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Composition of Comets and Interstellar Dust

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Abstract. Recent observational results from ground and space-based observatories in combination with laboratory simulations allow us to monitor the evolution, survival, transport and transformation of cosmic dust from molecular clouds and the diffuse interstellar medium, until their incorporation into Solar System material. The composition of comets encodes information on their origin and can be used as a tracer for processes which were predominant in the protosolar nebula. A comparison of the composition and abundances of interstellar molecules and cometary volatiles reveals a general correspondence, but discrepancies are also apparent. Detailed studies indicate that cometary ices are a mixture of original interstellar material with material that has been moderately to heavily processed in the pre-solar nebula. The inventory and distribution of ice and organic molecules in interstellar clouds and in comets and their common link are briefly described.

1. Introduction

Dense interstellar clouds are the birth sites of stars of all masses and their planetary systems. Interstellar molecules and dust become the building blocks for protostellar disks, from which planets, comets, asteroids, and other macroscopic bodies eventually form (see Mannings et al. 2000). Observations at infrared, radio, millimeter, and sub-millimeter frequencies show that a large variety of gas phase molecules are present in the dense interstellar medium (Ehrenfreund & Charnley 2000). Dust particles present in cold molecular clouds acquire icy grain mantles through accretion and reaction of atoms and molecules from the gas. Such grain mantles have been recently studied with the Short Wavelength Spectrometer (SWS) on-board ISO, which allowed us for the first time observations of the complete range between 2.5 and 200 μm, free of any telluric contamination. The most recent abundances of interstellar ices near high-mass, low-mass, and field stars and volatiles measured in the coma of comet Hale-Bopp are listed in Table 1. ISO-SWS and ground-based data show that the major organic species in interstellar ices are H_2O, CO, CO_2 and CH_3OH. The abundances of NH_3 (ranging from 3-16 % relative to H_2O ice) are currently under debate (Dartois & d'Hendecourt 2001). Organic species such as OCS, H_2CO, HCOOH, CH_4, and OCN^- are observed toward massive protostars on the few % level and upper limits have been determined from ISO spectra for C_2H_2, C_2H_5OH, and C_2H_6 (see Ehrenfreund & Schutte 2000 for a recent review).

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Table 1. Abundances of interstellar ices in different interstellar regions. The abundances of Hale-Bopp should be most compatible with values of the low-mass star Elias 29. However, low-mass protostars are faint and difficult to observe and only future observations with large telescopes will allow us to accurately measure species of low abundance.

Ice species	NGC7538:IRS9 high-mass protostar	Elias 29 low-mass protostar	Elias 16 field star	Hale-Bopp lp comet
H_2O	100	100	100	100
CO	16	6	25	20
CO_2	20	22	15	6-20
CH_4	2	<1.6	-	0.6
CH_3OH	5	<4	<3.4	2
H_2CO	5	-	-	1
OCS	0.05	<0.08	-	0.5
NH_3	13	<9.2	<6	0.7-1.8
C_2H_6	<0.4	-	-	0.3
HCOOH	3	-	-	0.06
O_2	<20	-	-	-

Comets are formed in the outer Solar System from left over planetesimals which were not integrated into planets. Presolar material in the outer solar nebula has been subjected to UV irradiation and ion-molecule reactions, but experienced probably little heating. Comet nuclei may therefore have preserved in their interior a large amount of pristine interstellar material. Observations of the coma allow us to infer the molecular inventory of the nucleus to some extent. The recent apparitions of comets Hyakutake and Hale-Bopp have revolutionized our understanding of the volatile chemical inventory of comets and the interstellar-comet connection (Crovisier & Bockelée-Morvan 1999). Observational and theoretical work on the nucleus and coma of Hale-Bopp is extensively summarized in the proceedings of the International Conference on Comet Hale-Bopp published in volumes 77-79 of Earth, Moon and Planets (1999). Radio observations of comet Hale-Bopp by Biver et al. (1997) showed that between 1.4 and 4 AU, the production rates of many simple molecules exhibited different dependencies on the heliocentric distance.

