, 874, 92
 Pontoppidan, K. M., Salyk, C., Bergin, E. A., et al. 2014, in *Protostars and Planets VI*, ed. H. Beuther, R. S. Klessen, C. P. Dullemond, & T. Henning, 363
 Pralnik, D., Bar-Nun, A., & Podolak, M. 1987, *ApJ*, 319, 993
 Qi, C., Öberg, K. I., Espaillat, C. C., et al. 2019, *ApJ*, 882, 160
 Schoonenberg, D. & Ormel, C. W. 2017, *A&A*, 602, A21
 Stammer, S. M., Birmstiel, T., Panić, O., Dullemond, C. P., & Dominik, C. 2017, *A&A*, 600, A140
 Stern, S. A., Weaver, H. A., Spencer, J. R., et al. 2019, *Science*, 364, aaw9771
 Stevenson, D. J. & Lunine, J. I. 1988, *Icarus*, 75, 146
 Tazzari, M., Testi, L., Ercolano, B., et al. 2016, *A&A*, 588, A53
 Terzieva, R. & Herbst, E. 2000, *MNRAS*, 317, 563
 van 't Hoff, M. L. R., Tobin, J. J., Harsono, D., & van Dishoeck, E. F. 2018, *A&A*, 615, A83
 van Terwisga, S. E., van Dishoeck, E. F., Cazzoletti, P., et al. 2019, *A&A*, 623, A150
 Visser, R., Bruderer, S., Cazzoletti, P., et al. 2018, *A&A*, 615, A75
 Wahl, S. M., Hubbard, W. B., Militzer, B., et al. 2017, *Geophys. Res. Lett.*, 44, 4649
 Walsh, K. J., Morbidelli, A., Raymond, S. N., O'Brien, D. P., & Mandell, A. M. 2011, *Nature*, 475, 206