TIME-DEPENDENT NUMERICAL MODELING OF DUST HALO FORMATION AT COMETS

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ABSTRACT

Evolution of gas and dust distributions following a spatially and temporally localized comet outburst was calculated using a hybrid kinetic-hydrodynamic method. In the inner coma the time-dependent continuity, momentum, and energy equations of the dusty gas flow were solved simultaneously using 12 dust sizes. Beyond 300 km a three-dimensional kinetic model (calculating the combined effects of solar radiation pressure, solar gravity, and cometary orbital motion) was used to calculate the trajectory of each individual dust grain. It was found that following the onset of the comet outburst a gas-dust blast wave propagates outward in the inner coma. About 15 minutes after the increased gas and dust production was initiated at the nucleus a new equilibrium was reached in the inner coma. The most important feature of this new steady state was the significant increase of the dust terminal velocities. These higher terminal velocity values resulted in larger apex distances for dust particles emitted during the outburst. The dust particles spend a relatively long time near their apex points (the cometary velocities are fairly small in this region); therefore the outburst generates long-lasting (~ 10 hr), distinct dust envelopes in front of the regular dust coma. This type of envelope was observed at several comets (cf. comet Donati).

Subject heading: comets

I. INTRODUCTION

Comets are highly variable celestial objects and exhibit spectacular changes with different time scales. The orbital motion results in variations with characteristic time scale of tens of days, but violent flareups, jets, expanding halos, tail discontinuities, etc., may develop within minutes or hours, although their decay phase usually lasts considerably longer.

It was recognized as early as the mid-1930s that gas outflow plays an important role in the cometary dust production process (Orlov 1935). Interacting two-component (gas and dust) models of released cometary material were published almost simultaneously by Probestin (1968), Brunner and Michel (1968), and Shulman (1969). A large number of papers dealing with various aspects of cometary flows have since been published (for recent reviews, see Mendis, Houpis, and Marconi 1985; Gombosi, Nagy, and Cravens 1986). Over the last 15 years a variety of approaches have been adopted, including hydrodynamic, dusty hydrodynamic, and kinetic models. However, even though both the formulation of the governing equations and the methods of solution have been improved significantly since the original works, until recently comet coma models have been based on steady state calculations. Recently Gombosi, Cravens, and Nagy (1985) and Kitamura (1986) have published the first time-varying dusty gas dynamic calculations of the inner coma region, where the gas-dust interaction takes place. In these calculations the time-varying gas continuity, momentum, and energy equations were solved simultaneously with the dust equations. Gombosi et al. (1985) have considered a spherically symmetric model and studied the temporal evolution of gas and dust structures formed in the immediate vicinity of the nucleus following sudden changes in the gas and dust production rates. Kitamura (1986) developed the first two-dimensional time-dependent model and applied it to study dusty jet structures generated by long-lasting, localized cometary active regions.

The main goal of this paper is to assess the role of inner coma gas-dust interaction on outer coma dust halo formation and evolution. In order to achieve this goal we combined the dusty gas dynamic inner coma model of Gombosi et al. (1985) with the kinetic dust model of Horányi and Mendis (1985) which calculates individual dust grain trajectories at larger cometocentric distances. The original method of Gombosi et al. (1985) was extended to include a realistic dust size distribution (with 12 dust sizes) and gas heating due to infrared radiation trapping (Marconi and Mendis 1986). This type of hybrid calculation enabled us to calculate both the small- and large-scale temporal and spatial evolutions of gas and dust distributions following a spatially and temporally localized comet outburst. This paper publishes a detailed description of the governing equations and applied methods of solution, together with a full set of the most interesting results; consequently, it is a natural continuation of a brief summary recently published in a special comet issue of Geophysical Research Letters (Gombosi and Horányi 1986).

