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Saturn's internal structure and carbon enrichment

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ABSTRACT

We use the clathrate hydrate trapping theory to calculate the enrichments in O, N, S, Xe, Ar and Kr compared to solar in Saturn's atmosphere. For this, we calibrate our calculations using two different carbon abundance determinations that cover the domain of measurements published in recent decades: one derived from the NASA *Kuiper* Airborne Observatory measurements and the other obtained from the *Cassini* spacecraft observations. We show that these two carbon abundances imply a different minimum heavy element content for Saturn. Using the *Kuiper* Airborne Observatory measurement for calibration, the amount of ices accreted by Saturn is found to be consistent with current interior models of this planet. On the other hand, using the *Cassini* measurement for calibration leads to an ice content in the planet's envelope that is higher than the one derived from the interior models. In this case, reconciling the interior models with the amount of C measured by the *Cassini* spacecraft requires that significant differential sedimentation of water and volatile species has taken place in Saturn's interior during its lifetime.

Key words. stars: planetary systems – stars: planetary systems: formation – solar system: formation

1. Introduction

The standard giant planet formation scenario, namely the so-called core accretion model (Pollack et al. 1996), has been extended by Alibert et al. (2004, 2005a,b) to include migration of the growing planet and proto-planetary disk evolution. These calculations show that the extended core accretion model can lead to the formation of two giant planets closely resembling Jupiter and Saturn in less than 3 Myr (Alibert et al. 2005b, hereafter A05b). Based on these formation models, Alibert et al. (2005c, hereafter A05c) also demonstrated that the volatile enrichments measured in Jupiter's atmosphere can be explained in a way consistent with the constraints set by internal structure modeling (Saumon & Guillot 2004, hereafter SG04). In this work, we follow the strategy adopted by A05c and utilize the thermodynamical conditions of the protoplanetary disk that led to the formation of Saturn (A05b) to calculate the volatile enrichments in its atmosphere. We then compare the calculated amount of required ices in Saturn with the content of heavy elements predicted by the internal structure models of SG04.

The carbon abundance in Saturn's atmosphere has been the subject of a large number of studies. In our calculations, we adopt two extreme values of C abundance that cover the domain of measurements published in the last 25 years (see Table 1). From the use of a haze model to derive volume mixing ratios in the near-IR bands, C has been shown to be enriched by a factor of 3.4 ± 0.9 (Kerola et al. 1997; *Kuiper* Airborne Observatory (KAO)) in Saturn's atmosphere compared to its solar value[1] (Lodders 2003; see Table 2). On the other hand, recent *Cassini* CIRS far-IR measurements lead Flasar et al. (2005) to infer a C enrichment of 8.8 ± 1.7 compared to solar from the fit of CH_4 rotational lines.

Moreover, from an indirect determination, nitrogen has been shown to be enriched by a factor of 3.1 ± 0.6 (Briggs & Sackett 1989; ground-based radio wavelength observations) in Saturn's atmosphere compared to solar. Briggs & Sacketts (1989) also estimated that S is enriched by a factor of ∼12 compared to solar in Saturn. However, this latter estimation seems to be uncertain due to the difficulty of distinguishing between the contribution to the opacity of H_2S from that of other compounds in the microwave spectrum (Hersant et al. 2004). For this reason, we assume in the present work that the abundance of S is still unknown.

2. Formation of Saturn

The model of Saturn's formation considered here is the one presented by A05b. In this model, Saturn forms from an embryo originally located at ∼12 AU. The proto-planet migrates inwards by following proto-Jupiter's trail and stops at the current

[1] Note that we use the central values of species abundances derived from Table 2 of Lodders (2003) in our calculations, contrary to A05b and A05c who adopted a set of values within the error bars to obtain the best fit possible of the volatile enrichments in Jupiter.

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Table 1. List of measurements of CH_4 abundances in Saturn's atmosphere published since 1981.

