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The Structure of the Solar Nebula From Cometary Composition

D. Bockelée-Morvan

Observatoire de Paris, 5 place Jules Janssen, F-92195, Meudon, France

F. Hersant

Institut für Theoretische Astrophysik, Tiergartenstr. 15, D-69121, Heidelberg, Germany

D. Gautier

Observatoire de Paris, France

J.-M. Huré

Observatoire de Paris and Université de Paris 7, France

Abstract. This paper presents an interpretation of cometary compositional data in the frame of an evolutionary 2D turbulent model of the Solar Nebula: D/H ratios, crystalline silicates and N_2/CO deficiency.

A number of models of the Solar Nebula have been published, but most of them are weakly constrained. Observational data acquired these last years improve the situation. It is currently admitted that accretion of matter in circumstellar disks is driven by turbulence (although its origin is still controversial). Among observational evidences are non-thermal velocity dispersions, UV and visible luminosity excesses in T Tauri stars and disk lifetime. Turbulence has been considered for a long time as responsible for angular momentum redistribution in the Solar System. Since the exact calculation of the turbulence at all scales requires an unrealistically large amount of computer time, modelers simplify the problem thanks to a prescription for turbulent viscosity that is proportional to the speed of sound and half-thickness H of the disk, with α as the proportionality factor (Shakura & Sunyaev 1973). On this basis, Hersant, Gautier, & Huré (2001) developed an evolutionary two-dimensional turbulent model for the solar nebula. This model is defined by three parameters: the initial accretion rate $\dot{M}_0$, the initial radius of the disk R_0 and the α parameter. The temporal evolution of the temperature T, surface density Σ, pressure P and height H throughout the nebula are computed using the decay of the mass accretion rates versus age observed for T Tauri stars (Hartmann 2000).

However, the large range of possible input parameters lead to a considerable number of different evolving Solar Nebulae. Solar system data, especially the isotopic composition of comets and of primitive meteorites, introduce strong additional constraints. The D/H ratio has been measured in H_2O in Comets Halley, C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp), and in HCN in Comet Hale-Bopp. The D/H ratio in OH has been measured in LL3 meteorites (for a review of all measurements, see Robert, Gautier, & Dubrulle 2000). From the analysis of these data, Drouart et al. (1999) and Hersant et al. (2001) obtained important conclusions: (i) a major part of water ices (strongly enriched in deuterium), falling from the pre-solar cloud on the nebula disk, vaporized outwards to 20–30 AU; as long as water did not condense, it subsequently exchanged its deuterium with H_2 of the nebula, which D/H ratio was equal to the protosolar value ($\sim 2\times10^{-5}$); (ii) the decrease of the initial D/H was much more efficient in the hot inner nebula than in the outer nebula where comets formed from icy grains; (iii) the material of the inner part of the nebula mixed by turbulent diffusion with that of the outer nebula; (iv) the D/H ratios measured in water in the Oort cloud comets are relics of the value reached in H_2O at the epoch when the gas condensed to form the pre-cometary ices; (v) a minor part of water ices either accreted late in the life of the nebula, or arrived late in the region of meteorite formation: their D/H ratio, higher than the value measured in comets, must be relics of that in the interstellar medium (ISM). Indeed, highly D-enriched phases coexist with less enriched (reprocessed) components in LL3 meteorites.

From their analysis, Drouart et al. (1999) and Hersant et al. (2001) showed that the D/H ratio measured in water in comets, and in the reprocessed part of OH in LL3 meteorites, constrains the temporal evolution of the radial distributions of temperature and density throughout the nebula. This considerably reduce possible values of $\dot{M}_0$, R_0 and α, namely: $2\times10^{-6} < \dot{M}_0 < 10^{-5}$ solar mass per year, $12.8 < R_0 < 39$ AU, $0.006 < \alpha < 0.04$ according to Hersant et al. (2001). Interestingly enough, values of D/H in HCN measured in Comet Hale-Bopp are reproduced with the same evolution schemes (Mousis et al. 2000; Hersant et al. 2001).

These models also succeed in the interpretation of the presence of crystalline silicates in comets. Their detection (see Crovisier et al. 2000; Wooden et al. 1999) was unexpected because silicates detected so far in the ISM are amorphous and that the crystallization requires temperatures much higher than expected in the outer nebula. Bockelée-Morvan et al. (2002) proposed that amorphous silicates coming from the outer regions were annealed in the inner hot nebula. Using the nebula models of Hersant et al. (2001) which fit cometary D/H ratios, they were able to reproduce the mass ratio of crystalline silicates over amorphous silicates observed in Comet Hale-Bopp, as a result of the subsequent mixing of the silicate variety formed in the inner nebula with the amorphous variety present in the region of formation of Oort cloud comets.

Another interesting product of the turbulent models of Hersant et al. (2001) is that they can be used to interpret the strong deficiency of N_2 with respect to CO observed in several Oort cloud comets. When the nebula cooled down, H_2O condensed in crystalline form at temperatures of about 150 K. As cooling further proceeded, the nebula reached temperature/pressure conditions for which various volatiles (H_2S, CH_4, CO, N_2, and noble gases) may be trapped in the form of clathrate hydrates (Iro et al. 2003). NH_3 is trapped as an hydrate. The trapping of CO and N_2 occurs, in principle, at similar temperatures. However, if the amount of available ice is not sufficient to trap both CO and N_2, the clathration of CO drastically dominates that of N_2. Iro et al (2003) have calculated that clathrate hydrates of N_2 cannot form if the H_2O/H_2 ratio (at

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the epoch of condensation of water) is less than 2.8 times the solar O/H ratio. In other words, N_2 was trapped in cometary grains only in regions where icy grains accumulated. The same approach is valid for argon. This noble gas has not been detected in any comet so far.

In the framework of the same clathration theory, the uniform enrichment in C, N and noble gases measured in Jupiter results from the clathration of volatiles (including CO, CH_4, N_2, NH_3, Ar, Kr and Xe) in the feeding zone of the planet, and from the accumulation of ices around 5 AU (Gautier et al. 2001). The theory of clathration also permitted Hersant, Gautier, & Lunine (2004) to predict that enrichments in Saturn, Uranus and Neptune should be strongly different (especially for noble gases) from those observed in Jupiter.

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