II. GOVERNING EQUATIONS

a) Gas-Dust Interaction Region

In general, the first step in the quantitative study of high-speed transonic flows is the use of lowest order conservation equations which describe the spatial and temporal evolution of the concentration, bulk flow velocity, and temperature of the gas. Cometary atmospheres are dominated by molecular species; consequently, in addition to their translational energy, the gas molecules also have an internal energy, which can vary from particle to particle and which is affected in the energy exchange occurring in collisions. In this case the continuity,
momentum, and energy equations can be written into the following form (see Burgers 1969):

\[ \frac{\partial \rho}{\partial t} = \rho \text{div} \mathbf{u} = \frac{\delta \rho}{\delta t}, \]

\[ \rho \frac{D\mathbf{u}}{Dt} + \text{grad} p - \rho \mathbf{G} = \rho \frac{\delta \mathbf{u}}{\delta t}, \]

\[ \frac{D}{Dt} \left( \frac{5}{2} p + nU \right) + \left( \frac{5}{2} p + nU \right) \text{div} \mathbf{u} + \text{div} (\mathbf{q}_i + \mathbf{q}_j) = \frac{\delta p}{\delta t}, \]

where \( D/Dt \) is the convective derivative \( (D/Dt = \partial/\partial t + [\mathbf{u} \text{ grad}]) \), \( \rho \) is the gas mass density, \( n \) is the gas number density, \( \mathbf{u} \) is the gas velocity, \( p \) is the gas pressure, \( U \) is the average internal energy per particle, \( \mathbf{q}_i \) is the translational heat flow, \( \mathbf{q}_j \) is the flow of internal energy, \( \delta \rho/\delta t \) is the mass density addition rate, \( \delta \mathbf{u}/\delta t \) is the momentum addition rate, \( \delta p/\delta t \) is the external heat source, and \( \mathbf{G} \) is the local gravitational acceleration. When the gas is in thermodynamical equilibrium, equipartition applies:

\[ U = \frac{1}{2} nkT, \]

where \( k \) is the Boltzmann constant \( (k = 1.38 \times 10^{-16} \text{ ergs K}^{-1}) \), \( T \) is the translational temperature, and \( n \) is the total number of internal degrees of freedom \( (n = [3 - 2\gamma]/[\gamma - 1]) \), where \( \gamma \) is the specific heat ratio.

In the innermost coma (where the gas drag accelerates the dust particles) the gas mean free path is much larger than the dust particle dimensions; consequently, the gas flow can be considered to be free molecular with respect to the dust grains. It is also usually assumed that the heavy dust grains have only negligible thermal motion (velocity dispersion) and collide only with gas molecules (Probstine 1968; Brunner and Michel 1968; Shulman 1969). Another simplifying assumption in this dusty gas transport treatment is that dust particles are conserved in the coma (no further sublimation, fragmentation, or recombination is allowed after the grain left the nucleus):

\[ \frac{\delta s_0}{\delta t} + \text{div} (f_d V_a) = 0, \quad r > R_a, \]

where \( f_d da \) is the phase space density of dust particles with radius between \( a \) and \( a + da \) and \( V_a \) is the dust particle velocity. By neglecting collisions between dust particles one can obtain the following equation of motion for an individual dust grain (see Weigert 1959):

\[ \frac{dV_a}{dt} = \frac{3}{4a_{\text{p}}^2} \rho C_B s_0 + G, \]

where \( \rho_a \) is the dust bulk density, while the relative Mach number \( (s_0) \) and modified drag coefficient \( (C_B) \) are the following (Probstine 1968):

\[ s_0 = \frac{\mathbf{u} - V_a}{(2RT)^{0.5}}, \]

\[ C_B = \frac{2\pi^{0.5} T^{0.5}}{3T^{0.5}} + \frac{2s_0^2 + 1}{\pi s_0^2} + \frac{4s_0^2 + 4s_0^2 - 1}{2s_0^2} \text{erf} (s_0), \]

where \( R \) is the gas constant \( (R = k/m, m \) being the mass of the gas molecule). In the presence of an external radiation field the energy balance equation for a dust particle is (Probstine 1968):

\[ C_s \frac{dT_a}{dt} = \frac{3}{a_{\text{p}}^2} (pT^{0.5}C_H + 0.25s_{\text{abs}} J_r - \varepsilon_{\text{emiss}} \sigma T_a^4), \]