CH_4/H_2 ($\times 10^{-3}$)	Solar enrichment	Reference	Measurement
2 ± 0.5	3.4 ± 0.9	Kerola et al. (1997)	KAO
$2^{+1.0}_{-0.8}$	$3.4^{+1.7}_{-1.4}$	Encrenaz & Combes (1982)	ground-based
$2.2^{+0.8}_{-0.2}$	$3.8^{+1.4}_{-0.3}$	Killen (1988)	ground-based
2.5	4.3	Tomasko & Doose (1984)	*Pioneer* IPP
3 ± 0.6	5.2 ± 1.0	Karkoschka & Tomasko (1992)	ground-based
4 ± 2	6.9 ± 3.4	Buriez & de Bergh (1981)	ground-based
4.2 ± 0.4	7.2 ± 0.7	Trafton (1985)	ground-based
4.4 ± 1.2	7.6 ± 2.1	Lellouch et al. (2001)	ISO-SWS
$4.5^{+2.4}_{-1.9}$	$7.7^{+4.1}_{-3.3}$	Courtin et al. (1984)	*Voyager* IRIS
5.1 ± 1.0	8.8 ± 1.7	Flasar et al. (2005)	*Cassini* CIRS

position of Saturn when the disk disappears. Planetesimals are accreted during the whole formation process, along proto-Saturn's migration pathway (between 12 and 9.8 AU). The resulting planet exhibits an internal structure comparable to that of the actual Saturn described by SG04[2], with a final core mass of ~6 $M_\oplus$ and a total mass of accreted planetesimals of ~13.2 $M_\oplus$. The thermodynamical conditions in the disk at the actual position of Saturn are used to calculate the composition of planetesimals that were accreted by the planet.

3. Composition of planetesimals in Saturn's feeding zone

In this work, we consider that abundances of all elements are solar and that O, C, and N exist only in the form of H_2O, CO_2, CO, CH_4, N_2 and NH_3 in the solar nebula gas-phase. Concerning the initial ratios of CO_2:CO:CH_4 and N_2:NH_3 in the solar nebula, for the sake of consistency, we adopt the same range of values as the ones derived by A05c to fit the observed enrichments in volatiles in Jupiter. Hence, we assume CO_2:CO:CH_4 = 40:10:1 to 10:10:1 for N_2:NH_3 = 1 and CO_2:CO:CH_4 = 10:10:1 for N_2:NH_3 = 10 in the vapor phase of the solar nebula. The considered values of CO_2:CO:CH_4 are consistent with ISM measurements (Allamandola et al. 1999; Gibb et al. 2004). The adopted values of N_2:NH_3 are compatible with thermochemical calculations in the solar nebula that take into account catalytic effects of Fe grains on the kinetics of N_2 to NH_3 conversion (Fegley 2000). In addition, S is assumed to exist in the form of H_2S ($H_2S/H_2 = 0.7 \times (S/H_2)_\odot$, following A05c) and other sulfur compounds in the solar nebula (Pasek et al. 2005).

We also assume that volatiles have been trapped during the cooling of the nebula in planetesimals either in form of pure condensates, as it is the case for CO_2, or in form of hydrates or clathrate hydrates, as it is the case for NH_3, N_2, CH_4, CO, Xe, Ar and Kr (see A05c for details). Note that the amount of available water ice is assumed to be sufficient to trap all volatiles except CO_2. Once condensed, ices are assumed to decouple from the gas and to be incorporated into growing planetesimals which may subsequently be accreted by the forming Saturn.

