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DUSTY COMETARY ATMOSPHERES

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ABSTRACT

This paper summarizes our present understanding of the physical processes controlling the dust and gas production of cometary nuclei and the evolution of the dusty gas flow in the inner coma. Special emphasis is being made to compile a self-consistent set of governing equations describing the accelerating dusty gas flow in a cometary atmosphere.

INTRODUCTION

The cometary atmosphere is a unique phenomenon in the solar system. Due to its negligible gravity the tiny nucleus of only a few kilometers produces a highly variable, extensive dusty atmosphere of dimensions ranging from 10^4 km to 10^5 km. The large spatial extension and continual expansion of a cometary atmosphere provides a convenient tool for studying the time history of atmospheric processes.

One of the most important features influencing cometary dynamics is the "retarded" nature of gas and dust production. The radiation reaching the surface and supplying energy for sublimation must first penetrate an extensive, absorbing dusty atmosphere. Any change in the gas and dust production alters the optical characteristics of the atmosphere, thus affecting the radiation reaching the surface at a later time.

Recently we had the first opportunity to investigate a cometary environment from close range and to collect a new and extremely valuable set of information about cometary atmospheres. This paper briefly overviews some of the present atmospheric models in light of the new spacecraft observations. For a detailed summary of these models we refer to recent comprehensive reviews /1,2/.

GAS AND DUST PRODUCTION

Our present understanding of cometary nuclei is based on Whipple's "dirty iceball" idea /3/ according to which the nucleus consists of a mixture of frozen volatiles and non-volatile dust. The most recent observations, together with other evidence, led Weissman to postulate that the nucleus is a primordial rubble pile of weakly-bound, small icy conglomerates /4/. Very recently the first images of the comet Halley nucleus inspired Gombosi and Houpis to propose an icy-glue model, suggesting that the nucleus is composed of rather large (tens of centimeters to hundreds of meters) porous refractory boulders "cemented" together with an ice-dust mixture /5/.

The chemical composition and physical structure of the active surface layers are very important factors affecting the mass, momentum and energy densities of the outflowing gas-dust mixture, as well as the relative abundance of various gas molecules. The prevailing view is that the solid components of cometary active regions form an extremely porous, low density, weak structure, rather than a coherent mass of rocky solids penetrated by gas or liquids that froze (cf. /4-6/). When the nucleus approaches the sun, it absorbs an increasingly larger flux of solar radiation thus increasing the vaporization rate of volatile molecules at the surface. The vaporized gases leave the surface and form an expanding exosphere. In this process the gas drags away some of those dust grains which have already been evacuated of their ice component, while a fraction of these dust grains may form an inert insulating layer (mantle) over the active surface. The development of such a mantle was modeled by Mendis and Brin /7/, Brin and Mendis /8/, and subsequently by Horanyi et al. /9/, Fanale and Salvail /10/, Podolak and Herman /11/, and Houpis et al. /12,13/. The thickness of the mantle varies with time because the continuous vaporization increases the thickness of the evacuated layer, and the "erosion" due to the drag of the outflowing gas decreases it. A schematic representation of such a mantle is shown in Figure 1.

At the surface the absorbed radiation energy is balanced by black body reradiation and downward heat conduction. Inside the mantle a small fraction of the downward conducted energy heats the outward diffusing gas, while most of the available heat is transported to the core/mantle interface, where the vaporization process takes place. Using the mantle thickness as a free parameter one can determine the surface and mantle/core interface temperatures together with the gas production rate by solving the energy balance and heat conduction equations (cf /2/):

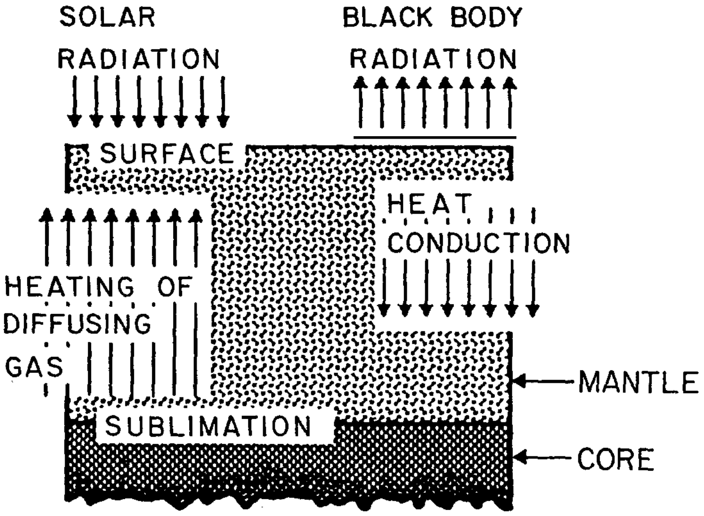

Fig.1. Schematic representation of energy transfer in a cometary mantle.

