ON THE IMPORTANCE OF DUST IN COMETARY NUCLEI

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Abstract. The icy conglomerate model introduced by Whipple more than 40 years ago has been widely accepted in cometary science because it is able to describe numerous cometary phenomena. In this model comets are described as a conglomerate of ices and dust where the ices represent the major component. However, some recent observations seem to favour dust rich comets. The purpose of this paper is to summarize the observational facts supporting the dominance of refractories in comets and to discuss the consequences of a dust dominated nucleus for cometary physics.

1. Introduction

The space missions to comet P/Halley in 1986 and refined astronomical observations during the last years provided interesting new details of cometary phenomena. However, comets still seem to be the most mysterious members of the Solar System. Numerous observational facts like erratic activity, outbursts, splittings, sudden disappearances of comets, or their diversity in appearance are not well understood. A reason for this unsatisfactory situation is that the formation, structure, and composition of comets – their physical nature – are only roughly understood. Some information on the formation and evolution of comets can be derived from their orbits and their composition. Whereas dynamical studies to the accretion times for the outer planets favour the Uranus-Neptune region as place of birth of comets (Safronov, 1969), cosmochemists (Yamamoto, 1991) explain the existence of strongly volatile molecules like S_2 and CO with cometary formation in the Kuiper belt beyond 50 AU. The composition of comets is deduced from spectrometric measurements in the cometary comae. The problem is that one observes with a few exceptions only the daughter molecules (dissociation products) and therefore has to speculate about the parent molecules in the nucleus. A major hint for the cometary structure comes from density estimations. They have, however, large error bars. In the case of comet Halley's density, estimations vary from 300 to 1500 kg m^{-3}. The abundance and composition of cometary dust has been the subject of ground based infrared-measurements (Zarnecki, 1990) and of in situ observations by means of infrared (Encrenaz and Knacke, 1991) and mass (Brownlee and

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Kissel, 1990). The physical and chemical properties of cometary dust were reviewed by McDonnell et al. (1991) and Jessberger and Kissel (1991). The ratio of dust to volatiles in comets has been controversially discussed. This basic quantity allows one to discriminate between various types of models.

The most widely accepted model for comets is the icy conglomerate model proposed by Whipple (1950) more than 40 years ago. It assumes that volatiles are the major components in comets and has been successfully applied in describing the basic features of comets as activity, nongravitational forces, the nature of dust and gas tails. However, it fails to explain some recent observations. The result of the Giotto mission that activity is only evident on about 20% of the illuminated surface of comet P/Halley (Keller et al., 1987) and the discovery of dust trails on orbits of several comets by the IRAS satellite (Campins et al., 1990) can be hardly understood within the icy conglomerate model. More recent models (Keller, 1989; Sykes and Walker, 1992) start from the dominance of dust in cometary nuclei.

The objective of this paper is to review the observations and measurements that provide arguments for a modification of the icy conglomerate model. The physical properties of dust dominated nuclei are discussed.

2. Observations

Refined ground based measurements in addition to the VEGA- and GIOTTO-missions to comet P/Halley and the extended GIOTTO-mission to comet P/Grigg-Skjellerup (McDonnell et al., 1993) have related more and more sophisticated details of comets. In the following some recent observations are discussed.

2.1. OBSERVED VS. REAL DUST/GAS RATIO

The dust/gas mass ratio is an important parameter for the characterization of comets. The dust mass in the coma is commonly derived from ground based measurements in the optical wavelength range (Jewitt, 1991). Newburn Jr. and Spinrad (1989), Storrs et al. (1992), Singh et al. (1992), and Sekanina (1991a) interpreted measurements of comets (partly coherent, partly heterogenous samples) and found mass ratios between 0.1 and 1. These results seem to support the icy conglomerate model. However, several observational circumstances lead to the tendency that optical measurements generally underestimate the amount of dust in comets.