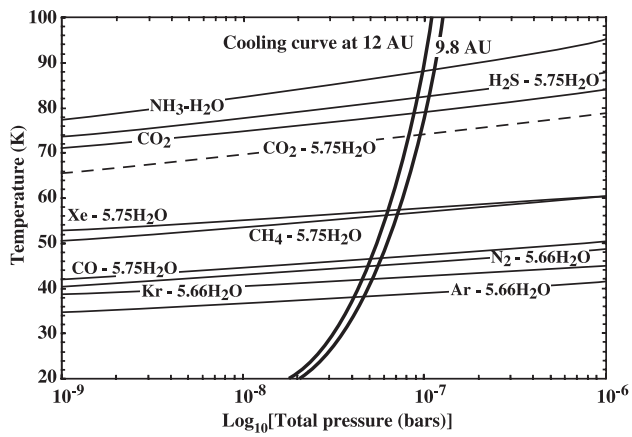

Fig. 1. Stability curves of the condensates considered in the present work, and evolutionary tracks of the nebula at 12 and 9.8 AU. Abundances of various elements are solar, with CO_2:CO:CH_4 = 30:10:1 and N_2:NH_3 = 1 in vapor phase. The condensation curve of CO_2 pure condensate (solid line) is shown together with that of the corresponding clathrate hydrate (dashed line). Species remain in the vapor phase as long as they stay in the domains located above the curves of stability.

Figure 1 represents the cooling curves of the nebula at 9.8 and 12 AU derived from the solar nebula model used by A05b, as well as the condensation curves for the various ices considered in this work. The stability curves of clathrate hydrates are derived from Lunine & Stevenson (1985) whereas we used a fit to the experimental data for the pure CO_2 condensate (Lide 1999). Figure 1 provides the condensation sequence of the different volatiles initially existing in vapor phase inside Saturn's feeding zone. The intersection between the cooling curve and the stability curve of the different condensates also gives the thermodynamic conditions at which the different ices are formed.

Using Eqs. (1) and (2) given in A05c, we can calculate 1) the minimum abundance of water required to trap all volatiles (except CO_2) in the solar nebula gas-phase to form clathrate hydrates or hydrates and 2) the composition of ices incorporated in planetesimals that were accreted by proto-Saturn.

[2] Detailed internal structure models of Saturn developed by SG04 indicate a maximum mass of heavy elements present in the envelope between nearly 0 and 10 $M_\oplus$, whereas the mass of the core varies between 8 and 25 $M_\oplus$. However, the minimum mass of the solid core might be decreased by up to ~7 $M_\oplus$ depending upon the extent of sedimented helium.

Table 2. Gas phase abundances (molar mixing ratio with respect to H_2) of major species in the solar nebula (from Lodders 2003) for CO_2:CO:CH_4 = 30:10:1 and N_2:NH_3 = 1.

Species i	x_i	Species i	x_i
O	1.16×10^{-3}	N_2	5.33×10^{-5}
C	5.82×10^{-4}	NH_3	5.33×10^{-5}
N	1.60×10^{-4}	S	3.66×10^{-5}
H_2O	1.66×10^{-4}	Ar	8.43×10^{-6}
CO_2	4.26×10^{-4}	Kr	4.54×10^{-9}
CO	1.42×10^{-4}	Xe	4.44×10^{-10}
CH_4	1.42×10^{-5}		

Table 3. Calculations of the ratios of trapped masses of volatiles to the mass of H_2O ice in planetesimals formed at 9.8 and 12 AU in the solar nebula. Gas-phase abundance of H_2O is equal to 8.11×10^{-4} (~4.9 times the value quoted in Table 2; see text), and gas-phase abundances of elements are assumed to be solar (Lodders 2003) with CO_2:CO:CH_4 = 30:10:1 and with N_2:NH_3 = 1 in vapor phase in the solar nebula. The abundance of H_2S is subsolar (see text).

	9.8 AU	12 AU
CO_2:H_2O	8.91×10^{-1}	9.13×10^{-1}
CO:H_2O	1.46×10^{-1}	1.45×10^{-1}
CH_4:H_2O	9.14×10^{-3}	9.23×10^{-3}
N_2:H_2O	5.26×10^{-2}	5.34×10^{-2}
NH_3:H_2O	4.67×10^{-2}	4.66×10^{-2}
H_2S:H_2O	4.28×10^{-2}	4.32×10^{-2}
Ar:H_2O	9.74×10^{-3}	9.94×10^{-3}
Kr:H_2O	1.34×10^{-5}	1.34×10^{-5}
Xe:H_2O	2.44×10^{-6}	2.45×10^{-6}

Since, as shown in Table 3, the composition of planetesimals does not vary significantly along the migration path of Saturn, we assume that all the ices contained in accreted planetesimals have an identical composition.

