Highlights of Astronomy, Vol. 13
International Astronomical Union, 2003
O. Engvold, ed.

From Interstellar Matter To Comets: A Laboratory View

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Abstract. Comets, formed in the cold outer parts of the solar system, provide a record of pristine material from the parent interstellar cloud. The investigation of outgassing curves from bright comets has provided a relationship to the abundances of interstellar ices and gas phase molecules. However, being porous and stratified in various layers of different densities and temperatures, the outgassing characteristics of comets can not always be directly reconciled with the interstellar composition. This is due to the structure of the nuclear ice component, which contains different coexisting ice phases, clathrates, and trapped gases. Ices, silicates and carbonaceous compounds - studied through astronomical observations and by laboratory simulations - serve as reference material to obtain information on cometary bulk material. A major fraction of cosmic carbon in the interstellar medium, comets and meteorites seems to be incorporated into complex aromatic networks, which are difficult to observe and to identify spectroscopically. However, recent measurements of the macromolecular structure and soluble organic species in carbonaceous meteorites provide a powerful tool to investigate the link of small bodies in the solar system.

1. Introduction

Cometary nuclei are formed in outer solar system environments and are porous aggregates of ice and refractory material. In 1986 several spacecraft performed a close fly-by of Comet Halley in order to perform in situ measurements that revealed the structure and composition of this comet. Since then observations of volatiles in the cometary coma over large parts of the electromagnetic spectrum are a crucial tool to obtain indirect information on the composition of cometary nuclei. Revealing the composition of comets provides clues to the formation of our solar system (e.g. Irvine et al. 2000).

2. Laboratory simulations

Ices, silicates and carbonaceous material - the major building blocks of the cometary nucleus - can be studied through astronomical observations and by laboratory simulations. Simulating interstellar dust and ice in the laboratory - the precursor material of comets - allows us to gain insights into the physical and chemical properties of cometary bulk material. Interstellar dust consists of micron-sized carbon or silicon grains which accrete ice layers in dense interstellar clouds, where the temperature is generally as low as 10K. In such cold environments atoms and molecules efficiently adsorb from the gas phase on dust surfaces. Small molecules and atoms can diffuse along the grain surface or within the ice, as do larger molecules when the temperature on the surface increases. Reactions will occur when two atoms, molecules, ions or radicals collide. In the absence of energy barriers this leads to the formation of new and usually more complex compounds. Thermal and energetic processing enhances the rate of reactions within the ice layers covering dust particles. At increased temperature, sublimation of newly formed species from the grain surface leads to further chemical evolution in the gas phase.

Table 1. Average interstellar ice abundances measured toward high-mass, low-mass protostars and in cometary comae. In contrast to cometary observations, there is no evidence for the presence of C_2H_6, C_2H_2, HCN nor S-bearing species (apart from tiny abundances of OCS) in interstellar ices. H_2CO and HCOOH have still to await a more firm detection.

Ice species	high-mass protostars	low-mass protostars	comets
H_2O	100	100	100
CO	1-20	1-60	5-20
CO_2	20	15-40	2-10
CH_4	1-4	-	0.2-1.2
CH_3OH	1-35	1-25	0.3-2
H_2CO	3	-	0.2-1
OCS	0.05-0.18	<0.08	0.5
NH_3	<5	-	0.6-1.8
C_2H_6	<0.4	-	0.4-1.2
HCOOH	3	-	0.05
O_2	<20	-	0.5 ul

Laboratory simulations of low temperature ices are achieved by condensing ices as pure gas or gas mixtures in a high-vacuum chamber on the surface of a cooled (10K) substrate. Most of the abundant ice species do have specific molecular vibrational transitions with energies corresponding to absorptions between 2.5 and 25 μm and can therefore be studied by infrared spectroscopy in transmission or reflection. Thermal processing by step-wise warming of the substrate and UV irradiation, using microwave-excited hydrogen flow lamps, allow the simulation of some of the environmental conditions prevailing in interstellar clouds. Such laboratory studies strongly increased our understanding of extraterrestrial ice chemistry (Ehrenfreund et al. 2003). Also experiments on surface diffusion, reaction and desorption behavior of icy species contributed to this success. Currently 36 ice absorption features attributed to 16 different molecules have been identified, leading to a detection rate of $\sim$ 1 infrared band per year. The ISO satellite strongly increased our knowledge on interstellar icy species, but also high resolution studies in telluric windows using large ground-based telescopes show exciting results (Pontoppidan et al. 2003). Table 1 shows a current overview of abundances measured for interstellar ices and for cometary volatiles. Carbonaceous chondrites are the most pristine types of meteorites and therefore provide a record of the physical and chemical conditions in the early solar system. These meteorites contain up to 5 weight % organic carbon, most of which is locked in insoluble kerogen-like material. Distinct organic compounds that have been identified in carbonaceous chondrites range from simple soluble species such as amino acids to polycyclic aromatic hydrocarbons (PAHs) and fullerenes (for a recent review see Botta & Bada 2002). The composition of soluble species, e.g. amino acids provide a powerful tool to investigate the link of small bodies in the solar system (Botta et al. 2002). The macromolecular material in these meteorites has recently been characterized (Sephton et al. 2000, Gardinier et al. 2000). However, its link to the interstellar aromatic network is yet to be understood. The organic inventories of carbonaceous meteorites display large and variable enrichments in deuterium, ^{13}C and ^{15}N which is indicative of their retention of an interstellar heritage.

3. Conclusion

The observations of low-mass stars, using ground and spaced-based telescopes and a broader consensus on cometary diversity will provide a better view on the interstellar-cometary connection in the future. Theoretical models indicate that bulk material in cometary nuclei contains coexisting ice phases, possibly clathrates and trapped gases. Furthermore the bulk material is stratified in density and porosity. Laboratory experiments identified different phase transitions within amorphous water ice which during cometary evolution will strongly influence the trapping and outgassing of volatiles. Therefore it remains questionable if the outgassing pattern of comets should essentially mimic the interstellar ice composition and if processing of interstellar matter within the solar nebula can ever be traced as such. The large fraction of solid aromatic networks assumed in the interstellar medium and measured in meteoritic material has to be present in comets. In order to understand the processes which led to the formation of our solar system and comets a comet rendezvous or comet sample return mission is mandatory.

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