A basic problem for the determination of the emitted amount of dust by scattered light is that only particles comparable in size to the wavelength of light are detectable. Grains much larger than 1 μm or smaller than 0.1 μm are not efficient at scattering optical wavelengths. Commonly the mass release q of dust with the density ρ and the size distribution function $f(a)$ is given by

$$q = \int_{a_{min}}^{a_{max}} \frac{4}{3}\pi a^3 \rho(a) f(a)\, da\,, \tag{1}$$

where a_{min} and a_{max} are the minimum and maximum sizes of the grains, respectively (Singh et al., 1992). $f(a)$ is often given by (Brin and Mendis, 1979)

$$f(a) = Ca^{-\gamma} \tag{2}$$

where γ has been derived by the same authors to be 3.5. The normalization constant C can be directly related to observations. For such a size distribution the main mass is represented by the small grains. Further, neither a_{min} nor a_{max} can be determined from optical measurements. From in situ dust measurements during the Halley missions (McDonnell et al., 1991), from the analysis of the dust jets (Knollenberg, 1994), from the discovery of cometary dust trails by the IRAS satellite (Campins et al., 1990), and from theoretical investigations (Coradini and Magni, 1977) we have learned that the dust mass represented by large grains in the millimetre to decimetre range has been strongly underestimated by extrapolation of results from scattered light. Knollenberg found that an exponent $\gamma = 2.5$ in Eq. (2) fits the observed dust jets well resulting in a size distribution where the major mass is represented by large grains. The observations of fireballs, radar measurements (Campbell et al., 1989), and meter-sized particles found in dust trails (Campins et al., 1990) demonstrate that maximum sizes of grains far beyond the optical wavelength are emitted from comets. Sykes and Walker (1992) derive a dust/ice ratio of about 3 including the large particles found in the cometary trails.

A further problem of estimating the dust/ice ratio in comets from the relations in the coma results from inhomogeneities of the nucleus. Dust should be released preferably from active regions that probably differ from inactive areas in their dust to ice ratio (Kührt and Keller, 1994). Therefore, the ratio in jets cannot be expected to be representative of the whole nucleus.

2.2. ACTIVITY OF COMETS

One of the most surprising results of the space mission to comet P/Halley was that the activity was only evident on about 20% of the illuminated surface (Keller et al., 1986). The dominance of inactive regions is also supported by IR-measurements where surface temperatures as high as 400 K were found (Combes et al., 1988). This value is much higher than the sublimation temperature of water ice (about 200 K). Ground based observations of many different comets recently surveyed by Sekanina (1991b) has shown that the restriction of activity to a minor fraction of the surface is a general feature even near perihelion.

This phenomenon is not clearly understood up to now. Models based on the icy conglomerate concept [e.g., Brin (1980), Fanale and Salvail (1984), Rickman et al. (1990), Orosei et al. (1995)] cannot explain the existence of stable inactive areas over wide parts of the cometary surface. Permanent mantles can only be generated by this kind of models for comets on Halley-like or Encke-like orbits if special geometrical orientations of the spin axis, extreme thermo-physical parameters, or doubtful model approximations are assumed (Kührt and Keller, 1994).

2.3. SPLITTING OF COMETARY NUCLEI

Splitting of cometary nuclei has been observed in many cases. It seems to occur anywhere on the cometary orbit (Sekanina, 1982). No correlation with physical parameters of the comets or their orbits has been established. Generally no particular cause is apparent with the exception of tidal disruptions of comets closely approaching Jupiter or the Sun. The most recent spectacular event of this kind was the split of comet P/Shoemaker-Levy 9 caused by tidal forces of Jupiter. Separation of small pieces seems to be frequent (Chen and Jewitt, 1994). Sometimes the break-up of a comet leads directly to its fading and loss. Splitting of cometary nuclei is probably their dominant loss mechanism. The occurrences, dynamics, and activity of the broken off nuclei were analyzed in detail in a series of papers by Sekanina (1977), Sekanina (1978) and Sekanina (1979). The frequent occurrences even at large heliocentric distances ($r_h > 9$ AU!) confirm that cometary nuclei are fragile. In some cases increased activity could be observed before or during the splitting (flare up). Some fragments have long lifetimes, some short ones. In most cases the medium and long term activity of the multitude of nuclei is hardly enhanced if compared to that before the splitting. This indicates that the fraction of active areas on the new surfaces stemming from the interior of the nucleus is similar to that of the surface of the original nucleus. Hence, the nuclei are heterogenous in the dust to ice ratio (see Sect. 3) and inert volumes predominate.