4. Enrichments in volatiles in Saturn

From the determination of the composition of the ices incorporated in the planetesimals (which depend on the initial gas-phase composition in the solar nebula) and the assumption of a mean *I/R* value for the accreted planetesimals, it is possible to calculate the expected enrichments in volatiles in Jupiter's atmosphere. In Table 4 we present the results of these computations and compare them to the observed enrichments for CO_2:CO:CH_4 = 30:10:1 and N_2:NH_3 = 1 (our nominal vapor phase conditions) in the solar nebula gas-phase. Our model reproduces the C and N ground-based enrichment measurements. The minimum fit of the airborne C and ground-based N measurements corresponds to an O enrichment of 5.4 times the solar value. From this, we predict that S, Ar, Kr and Xe are overabundant compared to solar by a factor of 2.1, 2.0, 2.2 and 2.6 respectively. In addition, these enrichments result from the accretion of 5.6 $M_\oplus$ of ices including 2.5 $M_\oplus$ of water in the envelope of Saturn. The resulting total content in heavy elements in Saturn is therefore compatible with the formation model of A05b and consequently with the internal structure model of SG04, provided the ratio of ices to rocks (*I/R*) is greater than or equal to ~0.7. Table 5 summarizes the ranges of required masses of ices in the envelope of Saturn, and the resulting O enrichments, to match both C and N ground-based measurements if the initial gas phase conditions are varied. It can be seen that O is enriched at least between 5.1 and 7.6 times the solar abundance in Saturn's atmosphere while the minimum mass of incorporated ices varies between 5.4 and 7.6 $M_\oplus$ in the giant planet. Under these conditions, the minimum *I/R* ratio required in Saturn varies between ~0.7 and 1.4 in order to be compatible both with the formation model of A05b and the internal structure model of SG04.

Table 4. Observed C and N enrichments in Saturn, and calculated enrichments in volatiles in the nominal model (CO_2:CO:CH_4 = 30:10:1 and N_2:NH_3 = 1).

Species	Observed		Calculated	
	(1)	(2)	(1)	(2)
C	3.4 ± 0.9^a	8.8 ± 1.7^b	2.8	7.1
N	3.1 ± 0.6^c		2.5	6.5
S			2.1	5.5
Ar			2.0	5.1
Kr			2.2	5.6
Xe			2.6	6.7

The observed values are taken from [a] Kerola et al. (1997); [b] Flasar et al. (2005); and [c] Briggs & Sackett (1989). Calculated enrichments are calibrated on the observed C enrichment with the same column label.

On the other hand, fitting the recent C measurement derived from *Cassini* data does not allow one to retrieve a value of N compatible with the measured one. In the nominal case, fitting the minimum value of the *Cassini* measurement implies overabundances compared to solar of N, S, Ar, Kr and Xe by factors of 6.5, 5.5, 5.1, 5.6 and 6.7 respectively. These calculations translate to an O enrichment of at least 13.9 times the solar value in the planet's envelope and require the accretion of at least 14.4 $M_\oplus$ of ices including 6.6 $M_\oplus$ of water. Following Table 5, if the initial gas-phase conditions are modified, the minimum mass of accreted ices varies between 13.7 and 18.3 $M_\oplus$, whereas the corresponding O enrichment ranges between 13.1 and 18.3 times the solar value in the giant planet's atmosphere. In all these cases, the minimum amount of required ices exceeds the mass of heavy elements accreted by the Saturn's formation model of A05b. Moreover, this minimum mass also exceeds the mass of heavy elements present in the planet's atmosphere derived by SG04 (of the order of ~10 $M_\oplus$). However, it is still compatible with the global amount of heavy elements predicted by SG04 ($\leq$30 $M_\oplus$).