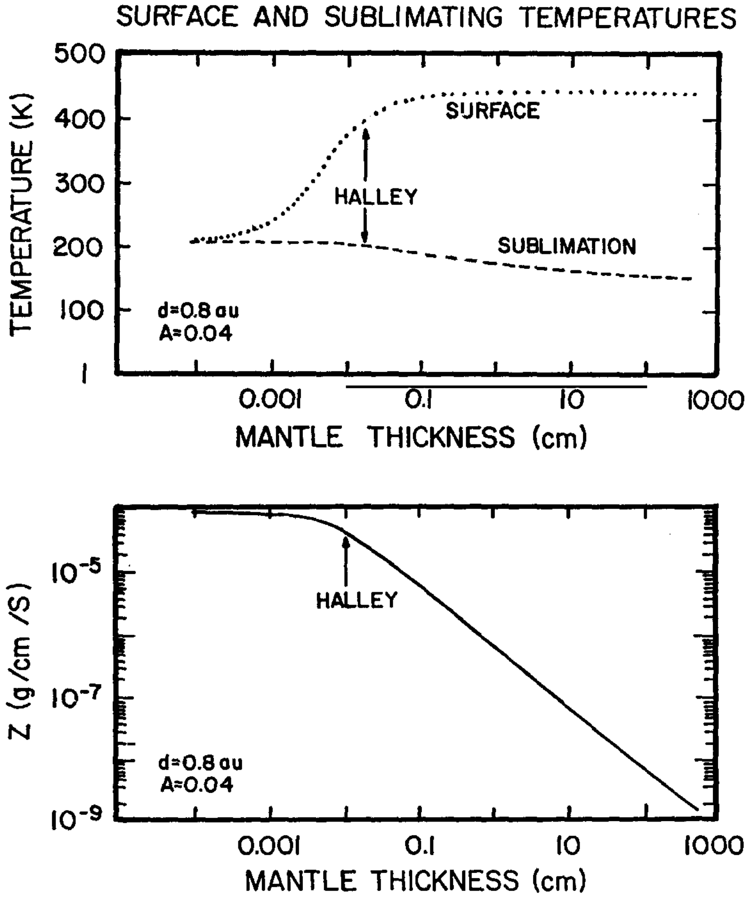

Fig. 2. Surface and sublimating temperature (upper panel) and active region gas production rate (lower panel) values as a function of mantle thickness.

$$(1 - A)\, I_{rad} - \varepsilon \sigma T_0^4 = B\,(T_L + T_0 - T_1) \tag{1}$$

$$B\,\Delta / \kappa_0 = \ln[1 + (T_0 - T_1)/T_L] \tag{2}$$

where A = surface albedo, ε = surface emissivity, σ = Stefan-Boltzmann constant (σ=5.67x10^{-5} erg cm^{-2} s^{-1} K^{-4}), I_{rad} = radiation energy flux, Δ = mantle thickness, κ_0 = mantle heat conductivity (a value of κ_0 = 60 erg cm^{-1} s^{-1} K^{-1} was adopted /14/), T_0 = surface temperature, T_1 = mantle/core interface temperature. The T_L and B quantities are defined as

$$T_L = \frac{2L}{3kN_A} \qquad\qquad B = 1.5\,k\,\eta\, z/m$$

where L = latent heat of vaporization per mole, k = Boltzmann constant (k=1.38x10^{-16} erg K^{-1}), N_A = Avogadro's constant (N_A=6.022x10^{23}molecules/mole), m = mass of the volatile molecule, η = area fraction of ice at the mantle/core interface. In a first approximation the gas mass production rate, z, can be expressed as

$$z = z_0 \frac{\exp(-3T_L/2T_1)}{T_0^{0.5}} (1 - 0.062\chi) \tag{3}$$

where χ = dust/gas mass production rate ratio (for comet Halley $\chi \approx 0.3$ /15,16/). For a water dominated comet z_0 = 9.65x10^8 g $K^{0.5}$ cm^{-2} s^{-1}, and T_L = 3851K.