where \( T_a \) is the dust grain temperature, \( C_s \) is the dust specific heat [in the present calculation, we take \( C_s = 8 \times 10^6 \text{ erg s}^{-1} \text{ K}^{-1} \) (Gombosi, Cravens, and Nagy 1985)], \( J_r \) is the external radiation energy flux, \( s_{\text{abs}} \) is the absorption coefficient of the dust grain, \( \varepsilon_{\text{emiss}} \) is the dust infrared emissivity (in the calculations \( \varepsilon_{\text{emiss}} = 0.95 \) values were adopted), \( \sigma \) is the Stefan-Boltzmann constant \( (\sigma = 5.67 \times 10^{-5} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ K}^{-4}) \). The recently corrected (Kitamura 1986) heat transfer coefficient, \( C_H \) (introduced by Probstine 1968), is the following:

\[ C_H = \frac{(2R)^{0.5}}{\gamma - 1} \Gamma \left[ 2\gamma + 2(\gamma - 1)s^2 \right. \]

\[ \left. - (\gamma - 1) \frac{\text{erf} (s_0)}{s_0} \right] - \frac{(\gamma + 1)}{T_a}. \]

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

\[ F_{\text{gs}} = \int f_d da \pi a^2 C_B \frac{\rho}{a_{\text{p}}^2} s_0 \sigma_a C_H(s_0, T_a), \]

\[ Q_{\text{gs}} = \int f_d da \pi a^2 \left[ V_a \sigma_a C_B(s_0, T_a) + 4T^{0.5}C_H(s_0, T_a) \right], \]

Here \( a_0 \) represents the minimum dust size \( (a_0 = 0.1 \mu \text{m}) \), while \( a_m \) is the maximal liftable dust particle radius (see Gombosi, Nagy, and Cravens 1986).

Following Probstine’s (1968) pioneering work, time-dependent, multidimensional, coupled partial differential equation system (eqs. [1]–[9]) was solved with various approximations. First, a steady state, spherically symmetric model was adopted using a single characteristic dust size (Probstine 1968). In this model the steady-state gas equations can be combined into one first-order differential equation which has a 0/0 type singularity at the sonic (or critical) point. In order to obtain a “physical” transonic solution, one has to “prescribe” the smooth behavior at the sonic point. During the next decade or so, the method was extended to include a realistic dust size distribution (Hellmich 1979; Gombosi et al. 1983) and/or multiple scattering of visible light on dust particles (Hellmich and Keller 1981; Weissman and Kieffer 1981, 1984; Marconi and Mendis 1982, 1983, 1984, 1986). Recently, Gombosi et al. (1985) have published the first time-dependent dusty-hydrodynamic model using spherical symmetry and a single dust size. Kitamura (1986) was the first to publish two-dimensional (axisymmetric) dusty gas dynamic solutions. Even though Kitamura’s (1986) model is time dependent, so far he has published only steady state results describing gas and dust distributions in a long-lasting dusty jet. At the same time, Sagdeev et al. (1985) analytically estimated the radial dependence of the angular extent of a dusty jet (\( \Theta \)) and obtained an approximate relation consistent with Kitamura’s (1986) numerical results:

\[ \ln (\Theta) \sim \frac{(\gamma - 1)}{2} \ln (r). \]
Kitamura's (1986) axisymmetric results show that inside a dusty gas jet the gas and dust distributions are not far from spherical symmetry, and consequently a time-dependent spherically symmetric dusty gas jet model seems to be a reasonable first approximation in describing temporal evolution of comet outbursts in the innermost coma (however, one has to be very cautious near the jet boundaries). In this case equations (1)-(3) can be approximated in the gas-dust interaction region \((r < 300 \text{ km})\) by the following expressions:

\[
\frac{\partial}{\partial t} (Ap) + \frac{\partial}{\partial r} (Ap\rho) = 0 ,
\]

\[
(15)
\]

\[
\frac{\partial}{\partial t} (Ap\rho) + \frac{\partial}{\partial r} (Ap\rho^2 + Ap) = A'p - AF_{gd} ,
\]

\[
(16)
\]

\[
\frac{\partial}{\partial t} \left( \frac{1}{2} Ap\rho^2 + \frac{1}{\gamma - 1} Ap \right) + \frac{\partial}{\partial r} \left( \frac{1}{2} Ap\rho + \frac{\gamma}{\gamma - 1} \right) Ap = AQ_{ext} - AQ_{gd} ,
\]

\[
(17)
\]

where \(A\) is the area function \((A'\) is the spatial derivative of \(A\)) and \(Q_{ext}\) is the external heat source rate.

