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Composition and origin of the atmosphere of Jupiter—an update, and implications for the extrasolar giant planets

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Abstract

New developments have led to this update of the composition and origin of Jupiter's atmosphere that were originally discussed in our Planet. Space Sci. 47 (1999) 1243 paper. Since Jupiter can provide important insight into the atmospheres of extrasolar giant planets (EGP), we also discuss here the possible implications of the first detection of an atmosphere on an EGP. The ammonia mixing ratio on Jupiter has now been determined directly from the Galileo probe mass spectrometer (GPMS) data, and its value relative to H_2 $(7.1 \pm 3.2) \times 10^{-4}$ in the 9–12 bar region, is found to be similar to the previously reported result inferred from the radio attenuation technique on Galileo. The Jovian $^{15}N/^{14}N$ ratio is found to be much lower than the terrestrial value at $(2.3 \pm 0.3) \times 10^{-3}$. A complete analysis of the various uncertainties in the GPMS data yields an H_2O mixing ratio of $6.0(+3.9, -2.8) \times 10^{-4}$ at 19 bar in the hotspot, and a trend of increase with depth; all other mixing ratios and error bars remain unchanged. CH_3, previously detected on Saturn and Neptune, has now also been detected in the atmosphere of Jupiter recently by Cassini. Benzene is the heaviest hydrocarbon detected to date in the atmospheres of Jupiter and Saturn. Abundances inferred from Infrared Space Observatory measurements are $9(+4.5, -7.5) \times 10^{14}$ and $4.7(+2.1, -1.1) \times 10^{13}$ cm^{-2} for pressures less than 50 and 10 mbar on Jupiter and Saturn, respectively. Finally, we propose that the recently detected sodium in the atmosphere of the EGP orbiting HD 209458 may have mainly a post-accretionary extraplanetary origin, rather than being primordial.
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1. Introduction

Since the publication of our paper, "A comparison of the atmospheres of Jupiter and Saturn: deep atmospheric composition, cloud structure, vertical mixing, and origin", Planet. Space Sci. 47 (1999) 1243 (hereafter A99), certain important new results have become available that warrant an update of that paper. In particular, further analysis of the Galileo probe mass spectrometer (GPMS) data has permitted the first "direct" measurement of ammonia and its nitrogen isotopic composition in the deep well-mixed atmosphere of Jupiter. Benzene has been detected "globally" in the stratospheres of Jupiter and Saturn by the Infrared Space Observatory (ISO). Methyl radical, CH_3, has at last been detected in the atmosphere of Jupiter with the infrared spectrometer CIRS on the Cassini spacecraft, thus confirming the existence of this crucial precursor to the formation of complex hydrocarbons on all giant planets except Uranus

(whose smaller CH_3 abundance together with the relatively low homopause level make the detection challenging). Further refinement in the D/H ratio from ISO brings the result satisfactorily close to the Galileo probe value reported previously. Finally, a thorough analysis of uncertainties in the GPMS data has allowed us to place more realistic error bars on many species, particularly the condensible volatiles, NH_3, H_2S, and H_2O in the deep atmosphere. It is noteworthy also that a recent determination of the He/H ratio in the atmosphere of Saturn based "solely" on the analysis of Voyager infrared (IRIS) data, is found to be at least 3–5 times greater than the previous highly depleted value based on the combined Voyager radio science and infrared (RSS-IRIS) data. The new value of He/H in Saturn's atmosphere is closer to the Jupiter value and essentially removes the necessity of any large-scale condensation of helium in the interior of Saturn. The new value of He/H for Saturn also fits evolutionary models better (Hubbard et al., 1999). H_3^+, the only ion ever identified on Jupiter, has now been detected also in Saturn's auroral regions. However, the H_3^+ emission intensity is found to be only 1–7% that of Jupiter's H_3^+, perhaps due to Saturn's lower exospheric

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temperature, lower magnetospheric energy input and the higher homopause level.

In this paper, we will present (i) an update of the composition of Jupiter's atmosphere, (ii) for completeness, an updated composition of Saturn's atmosphere, (iii) a discussion of new developments on the origin of Jupiter's atmosphere, and (iv) a brief discussion of the possible origin of sodium in the atmosphere an extrasolar giant planet. Other aspects of the atmospheres of Jupiter and Saturn that were discussed in a comprehensive and comparative manner in our previous work, A99, remain essentially unchanged. Only new references will be cited in this paper. The reader would find the current paper to be most beneficial when read in conjunction with our previous publication, A99, on this subject.

