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Comets: coma and beyond

There is no clear definition of what the coma of a comet is. Most frequently it means the faint visible halo around comets, and in other context it denotes material that reflects or emits electromagnetic radiation (including light) back to observers. In this chapter we shall use the word 'coma' to describe all materials around the cometary nucleus, solids and volatiles, neutral and charged, irrespective how effectively a certain component is able to scatter or emit radiation. The origin of the coma is the nucleus itself, and we shall discuss the processes that eject or emit materials from the surface to the cometary atmosphere and beyond. We consider only physical processes; coma chemistry is not the topic of this chapter. It is unavoidable to take into account in this context the structure and the physics of the cometary surface layer as well, because this is the source of the coma. Comets are believed to contain pristine materials from the period when the Solar System was born; the cometary surface, however, has been exposed to many perturbations (cosmic rays, solar wind, heat cycles, etc.) and it definitely cannot be considered as pristine. How deep we have to dig to find unprocessed material is an open question. There is only limited experimental evidence on surface evolution obtained in simulations, and we have to rely mostly on guesses.

It is also important to note that *in situ* experimental investigation of comets is limited to a few flyby missions; most of our knowledge comes from astronomical observations. It is a matter of debate, however, as to what extent the observed coma features can be directly related to the properties of the nucleus. If a jet is seen in the coma, astronomers prefer to connect it with a source below it on the nucleus surface. However, as Crifo and Rodionov (1999a) have pointed out, two active sources on an aspherical nucleus can easily mimic the appearance of a jet between the sources, and it is much stronger than those visible above the actual active regions. This should make us cautious with inferences, but such caution is lacking in many publications. The complicated rotational motion of the generally irregularly shaped nucleus also renders inferences difficult. Even the free rotation of an irregular body strictly speaking is aperiodic in the ecliptic frame of reference; and in the frame of reference attached to the angular momentum vector the time variation of two of the Euler angles is characterized by two different periods, and the variation of the third Euler angle is aperiodic in general. The rotational motion under the effect of the torque due to nuclear activity can be even more complex. Filtering out all these details from ground-based observations is almost an impossible task, especially if the direct inference between coma and fixed sources on the rotating nuclear surface is also in question.

If we browse publications of the 1960s to find out what they contained about planets, we frequently find quite basic statements that were disproved later, after *in situ* measurements were done. When considering comets, we have to bear in mind that nobody has ever landed on a comet, and no nucleus has ever been explored from a close distance. At comet Halley, the Giotto probe took the highest resolution images from a distance of about 1200 km, with a nominal resolution of about 27 m; these images covered part of the nucleus. The two Vega craft imaged the nucleus from about 8500 km with a resolution of about 150 m. In these missions the high relative velocity between the nucleus and the spacecraft made dust analysis difficult, because no dust detector could be appropriately calibrated before launch. Formation of a plasma cloud due to the high impact velocity on the target surface, and its influence on data analysis in certain cases is still an open issue. Dust size measurements

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made by different techniques differ in fine details. Modelling of the coma and the nucleus surface received a new impetus when the Rosetta mission of the European Space Agency was approved to explore and land on comet Wirtanen. The spectacular appearance of comet Hale-Bopp in 1997 also initiated new research.

In this chapter we first review models of cometary surfaces, to the level necessary to understand how the coma develops and what the boundary constraints are for the models for the acceleration of dust/gas mixtures. Next we discuss cometary atmospheres, both the regions where the properties of neutral gas are dominated by collisions, and where collisions cease to be present. We review the results of in-flight dust experiments, and we finish with a brief overview of the charged particle environment of comets.

THE SURFACE OF COMETS

It is the ‘dirty snowball’ vision of Whipple (1950) that lies at the heart of all comet models. Accordingly, to a zero-order approximation the surface is like the surface of a dirty snowball. The ‘dirt’ is not homogeneous, the chemical composition of the dirt varies depending on location, which is convincingly proved by the existence of chemically different jets in the coma (A’Hearn *et al*. 1986, Cosmovici *et al*. 1988, Clairemidi *et al*. 1990), and it is conceivable that there are inhomogeneities in other physical quantities as well. This entails that cometary activity might not be uniform, and though we cautioned against a direct inference from coma to surface, we are certain that this inhomogeneity is reflected in coma properties as well. Comets are irregularly shaped. The three-dimensional shape of comet Halley could be reconstructed based on the Vega flyby images, and Giotto contributed with a single view only (Szegö *et al*. 1995). The area of the sunlit nucleus surface varies as the object rotates, this is a natural cause of anisotropy.