The results for a heliocentric distance of 0.8 AU (Halley encounter distance) are shown in Figure 2. The radiation energy density at the nucleus was assumed to be that of the unattenuated solar radiation /1/, the surface albedo was assumed to be 0.04 /17,18/, and a value of 8x10^6 erg/g/K was adopted for the dust specific heat /14/. Inspection of Figure 2 reveals that a mantle thickness of about 1 cm increases the surface temperature well above 400K, thus drastically reducing the fraction of the absorbed radiation energy available for supporting vaporization (almost all absorbed energy is reradiated by black body radiation).

At the time of the VEGA-1 encounter comet Halley had a total gas production rate of about 10^{30} molecules/sec /15/ and an active area of about 50 km^2 /18/; consequently, the average gas production rate of the active region was about 6x10^{-5} g/cm^2/sec. This value indicates that the evacuated dust layer covering the active area is typically 0.01 cm thick. This mantle thickness predicts a surface temperature around 400K, which is in good agreement with the VEGA infrared observations indicating an average surface temperature well in excess of 300K /19/.

GAS AND DUST FLOW

It was recognized as early as the mid 1930's that gas outflow plays an important role in cometary dust production /20/. As the vaporized gases leave the surface they drag away some of those dust grains which have already been evacuated of their ice component. The gas drag force accelerates the dust particles to terminal velocities comparable with the gas flow velocity. In early treatments of the gas-dust interaction it was assumed that the dust drag coefficient was independent of the gas parameters and that the gas velocity was constant in the dust acceleration region.

A two component treatment of the gas-dust interaction was published by Probstein in the late 1960's /21/. Probstein made the assumption that the heavy dust grains have no random motion and collide only with gas molecules. He also pointed out that the gas mean free path was much larger than dimensions of the dust particles, consequently the gas flow could be considered to be free molecular relative to the dust component.

Even though both the mathematical formulation and the methods of solution of the gas-dust interaction problem have been improved significantly since Probstein's original work, cometary dusty gas flow calculations are still based on the Probstein approach /22-29/. In these models the mass, momentum and energy conservation equations of the single fluid neutral gas are the following:

$$\frac{D\rho}{Dt} + \rho\, \mathrm{div}(\underline{u}) = 0 \tag{4}$$

$$\rho \frac{D\underline{u}}{Dt} + \mathrm{grad}(p) - \rho\, \underline{G} = -\underline{F}_{gd} \tag{5}$$

$$\frac{D}{Dt}\left(\frac{1}{\gamma - 1} p\right) + \left(\frac{\gamma}{\gamma - 1} p\right) \mathrm{div}(\underline{u}) + \mathrm{div}(\underline{q}) = Q_{ext} - Q_{gd} \tag{6}$$

where ρ = mass density, p = gas pressure, $\underline{u}$ = gas velocity, $\underline{q}$ = heat flux, $\underline{F}_{gd}$ = gas to dust momentum transfer rate, Q_{gd} = gas to dust energy transfer rate, Q_{ext} = external heating rate. The equation of motion of an individual dust grain is:

$$\frac{d\underline{V}_a}{dt} = \frac{3}{4a\rho_a} p\, C_D\, \underline{s}_a + \underline{G} \tag{7}$$

where a = dust particle radius, $\underline{V}_a$ = dust particle velocity, ρ_a = dust grain bulk density. The dimensionless gas-dust relative velocity, $\underline{s}_a$, and the modified drag coefficient are

$$\underline{s}_a = \frac{\underline{u} - \underline{V}_a}{(2\,R\,T)^{0.5}} \tag{8}$$

$$C_D = \frac{2\,\pi^{0.5}\,T_a^{0.5}}{3\,T^{0.5}} + \frac{2\,s_a^2 + 1}{\pi^{0.5}\,s_a^2}\exp(-s_a^2) + \frac{4\,s_a^4 + 4\,s_a^2 - 1}{2\,s_a^3}\,\mathrm{erf}(s_a) \tag{9}$$

where R = k/m, T = gas temperature, T_a = dust grain temperature, and $s_a = |\,\underline{s}_a|$. In the presence of an external radiation field the energy balance equation for a single dust particle is:

$$C_a \frac{dT_a}{dt} = \frac{3}{a\rho_a}\left(p\,T^{0.5}\,C_H + 0.25\,\varepsilon_{abs}\,I_{rad} - \varepsilon_{emiss}\,\sigma\,T_a^4 \right) \tag{10}$$

where C_a = dust specific heat, ε_{abs} and ε_{emiss} are the dust absorption and infrared reemission emissivities, respectively, while

$$C_H = \frac{(2\,R)^{0.5}}{(\gamma - 1)}\,\Gamma_s \left(2\gamma + 2(\gamma-1)s_a^2 - \frac{(\gamma-1)\,\mathrm{erf}(s_a)}{s_a\,\Gamma_s} - (\gamma+1)\frac{T_a}{T} \right) \tag{11}$$

where

$$\Gamma_s = \pi^{-0.5}\exp(-s_a^2) + (0.5/s_a + s_a)\,\mathrm{erf}(s_a)$$

Finally, the dust size distribution function, f_a, must obey the following continuity equation:

$$\frac{\partial f_a}{\partial t} + \mathrm{div}(f_a\,\underline{V}_a) = 0 \tag{12}$$

The gas to dust momentum and energy transfer rates can be obtained by integrating over all dust sizes:

$$\underline{F}_{gd} = p \int_{a_0}^{a_m} da 2\pi\, a\, f_a\, \underline{s}_a\, C_D \tag{13}$$

$$Q_{gd} = p \int_{a_0}^{a_m} da 2\pi\, a\, f_a\, (\underline{V}_a\, \underline{s}_a\, C_D + 4\,T^{0.5}\,C_H) \tag{14}$$

where a_0 and a_m represent the minimum and maximum dust sizes. External gas heating is mainly caused by photochemical and radiative heating/cooling processes (cf /2/), $Q_{ext} = Q_{phc} + Q_{IR}$. The main contribution to the photochemical heating rate comes from the photodissociation of water molecules (cf /31/):

$$Q_{phc} = Q_0 \frac{n}{d} \exp(-\tau_{UV}) \tag{15}$$

where n = ρ/m, = 2.8×10^{-17} erg cm^{-3} s^{-1}, d = heliocentric distance (AU), τ_{UV} = ultraviolet optical depth. Two main processes contributing to the infrared radiative heating/cooling term are the infrared radiation from the H_2O molecules /32,33/ and the radiative trapping of the dust thermal radiation /29/. The combined effect of these processes can be approximated as (cf /2/):

$$Q_{IR} = -\,Q_{emiss}\,n\,\exp(-\tau_{IR}) + h_{IR}\,q_{abs}\,\sigma\,[1 - \exp(-\tau_{IR})] \int_{a_0}^{a_m} da\, a^2\, f_a\, T_a^4 \tag{16}$$

where σ = Stefan-Boltzmann constant ($\sigma = 5.67\times10^{-5}$ erg cm^{-2} sec^{-1} K^{-4}), h_{IR} = infrared trapping efficiency ($h_{IR} \approx 1$), q_{abs} = relative width of absorbing bands with respect of the infrared spectrum emitted by dust ($q_{abs} \approx 0.001$), and

$$Q_{emiss} = \begin{cases} 4.4\times10^{-22}\,T^{3.35} & T<52K \\ 2.0\times10^{-20}\,T^{2.47} & T\geq52K \end{cases}$$

In a spherically symmetric, steady-state case the gas continuity, momentum, and energy equations can be combined to yield the following first order differential equation for the gas velocity:

$$\frac{du}{dr} = \frac{u}{M^2-1}\left(\frac{2}{r^2} - \frac{F_{gd}}{p} + \frac{(\gamma+1)\,(Q_{gd} - Q_{ext})}{\gamma u p}\right) \tag{17}$$

where M = gas Mach number, A = area function (A~r^2), and A' = spatial derivative of the area function. Equation (17) is a solar wind type equation, which has a singularity at the sonic point (M=1). Figure 3 shows the various classes of mathematically possible solutions to equation (17). Inspection of Figure 3 reveals that most solution classes are non-physical; physical solutions must be single value functions of the cometocentric distance and must have an outflow Mach number of M≤1. It can be easily seen that there are only two potentially physical solutions. One,the comet "breeze" starts subsonically, reaches a maximum Mach number value of M<1, and then turns back and decreases towards an asymptotic value of M=0. It can be shown that this solution will provide a finite gas pressure in infinity, which makes this solution unphysical, too. The other solution which is the only physical solution, is the transonic comet "wind". The comet wind starts subsonically at the nucleus, goes through the singular sonic point, and then accelerates further.