2. Composition

The composition of the atmosphere of Jupiter as presently known is presented in Tables 1 and 2. For comparison, the presently known values for Saturn are also given. In particular, more realistic error bars are now given for the values of water, ammonia and hydrogen sulfide in Jupiter's atmosphere. Uncertainties in the GPMS data due to counting statistics, detector saturation effects, and pressure dependence of calibration constants obtained either on the flight unit itself or a nearly identical engineering unit have all now been included (Wong, 2001). The central values of H_2S, and H_2O remain essentially unchanged, however. An updated illustration of the H_2S and NH_3 mixing ratio variation with depth is given in Figs. 1 and 2. The GPMS determination of the ammonia abundance in the deep well-mixed atmosphere of Jupiter is a new result that is discussed in detail below. The central value of the ammonia mixing ratio in the 8–10 bar region, where it reaches a uniform value, is found to be similar to that determined by the radio attenuation technique for the hotspot entry site of the Galileo probe. The $^{15}N/^{14}N$ ratio on Jupiter has now been determined by two independent techniques—IR measurements of NH_3 in 9.5–11.5 μm range from ISO, and the in situ GPMS measurements of NH_3. It is noteworthy that the two results are similar, despite the fact that the ISO data represent essentially a global average and correspond to the region above the ammonia condensation level, whereas the GPMS results are for a meteorologically anomalous region of Jupiter, a hotspot, and they correspond to the region below the ammonia condensation level. The $^{15}N/^{14}N$ ratio has recently been reported (Owen et al., 2001; Mahaffy et al., 2000) and is significantly lower than the terrestrial value that has often been assumed to be the average solar system value in the absence of other measurements.

2.1. NH_3 abundance

Further analysis and laboratory studies based on the GPMS Engineering Unit (EU) have allowed us to refine our estimate of the NH_3 abundance in the 8.6–12.0 bar portion of the descent. The GPMS value is $(7.1 \pm 3.2) \times 10^{-4}$ (Table 1). This value replaces the upper limit previously reported (Niemann et al., 1998). Although ammonia is a significant minor species, the large error bars reflect the strong interaction of this molecule with the walls of the vacuum chamber as described below.

During the 8.6–12.0 bar measurement period, direct sampling of the atmosphere took place through the second inlet system. The final gas path to the ionization region of the mass spectrometer for this sampling was a glass capillary leak (designated DL2) that released gas directly into the ionizing electron beam of the ion source. For most gases this allowed an enhancement in the directly sampled gas compared to gas that was ionized after interactions with the walls of the mass spectrometer. However, ammonia interacts strongly with the interior vacuum walls of the ion source (Niemann et al., 1992) and the contribution to its signal from gas released from the walls is higher than for most of the other species measured. This measurement is further complicated by release of a considerable amount of NH_3 into the ion source from the preceding enrichment cell experiment. Some fraction of this ammonia is adsorbed on the walls of the ion source and subsequently released by the introduction of atmospheric gas through the leak DL2. The studies on the EU confirm that the decay of this ammonia produced in the enrichment cell can be modeled by an exponential decay function. Fig. 3 shows the a fit of the GPMS ammonia 17 amu signal as a sum of a contribution from an exponential decaying signal and another fraction proportional to the amount of gas entering the ionization region as represented by the 13 amu contribution from a methane fragment.

2.2. $^{15}N/^{14}N$ ratio

We recently derived a $^{15}N/^{14}N$ ratio of $(2.3 \pm 0.3) \times 10^{-3}$ from measurements of the ratio the GPMS signals produced by the doubly charged ammonia species $^{15}NH_3^{2+}$ and $^{14}NH_3^{2+}$ (Owen et al., 2001; Mahaffy et al., 2000). Measurement of this ratio is not impacted by the surface interactions of ammonia in the ion source of the mass spectrometer described above. Early attempts to derive this isotope ratio had focused on the signals at 17 and 18 amu from $^{14}NH_3^+$ and $^{15}NH_3^+$. Unfortunately, the contribution to the 18 amu signal from H_2O^+ masks the ammonia signal at 18 amu and only broad limits on the $^{15}N/^{14}N$ ratio can be obtained by studying the transient behavior at the beginning of the enrichment cell experiment, where the signals from water and ammonia are increasing at different rates as they are released from the enrichment cells.