Table 5. Minimum mass of accreted water (M_{water}), minimum mass of accreted ices (M_{ices}) and corresponding minimum O/H abundance (compared to solar value) in Saturn's atmosphere required to fit the observed C enrichments. Calculations are presented for the minimum fits of both KAO C and ground-based N measurements (Kerola et al. 1997; Briggs & Sackett 1989) and *Cassini* C measurement (Flasar et al. 2005) in Saturn's atmosphere. Ranges of CO_2:CO:CH_4 and N_2:NH_3 gas-phase ratios used here are those determined by A05c (see text).

		N_2:NH_3 = 1				N_2:NH_3 = 10
		CO_2:CO = 4	CO_2:CO = 3	CO_2:CO = 2	CO_2:CO = 1	CO_2:CO = 1
KAO	$M_{water}/M_{\oplus}$	2.2	2.5	3.0	4.0	4.6
	$M_{ices}/M_{\oplus}$	5.4	5.6	5.9	6.6	7.6
	O/H	5.1	5.4	5.8	6.6	7.6
Cassini	$M_{water}/M_{\oplus}$	5.7	6.6	8.0	11.0	11.2
	$M_{ices}/M_{\oplus}$	13.7	14.4	15.7	18.2	18.3
	O/H	13.1	13.9	15.2	18.0	18.3

5. Discussion and conclusions

In the framework of the clathrate hydrates trapping theory and using the gas-phase abundances of major volatile species in the solar nebula used by A05c to fit the volatile enrichments in Jupiter, we have calculated the enrichments in O, C, N, S, Xe, Ar, and Kr with respect to their solar abundances in the atmosphere of Saturn. Two different measurements of the abundance of carbon in Saturn have been considered for the calibration of our calculations, namely the ground-based determination derived by Kerola et al. (1997) and the recent *Cassini* measurement as published by Flasar et al. (2005).

Using the near-IR determination of C by Kerola et al. (1997), we are able to fit the measured value of N enrichment. Moreover, the predicted amount of ices accreted by Saturn is consistent with the formation model of A05b and the internal structure model of SG04, provided the minimum *I/R* ratio required in the giant planet varies between ~0.7 and 1.4, a value compatible with the recent *Cassini* determination of Phoebe's low density (1630 kg m^{-3}; Porco et al. 2005).

On the other hand, using the recent far-IR determination of C reported by Flasar et al. (2005), the measured value of N enrichment could no longer be reproduced. In addition, the amount of ices accreted by Saturn exceeds the mass of heavy elements predicted by the A05b model. This difference is likely to be due to the assumptions made by A05b in the calculation of the planetesimal's disk (see also Alibert et al. 2005a, for details).

Furthermore, the amount of heavy elements required to explain the *Cassini* measurement that should be currently in Saturn's envelope appears incompatible with the results of the internal structure modeling by SG04 (Table 5). In addition, in order to explain only the value of C enrichment given by Flasar et al. (2005), one needs to invoke the accretion of at least 10.8 $M_{\oplus}$ of ices (including a minimum of 3.9 $M_{\oplus}$ of water) in the envelope of Saturn with our nominal gas-phase conditions, an amount slightly exceeding the maximum mass of heavy elements predicted in this zone by SG04. The discrepancy is higher if one adds the amount of ices required to trap N_2 and NH_3 as clathrate hydrates or hydrates in planetesimals: the measured abondance of N by Briggs & Sackett (1989) requires as a minimum the additional accretion of 0.9 $M_{\oplus}$ of ices, whereas assuming an enrichment of N of 6.5 (as predicted by our calculations) requires the accretion of a minimum of 2.3 $M_{\oplus}$ of ices. Therefore, in order to reconcile Saturn's internal structure models and the C measurement made by the *Cassini* spacecraft, one must then suppose a sedimentation of some of the accreted water onto the core, although the major part of other accreted volatiles would have remained in the atmosphere. This assumption is compatible with the work of Fortney & Hubbard (2003, 2004) who argued that a significant oxygen depletion may have occurred in Saturn's atmosphere during its thermal history. This may be due to the immiscibility of oxygen in hydrogen at high temperature and pressure conditions (Fortney & Hubbard 2003).