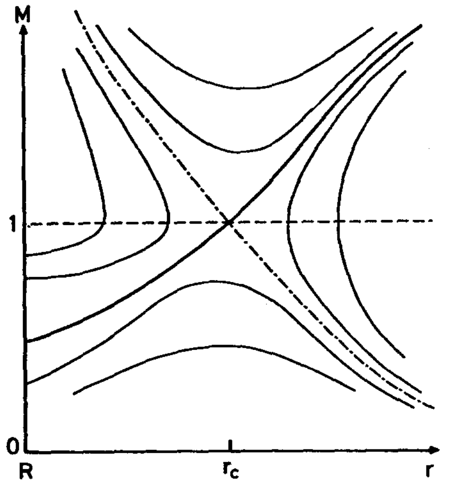

Fig. 3. Possible types of solution for equation (17). The only physical solution is the transonic "comet wind".

It is a little surprising that the physical solution of equation (17) is a transonic accelerating gas flow. At first it may not be obvious which is the external effect "accelerating" the gas and enabling it to become supersonic. In order to visualize this effect let us consider first the limiting case, when there is no dust in the system ($F_{gd} = 0$, $Q_{gd} = 0$) and we neglect the external heat sources, too ($Q_{ext} = 0$). This is equivalent to seeding at the source an already established steady, radial, isentropic inviscid compressible source flow. In this case the gas flow properties can be obtained from the well known solution for a supersonic source in which the Mach number at the nucleus (source) surface is taken to be 1 in order to satisfy the appropriate boundary conditions at infinity and at the source. In other words the solution describes a free unrestricted discharge of a reservoir (containing stationary gas) to vacuum. The situation changes dramatically when the outflowing gas has had a chance to drag away dust. In this case the value of the terms inside the parenthesis in equation (17) first decrease then reach the minimum value at the sonic point (and in effect creating a 0/0 type singularity) and then increase. This shows that the dust interaction (the dominant external effect near the nucleus) can be visualized using the concept of a Laval nozzle: first the outflow geometry "narrows", and then "opens up". In short, the presence of dust forces the gas flow to start at the nucleus with subsonic velocity, thus actually decelerating it. The sonic transition would have been impossible without the presence of dust. The situation strongly resembles the steady-state solar wind equation, first solved by Parker /34/. The gravitational effect of the sun for the solar wind corresponds to frictional forces between the dust and gas for the outflowing cometary gas.