However, a determination of the $^{15}N/^{14}N$ ratio in ammonia can be obtained from the doubly charged species. $^{15}NH_3^{2+}$ produces a signal at 9 amu while $^{14}NH_3^{2+}$ produces a signal at 8.5 amu. Since the focus of the measurement sequence established prior to launch of the Galileo space-

Table 1

Composition of the atmospheres of Jupiter and Saturn[a]

Species	Jupiter	Saturn
Mixing ratios relative to H_2[b]		
Major species		
H_2	1.0	1.0
He	0.157 ± 0.0036	0.11–0.16[c]
Principal minor species		
H_2O	Global: see text	$(2$–$20) \times 10^{-9}$ ($p < 0.3$ mb)
	$(2$–$20) \times 10^{-9}$ (upper stratosphere)	greatly subsaturated at 3 bar
	$\leqslant 10^{-6} (\leqslant 4$ bar, hotspot)	
	$(5.6 \pm 2.5) \times 10^{-5}$ (12 bar, hotspot)	
	$6.0(+3.9, -2.8) \times 10^{-4}$ (19 bar, hotspot)[d]	
CH_4	$(2.1 \pm 0.4) \times 10^{-3}$	$4.5(+2.4, -1.9) \times 10^{-3}$
CH_3	Detection (polar region)[e,f]	$(1.5 - 7.5) \times 10^{13}$ cm^{-2} (stratosphere)
C_2H_6	$(1$–$5) \times 10^{-6}$ (stratosphere)	$(3 \pm 1) \times 10^{-6}$ (stratosphere)
C_2H_2	$(3$–$10) \times 10^{-8}$ (stratosphere)	$(2.1 \pm 1.4) \times 10^{-7}$ (stratosphere/20–50 mb, northern hemisphere)
	$< 2.5 \times 10^{-6}$ (1–10 µbar)	$(5 \pm 1) \times 10^{-8}$ (southern hemisphere)
C_2H_4	$(7 \pm 3) \times 10^{-9}$ (north polar region)[g]	$(2 - 3) \times 10^{15}$ cm^{-2} (non-auroral)[h]
	$(2 - 3) \times 10^{15}$ cm^{-2} (non-auroral)[h]	
C_3H_4	$2.5(+2, -1) \times 10^{-9}$	6×10^{-10} (< 10 mb)
	(north polar region)	
C_3H_8	Detection	
C_4H_2	Detection (polar region)[e,f]	9×10^{-11} (10 mb)
C_6H_6	$9(+4.5, -7.5) \times 10^{14}$ cm^{-2}	$4.7(+2.1, -1.1) \times 10^{13}$ cm^{-2}
	(midlat, $p \leqslant 50$ mbar)[i]	(global, $p \leqslant 10$ mbar)[i]
	$2(+2, -1) \times 10^{-9}$	
	(north polar region-stratosphere)[g]	
NH_3	$\sim (0.2 - 1) \times 10^{-5}$ (0.5–2 bar, hotspot)[j]	$\sim 6 \times 10^{-4}$ (global)
	$(3.3 \pm 1.5) \times 10^{-4}$ (4 bar, hotspot)[k]	
	$(8.1 \pm 1.16) \times 10^{-4}$ (8 bar, hotspot)[k]	
	$(7.1 \pm 3.2) \times 10^{-4}$ (9–12 bar, hotspot)[d,l]	
H_2S	$< 2 \times 10^{-8}$ (< 0.7 bar, global)[m]	$< 2 \times 10^{-7}$
	$< 1 \times 10^{-7}$ ($\leqslant 4$ bar, hotspot)[n]	
	7×10^{-6} (8.7 bar, hotspot)[n]	
	$(7.7 \pm 0.5) \times 10^{-5}$ (16 bar, hotspot)[n]	
Disequilibrium species		
PH_3	$(1$–$2) \times 10^{-7}$ (0.2 - 0.6 bar)	$7(+3, -2) \times 10^{-6}$ (> 400 mb)[o]
	6×10^{-7} (> 1 bar)	$(3 \pm 1) \times 10^{-6}$ (100–1000 mb)[o]
CO	1.6×10^{-9}	$(1 \pm 0.3) \times 10^{-9}$
CO_2	4×10^{-10} (if uniform above 10 mb)[p]	3×10^{-10} (< 10 mb)[p]
	3×10^{-9} (if uniform above 0.1 mb)[p]	
GeH_4	$(7 \pm 2) \times 10^{-10}$	$(4 \pm 4) \times 10^{-10}$
AsH_3	$(2.2 \pm 1.1) \times 10^{-10}$	$(3 \pm 1) \times 10^{-9}$
Other minor constituents		
H	Variable	
$(H_2)_2$	Variable	
HCl		1.1×10^{-9} (tentative)
Cl	Tentative detection	
H_3^+	Variable[q]	Detection (auroral regions).
		Intensity 1–7% that on Jupiter[r]

[a] Updated from Atreya et al. (1999). References to previously reported results are given in this paper (A99). Only references for updated values are given below.