Comets are always exposed to cosmic rays, which is the dominant radiation when they are in the Oort cloud. Their interaction with the local interstellar material also affects surface evolution, but as we do not have much knowledge of the details, we shall not discuss it here. The penetration depth of cosmic rays depends on their energy and on the local density; moderately relativistic charged particles lose energy in matter primarily by ionization. From ground experiments it is known (Caso *et al*. 1998) that the energy loss of protons more energetic than 1 GeV is a few $MeVg^{-1}cm^2$. For less energetic particles it grows considerably more; for example, 100 MeV protons penetrate a few centimetres into water ice. Cosmic radiation may trigger chemical reactions leading to surface differentiation, among others to the creation of impermeable chemical layers (Moore *et al*. 1983).

The solar wind can reach the surface of comets when cometary activity is low, that is at large distances from the Sun. It is known that dust can absorb solar wind ions and re-emit them as neutrals; this process is also likely to occur in comets. However, it is unlikely that the solar wind causes profound physical changes, and therefore we do not discuss this effect any further.

As a preparatory activity to a landing on comet 46P/Wirtanen, researchers have worked out a nucleus reference model (Möhlmann 1999), which is the best summary of our current knowledge of the thermal, mechanical and electromagnetic properties of the cometary surface. Ground simulations of the properties of ice–dust mixtures (e.g. Thiel *et al*. 1995) significantly contributed to this. Our focus here, however, is more limited; we are interested only in models that can describe how dust and gas can be released from the surface layer.

The first models concentrated on reproducing the inbound and outbound brightness curves of comets often showing an asymmetry at the same heliocentric distance. Whipple (1950) was the first to introduce the mantle as the likely surface layer of the nucleus, consisting of solid materials after the volatile component evaporated. Mendis and Brin (1977) suggested that erosion takes place, with particles smaller than a critical size being carried away by the outflowing gas. This was developed further by Horanyi *et al*. (1984) in the framework of the friable sponge model. The key assumptions of this model are that the dust loss rate is proportional to the momentum flux of the outflowing vapour, and that erosion takes place only in a thin surface layer (Figure 1). The gas is released from the surface of the icy core (a frozen dust–ice mixture), covered or uncovered by the dust mantle. This implies that the size distribution of the grains remains constant in the mantle with time,

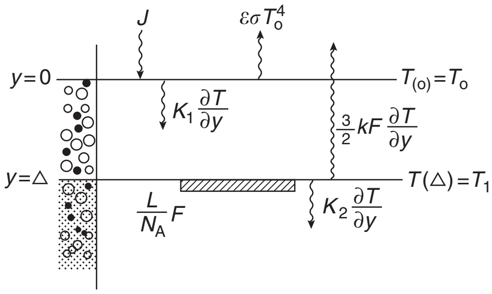

Figure 1 The ‘friable sponge’ surface model. The upper layer, the dust mantle, consists of degassed dust particles. Under the dust layer there is a dust–ice mixture. The heat flows are indicated, the sublimated vapour is in thermal equilibrium with the local mantle. L is the latent heat, N_A is the Avogadro number, F is the flux of sublimated vapour and K_1 and K_2 are is the thermal conductivities of the mantle and the core, respectively. (After Horanyi *et al.* 1984, Figure 1.)

independent of the thickness of the mantle. As this requires that all sizes are removed at the same rate, it is allowed that larger grains be broken into smaller pieces (friability).

The thermal balance on the dusty surface is given by the following equation:

$$(1-a)Je^{-\tau} - \varepsilon\sigma T_o^4 + D = -K\frac{\partial T\,(\text{at } y=0)}{\partial y} \tag{1}$$

where a is the surface albedo, J is the solar energy flux, τ is the optical depth of the coma, ε is the thermal emissivity of the surface, σ is the Stephan–Boltzmann constant, T_o is the temperature at the surface, D is the heat due to diffuse radiation from the coma, K is the thermal conductivity, and y is the distance measured from the surface downward. In this model the thermal conductivity can be expressed as $K = a + bT^3$; for the meaning of a and b see Horanyi *et al.* (1984).