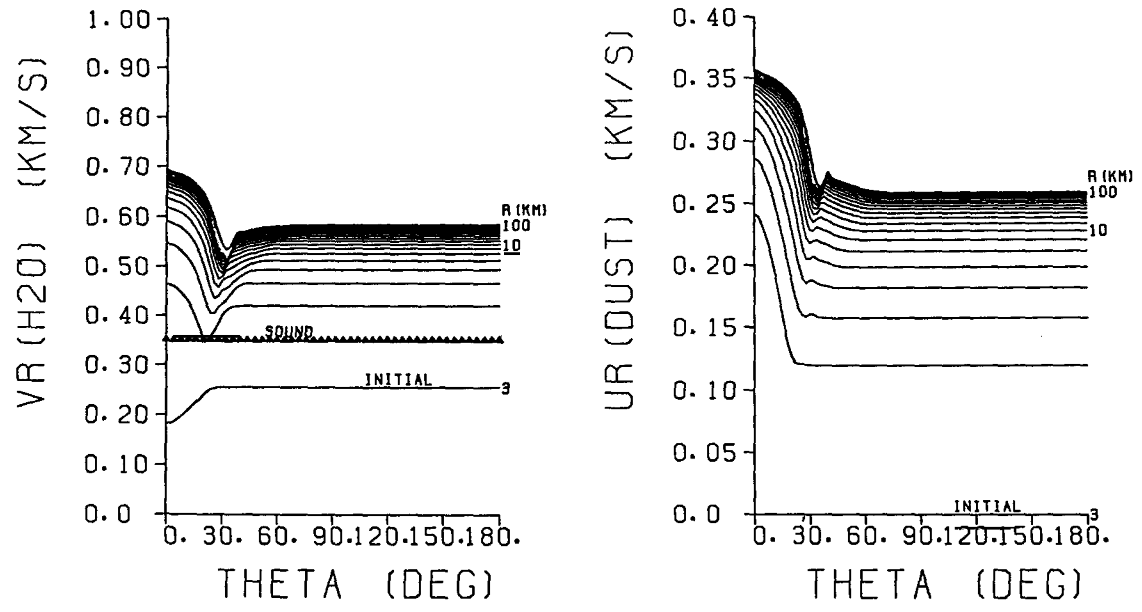

Fig. 4. Gas and dust radial velocities as a function of azimuthal angle in an axisymmetric jet model /31/.

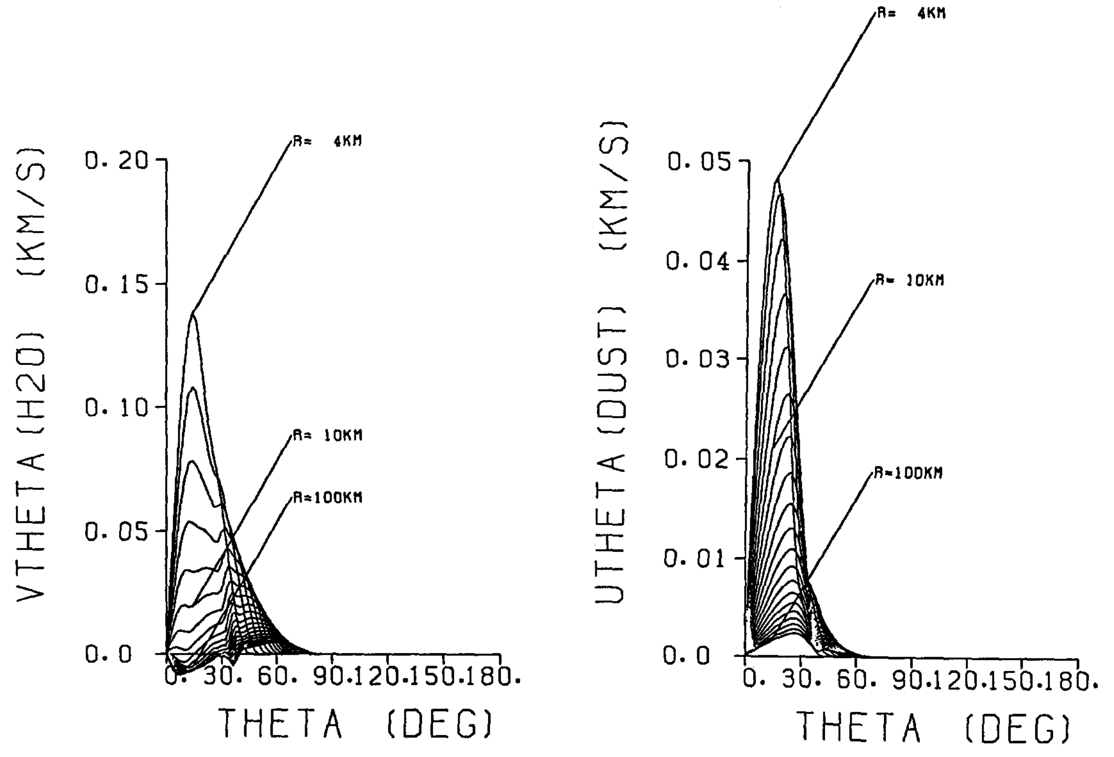

Fig. 5. Gas and dust azimuthal velocities as a function of azimuthal angle in an axisymmetric jet model /31/.

