LONG DUST TRAILS OF SHORT PERIOD COMETS

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1. Introduction

Comets constitute an important source for the zodiacal dust cloud. Mainly large particles are contributed because the smaller particles are emitted into hyperbolic orbits relative to the sun. Radiation pressure force reduces the effective solar gravitational attraction. Information about large cometary particles can be derived from a variety of sources requiring quite different observational techniques. Many distinct meteor streams are connected to orbits of short period comets. These streams contain large dust particles that are very little influenced by radiation pressure force. In some cases such as the η Aquarids and Orionids connected to comet Halley the total mass and the age of the meteors have been derived (Hughes, 1987; Hajduk, 1987). The mass of the streams is 5 to 10 times larger than the present mass of the nucleus and their lifetime corresponds to 2000 to 3000 orbital periods. Visible meteors are typically 10^{-2} g and more of centimetre size.

Radar observations of comets coming close to the earth revealed the presence of clouds of large dust particles around cometary nuclei (Campbell et al., 1989; Harmon et al., 1989) dust particles are so numerous that their reflection can obscure the signal from the cometary nucleus itself. The observed particles had to be of the size of the radar wavelength typically around 10 cm. Little is known about the nature and physics of these clouds. Are the particles gravitationally bound? What is the total mass contained in these clouds? The radar signal are yet too noisy to extract more significant observations. Comet IRAS-Araki-Alcock was observed at a distance of only 0.033 AU. Its radar cross section corresponded to a few km^2.

The infrared satellite IRAS observed dust trails concentrated near the orbits of short period comets (Sykes et al., 1986). Dust particles were found in some cases all around the orbit, in other cases in front of and trailing the nucleus. The outflow velocities of the observed particles are small, in the range of a few metres per second, their sizes range around a few millimetres (comet P/Tempel 2 (Sykes et al., 1990)). The IRAS data have not been fully reduced and more results can be expected. Analytical tools (models of the dust density distribution) have been developed and first results are reported in the second part of the paper.

In the visible wavelength range the large particles can hardly be observed since their scattered light is masked by the much more numerous small particles in the range from submicron to several 100 µm. The observations of anomalous tails under special geometric circumstances are exceptions and yield limited information on larger particles (e. g. Richter and Keller (1988)).

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The attitude of the Giotto was disturbed during its encounter with comet Halley in March 1986. The Halley Multicolour Camera (HMC) recorded several distinct dust impacts that allowed for direct determinations of lower mass limits of the particles causing the perturbations (Curdt and Keller, 1988). Calculation of the accumulated flux yields 2 additional points of measurements in the flux vs. mass diagram (see Fig. 3 of Curdt and Keller (1990) substantiating the extrapolation by McDonnell et al. (1987)). The dust mass distribution of comet Halley is dominated by large millimetre size particles and the total dust distribution is comparable to that of the gas (ratio ≥ 1). The impact events observed by HMC have been further analysed and the outflow velocities of the particles have been determined. The properties of these particles resemble in many respects the particles observed in the cometary dust trails by IRAS. Some relevant results are summarized in the following section and discussed with respect to the properties of trail particles.

1.1 PARTICLES NEAR THE NUCLEUS OF COMET HALLEY

Five clearly discernable events were selected for analysis. 2 occurred at distances around 8 10^4 km, 3 closer than 1.5 10^4 km. Further in the events became too numerous to be clearly separated. The characteristics of the 5 dust particle impacts are listed in Table I. Keplerian trajectories connecting the nucleus and the point of observation could be determined assuming that the particles had been emitted in direction towards the sun (Richter et al., 1990). Under these conditions all observed particles could have left the nucleus shortly before or after perihelion. The close in particles are about a factor of ten more massive (around 10 mg) than the ones observed earlier. Their outflow velocities, however, are considerably smaller than predicted by hydrodynamical calculations of the gas drag. Figure 1 displays solutions for the outflow velocity and ejection angle, Θ (corresponding to the zenith angle relative to the sun direction) for particle number 4. Velocities in the range from 20 to 30 km as predicted by the gas dynamic models (Gombosi et al., 1986) require ejection on the night side ($\Theta > 90°$) of the nucleus a few days before observation! Alternatively, these particles could have been ejected from the nucleus at much earlier times long before comet Halley passed its perihelion. The calculations show solutions with reasonable zenith angles (below 30°) for times hundreds of days before perihelion requiring outflow velocities below 10 m s^{-1}. These particles resemble the particles found in the dust trails observed by IRAS: same size range, similarly low outflow velocities. It is possible that HMC and the Giotto encountered these old particles that stay in the vicinity of the nucleus for a long time. In this case the larger particles would not result from the production shortly before encounter. The excess of large particles in the actual cometary dust production rate may not be as big as deduced in the papers quoted above.

If these particles were indeed members of the "trail" population they may have been liberated from the nucleus years before the Giotto encounter. When comet Halley was recovered at a heliocentric distance of more than 11 AU a weak coma was present in the images. The analyses of the dust trails of shorter period comets (typically comet P/Tempel 2) showed that the dust trails comprise particles released many orbital periods ago and along most of the cometary orbit.