2. The link between interstellar and cometary matter

Cometary volatiles and their relative proportions are more compatible with interstellar solid state abundances (not with interstellar gas phase species). A comparison of interstellar and cometary ices using recent ISO data has revealed a general correspondence in the composition of cometary and interstellar ices, but discrepancies are also apparent (Ehrenfreund & Charnley 2000). If interstellar icy grains are incorporated unaltered into comets, ice species should be observed in comets at varying heliocentric distances due to the morphology of different ice-types, present in molecular clouds. Bockelée-Morvan & Rickman (1999) discuss that gas production curves of Hale-Bopp show no strict correlation between heliocentric variation and volatility of pure ices. Figure 1 shows the distribution of different interstellar ice-types in the line-of-sight toward embedded protostars. Volatile apolar (H_2O-poor) ices are dominated by CO (and probably N_2) and reside in cold dense clumps, far from the protostar. Evaporation of CO from such a grain population could contribute to cometary CO outgassing observed at large heliocentric distances. Extensive ice segregation in the close vicinity of massive protostars has been observed with ISO (Ehrenfreund & Schutte 2000). These observations revealed a new ice-type, which is partly crystalline and dominated by ice clusters and clathrates (Ehrenfreund et al. 1999).

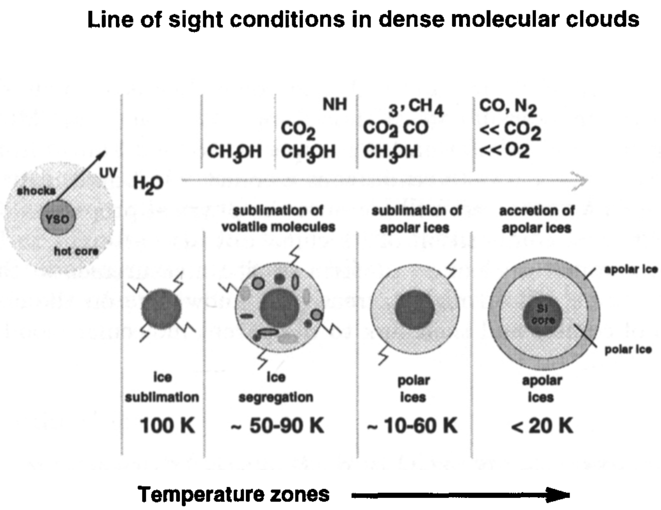

Figure 1. The distribution of different ice types in the line-of-sight toward massive protostars.

Grains which experienced ice segregation are characterized by segregated boundary phases of nearly pure ice which are however sublimed at a temperature different than pure ice or when entrapped in H_2O ice. It has been shown that ice segregation strongly affects the molecules CO_2 and CH_3OH which are tied up in intermolecular complexes on interstellar grains (Ehrenfreund et al. 1998). The few ISO observations of CO_2 in the coma of Hale-Bopp showed that the outgassing profile of CO_2 is not linked to H_2O between 3-5 AU (Bockelée-Morvan & Rickman 1999). CH_3OH, also observed at large heliocentric distances, shows similar sublimation characteristics as H_2S (a molecule of much lower sublimation temperature). The cometary outgassing curve for H_2S can currently not be compared to interstellar data, because this species was not yet detected in interstellar grains. H_2O dominated ice populations (which have varying abundances of CO, CH_4, NH_3, CO_2, CH_3OH and other species encaged) are more difficult to trace because here the sublimation temperature of a given species is determined by the exact concentration and distribution of the various molecules in the matrix. Additionally, it has to be taken into account that interstellar grains may be composed of onion-type layers. This brief outline should illustrate that the comparison of outgassing curves with the characteristics of interstellar icy grains may help to reconstruct the pristinity of comets.

3. Conclusion

The detailed knowledge of the composition and morphology of interstellar ices, recently determined with ISO, provide a new tool to test the link between interstellar and cometary material and to what extent presolar material has been altered during Solar System formation. More evidence has been obtained that chemical diversity occurred in the giant planets nebular regions as witnessed by recent observations. Observations of the short-period comet 21P/Giacobini-Zinner show deficiency of ethane and CO, and comet Lee is strongly depleted in CO compared to long-period comets Hale-Bopp and Hyakutake (Mumma et al. 2000). A large amount of information is expected to be obtained from space missions currently on their way to rendezvous a comet. On-board instrumentation on the ROSETTA spacecraft will measure the physical properties of comet Wirtanen, the chemical composition of its coma but also attempt to land for the first time on a comet nucleus to perform in situ measurements. Such unprecedented encounters will strongly increase our knowledge on the chemistry and composition of comets and their link to the parent molecular cloud.

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