[b] Mixing ratios are given relative to H_2, in order to facilitate comparison to the solar values. Mole fractions may be calculated by dividing the species number density by the atmospheric number density, thus the mole fractions of H_2 and He in Jupiter's atmosphere, e.g., are 0.864 and 0.136, respectively. In the case of Saturn, mixing ratios and mole fractions are nearly equal assuming the very low helium abundance derived in 1984; however, the new value of He/H_2 (0.11–0.16, ref a), if confirmed by Cassini, would reduce the species mole fractions somewhat. In certain instances, column abundance rather than mixing ratio is reported, following the convention used in the original measurement. Isotopic and noble gas results are listed in the Table 2.

[c] Conrath and Gautier (2000) this supercedes the value of 0.034 ± 0.028 (or 0.2 ± 0.1 relative to the sun) reported by Conrath and Gautier (2000).

[d] Uncertainty from Wong et al. (2002); value from A99.

[e] Kunde et al. (2002).

[f] Flasar (2001).

[g] Kim et al. (1985).

[h] Bezard et al. (2001b).

[i] Bezard et al. (2001a).

[j] Sromovsky et al. (1998).

[k] Folkner et al. (1998).

[l] Mahaffy et al. (1999).

[m] Larson, et al. (1984).

[n] Niemann et al. (1998).

[o] The Saturn PH3 values listed here are from Table 1 of Atreya et al. (1999). For the most part, they overlap with Orton et al. (2001) values (7.6×10^{-6} at 645 mb, dropping to 4.3×10^{-7} at 150 mb).

[p] Feuchtgruber et al. (1999).

[q] Drossart et al. (1989). Also detected by Cassini and Galileo infrared imaging spectrometers, Drossart (2001).

[r] Stallard et al. (1999).

Table 2
Elemental and isotopic abundances[a]

Elements	Sun[b]	Jupiter/Sun	Saturn/Sun
Elemental ratios			
He/H	0.0975	0.807 ± 0.02	0.56–0.85
Ne/H	1.23×10^{-4}	0.10 ± 0.01	
Ar/H	3.62×10^{-6}	2.5 ± 0.5[c]	
Kr/H	1.61×10^{-9}	2.7 ± 0.5[c]	
Xe/H	1.68×10^{-10}	2.6 ± 0.5[c]	
C/H	3.62×10^{-4}	2.9 ± 0.5	~ 6
N/H	1.12×10^{-4}	3.6 ± 0.5 (hotspot, 8 bar)[d] 3.2 ± 1.4 (hotspot, 9–12 bar)[e,f]	2–4 (uncertain)
O/H	8.51×10^{-4}	0.033 ± 0.015 (hotspot, 12 bar)[g] $0.35(+0.23, -0.16)$ (hotspot, 19 bar)[e,f]	
P/H	3.73×10^{-7}	0.82	5–10
S/H	1.62×10^{-5}	2.5 ± 0.15 (hotspot, 16 bar)	

Elements	Sun	Jupiter	Saturn
Isotopic ratios			
$^{13}C/^{12}C$	0.011	0.0108 ± 0.0005	0.011
$^{15}N/^{14}N$	$< 2.8 \times 10^{-3}$[h]	$(2.3 \pm 0.3) \times 10^{-3}$ (0.8–2.8 bar)[i] $1.9(+0.9, -1.0) \times 10^{-3}$ (0.2–1.0 bar)[j]	
$^{36}Ar/^{38}Ar$	5.77 ± 0.08	5.6 ± 0.25[c]	
$^{136}Xe/Xe$	0.0795	0.076 ± 0.009[c]	
$^{134}Xe/Xe$	0.0977	0.091 ± 0.007[c]	
$^{132}Xe/Xe$	0.265	0.290 ± 0.020[c]	
$^{131}Xe/Xe$	0.217	0.203 ± 0.018[c]	
$^{130}Xe/Xe$	0.0435	0.038 ± 0.005[c]	
$^{129}Xe/Xe$	0.274	0.285 ± 0.021[c]	
$^{128}Xe/Xe$	0.022	0.018 ± 0.002[c]	
$^{20}Ne/^{22}Ne$	13.81 ± 0.08[k]	13 ± 2[c]	
$^{3}He/^{4}He$	$1.5 \pm 0.3 \times 10^{-4}$ (meteoritic)	$1.66 \pm 0.05 \times 10^{-4}$	
D/H	$2.1 \pm 0.5 \times 10^{-5}$[l] $3.0 \pm 0.17 \times 10^{-5}$[m] *protosolar* values	$2.6 \pm 0.7 \times 10^{-5}$[n] $2.25 \pm 0.35 \times 10^{-5}$[o]	$1.7(+0.75, -0.45) \times 10^{-5}$[o]

[a]Updated from Atreya et al. (1999). References to previously reported results are given in this paper (A99). Only references for updated values are given below.