1.2 PARTICLES RELEASED ALONG THE COMETARY ORBIT

Analyses of cometary tails are complicated because dust particles emitted from the nucleus at a wide variety of orbital positions contribute to the density at any one point. "Old" particles have orbited the sun many times. The positions of particles oscillate perpendicular to the orbital plane but also relative to the nucleus in the orbital plane. In addition one and the same particle (characterized by its ß value, the ratio of radiation pressure force to gravity) will reach different positions depending on the moment of its release along the orbit.

Some of these effects are illustrated in the following section. The calculations were performed for comet Tempel 2 for the time of observation when the comet passed through the ecliptic on 22.5 July 1983. This point of time lies inside the interval of IRAS observations of the cometary trail. The orbital parameters of comet Tempel 2 are: period (5.29 a), perihelion distance (1.38 AU), and inclination of orbit (12.4°).

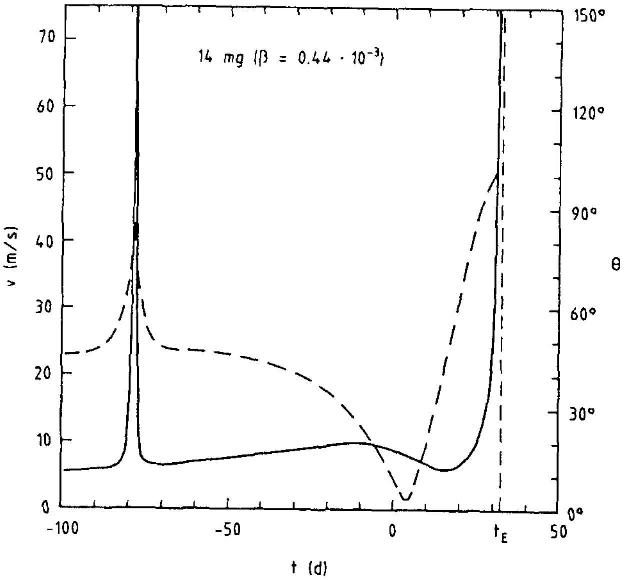

Figure 1. Solutions of trajectories connecting the nucleus and the location of impact for event No 4, characterized by the emission velocity (left ordinate) and zenith angle (right ordinate, dashed line), are displayed as function of time of release relative to the perihelion of comet Halley.

2. The trail width

The high resolution mode used for observations of specific targets could resolve the width of the cometary trail to about 4 arcmin (Sykes et al., 1990). A particle released from the nucleus with a velocity component $v_\perp$ perpendicular to the comet's orbital plane will pass this plane again at a the opposite nodal line at a true anomaly different by 180°. This behaviour explains, the two minima of the curve shown in Fig. 2. The comet's true anomaly at the time of observation is 36.6°. The curve depicts the distance of a particle released with $v_\perp = 1$ km s^{-1} perpendicular to the orbital plane of the comet as seen from earth and measured by its offset angle, δ. The total width of the trail would be twice this ordinate value. The actual offset angle of a particle strongly varies with time of release between 0 (nodal line) and $\approx$ 0.5 arcmin (for $v_\perp = 1$ m s^{-1}). The average offset angle is smaller and probably more characteristic for the width of the cometary trail. The IRAS observations limits $v_\perp$ to < 8 m s^{-1}.

2.1 ORBITAL PERIODS OF RELEASED DUST PARTICLES

The distribution of dust particles along a cometary orbit, i.e. their distances from the nucleus as a function of time is determined by the differences of the orbital periods of the particles relative to that of the nucleus. The orbital period of a released particle depends on its effective

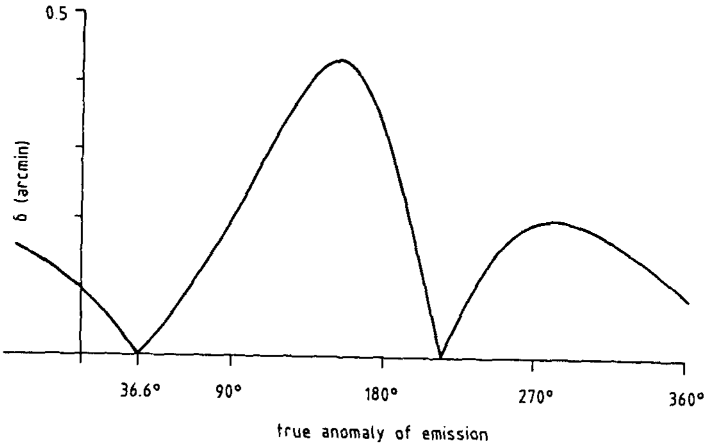

Figure 2. The offset angle of a particle released with $v_\perp = 1$ m s^{-1} as function of true anomaly of comet P/Tempel 2 seen from earth.

ß value and on its velocity (direction and magnitude). But it also depends on the time, i.e., orbital position, of the release. This is shown in Fig. 3 where the abscissa is the true anomaly of the particle release. Assuming that the ejection velocity of a particle is zero the relative change in orbital period, T, as a function of ß can be approximated by $\frac{1}{T}\frac{\partial T}{\partial \beta}\Big|_{\beta=0}\cdot\beta$ (left hand side of left ordinate).

