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Interpretation of the $^{14}N/^{15}N$ ratio measured in Saturn's ammonia

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Abstract

1. Introduction

The recent derivation of a 1-sigma lower limit for the $^{14}N/^{15}N$ ratio in Saturn's ammonia, which is found to be ∼500 [1], prompts us to revise models of Saturn's formation using as constraints the abundances of heavy elements inferred in its atmosphere. This lower limit is found consistent with the $^{14}N/^{15}N$ ratio (∼435) measured by the Galileo probe at Jupiter and implies that the two giant planets were essentially formed from the same nitrogen reservoir in the nebula, which is N_2 [1]. However, in contrast with Jupiter whose C and N enrichments are uniform, carbon is more than twice enriched in Saturn's atmosphere compared to nitrogen. This non-uniform enrichment at Saturn, considered with the recent derivation of a lower limit for the $^{14}N/^{15}N$ ratio, challenges the formation models elaborated so far. Here we propose an alternative formation scenario that may explain all these properties together.

2. Measurements at Saturn

Tables 1 and 2 summarize the isotopic ratios and elemental abundances measured in Saturn's atmosphere (see [2] and references therein for details). The lower limit of the $^{14}N/^{15}N$ ratio in Saturn's ammonia was derived from TEXES/IRTF observations [1]. Others isotopic ratios measured in Saturn are D/H in H_2 (determination from ISO-SWS) [3] and $^{12}C/^{13}C$ in CH_4 (Cassini/CIRS observations) [4]. Meanwhile, only the abundances of CH_4, PH_3, NH_3 and H_2O, and indirectly that of H_2S, have been measured in Saturn. The abundance of CH_4 has been determined from the analysis of high spectral resolution observations from CIRS [4]. PH_3 has been determined remotely in Saturn from Cassini/CIRS observations at 10 μm [5]. The NH_3 abundance is taken from the range of values derived by [6] from Cassini/VIMS 4.6–5.1 μm thermal emission spectroscopy. Tropospheric H_2O has been inferred in Saturn via ISO-SWS [7]. However, H_2O is unsaturated at this altitude (∼3 bar level), implying that its bulk abundance is probably higher than the measured one. The H_2S abundance is quoted from the indirect determination of [8]. The He abundance in Saturn's atmosphere derives from a reanalysis of Voyager's IRIS measurements [9].

Table 1: Isotopic ratios in Saturn

Isotopic ratio	Saturn η	 $\Delta\eta$	Reference
$^{14}N/^{15}N$ (in NH_3)	$500^{(a)}$	–	[1]
D/H (in H_2)	1.70×10^{-5}	$^{+0.75}_{-0.45} \times 10^{-05}$	[3]
$^{12}C/^{13}C$ (in CH_4)	91.8	$^{+8.4}_{-7.8}$	[4]

$^{(a)}$This is a lower limit.

Table 2: Enrichments in Saturn relatives to Protosun

Species	Saturn E	 $\Delta E^{(a)}$	References
C	9.90	1.05	[4]
N	0.53–4.07	–	[6]
$O^{(b)}$	$\sim 10^{-4}$	–	[7]
P	11.54	1.35	[5]
S	15.87	–	[8]
He	0.71	0.14	[9]

$^{(b)}$this is a lower limit; $^{(c)}$this is a upper limit.

3 Previous formation models

Two formation models trying to match Saturn's volatiles enrichments have been elaborated so far. [10]

assumed that Saturn formed at ~50K and found that the ices trapped in Saturn's building blocks were constituted from CH_4 and H_2S trapped in clathrates, NH_3 in hydrates, and CO_2 as pure ice. CO and N_2 were not trapped in the feeding zone and hold well mixed with H_2 until gases collapsed onto the core of the planet. As a result, [10] found that it is possible to match the C, N and S enrichments measured at Saturn from the only incorporation of NH_3, CH_4 and CO in solids. However, their scenario is ruled out because it predicts that Saturn's $^{14}N/^{15}N$ should be intermediate between those of Jupiter and the Earth. Alternatively, [11] proposed that Saturn may have formed at cooler temperature (~20 K) in the disk. In this scenario, not only CH_4, H_2S and CO_2 were trapped in solids following the same condensation sequence as in [10], but CO and N_2 were equally trapped in clathrates. [11] did not reproduce the non uniform C and N enrichments observed in Saturn but their model gives a $^{14}N/^{15}N$ ratio consistent with the lower limit since it considers primordial N_2 as the main nitrogen reservoir.

4 A new scenario consistent with the observations

As mentioned above, the upper limit for the $^{14}N/^{15}N$ ratio found by [1] implies that Saturn's nitrogen was essentially in the form of N_2 at the time of its formation. On the other hand, the higher C enrichment (compared to N) found at Saturn imposes that CH_4, CO_2 and CO were trapped in the solids accreted by its envelope, while at least N_2 was untrapped and remained mixed with the feeding zone H_2. It has been shown that, at nebular conditions, the trapping competition between N_2 and CO in clathrates greatly favors the trapping of the latter molecule to the expense of the former [12]. In these conditions, CO would be trapped with CH_4 and CO_2 in multiple guest clathrates at ~50K [12] while N_2 would remain in the disk's gas phase. If one assumes that Saturn formed at a higher temperature than the one required for N_2 condensation and trapping in solids, then the resulting nitrogen enrichment in the envelope should be moderate, compared to that of carbon. On the other hand, gaseous N_2 would still remain the main N-bearing reservoir accreted by Saturn at the time of the envelope collapse, implying that the resulting $^{14}N/^{15}N$ ratio should match the inferred lower limit.

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