COMETS

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1. Introduction

Comets, the most pristine members of our solar system, are faint at large heliocentric distances ($r_h > 3$ au) and therefore difficult to observe. Data reduction of these faint objects (periodic comets) is time consuming and hence most often just preliminary results can be discussed. Only the orbits of short periodic comets can be predicted and most of those that have been accessible for ISO have been covered within the guaranteed time programme. About 10 proposals were accepted by the selection for open time proposals. A target of opportunity team was formed. The outstanding comet Hale-Bopp (C/1995 O1), one of the brightest and therefore most active comets of this century, was suggested and accepted as TOO. The important results from the ISO cometary programme are derived from its observations. In addition to the observations of "classic" comets the newly detected (Jewitt and Luu, 1993) transneptunian objects, probably objects from the Kuiper belt, are observed in an attempt to determine their physical properties.

2. Short Period Comets

The short period comet P/Kopff, once selected as target for the American CRAF mission, was observed by several groups. Its activity was weaker than predicted. Nevertheless, scans with ISO-CAM (Davies *et al.*, 1997) confirmed the existence of a cometary dust trail and showed that this trail had changed since it was first detected by IRAS (Davies *et al.*, 1984; Sykes *et al.*, 1986) in 1983. This change reflects variations of the dust production rate from cometary orbit to orbit on time scales comparable to the orbital period. Several but not all observed comets display these dust trails. Decimetre size particles were detected in several cases and could well be a major source for cometary mass loss and an important source for the replenishment of zodiacal dust. From the geometric extent and cross section the dynamical age of the comet in its present orbit can be estimated.

The observations of the dust coma of comet P/IRAS (Lisse, priv. com.) cover the wavelength range from the visible out to 100 μm. The spectral distribution shows scattered light out to a few microns (depending on the heliocentric distance (and hence the temperature of the dust grains), then the transition to blackbody radiation usually within an excess due to the silicate features of small grains. At even longer wavelengths the emissivity of the tiny grains is restricted and the emission is suppressed below the blackbody curve. Size distribution and scattering properties of the dust grains can be inferred from these photometric observations.

Comet P/Wirtanen is the target of the ESA Rosetta mission that will meet the comet in 2011 and stay in rendezvous over large parts of its orbit. The preperihelion ISO observations of the inner dust coma provide data for the planning of the Rosetta mission. Modelling of the observed isophotes showed that the dust production of this comet is exceptionally weak, about 1 to 2 kg s^{-1} at a heliocentric distance of 2.5 to 2 au (Colangeli *et al.*, 1997). This is about one or two orders of magnitudes smaller than values derived for other comets (even compared to other short period comets) and confirms that P/Wirtanen is small comet.

A somewhat peculiar comet is P/Schwassmann-Wachmann 1 that revolves around the sun on an almost circular orbit beyond Jupiter. Its erratic activity cannot be kindled by sublimation of water ice but is driven by CO_2 or CO. The ISO observations show that the cometary nucleus is

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surrounded by relatively large particles (ice or dust?) that radiate with the appropriate blackbody temperature ($T \approx 110$ K) for its heliocentric distance. This contribution to the IR signal of the nucleus is apparent even when the coma is not detectable in the visible (Grün, priv. com.).

Even further out beyond the orbit of Neptun objects in the size range of tens to hundreds of kilometres were detected (Jewitt and Luu, 1997). In the meantime almost 40 objects are known, some of them on more elliptic orbits reaching distances of about 80 au from the sun. The ISO observations (Ip and Thomas, priv. com.) will permit to determine the diameters of a few objects and their albedos independently. A major step forward can be expected in the understanding of the nature of these objects once the ISO observations are reduced.

3. Comet Hale-Bopp

The target of opportunity object (TOO) comet Hale-Bopp (C/1995 O1) is an exceptionally bright and active comet (Fig. 1) even though it is not a new comet (i.e. it passed through the inner solar system some thousand years ago). It was active long before it reached the orbit of Jupiter and has been observed in an outstanding campaign with instruments located all over the world. The unique spectroscopic observations by ISO were performed at heliocentric distances of 4.6 (Crovisier *et al.*, 1996) and 2.9 au (Crovisier *et al.*, 1997) before the comet reached its perihelion. During the extended mission further observations are planned in December 1997.