The present model considers a water vapor-dominated cometary atmosphere \((\gamma = 4/3, m = 3 \times 10^{-23} \text{ g})\). When determining the external energy source rate, \(Q_{ext}\), we tried to retain simplicity as much as possible, yet include the most important processes. It seems to be generally accepted that the main contribution to the photochemical heating of an H₂O-dominated inner coma is due to photodissociation of water molecules (see Mendis, Houpis, and Marconi 1985; Huebner 1985). The solar radiation scattered within the coma is partially trapped and it more or less compensates for the reduction of the direct radiation (Mendis et al. 1985); consequently, the photochemical heating rate can reasonably be approximated using the unattenuated solar radiation. Using this assumption the photochemical heating rate can be approximated in the inner coma as (Gombosi et al. 1985):

\[
Q_{phe} = 2.8 \times 10^{-17} \frac{n}{d} ,
\]

\[
(18)
\]

d where \(Q_{phe}\) is in units of ergs cm⁻³ s⁻¹ and \(d\) is the Sun-comet distance (in astronomical units).

An other important heat source (or sink) is the gas interaction with the infrared radiation field. It was pointed out by various authors (see Crovisier 1984; Marconi and Mendis 1986) that most of the dust thermal radiation is emitted in the 1–20 \(\mu\)m wavelength range, where several rotational and vibrational transitions exist for the highly dipolar water molecules, and they have very large resonance absorption cross sections \((\sim 4 \times 10^{-14} \text{ cm}^2\); Huebner 1985). In a collisionless gas the resonant radiation is continuously absorbed and reemitted by the water molecules; in other words, it is trapped by the gas. Marconi and Mendis (1986) were the first to recognize that in the collision-dominated inner coma a large fraction of the rotational/vibrational excitation energy of water molecules can be transformed via collisions into translational energy, thus increasing the gas translational temperature. This new heating is the opposite of the radiative cooling (Shimizu 1976; Crovisier 1984) in which it is assumed that molecular collisions excite the water molecules and the excitation energy is lost by emission of infrared radiation. Marconi and Mendis (1986) derived an approximate formula to describe the combined effect of the Shimizu (1976) cooling (as modified by Crovisier 1984) and the gas heating due to infrared radiation trapping:

\[
Q_{IR} = -Q_{emiss} n \exp (\tau) + \eta_{IR} Q_{abs} [1 - \exp (-\tau)] \int_0^{\infty} da \alpha_f, T_a^4 ,
\]

\[
(19)
\]

where \(\eta_{IR}\) is an efficiency factor (its value is around unity), \(Q_{abs} \approx 10^{-2} \text{ ergs cm}^{-3} \text{ s}^{-1}\) (Marconi and Mendis 1986). The cooling term can be expressed as (Crovisier 1984):

\[
Q_{emiss} = \begin{cases} 4.4 \times 10^{-22} T_a^{3.35} , & T < 52 \text{ K} , \\ 2.0 \times 10^{-20} T_a^{2.47} , & T \geq 52 \text{ K} , \end{cases}
\]

\[
(20)
\]

and the optical depth, \(\tau\), is defined by the following expression (see Gombosi et al. 1986):

\[
\tau = \sigma_{abs} \int_0^{\infty} dr' m(r') ,
\]

\[
(21)
\]

It can be seen that at large cometocentric distances \((\tau \ll 1)\) \(Q_{IR}\) gives back the well-known Shimizu cooling, while in a dense coma \((\tau \gg 1)\) expression (19) describes a strong heat source. For most active comets \(\tau \approx 1\) in the gas-dust interaction region; consequently, expression (19) should be used instead of the more conventional Shimizu (1976) cooling term.