3. The icy dirt ball model and its consequences

Stimulated by the GIOTTO images Keller (1989) suggested the concept of an icy dirt ball. The microstructure of a cometary nucleus is here characterized by refractory material rather than by ice*. From analyzing IRAS mea-

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* Whipple used the descriptive expression *Tundra* model in his summary of the meeting.

surements of cometary dust trails Sykes and Walker (1992) came to a similar conclusion. Kührt and Keller (1994) investigated the physical behaviour of dust dominated nuclei.

3.1. ACTION OF COHESIVE FORCES

Cohesive forces act between dust grains because they touch each other. In contrast to cohesive bonding between ice grains a dust conglomerate cannot be eroded by thermal energy. This is an important consequence of the icy dirt ball model.

The importance of binding forces for cometary modelling has often been mentioned but corresponding effects have rarely been included in the models. The significance of cohesive forces becomes readily apparent if one compares their strengths to those of cometary gravity and vapour pressure forces. Vapour pressure does not exceed 100 Pa even for the very high sublimation temperature of 250 K (Kührt and Keller, 1994). Chokshi et al. (1993) analyzed van der Waals forces between grains in the primordial nebula. Strength values ranging from 10^2 to 10^5 Pa can be derived for conglomerates of mm-sized to μm-sized grains in agreement with measurements. Whipple (1982) derived an upper limit for the tensile strength of comets of 10^4 Pa based on the analysis of cometary spins and size statistics of the nuclei. A strength of 10^2 to 10^3 Pa was found for lunar regolith from investigations during the Apollo program (Mitchell et al., 1973). Saunders et al. (1986) and Storrs et al. (1988) found a tensile strengths of filamentary sublimate residues of about 10^4 Pa from laboratory investigations. Fireballs that probably originate from comets have a mechanical strength of 10^3 to 10^6 Pa (Wetherill and ReVelle, 1982).

Therefore, the cohesive strength within a matrix structure of refractory material generally exceeds the vapour pressure of water ice in comets.

3.2. COMETARY SURFACE CRUSTS

A consequence of the cohesiveness of nuclei is the depletion of the outermost surface layers from volatiles. A stable crust is formed. In contrast to loose mantles that are described by numerous models [for a review see Kührt and Keller (1994)] cohesive crusts are stable against the vapour pressure even at heliocentric distances smaller than 1 AU. It should be emphasized that the cohesiveness within a dust layer accumulated at the surface but without bonds to the interior does not stabilize the surface layer.

Kührt and Keller (1994) developed a thermal model for stable cometary crusts. They found that:

- The thickness of surface crusts is between 10 cm and 10 m. It depends mainly on the value of the heat conductivity. Porosity, pore size, and orbit parameters are of minor importance.

- The vapour pressure exceeds gravitational pressure for all reasonable parameters. This means that loose dust mantles are blown off. Cohesive forces may withstand the gas pressure, large parts of the cometary surface are covered by a stable cohesive crust.

3.3. ACTIVITY AND INHOMOGENEITY OF COMETARY NUCLEI

A crust on the surface drastically reduces cometary activity because it shields the volatiles below from insolation. Figure 1 shows the development of the (maximum) diurnal gas flux through a well conducting and a badly conducting crust for a comet Halley-like orbit. Activity is strongly quenched to less than 1% of the free sublimation level depending on the heat conductivity in the refractory crust. Therefore, crusts can explain the observed stable inactive regions on comets (see Sect. 2) in a natural way. It can be further seen that the thermal inertia of the crust causes a hysteresis behaviour of the activity.

On the night side of a comet free sublimation stops whereas the low activity through the crust is hardly depressed because the crust stores the heat (Fig. 2). A low night side activity level of 0.1% to 1% is consistent with the images taken during the Giotto fly-by (Knollenberg, 1994).