[b]Anders and Grevesse (1989). It is important to note that recent reanalysis by Holweger (2001) including the effects of non-LTE and solar granulation in the solar photospheric abundances has resulted in lower O/H and higher C/H "central" values than those given in the Table (Anders and Grevesse) . However, the uncertainties in the Holweger values are large, so that O/H [X10^4] lies between 4.55 and 6.52 with a "central" value of 5.45, and C/H [X10^4] lies between 3.05 and 5.00 with a "central" value of 3.91. Using the central values gives an O/C = 1.4! On the other hand, considering the highest O/H and the lowest C/H values from Holweger yields an O/C of 2.14 which is in quite a good agreement with Anders and Grevesse's 2.35 which itself has an uncertainty of approximately ±10%. In view of this, our recommendation for the time being is to continue using the Anders and Grevesse (1989) solar elemental abundances as a reference, keeping in mind that the uncertainties in the O and C abundances could be much greater. Similarly Grevesse and Sauval (1998) advocate somewhat different solar elemental abundances for Ar, Kr, Xe, N and S than Anders and Grevesse, but with overlapping range considering the uncertainties in the two determinations. Again, we have chosen to continue using the Anders and Grevesse (1989) solar elemental abundances as the reference until firmer results are available.

[c]Mahaffy et al. (2000). Normalized to 1.0 for xenon isotopes measured. Only ^{126}Xe and ^{124}Xe, which together make up 0.2% of the total xenon (solar) could not be measured by the GPMS. The xenon error bars in the Mahaffy et al. (2000) paper are with respect to the ratio of each isotope to its non-radiogenic terrestrial value.

[d]Folkner et al. (1998).

[e]Uncertainty from Wong et al. (2002); value from A99.

[f]Mahaffy et al. (1999).

[g]Niemann et al. (1998).

[h]Hashizume et al. (2000); a review of earlier extensive solar wind $^{15}N/^{14}N$ measurements from the lunar record is given by Kerridge (1993); this result does not agree with a recent SOHO result of $(5.5 \pm 1.38) \times 10^{-3}$ from Kallenbach et al. (1998).

[i]Owen et al. (2001), GPMS measurement samples largely from below the NH_3 condensation level.

[j]Fouchet et al. (2000), ISO IR measurement samples largely from above the NH_3 condensation level.

[k]Pepin et al. (1999).

[l]Geiss and Gloeckler (1998).

[m]Gautier and Morel (1997).

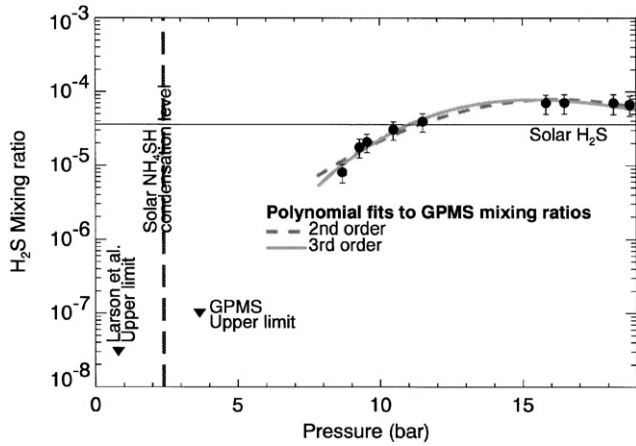[n]Mahaffy et al. (1998).

[o]Lellouch et al. (2001).