In the present set of calculations 12 dust sizes were used logarithmically spaced between 0.1 and 100 \(\mu\)m \((a = 0.13, 0.24, 0.42, 0.75, 1.33, 2.37, 4.22, 7.50, 13.34, 23.71, 42.17, 74.99 \mu\)m). The dust bulk density was taken from Divine and Newburn (1983):

\[
\rho_d = \rho_0 - \rho_1 \frac{a}{a_1} ,
\]

\[
(22)
\]

where \(\rho_0 = 3 \text{ g cm}^{-3}\), \(\rho_1 = 2.2 \text{ g cm}^{-3}\), and \(a_1 = 2 \mu\)m. The dust particles were assumed to follow a Hanner-type distribution function at the nuclear surface (Hanner 1983):

\[
f_a = f_0 \left( 1 - \frac{a}{a_0} \right)^M \left( \frac{a_0}{a} \right)^N ,
\]

\[
(23)
\]

where \(f_0\) is a normalization constant, \(a_0 = 0.1 \mu\)m, \(M = 12, N = 4.2\) (Divine et al. 1986).

At the surface of the nucleus the reservoir outflow model (Gombosi et al. 1985) was adopted. In this model the sublimating surface is replaced by a reservoir containing a stationary perfect gas with the surface temperature and sublimation pressure. The gas from the reservoir is discharged to the low-pressure external medium either directly or through a thin layer of porous dust covering the nuclear surface. The time-dependent gas and dust production parameters are determined by the pressure difference and the dust friability parameter (defined by Horányi et al. 1984).

### b) Computation of “Interplanetary” Dust Trajectories

At a distance of \(\sim 300 \text{ km}\) the dust particles reach their terminal velocities and decouple from the outflowing gas (see Keller 1983; Gombosi, Nagy, and Cravens 1986). Beyond this distance the gas-dust interaction can be neglected and the radiation field can be approximated by the unattenuated solar radiation. In calculating the trajectories of dust grains in this region, traditionally only two forces have been taken into account: solar gravity and radiation pressure, the gravity of
the small cometary nucleus itself being negligible (see Mendis, Houpis, and Marconi 1985 for a recent review). Wallis and Hassan (1982) and Horanyi and Mendis (1985) have pointed out the potential importance of dust charging, but in the present calculation we neglect the modifications caused by electromagnetic forces. The equation of motion of a dust particle in an inertial frame of reference can be expressed as

$$\frac{dV_a}{dt} = -\frac{2}{4\pi D_a} F_{rad,a} e_{cs} + G_{sol},$$

(24)

where $e_{cs}$ is a unit vector pointing from the comet towards the Sun and $G_{sol}$ is the solar gravitational acceleration. The radiation pressure force per unit surface area ($F_{rad,a}$) is (see Mendis et al. 1985):

$$F_{rad,a} = \frac{1}{cd^2} \int_0^\infty d\lambda Q_{sc}(\lambda, a) S_0(\lambda),$$

(25)

where $c$ is the velocity of light, $S_0(\lambda)$ is the solar flux at 1 AU, and $Q_{sc}(\lambda, a)$ is the scattering efficiency of dust particles. Throughout this calculation the value of the integral in expression (25) was approximated using the results of Hellmich and Schwemm (1983).

In the present model the coupled spherically symmetric time-dependent dusty gasdynamics problem was solved between the surface and 300 km. Beyond 300 km equation (24) was individually solved for a large number of dust particles—taking into account solar gravity, radiation pressure, and the orbital motion of the nucleus. The magnitude of the initial (or "injection") velocities (at $r = 300$ km) of the individual dust particles were obtained from the dusty gasdynamics problem. It was assumed that the dust particle velocity vectors were radial (in the comet's frame of reference) at the cometary distance $r = 300$ km. This method is quite similar to the one adopted by Hellmich and Schwem (1983), with the main difference being that we considered a time-dependent dust injection velocity and size distribution profile at the gas-dust decoupling distance, and then followed each dust particle trajectory individually.

The present model represents the first comprehensive attempt to calculate the temporal evolution of large-scale gas and dust characteristics following a localized comet outburst. At the same time the model has several limitations and shortcomings; most questionable is the assumption of spherical symmetry in the inner coma ($r < 300$ km). In the next step we intend to improve the model by developing a multidimensional dusty gasdynamic code with improved chemistry and gas-dust interaction model.