The simultaneous observations of the most important parent molecules H_2O, CO_2, and CO were possible for the first time. ISOPHOT-S observations in September 1996 allow one to determine the production rates of these species at $r_h = 2.9$ au, while the earlier observations provided only upper limits for H_2O and CO. These observations by themselves demonstrate that the ratio of production rates varies with heliocentric distance and they underline that the early activity of comets is due to the much more volatile CO or CO_2. The symmetric molecules H_2O and CO_2 cannot be observed in the radio domain or in the visible. The dissociation product of water OH is a good substitute for the determination of water production. CO_2 has no counterpart because its dissociation product CO is itself a parent molecule and a dissociation product of several other possible parents. The compilation of production rate variations with heliocentric distance of various species (Fig. 2) observed with radio telescopes (Biver *et al.*, 1997) show that each species follows essentially its own law. CO dominates beyond 3.5 au when water cannot sublime in larger quantities. The ISO observations of CO_2 fit well. The increase in production of CO_2 is steeper than that of CO but not quite as steep as that of H_2O as is expected due to its intermediate volatility. The diagramme demonstrates that the molecular production rates at larger heliocentric distances do not represent the true mixing ratios of the components in the nucleus.

The ortho to para ratio of the water molecules was derived from SWS observations suggesting a formation temperature of about 25 K but certainly below 60 K. This is a confirmation of results found for comet Halley (Mumma *et al.*, 1987) and puts the place of birth of the cometary ice beyond the planetary system and suggests that cometary nuclei contain unprocessed interstellar grains.

The 7 to 45 μm spectrum of Hale-Bopp with SWS (resolution $\lambda/\delta\lambda \approx 500$) shows a wealth of features in the dust emission. Details of the silicate peak at 11.3 μm indicate crystalline olivine as the emitter. Most peaks distributed over the 16 to 30 μm interval were not visible in earlier observations of comet Halley of much poorer quality. The crystalline olivine seems to be magnesium rich (forsterite). A comparison of the Hale-Bopp spectrum with those of Vega-type circumstellar disks reveals remarkable similarities. Indeed the ISO spectrum of HD 10045 (Waelkens *et al.*, 1996) shows many features resembling those of the Hale-Bopp spectrum. This similarity suggests a link between the primordial solar system preserved in comets and the dust around young stars where planetary systems may be forming. Comets may be low density aggregates of interstellar dust and ices as observed looking at i.e., the protostellar object RAFGL 7009S (Ehrenfreud *et al.*, 1997).

4. Summary

Comets are very interesting targets for ISO observations. However, normal (short period) comets are very difficult to observe because they are weak and extended objects difficult to separate from the background, fast moving and become bright only close to the sun when they are inaccessible to ISO. Observations concentrate on dust production rates and the physical nature of the particles and their scattering properties. Larger particles are only detectable in the IR.

ISOCAM and visible images of Hale-Bopp

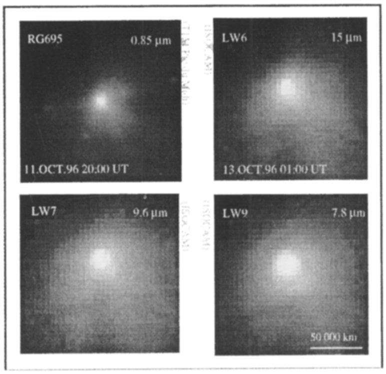

Figure 1. Structures in the coma of comet Hale-Bopp become more and more diffuse with increasing wavelength (Jorda and Lamy, priv. com.).

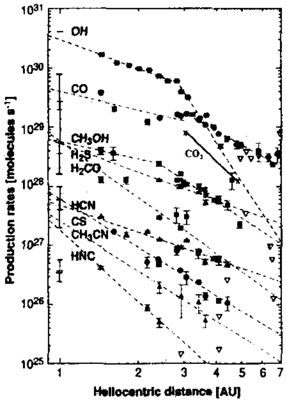

Figure 2. The CO_2 production rates derived from ISO observations (Crovisier *et al.*, 1997) fit well into the compilation of production rates derived from radio observations (Biver *et al.*, 1997).

The fortuitous appearance of the extraordinarily bright and therefore active comet Hale-Bopp made it possible to take full advantage of the superb capabilities of the complement of ISO instruments. The three most abundant molecules H_2O, CO_2, and CO were observed simultaneously for the first time. The large amounts of CO that were responsible for the early activity of comet Hale-Bopp at 7 au, the low formation temperature of water ice, and the striking similarity of many dust features to those of dust in circumstellar disks all point into the direction that cometary nuclei may be fluffy agglomerations of interstellar grains.

Comets of our solar system seem to be an accessible reservoir for the material that is observed around young stars and during the formation of new planetary systems. The observations of comets and the analyses of their composition could provide a wealth of information about the composition of interstellar material and the formation of planetary systems. Comets are the link that allows us to learn about other solar systems on one side but also to learn about our planetary system from astronomical objects.

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