COMETS AND CONSTRAINTS ON SOLAR SYSTEM FORMATION

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Abstract

New and important data have been obtained during the 1985-1986 return of comet Halley, including in situ observations of the nucleus and the coma. Since the interpretation of the observations is not straightforward, the results are presented in a rather conservative manner. Some clues to the solar system formation are suggested, e.g. the shape of the nucleus, its low density, the estimated mass of the Oort cloud, the elemental abundances in comet Halley. Constraints related to isotopic abundances (deuterium enrichment, possible anomalies in carbon isotopes) and to cometary dust (complex organic compounds, submicron sized dust particles) are extensively discussed.

1. Comets : a post-Halley overview

1.1. COMET HALLEY NUCLEUS

The most spectacular results obtained from the Halley's comet flybys - by a flotilla of five spacecraft from three space agencies - are related to its nucleus morphology. Detailed analysis of the Vega and Giotto space probes images revealed the dark silhouette of the nucleus against the solar light scattered in dust jets and filaments. Ejected dust and gas mostly came from active regions (on the illuminated side), which only covered about 10% of the total surface. The overall shape could be approximated by an ellipsoid of 16 km x 8 km x 8 km. The surface topography was similar to chains of hills, craters, mountains and ridges. It is likely that a few meters of material are lost at each perihelion passage and that such a morphology is due to erosion by sublimation. However, the observed large scale inhomogeneities, together with the elongated shape, suggest that the nucleus has been built up from smaller bodies in a 1 to 5 km size range (Keller et al., 1987 ; Keller, 1990 ; Sagdeev and Szegö, 1990).

At the time of the Halley's flybys, the surface of the nucleus was generally warm, with a geometric albedo of a few percent and a reddish black colour (Thomas and Keller, 1989). It is likely that cometary surfaces are covered by a porous mantle of very low thermal conductivity. This hypothesis is in agreement with recent estimates of the density, in a 0.1 to 0.6 g cm^{-3} range (Sagdeev et al., 1988 ; Rickman, 1989). Such a low density has some implications, both for the cometary origin and for the mass of the

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Oort cloud. Since low velocities are required for the aggregation of the cometary material, it confirms an outer planetary region of formation. The mass of the Oort cloud is not well known because of uncertainties in the bulk density of cometary nuclei and in the nucleus size distribution ; recent estimates for the total cloud mass (outer cloud, inner cloud, Kuiper belt) range from 14 to 1000 Earth masses, with an original mass that could have been about a factor of 2 to 5 larger (Bailey and Stagg, 1988 ; Marochnik et al., 1988 ; Weissmann, 1985, 1991).

1.2. COMET HALLEY COMA

The gas and dust production in the coma was asymmetric, arising from the active areas on the surface. The dust-to-gas mass ratio could have been as high as about two (Jessberger and Kissel, 1991) Almost one hundred different species (inorganic, organic, metals, ions) have been identified, either from ultraviolet, visual, infrared and radiowave spectroscopy, or from peaks in mass spectra during the flybys (Delsemme, 1991 ; Huebner et al., 1991 ; Geiss et al., 1991).

Water vapor was by far the main component ; its abundance was about 80% by volume of the gas in the coma. The second most abundant gas was carbon monoxide ; about two thirds were released slowly from an extended source in the coma (Eberhardt et al., 1987a). An important fraction of volatiles is indeed trapped on dust grains in complex organic molecules, some of which are rapidly disintegrated and give rise to carbon monoxide and cyanide jets (A'Hearn et al., 1986). Due to various reactions (photodissociation, photoionization, ion-molecule reaction, and dissociative recombination), the chemical composition in the coma is different from that of the volatiles in the nucleus. Apart from water vapor and carbon monoxide, the other parent gases (e.g. carbon dioxide, methane, ammonia, molecular nitrogen, formaldehyde, hydrogen cyanide) contributed with at most a few percent to the coma gas (Krankovsky and Eberhardt, 1990 ; Krankovsky, 1991).

Taking into account the fact that some elements are found both in volatiles and in more stable molecules, the elemental abundances are estimated to fit broadly those of the Sun, apart from the expected deficiency in hydrogen and helium, and the coma depletion in carbon and nitrogen (Geiss, 1987 ; Encrenaz et al., 1988). The missing carbon is likely to be trapped in refractory organics on some dust grains. The apparent deficit of nitrogen could be explained if nitrogen was mainly present under a molecular form when Halley formed ; it has been suggested that methane and ammonia originated in an heterogeneous mixture of condensates from interstellar cloud, solar nebula and subnebula material (Prinn and Fegley, 1989 ; Krankovsky and Eberhardt, 1990).

2. Constraints related to isotopic abundances

The isotopic composition provides clues to the formation (and chemical history) of the cometary matter. Isotopic abundances derived from measurements in comet Halley gaseous coma have been reported and extensively discussed (Vanysek, 1991).