Fig. 1. The H_2S mixing ratio to H_2 variation with pressure as in Atreya et al., 1999, except: black circles indicate GPMS mixing ratios derived from [34]/[13] count ratios, with error bars indicating 1-sigma uncertainties; uncertainties include contributions from a number of instrumental and calibration effects. Detailed discussions of GPMS error analysis are given by Wong (2001) and Wong et al. (2002). The base of the NH_4SH cloud is predicted to be at 2.2 bar level for solar NH_3/H_2 and H_2S/H_2 (A99), as shown by the vertical broken line.
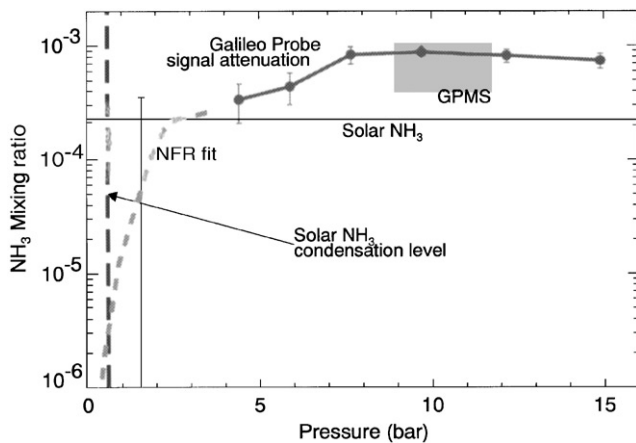
Fig. 2. The NH_3 mixing ratio to H_2 variation with pressure as in Atreya et al., 1999, except: the ratio uses data from count ratio [17]/[13] between the pressures of 8.9 and 11.7 bar; the GPMS mixing ratio is $7.1(\pm 3.2) \times 10^{-4}$ with 1-sigma uncertainties calculated as described in Wong et al. (2002). The base of the NH_3 cloud is predicted to be at 720 mbar level for solar NH_3/H_2 (A99), as shown by the vertical broken line.

craft was largely on singly charged species and not on these doubly charged species there is only a single 8.5 amu measurement in this data set (at data step 5696) at a pressure of 17.2 bar. Nevertheless, we recently established that the value of the 8.5 amu signal can be predicted at any point in the probe descent where the 17 amu signal is not saturated by determining the ammonia fractional contribution to 17 amu. The NH_3^+/NH_3^{2+} ratio is then established from both the flight data itself and associated studies on the engineering unit presently operational in our laboratory. There is one measurement period where the GPMS analyzed an enriched

gas sample obtained from the Jovian atmosphere between 0.8 and 2.8 bar. The spectra from that sample give a strong signal at 9 amu. It is from this enrichment cell data set that our best value of this ratio is established.

The Jovian $^{15}N/^{14}N$ ratio may provide the best value for this protosolar ratio since obtaining this measurement directly and indirectly from solar wind measurements has produced contradictory results. Since this ratio is predicted to change substantially as the atmospheres of Titan and Mars, for example, evolve through loss processes, the current terrestrial $^{15}N/^{14}N$ ratio is not necessarily the best starting value for such models.

3. Origin

Because of a new development, a brief overview of the origin of Jupiter's atmosphere is given first, followed by a discussion of the recent new proposal. The heavy elements, C, N, S, Ar, Kr, and Xe, in Jupiter's atmosphere are all found to be enriched by a factor of 2–4 relative to their solar ratios to hydrogen. Three scenarios—all leading to cold planetesimals—were proposed as possible explanations for the enriched abundances of the heavy elements (Owen et al., 1999; A99). They are: formation of Jupiter at 30 AU or greater and subsequent migration to its present orbit, much cooler solar nebula at 5 AU, or an extremely low temperature of $\leqslant 30$ K of the planetesimals that trapped and supplied the volatiles containing the heavy elements. The last was found to be the most plausible scenario. Laboratory measurements on the trapping of volatiles in amorphous ice lend support to this idea. The phase of the ice in the interstellar cloud would be amorphous.