III. RESULTS AND DISCUSSION

The combined hydrodynamic-kinetic method described in the previous section was used to establish the possible role of spatially localized dusty gas outbursts on cometary dust halo formation. The calculation was started with a steady state, spherically symmetric initial condition. The nucleus was assumed to have a radius of 3 km with a 200 K isothermal surface temperature, resulting in uniform gas and dust production rates of $1.1 \times 10^{-5}$ g cm$^{-2}$ s$^{-1}$ and $2.9 \times 10^{-6}$ g cm$^{-2}$ s$^{-1}$, respectively (the dust/gas production rate ratio was 0.27). The heliocentric distance was $d = 0.83$ AU, corresponding to comet Halley's position on 1986 March 9 (date of the Vega 2 encounter). At a time $t = 0$ a spatially and temporally localized surface temperature jump (from 200 to 210 K) caused a comet outburst, resulting in 4 times larger gas and dust production rates ($4.3 \times 10^{-5}$ g cm$^{-2}$ s$^{-1}$ and $1.2 \times 10^{-5}$ g cm$^{-2}$ s$^{-1}$, respectively) in this localized region.

In the first step the time-dependent dusty gas flow equations (Eqs. [15]–[17]) were solved, together with the dust particles' equation of motion (Eq. [5]) and the energy balance equation (Eq. [6]). The coupled time-dependent differential equation system was solved using a modified Godunov first scheme method (see Gombosi et al. 1985). This numerical scheme is very convenient for describing the temporal evolution and propagation of shock waves and other discontinuities which naturally evolve in our outburst model.

Figure 1 shows the temporal evolution of the radial gas velocity profile following the comet outburst. Inspection of

![Figure 1](image_url)

**Fig. 1.**—Gas velocity profiles obtained following the onset of a comet outburst at $t = 0$ s. Numbers marking the various curves represent the time (in seconds) elapsed since the beginning of the outburst.
Fig. 2.—Dust velocity and number density profiles in the inner coma. Upper left panel shows velocity profiles of 0.42 μm particles, while in upper right panel differential dust number density distributions are presented for the same particle size. Two lower panels show the same quantities for 4.2 μm dust grains. Numbers marking the various curves represent the time (in seconds) elapsed since the beginning of the outburst.
Figure 1 reveals that a fast blast wave is generated by the sudden pressure increase at the nucleus. As the blast wave moves through the innermost coma it weakens as a result of the energy and momentum dissipation caused by the gas-dust interaction. The evolution of the velocity and number density profiles for two characteristic dust sizes (0.42 and 4.2 \( \mu m \)) are presented in Figure 2. It can be seen that the 10 K surface temperature increase results in larger dust velocities, as well as increased gas and dust production rates. The dust grain velocity increase is localized to a narrow (but slowly expanding) region: this region moves outward as a dust front. The dust density exhibits a peak in this transition region, primarily because the particle flux has already jumped to its increased post outburst level, but the velocity has not increased to its new value yet. The broadening density peak (which might be a factor of 10 higher than the background) is propagating outward in the inner coma. The velocity of this peak is \( \sim 0.1-0.2 \) \( \text{km s}^{-1} \), depending on the dust size.

Calculated terminal velocity distributions are shown in Figure 3. It is interesting to note that the dust terminal velocities are considerably higher during the outburst than before. The increase is \( \sim 20\% \) for the smallest dust grains (\( \alpha = 0.13 \mu m \)), while large particles (\( \sim 100 \mu m \)) exhibit an \( \sim 100\% \) velocity increase. It can be seen from Figure 2 that most of the excess velocity is gained in the immediate vicinity of the nucleus. According to the Probst (1968) model of gas-dust interaction, the acceleration of dust particles is proportional to the product of the gas pressure and a function of the gas-dust relative Mach number, \( s_d \) (defined by eqn. 7); consequently, the increased gas pressure in the active cometary region results in higher acceleration of dust grains.