2.1. D/H RATIO

Since almost the entire amount of deuterium has been synthesized in the early Universe, the D/H ratio (roughly about 2×10^{-5} in the interstellar medium) is a critical parameter for the estimation of the baryonic density, i.e. for the test of cosmological models. It is however well known that the observed deuterium abundances may be affected by ion-molecule reactions which, in dense molecular clouds, take place at very low temperatures and concentrate deuterium at the expense of hydrogen (Vanysek and Vanysek, 1985 ; Geiss, 1987).

Although hydrogen is an important species in comets, the D/H ratio is not obtained directly by spectrography. The Ly α deuterium line, on the wing (at 0.03 nm) of the strong Ly α hydrogen line is hardly detectable since ultraviolet spectrography lacks of very high resolution. The D/H ratio has to be derived from deuterated molecule measurements, either by spectrography / remote sensing or by mass spectrometry / in situ analysis (Levasseur-Regourd, 1988).

The International Ultraviolet Explorer satellite observations of comets give an upper limit of OD/OH of the order of 4.8×10^{-4} (A'Hearn et al., 1985). Giotto neutral gas mass spectrometer observations provide an isotopic ratio of $0.6 \times 10^{-4} < H_2DO^+/H_3O^+ < 4.8 \times 10^{-4}$. The cometary volatile material is therefore likely to be enriched in deuterium by a factor of about 10 relative to the interstellar medium (Eberhardt et al., 1987b).

Despite the relatively wide limits on the deuterium abundance in comet Halley, it can be assumed that the D/H ratios are comparable in comets and in solar system objects such as the Earth (standard mean ocean water ratio of about 1.6×10^{-4}), Titan, Uranus and Neptune. Primordial abundances have been observed in solar system bodies such as Jupiter and Saturn where hydrogen accreted in a gaseous form from the protosolar nebula. Two reservoirs of deuterium could have existed in the solar system, the enrichment of one of these reservoirs occurring before the solar system and the cometesimals were formed (Owen et al., 1986).

2.2. HEAVIER ELEMENTS

Several measurements of the $^{12}C/^{13}C$ ratio have been attempted. Due to a possible blending of the bands (e.g. CH for C, NH_2 for C_2), and to the difficulty in the interpretation of mass spectroscopy data, the results are still controversial. A value of (65 ± 9), to be compared with the Solar System value of about 90, has been used to suggest various scenarios for the origin of comet Halley (Wyckoff et al., 1989). The large dispersion of the data could be a clue to the existence of presolar particles, from different nucleosynthesis sites, in cometary grains. However, as the isotopic composition of the bulk carbon in Halley is still unknown, any conclusion seems premature (Krankovsky and Eberhardt, 1990 ; Jessberger and Kissel, 1991).

Ground based spectra analysis has provided, for the nitrogen isotope ratio $^{14}N/^{15}N$, a lower limit of 200, in agreement with the bulk Solar System ratio (Wyckoff et al., 1989). By in situ mass spectrometry in the inner coma, the $^{18}O/^{16}O$ ratio has been found to be equal to (0.0023 ± 0.0006) and the $^{34}S/^{32}S$ ratio has been found to be equal to (0.045 ± 0.010) ; these two values compare quite well with the terrestrial ones. There are no significant deviations from the terrestrial ratios either for $^{26}Mg/^{25}Mg$ or for $^{56}Fe/^{54}Fe$ (Solc et al., 1987 ; Geiss, 1987).

3. Constraints related to cometary dust

The existence of complex organic molecules in cometary comae has allowed various authors to assume that interstellar grains, covered by a frost of organic molecules, were present in the molecular cloud that collapsed in the accretion disk (Delsemme, 1991). However, because of the observational conditions, what can safely be said about the properties of the individual grains is relatively limited.

3.1. ELEMENTAL COMPOSITION

The composition of the dust released from the surface of comet Halley nucleus has been measured by the dust mass spectrometers flying through Halley's coma on board the Vega and Giotto spacecraft. Due to the high impact velocities (about 70 km s^{-1}), most of the molecules were destroyed. As mentioned previously, the elemental abundances were found to be similar to the solar ones. There is a good agreement with type I carbonaceous chondrites abundances (Jessberger et al., 1988 ; Brownlee and Kissel, 1990).

A high degree of variability was found between individual grains. One of the most significant results of the flybys was the discovery of the so-called "CHON" particles, made of molecules with C, H, O, and N, with minor amounts of magnesium, silicon and iron. About approximately one third of the dust consisted of CHON, one third was a mixture of CHON and silicates, whereas the last third contained no low atomic number elements except oxygen (Langevin et al., 1987 ; Kissel and Krüger, 1987). These results support the idea that carbon escapes from the cometary nucleus with dust in the form of organic compounds.