Recently, Gautier et al. (2001a, b) have argued that the nature of ice that gets formed upon condensation of water vapor is crystalline, not amorphous, when the temperature of the feeding zone of Jupiter at 5 AU drops to 150 K. With further cooling, most of the water condenses as crystalline ice, leaving behind insignificant amounts of amorphous ice. Therefore, these authors suggest an alternate hypothesis that relies on the trapping of volatiles containing the above heavy elements in clathrate hydrates in the cooling feeding zone of Jupiter. If this scenario is correct, Gautier et al. (2001b) estimate that the water abundance, hence the O/H ratio in Jupiter's atmosphere, would be at least 9.4 times solar, i.e. more than twice that predicted by the cold icy planetesimals hypothesis, and more than two times greater than the abundance of the other heavy elements. This interesting alternative to the cold planetesimal hypothesis is not yet supported by laboratory experiments demonstrating the formation of clathrates under the temperature and pressure conditions postulated for the Jupiter feeding zone. It also overestimates the abundance of sulfur on Jupiter, and the authors' explanation for this calculated overabundance— that a substantial amount of sulfur is consumed in the inner solar nebula through the reaction of H_2S with Fe alloy
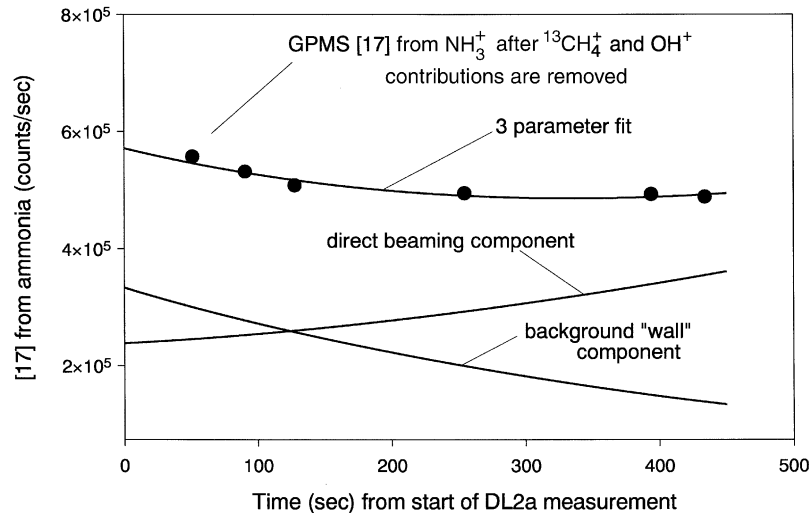
Fig. 3. The separation of the signal from the exponential decay of previously adsorbed NH_3 from the surfaces of the mass spectrometer and from NH_3 entering the ionization region from the capillary leak that directly sampled the atmosphere is illustrated.

grains to form troilite (FeS)—is quantitatively unsupportable. Finally, it is worth noting that to form the clathrate of argon, solar nebula temperatures of $\leqslant 38\,K$ are required (Gautier et al., 2001b), again placing a remarkably low-temperature constraint on the proto-Jovian environment. In principle, it is easy to distinguish between these two hypotheses by measuring the mixing ratio of water in the well-mixed portion of Jupiter's atmosphere. The factor of more than two difference between the two models would be obvious. Unfortunately, the Galileo probe measurements stopped at 22 bar—not deep enough for water to have reached its well-mixed abundance in the hot-spot entry site of the probe. Regardless of the exact cause of the heavy element enrichment, it is important to note that we know of no solid planetesimals today that have this solar composition of the noble gases, sulfur and nitrogen relative to carbon. Yet these building blocks of Jupiter comprise a total mass of 12–18$M_\oplus$, assuming the abundant elements in the planet are well-mixed. If these same unknown planetesimals contributed the heavy elements to the other giant planets, they must have been the most abundant solid material in the early solar system (Owen and Encrenaz, 2002).

4. Implications for extrasolar giant planets

A comprehensive understanding of the formation of Jupiter and its atmosphere is important in its own right. Additionally, it could have far reaching implications for the extrasolar giant planets (EGP) that are found to exist in close proximity to their parent stars. We illustrate this point by examining the first detection of an atmosphere on an extrasolar giant planet in the context of Jupiter in our solar system. This EGP is found to orbit a sun-like star, HD 209458, at a distance of 0.0468 AU. Since the planet

was detected by both the Doppler technique (radial velocity) and the transit method, it was possible to determine its orbital and physical characteristics (Charbonneau et al., 2000). The radius, mass and density of the planet, respectively, 1.347 R_{Jup}, 0.63 M_{Jup}, and 0.35 g cm^{-3}, i.e. about half the density of Saturn, place it in the same class as the gas giants in our solar system. Thus the HD 209458 system could be assumed similar to the Jovian system in our own solar system.

Sodium was detected in the atmosphere of the above EGP by measuring the Na D1 and D2 resonance doublet at 589.3 nm with HST STIS (Charbonneau et al., 2002). The authors estimate the abundance of sodium to be greatly depleted relative to solar, assuming a cloudless planetary atmosphere. These authors suggest several scenarios including cloudy atmosphere, chemical or thermochemical removal of sodium in the planet's interior, and ionization as possible explanation for the subsolar value of sodium. In view of these difficulties and others (such as non-thermal escape due to the relatively high stellar UV flux at the planet, tropospheric cold-trap, etc.) it is not apparent whether primordial sodium could even exist in measurable quantities in the atmosphere. Therefore, we suggest that there may be yet another scenario for explaining the depleted amount of sodium in the EGP atmosphere. We propose that instead of being primordial, the observed sodium may be largely of some non-planetary origin. This assumes that the EGP formed and started out its life like Jupiter so that it was initially colder.