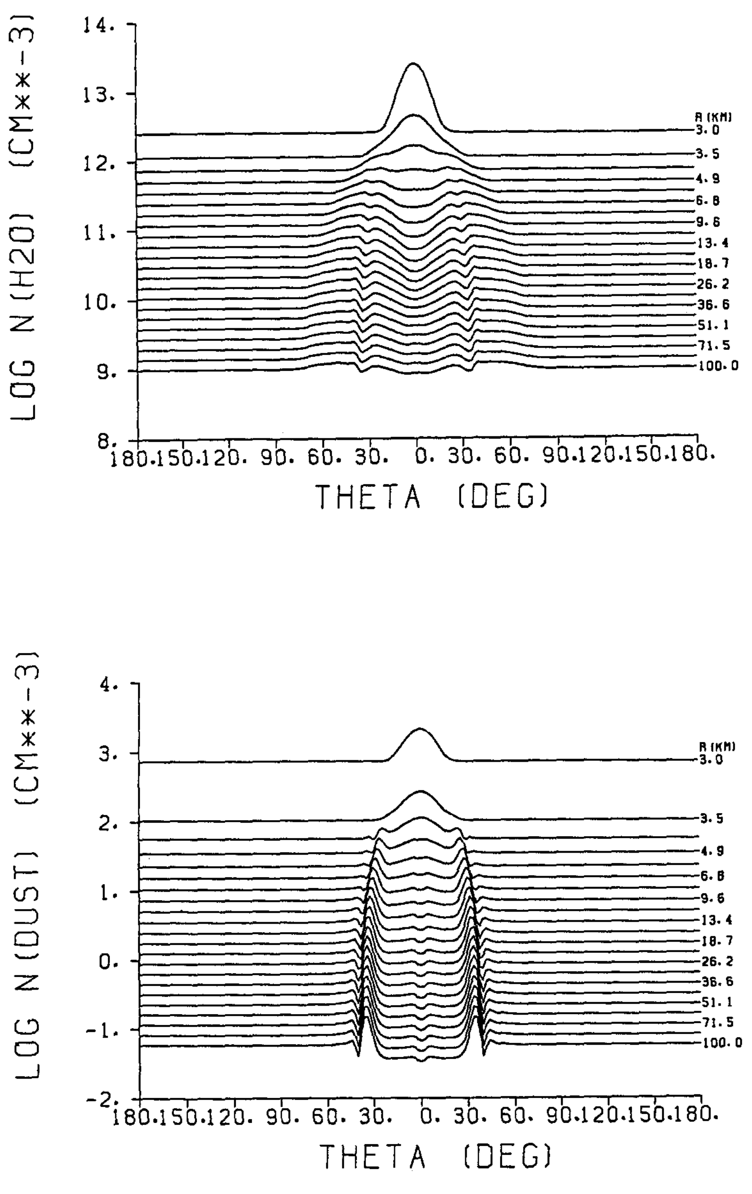

Fig. 6. Gas and dust densities as a function of azimuthal angle in an axisymmetric jet model /31/.

Since the original work of Probstein /20/ several solutions were published to equations (4) -(14) using different levels of approximations /22-29/. Recently Kitamura /31/ published the first time-dependent axisymmetric gas jet calculation describing inner coma gas and dust distributions following a long lasting, spatially localized comet outburst. The jet profile at the surface was approximated by a Gaussian function with a half width of 10°. The main feature of Kitamura's numerical results is that the narrow outburst results in a conical jet. The physical reason for this conical jet formation is twofold: first of all the horizontal gas pressure gradient at the surface initiates a lateral gas transport which quickly pushes the gas density peak to ~ 30°, secondly, near the nucleus the dust grains attain a tangential velocity which is comparable to their radial velocities, thus depleting the dust population along the $\Theta=0^{\circ}$ line. Further away from the nucleus the gas and dust particles lose most of their tangential velocities, consequently the modified dust structure "freezes" at a cometocentric distance of about 10 km. The result of these two processes is a laterally varying dust/gas mass ratio, resulting in different loading effects and causing different gas terminal velocities. Figures 4 - 6 (taken from Kitamura /31/) show these effects in more detail. The final result is that a slow, high density conical dust jet is formed around $\Theta \sim 30^{\circ}$. Inside the jet cone the dust is faster than the ambient population, consequently the dust number density is smaller.

SUMMARY

In this paper the governing equations of accelerating dusty gas flows in inner cometary atmospheres were summarized. The first *in situ* observations of comet Halley have indicated that the active surface of the nucleus is covered by a thin insulating mantle. The results of the first multidimensional dusty gas dynamical calculation /31/ were also reviewed pointing out that this model represents a significant improvement in describing dusty gas jets, even though it has certain limitations. In the near future one can expect a new generation of dusty gas dynamic models using more realistic input parameters and distribution deduced from the VEGA, SUISEI and GIOTTO results, further improving inner coma modeling.

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