3.2. MOLECULAR COMPOSITION

Some masses of the ions inside Halley's coma have been derived from Giotto positive ion cluster analyzer data, assuming that they are proportional to the measured energy / charge ratio. Peaks at 35, 37 and 39 atomic mass units are attributed to various ions, the progenitors of which are likely to be CHON organic dust grains (Korth et al., 1989; Marconi et al., 1989, 1990). The $C_3H_3^+$ ion could be a dissociation product of hydrocarbon chain molecules. The existence of complex molecules, which could have been produced on ices or dust icy coatings is strongly suggested by the detection of an ordered series of mass peaks at 31, 45, 60, 75, 91 and 105 amu. The regular spacing of 15 amu seems to be a general characteristic of CHON molecules, (Mitchell et al., 1989). It may also be attributed to dissociation products of polyoxymethylene (Huebner, 1987).

The Giotto ion and neutral mass spectrometers have also provided in situ identifications of complex organic molecules, e.g. methanol, acetaldehyde, ethylalcohol and various hydrocarbons (Geiss et al., 1991). Formaldehyde is confirmed to partly originate from an extended source ; it is likely to be released from grains over time of the order of hours.

3.3. SIZE DISTRIBUTION

The size distribution has been measured by impact sensors on board the Vega and Giotto spacecraft (Mazets et al., 1987 ; McDonnell et al., 1989). An unexpected amount of submicron size particles was found, together with large grains, up to about 100 µm.

The size distribution can be explained by a combination of jetting and fragmentation (McDonnell and Pankiewicz, 1990).

The gas outflowing from active regions on the surface of the nucleus accelerates the dust ejected along jets in the sunward direction ; such jets are characterized by a rapid evolution of the optical properties of the scattering dust grains (Renard et al., 1991). The radial evolution of the optical properties of interplanetary dust grains is also likely to be due to a slow decay of cometary dust particles (Levasseur-Regourd et al., 1991). Submicron dust particles, originally glued together by water ice or organic compounds, are fragmented in flight as a result of collisions and of sublimation due to heating. The observed size distribution is compatible with the hypothesis that cometary dust grains are made of fluffy aggregates of interstellar dust particles (Greenberg, 1984, 1990).

4. Conclusions

4.1. THE CONSTRAINTS

The deuterium abundance in comet Halley is found to be enriched by a factor of about 10 relatively to the assumed protosolar value. It suggests a low temperature in the environment of the cometesimal formation and the existence of two distinct primordial reservoirs of deuterium in the solar system. The $^{12}C/^{13}C$ ratio may be the same as the terrestrial one, but some anomalies cannot be excluded. Abundances of the stable isotopes of elements heavier than carbon appear to be identical to the terrestrial ones.

The composition of Halley's dust grains is found to be heterogeneous, with roughly one third of the grains dominated by carbon and low atomic weight elements. Although the molecular composition of the CHON grains is still poorly known, it is likely that these grains are fluffy aggregates of submicron sized particles which could have an interstellar origin. These particles were the building blocks for composite low density dust grains, with later formation of cometary nuclei in the protosolar nebula.

4.2. THE FORMATION OF COMETS

Various locations had been considered for the formation of comets : 1) the Uranus-Neptune region, 2) the protosolar disk beyond Neptune and Pluto, 3) the outer solar nebula at very low temperatures, 4) the interstellar medium. Isotopic and elemental abundances derived from Halley's comet studies are well in agreement with a solar system origin, and thus rule out the fourth hypothesis. On the other hand, there are several observations which give evidence that comets have preserved some of the matter (e.g. interstellar dust grains) from the parent interstellar cloud and that they condensed at low temperatures, ruling out the first hypothesis.

Being more specific is certainly difficult (Yamamoto, 1991 ; Delsemme, 1991). To quote Fred Whipple in his conclusion for "Comets in the post-Halley era" (1991) : "Imagine an explorer who can study these floating trees (toward the mouth of the Amazon river) and from this study alone must deduce the place and nature of the forest from which they were uprooted...". Some constraints on the formation of the solar system have already been derived from the extensive observations of comet Halley, while many new questions have been raised.

Most of them will hopefully be answered through future remote sensing studies of ageing cometary dust both in cometary comae and in the interplanetary dust cloud, and through future in situ missions. The Giotto spacecraft in now on course to rendezvous in July 1992 with P/Grigg-Skjellerup , an inactive comet which should provide an interesting comparison with Halley. Later on, the Comet Nucleus Sample Return Mission / Rosetta should allow us to recover some samples of the pristine cometary material that survived the solar system formation unharmed.

References

Four recently published volumes, that review some of the most important results, are extensively quoted : "Comet Halley, investigations, results interpretations", Vol. 1 and 2, J. Mason ed., Ellis Horwood, 1990, and "Comets in the post-Halley era", Vol.1 and 2, R.L. Newburn, M. Neugebauer and J. Rahe eds., Kluwer Academic Publishers, 1991. Further references may also be found in "Origin and evolution of interplanetary dust", A.C. Levasseur-Regourd and H. Hasagawa eds., Kluwer Academics Publishers, 1991.

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