In our own solar system, sodium has not been detected in Jupiter's atmosphere. Even though sodium must have been incorporated into Jupiter during its accretion, it was most likely differentiated to the planet's interior. Under the extremely high pressures and temperatures of the interior its likely fate would be some molecular form upon combining with ambient species such as hydrogen, silicon, chlorine,

sulfur, etc., and little atomic sodium. Removal of sodium from Jupiter's interior to its upper atmosphere is kinetically difficult, and most likely this is the case also for the Jupiter-type extrasolar giant planet in whose atmosphere it has been detected. This would be so, despite the relatively high surface temperature of as much as 1400 K and presumably the expected high interior temperatures of the EGP. Moreover, the high stellar flux at the EGP in question may result in a radiative zone that extends deep into the troposphere, hence a less convective upper troposphere (T. Guillot, pers. comm., 2002). This too would prevent the removal of large quantities of sodium from the planet's interior to its troposphere. Thus, there is perhaps another explanation for the depleted amount of sodium detected in the atmosphere of the giant planet around HD 209458. We propose that rather than being primarily intrinsic, i.e. primordial, this sodium may have had its origin largely in some post-acrretionary source. Such sources of extraplanetary material include the influx of debris, meteorites and comets that are known to carry sodium in the solar proportion (i.e. $Na/Si = 5.7 \times 10^{-2}$, see e.g. Grün and Jessberger, 1990; Anders and Grevesse, 1989), rings, or a volcanically active satellite such as Io. Ablation of the extraplanetary material upon entry would introduce sodium into the atmosphere of the EGP as well as Jupiter. In Jupiter's atmosphere, this sodium would go undetected, since it is expected to condense out due to the relatively low temperature in the relevant part of the atmosphere. On the other hand, the presumably high temperature in the atmosphere of the extrasolar giant planet around HD 209458 could allow sodium to remain in the vapor form, permitting its detection.

The lack of knowledge of the composition, albedo, thermal structure and the vertical transport in the atmosphere of the EGP prevents one from being very quantitative about the flux of sodium (and its carriers) required to explain the sodium doublet observation. However, some clues could be gleaned from the bright sodium doublet airglow (2–10 kR) arising from the sodium layer in the earth's upper mesosphere. The Na column density inferred from these observations is $(1–10) \times 10^9$ cm^{-2}. Such an abundance of sodium is low enough that it could be supplied easily by a relatively small influx of material from any of the above extraplanetary sources mentioned in the context of the EGP. In fact, the flux required could be even smaller considering the fact that the EGP (at 0.0468 AU) receives nearly 500 times the stellar flux the earth does at 1 AU from the sun.

5. Conclusion

The composition of a planetary atmosphere provides useful and crucial information on the current physio-chemical processes and dynamics on the planet. It also gives significant insight into the very origin and evolution of the atmosphere as well as the formation of the planet itself. In the case of Jupiter, a thorough understanding of its atmospheric composition—especially in the deep well-mixed part from which elemental abundances are obtained—has taken on a far greater significance ever since the discovery of dozens of extrasolar giant planets. The above discussion on the possible origin of sodium in the atmosphere of the gaseous giant planet around HD 209458 is necessarily biased by the current models of the accretion of Jupiter and the origin and evolution of its atmosphere. These models are based on a limited set of presently available data, largely from the Galileo probe. Besides being from a single location, the data are for the meteorologically anomalous entry site of the probe. Although important information on many heavy elements has become available for the first time, the abundance of water, which was presumably the original carrier of the heavy elements in the form of icy planetesimals, continues to remain a mystery in the deep well-mixed part of Jupiter's atmosphere.

A complete *global map* of the abundance of all accessible heavy elements in the deep well-mixed atmosphere of Jupiter will be essential for developing an unambiguous model of the formation of Jupiter and the subsequent origin and evolution of its atmosphere. A well thought out and carefully instrumented multiprobe mission to Jupiter, that combines the composition measurements with other critical observations including winds, is most desirable to achieve this ambitious goal. The determination of water and ammonia abundance only is possible by remote sensing in the microwave from a spacecraft flying under Jupiter's radiation belts, provided that laboratory measurements of the opacities of potential microwave absorbers to pressures exceeding 100 bar have been made and fully characterized. The Jupiter results, when combined with atmospheric composition measurements of the extrasolar giant planets, will be valuable in unraveling the mystery of the formation of solar systems and the atmospheres within them.

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