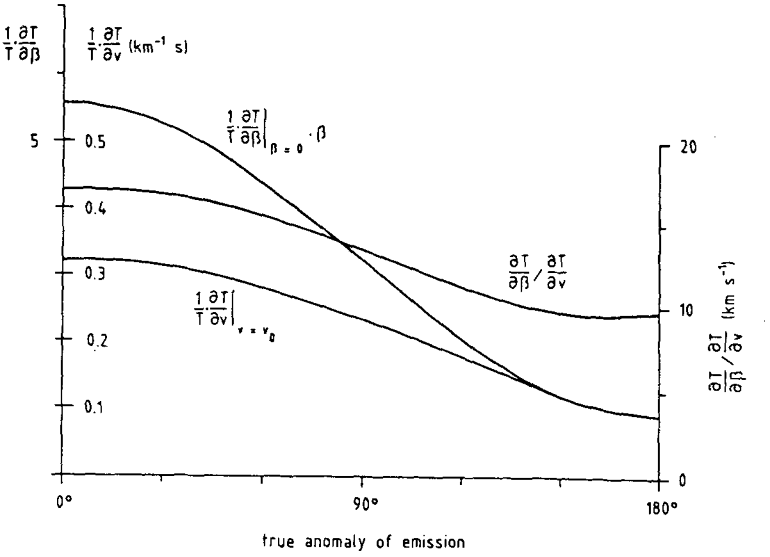

Figure 3. The change of period of particles released along the orbit of comet P/Tempel 2. Partial derivations and their ratio at zero emission velocity and ß=0 are displayed as functions of true anomaly of comet P/Tempel 2. v_0 is the velocity of the cometary nucleus.

A release around perihelion (true anomaly = 0) is most effective, here the relative increase in the particle periods is 5 times larger then at aphelion.

The effects of ejection velocity can be studied by looking at the quantity $\frac{1}{T}\left.\frac{\partial T}{\partial v}\right|_{v=v_0}$, where v_0 is the orbital velocity of the comet at time of particle release. Again the effect is strongest at perihelion (left hand side, right ordinate) however, the relative variation is only little more than a factor 2. Particles released with a small velocity component in direction of the nucleus velocity will acquire orbits with a longer period and trail the cometary nucleus after some time.

The effects of outflow velocity and β value of a particle can compensate each other. The ejection velocity Δv (into the direction opposite to the cometary motion) that compensates the effect of radiation pressure yielding $\Delta T = 0$ can be derived from $\Delta v = \frac{\partial T}{\partial \beta} \cdot \left(\frac{\partial T}{\partial v}\right)^{-1} \cdot \beta$. The behaviour of Δv as function of true anomaly is given as the third curve of Fig. 3 (right hand ordinate). Particles released at perihelion require the largest velocity for compensation so that they stay with the nucleus. The difference between perihelion and aphelion is not pronounced.

For a particle with $\beta = 0.5 \cdot 10^{-3}$, typical for particles impacting the Giotto spacecraft (see Table I), an ejection velocity of ≈ 9 m s^{-1} would compensate for the particles reduced effective solar attraction. This value is similar to $v_\perp$ derived from the width of the dust tail.

TABLE I

The columns represent the event number, the distance to the nucleus when the impact occurred, the median mass (1.4 times the minimum mass) of the particle, the ratio β, the minimum ejection angles, the corresponding emission times with respect to the comets perihelion, the emission velocities, and corresponding velocities derived from gas dynamic calculations (Gombosi et al., 1985).

No	Distance to nucleus [km]	m=1.4 m_0 [mg]	β 10^{-3}	θ_{min} [°] zenith	t [d]	v [m s^{-1}]	v [m s^{-1}] Gombosi
1	$8.6 \cdot 10^4$	1.4	0.95	5.9	-9	40	31
2	$7.6 \cdot 10^4$	0.7	1.20	5.2	-6	41	36
3	$1.48 \cdot 10^4$	7	0.56	3.2	0.5	13	26
4	$0.71 \cdot 10^4$	14	0.44	2.3	4.5	8	24
5	$0.45 \cdot 10^4$	7	0.56	1.4	8.5	7.6	27

3. Discussion

The initial, preliminary, calculations show that particle velocities derived from the widths of cometary trails (the example is comet P/Tempel 2) are of similar magnitude as the velocities required for compensation of the reduced solar attraction of released particles. Many of these particles can stay close to the nucleus for extended times.

A release at aphelion requires a smaller compensating velocity as at perihelion. The presented calculations demonstrate the complexity of a determination of a dust particle density distribution. Questions such as the variation of production rates as function of orbital position are still open. What are the mechanism of release at large heliocentric distances? Can particles be trapped in the comet's vicinity by gravitation to form an extended source such as the clouds of large particles observed by radar? And in connection with the observations by the Halley Multicolour Camera: can the density of old (trail) particles be large enough to explain the impacts during encounter?

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