A number of ground-based C measurements such as those of Buriez & de Bergh (1981) and Trafton (1985) are in agreement with the *Cassini* CIRS data, along with the *Voyager* IRIS data utilized by Courtin et al. (1984) and the ISO-SWS determination by Lellouch et al. (2001; see Table 1). This implies that the *Cassini* determination would be more representative of the carbon abundance in Saturn's atmosphere than that of Kerola et al. (1997). On this basis, we note that our global oxygen abundance in Saturn is at least ~two times higher than that predicted by Visscher & Fegley (2005) from net thermochemical reaction calculations in its atmosphere. On the other hand, the calculations of Visscher & Fegley (2005) are consistent with the current Saturn's atmospheric composition and may not be valid for the whole planet.

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References

Alibert, Y., Mordasini, C., & Benz, W. 2004, A&A, 417, L25
Alibert, Y., Mordasini, C., Benz, W., et al. 2005a, A&A, 434, 343
Alibert, Y., Mousis, O., Mordasini, C., et al. 2005b, ApJ, 626, L57 (A05b)
Alibert, Y., Mousis, O., & Benz, W. 2005c, ApJ, 622, L145 (A05c)
Allamandola, L. J., Bernstein, M. P., Sandford, S. A., et al. 1999, Space Sci. Rev., 90, 219
Briggs, F. H., & Sackett, P. D. 1989, Icarus, 80, 77

Buriez, J. C., & de Bergh, C. 1981, A&A, 94, 382
Courtin, R., Gautier, D., Marten, A., et al. 1984, ApJ, 287, 899
Encrenaz, T., & Combes, M. 1982, Icarus, 52, 54
Fegley, B. Jr. 2000, Space Sci. Rev., 92, 177
Flasar, F. M., Achterberg, R. K., Conrath, B. J., et al. 2005, Science, 307, 1247
Fortney, J. J., & Hubbard, W. B. 2003, Icarus, 164, 228
Fortney, J. J., & Hubbard, W. B. 2004, ApJ, 608, 1039
Gibb, E. L., Whittet, D. C. B., Boogert, A. C. A., & Tielens, A. G. G. M. 2004, ApJS, 151, 35
Hersant, F., Gautier, D., & Lunine, J. I. 2004, Planet. Space Sci., 52, 623
Karkoschka, E., & Tomasko, M. G. 1992, Icarus, 97, 161
Kerola, D. X., Larson, H. P., & Tomasko, M. G. 1997, Icarus, 127, 190
Killen, R. M. 1988, Icarus, 73, 227
Lellouch, E., Bézard, B., Fouchet, T., et al. 2001, A&A, 670, 610
Lide, D. R. 1999, CRC Handbook of Chemistry and Physics, ed. D. R. Lide (Boca Raton: CRC press LLC), 6
Lodders, K. 2003, ApJ, 591, 1220
Lunine, J. I., & Stevenson, D. J. 1985, ApJS, 58, 493
Pasek, M. A., Milsom, J. A., Ciesla, F. J., et al. 2005, Icarus, 175, 1
Pollack, J. B., Hubickyj, O., Bodenheimer, P., et al. 1996, Icarus, 124, 62
Porco, C. C., Baker, E., Barbara, J., et al. 2005, Science, 307, 1237
Saumon, D., & Guillot, T. 2004, ApJ, 609, 1170 (SG04)
Tomasko, M. G., & Doose, L. R. 1984, Icarus, 58, 1
Trafton, L. 1985, Icarus, 63, 374
Visscher, C., & Fegley, B. 2005, ApJ, 623, 1221