The icy dirt ball model and the formation of a stable crust do not explain the strongly localized jet-like cometary activity (Sekanina, 1993). A plausible explanation for the variable behaviour of different surface areas is the assumption of a structurally inhomogeneous nucleus. This picture is compatible with a comet consisting of several cometesimals formed under different conditions in the solar nebula resulting in a varying dust/ice ratio within the nucleus. The dust/ice ratio governs the formation of stable crusts and spots of relatively stable activity, respectively. According to this picture activity originates from regions where the volatile component (ice) is so abundant that stable insulating crust cannot build up. Observations indicate that cometary activity sources are typically stable over many orbits (Sekanina, 1993). An active region embedded in an inactive area produces the observed jet-like activity (Knollenberg, 1994).

Cohesive, dust dominated clusters smaller than the critical size beyond which they become bound by gravity (typically decimetre to metre size) can leave the nucleus after the volatiles in their pores have been sublimated. Then the heat wave can erode the dust-ice bridges below the dust cluster. The escaping fluffy dust agglomerates form the dust trails or reach Earth

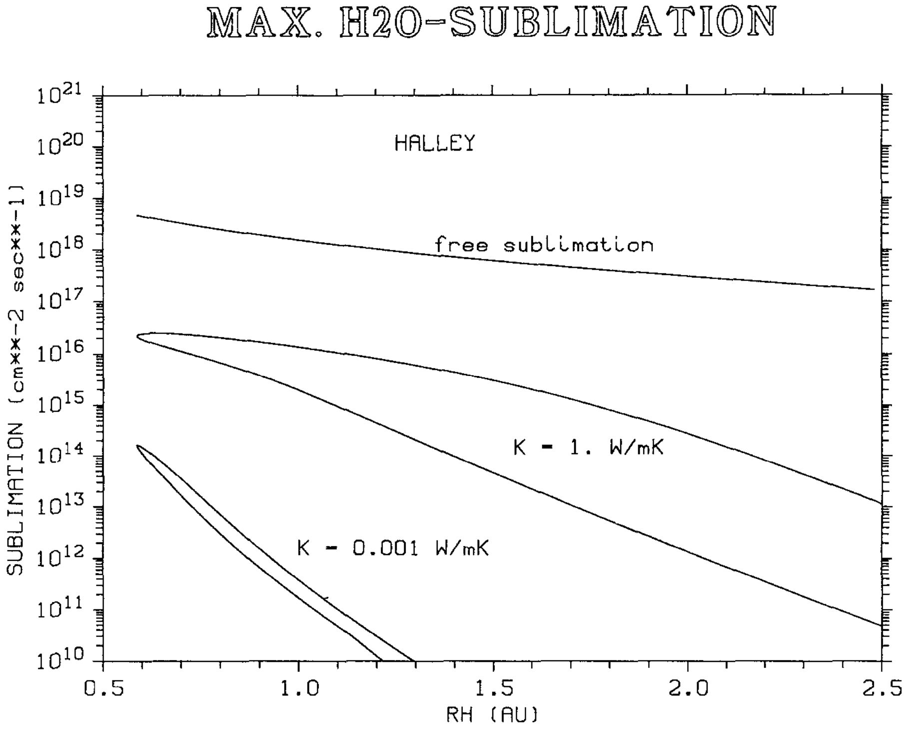

Fig. 1. Modelled maximum diurnal sublimation rates from the equator of a rotating cometary nucleus are shown. The curves depict cases of free sublimation and of an area with a crust. Two extreme values are taken for the heat conductivity corresponding to different thicknesses of the crust. An orbit similar to that of comet Halley, an obliquity of 0, and a rotation period of 50 h have been assumed.

as fireballs. Larger boulders can be separated from the nucleus by splitting processes that seem to be common (Sekanina, 1982; Chen and Jewitt, 1994).

Consequently, the introduced model of an inhomogeneous nucleus structure can explain several features of cometary activity.