There is a general agreement that the heat flux, J, due to solar irradiation is attenuated by the already existing coma. Its intensity depends on the heliospheric distance, the local incidence angle and that part reflected back in proportion to the surface albedo (first term of eqn (1)). The nucleus as a black body also irradiates heat proportional to its thermal emissivity (second term of eqn (1)), and the existing coma not only attenuates the incoming flux, but due to scattering and re-radiation, it contributes to local heating. The amount of heat reaching the surface due to the coma is a matter of debate. The 'rule of thumb' accepted nowadays is that this balances the attenuation (Salo 1988). The back-scattered heat from the coma is definitely not enough to maintain sizeable surface activity on the dark side; at least there is no evidence for such processes on the images taken during the Halley flybys.

In all surface models it is of paramount importance as to how heat is conducted inside, this accounting for the various gas production rates (Rickman 1991). The net heat flux on the surface is conducted inside through the degassed mantle, warming up the upward-flowing vapours. Models differ as to whether there is a local thermal equilibrium between the local mantle and vapour temperature. At the bottom of the degassed mantle the heat flow reaches the pristine core where the ice–dust mixture resides and is sublimated, the sublimation rate is governed by the Clausius–Clapeyron equation. In the simple friable sponge model all the heat is used on sublimation. The gas production rate remains constant until the mantle thickness reaches a value of about 10^{-2} cm, and then it decreases sharply with increasing mantle thickness. The surface temperature for 'pristine ice–dust' is the sublimation temperature, and as the mantle thickness increases it reaches the black-body temperature. The mantle thickness varies dynamically, and this can account for by the observed inbound/outbound asymmetry of the coma brightness.

In this model there is only one volatile component, and whereas it reproduces the basic dust-emission process, it evidently cannot elucidate the flux variation of the different gases as a function of heliocentric distance. A wide variety of models has been developed to remedy this and some other simplifications in the thermal properties. The most important modification is that gas is released not only from the ice surface, but from deeper layers as well. An excellent summary of these is given by Klinger *et al.* (1996). We follow this paper when summarizing the new features: (a) the gas phase contributes to the heat transfer to deeper layers; (b) volatiles are able to diffuse into deeper layers where they recondense; (c) sublimation can occur at various depths depending on the volatility of the different ices; (d) there is more than one ice phase, the water ice initially is in an amorphous phase that will become a crystalline phase; and (e) the pore size varies during the ougassing process. Such a surface model is shown in Figure 2. Most of these assumptions were verified by the KOSI comet simulation experiments (see references in Klinger *et al.* 1996).

In the following we discuss specifically the model developed by Podolak and Prialnik (1996). They assumed that the mantle layer is composed of dust, amorphous ice, crystalline ice, water vapour and gases such as CO and CO_2 trapped in the amorphous ice. The trapped gases are released when the transition from the amorphous to the crystalline phase takes place, but the gases released can recondense on pore walls and their sublimation may occur at a later stage. The gas flow is a free molecular flow, because the mean free path in the mantle is much larger than the pore sizes. The dust in this model is not only liberated from the surface, but may slowly move through the pores in the vertical direction,

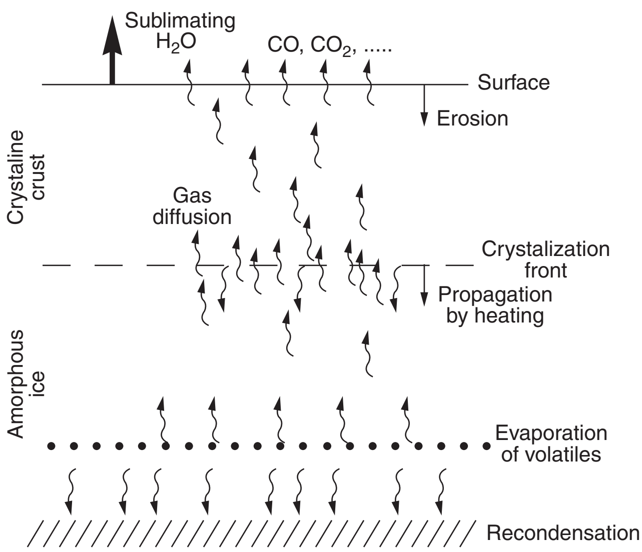

Figure 2 Schematic of a possible surface structure with different ice phases. (After Rickman 1991, Figure 10.)

though it is allowed that dust can move horizontally when the vertical path is blocked. All the pores are permeable to gas. Based on these and on some more specific assumptions, the probability of a dust particle leaving the mantle can be calculated. The one-dimensional mass and energy equations are solved only for the gas–ice mixture, the dust basically is treated separately, and only the dust and gas fluxes are coupled. These considerations lead to a stratified mantle structure: there is a highly porous dust layer on the top, followed deeper by a dense layer of crystalline ice and dust and, below that there is a layer of amorphous ice and dust, including other frozen-in volatile components at various depths (the frozen CO_2 is closer to the surface than the frozen CO). This model reproduces very well the observed gas emissions; namely that the CO production rate is higher at large heliospheric distances than that of water, but this ratio changes dramatically as the comet approaches the Sun. This proves that the coma composition does not reflect the composition of the nucleus.