The effect of the increased dust terminal velocities on the dust coma was calculated using the three-dimensional kinetic model outlined earlier. Figure 4 shows four spatial distribution snapshots of 0.42 \( \mu m \) size dust particles projected onto the orbital plane following a 2 hr long, 30\(^\circ\) wide subsolar outburst. Six hours after the onset, the leading edge of the outburst population has already reached the apex distance of pre-outburst particles. At \( t = 18 \) hr the new dust grains reach their apex distance. It is obvious that larger injection velocities result in larger apex distances, because the antisinward force acting on a given size particle needs longer time to turn around an originally faster grain. At \( t = 18 \) hr a gap can be observed between the outburst ejected dust particles and the “old” dust coma. Similar gaps have been observed at various comets, for instance at comet Donati (see Horányi and Mendis 1985). Later the outburst generated dust population starts to move antisinward under the influence of solar radiation pressure; 30 hr after the outburst the newly formed dust halo and the old coma again overlap. After 42 hr the dust halo has already moved down to the tail, and then it slowly dissolves in the background. Similar snapshots of the 4.2 \( \mu m \) population are shown in Figure 5. The general behavior of these particles is very similar to that of the 0.42 \( \mu m \) ones; the major difference is that the velocities and accelerations are much smaller, and consequently the characteristic time scale is much larger. In this case the orbital motion of the comet also starts to show some influence on the dust trajectories, causing slight asymmetries (this asymmetry becomes more pronounced for even larger grains).

We repeated the kinetic part of the calculation for an outburst located 45\(^\circ\) from the subsolar point pointing toward the orbital motion. Figure 6 shows spatial distribution snapshots of 0.42 \( \mu m \) size dust particles projected onto the orbital plane. It can be seen that a distorted dust halo is formed as a result of the asymmetric geometry; this halo evolves in a manner basically similar to that of subsolar outburst. Around \( t = 18 \) hr a distinct dust halo is formed which later broadens and dissolves as it moves toward the tail.

IV. SUMMARY

Evolution of gas and dust distributions following a spatially and temporally localized comet outburst was calculated using a kinetic-hydrodynamic hybrid method. In the inner coma (\( r < 300 \) km) the time-dependent continuity, momentum, and energy equations of the dusty gas flow were solved simultaneously, assuming spherical symmetry within the jet and a Probst (1968) type gas-dust interaction model. In this region

![Dust terminal velocity distributions before and 60 minutes after the onset of the comet outburst](image_url)
UNIT LENGTH = $10^4$ km

Fig. 4.—Snapshots of 0.42 μm dust particles following a 30° wide subsolar outburst occurring at $t = 0$
UNIT LENGTH = $5 \times 10^4$ km

Fig. 5.—Snapshots of 4.2 μm dust particles following a 30° wide subsolar outburst occurring at $t = 0$
UNIT LENGTH = 10^4 km

Fig. 6.—Snapshots of 0.42 μm dust particles following a 30° wide subsolar outburst located 45° from the subsolar point occurring at t = 0
a combined photochemical-dust infrared heat source resulted in significant gas heating. In the calculation, 12 dust sizes (logarithmically spaced between 0.1 and 100 μm) were used: dust particles were assumed to follow a Hanner-type size distribution at the surface with a spectral index of -4.2. Beyond 300 km a three-dimensional kinetic model was used to calculate the trajectory of each individual dust grain. In the dust equation of motion solar radiation pressure, solar gravity, and cometary orbital motion were taken into account. At the gas-dust decoupling interface (located at a cometocentric distance of 300 km) dust particles were ejected radially (in the cometocentric frame of reference) with their size-dependent terminal velocities determined by the dusty gasdynamic part of the model. The number of injected dust particles was proportional to their number density at the interface surface.

It was found that following the onset of the comet outburst a gas-dust blast wave propagates outward in the inner coma. About 60 minutes after the increased gas and dust production was initiated at the nucleus a new equilibrium was reached in the inner coma. The most important feature of this new steady state was the significant increase of the dust terminal velocities, due to the increase of gas pressure. These higher terminal velocity values resulted in larger apex distances for dust particles emitted during the outburst. Since the dust particles spend a relatively long time near their apex points (the cometocentric velocities are fairly small in this region), the outburst generates a long-lasting (~10 hrs), distinct dust envelopes in front of the regular dust coma, which later propagate toward the tail and dissolve. This type of envelope was observed at several comets (cf. comet Donati).

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