3.4. AGING OF COMETS

From the analysis of non-gravitational forces Rickman et al. (1991) derived that the relative part of the inactive surface area becomes larger the older the comets are and the lower their perihelion distance is. Kresák (1991) and Rickman et al. (1991) found that comets show the tendency of fading with age. This is consistent with the scenario described above. Crusted areas remain inactive and active regions become less important because they disappear after the volatiles are consumed. The last stage of such a development

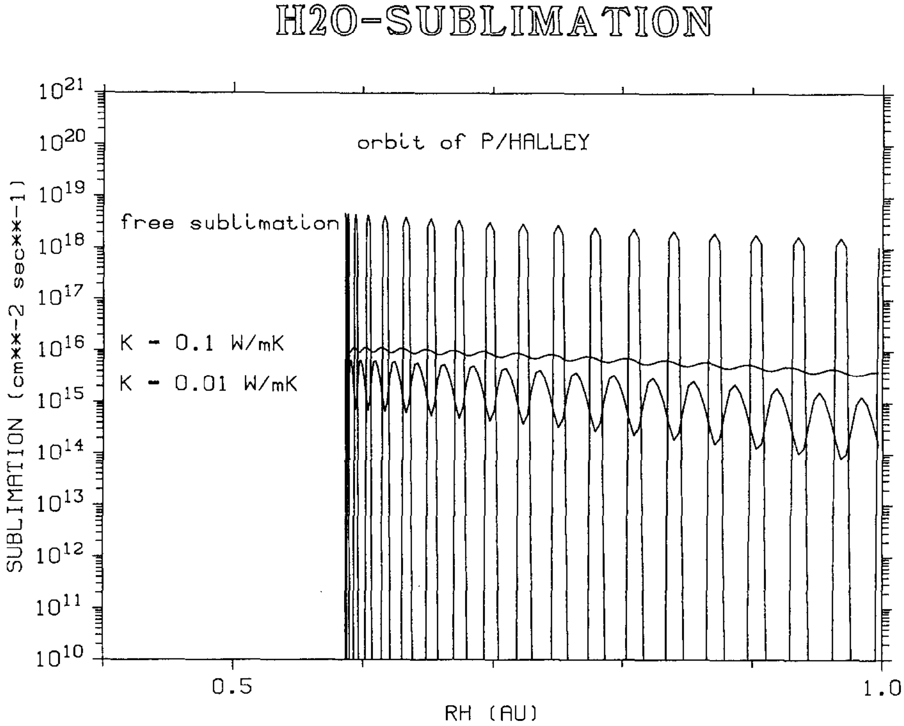

Fig. 2. Diurnal variation of the activity at perihelion; same conditions as in Fig. 1.

is a dormant body with an asteroid-like behaviour. It should still contain ice but it has no or rather low activity because it is completely covered by a depleted crust. Several candidates for such objects have been identified (Yeomans, 1991).

4. Conclusions

Despite the progress in the observational techniques the nature of comets is not yet well understood. Speculations about their origin and structure will prevail at least until the in situ measurements of the planned ROSETTA mission. Without doubt the physical consistence of the microstructure of cometary nuclei is a key point for the understanding of origin, activity, and death of comets.

The introduced model postulates an inhomogeneous, dust rich comet and can explain some observational facts such as the restricted activity and some aspects of cometary aging. General consequences of the presented investigations are:

- The cohesive strength of cometary nuclei is orders of magnitude stronger than gravitational pressure and higher than the vapour pressure ($P_{\mathrm{coh}} > P_{\mathrm{vap}} > P_{\mathrm{grav}}$) and must be incorporated in cometary models.

- Comet models based on heterogeneous (varying dust to ice ratio) cohesive nuclei can explain the observations. Structural inhomogeneities and a varying dust/ice ratio can be the key to the understanding of local activity and large scale inactivity of comets. Dust and ice clusters may be substructures of cometesimals or cometesimals from different origins. Ice rich clusters on the surface yield the active areas. Depleted dust clusters too big to be removed by gasdynamic forces form the stable crust. Small dust clusters can be ejected after they have been depleted of volatiles and conduct the heat to the underlying ice.

- Dust/gas ratios derived from sampling the coma underestimate the mean ratio in the nucleus.

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