These models are one-dimensional, with variations only in the radial directions being considered. This was remedied by Enzian *et al*. (1999) who developed a multidimensional rotating nucleus model, though still a spherical one, made up of a porous dust–ice matrix composed of water and CO. Heat and gas diffusion was allowed both in the radial and meridional directions. They found a near-uniform CO production, with water production and surface temperature showing local variations connected with the incoming heat flux.

Whereas these models are significant steps towards an understanding of cometary activity, there are still unresolved problems and controversies; for a review see, for example, Crifo and Rodionov (1999b). The model of Enzian *et al*. (1999) can barely account for the observed water production rate, even assuming that the surface is pure ice, and the radius is at the upper limit of the observations. As a pure ice surface is very unlikely, one tends to assume that bigger chunks of surface material can be released emitting gas in flight as well. This scenario is seemingly supported by radar observations (e.g. Harmon *et al*. 1997) indicating that the surfaces of several comets are rough on the centimetre scale; however, how such large pieces can be carried away is still very much a matter of debate.

CHARGING OF THE DUST IN FLIGHT AND THE COMETARY SURFACE

Dust particles and the surface of a cometary nucleus can be charged due to the ultraviolet radiation of the Sun and the escaping flux of photoelectrons. The current carried by the charged components of the solar wind is important when it can reach the cometary surface. In general, secondary ion currents are negligible. Horanyi (1996) gives an excellent review of charged dust dynamics in the Solar System. The motion of a dust particle is determined by the forces acting on it: the Lorenz force due to its own charge, gravitational forces and light pressure. In a coordinate system attached to the rotating nucleus, inertial forces should also be taken into account. Charging is relevant for those cases when the force due to charging is of the same order of magnitude as the other forces acting on the dust particle; typically for particles of a few micrometres in the vicinity of a few tens of metres of the nucleus.

The evolution of the charge created on the surface of an insulator is described by the following equation (Horanyi 1996):

$$\frac{dQ}{dt} = \sum_k J_k \qquad (2)$$

where J_k represents the charging currents. In a stationary case the left-hand side is zero.

In general, the flux of current density of particles, characterized by a distribution function $f(\mathbf{v})$, bombarding a surface with potential Φ, is given as

$$J = \int_{v^*}^{\infty} v^2\,dv \int_0^{\pi/2} \sin\vartheta\,d\vartheta \int_0^{2\pi} d\psi\, v\cos\vartheta\, f(\mathbf{v}) \qquad (3)$$

where v^* is chosen for each plasma species so that $mv^{*2}/2 - e\Phi > 0$; that is, the integration volume in velocity space depends on the surface potential. It is easy to see that the limit of the integration is different if the Φ surface potential is positive or negative. If the size, a, of the dust particles is smaller than the characteristic Debye lengths, the surface we need to take into account for grain charging is the total surface, which is $4\pi a^2$ in the case of a spherical grain.

The actual formulae specifying the different charging currents are quite complicated, and are not given here. The potential distribution in the dusty plasma sheath above the nucleus can be obtained from the Poisson equation. At infinity the potential and the electric field should be zero.

The nightside surface potential differs: obviously there is no UV flux and the effect of the solar wind is also different. Electrons, due to their high thermal velocity, do reach the nightside surface, and the form of the charging current does not differ from that of the dayside. For protons, however, the situation is modified. Though the diameter of the nucleus is negligible compared to the proton gyroradius, since the flow velocity is higher than the proton thermal velocity, only a fraction of the proton distribution reaches the surface, those for which the gyration results in effective backward motion in the cometocentric system. As the nightside surface potential becomes negative, more protons can reach the surface. The estimated potential on the nightside can be as large as -1 kV, deflecting the bulk kinetic energy of the solar wind protons moving past the comet.

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