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GRANT NGR 09-015-159

Final Report

Principal Investigator

Dr. Zdenek Sekanina

Prepared for

National Aeronautics and Space Administration
Washington, D.C. 20546

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1. Introduction

The following is a summary of the research completed at the Smithsonian Astrophysical Observatory under Grant NGR 09-015-159. Details can be found in the respective Semiannual Progress Reports Nos. 1 through 18 and in the published papers, the list of which is attached.

2. Application of the Finson-Probstein Approach to the Dust Tail of Comet Bennett 1970 II

This work has led to the determinations of the size-density distribution function of the emitted dust particles; the emission rate of the dust; the particle ejection-velocity distribution; and the comet's nucleus radius. It is concluded that the drag force acting on the dust must have essentially been due to water vapor and that the ratio of the rate of emission of dust to the rate of emission of gas was about 0.5.

3. A Study of Sungrazing Comet 1887 I

The results indicate that the straight and narrow tail of Comet 1887 I was a synchrone formed by solid material shattered during an explosion in the comet's nucleus that took place about 5.5 hr after perihelion. The total mass of the tail appears to be between 10^{14} and 10^{15} g, which represents a sphere of about 1 km in diameter. It is likely that no major body with a sufficient reservoir of volatile substances survived the event — the probable reason why no nucleus was ever observed. The width of the tail, typically 1°, corresponds to a lateral expansion of about 1 km/sec, consistent with the expected ejection velocity.

4. Icy Tails of Comets at Large Distances from the Sun

The observed orientation of the tails of the distant comets is shown to be consistent with the mechanical theory. Contrary to previous investigations, it is concluded that no forces other than solar gravity and radiation pressure need be considered to explain the strongly nonradial orientation of the tails. The results indicate that the "age" of the tails is up to 5 years and that the corresponding emission distances range between 5 and 15 A.U. from the sun. From the "edge-on" tail orientations it is concluded that the tails are situated with high precision in the comets' orbit planes. Analysis of the visible lengths of the tails indicates that particles emitted from the comets must be subjected to extremely low accelerations, not exceeding 1% of the solar gravity, and that therefore they are very heavy particles, at least 0.01 cm in size. The absence of particles smaller than about 0.01 cm contradicts all known particle-size distributions ever studied in connection with comets, except for the Delsemme-Wenger distribution of grains of the clathrate hydrate of methane, whose lifetime is shown to be practically infinite at heliocentric distances over 4 A.U. However, only ices much more volatile than water snow can supply drag acceleration sufficient to strip away such grains. An assumption of dirty clathrate grains can explain the discrepancy between the size distribution of solid material at large heliocentric distances and that at moderate to small distances. Micron and submicron dust particles, bound to the grains far from the sun, are set free when the grains start to evaporate appreciably. The observed fact that the tails of the distant comets do not substantially broaden with the distance from the nucleus can be explained by very low ejection velocities of the grains. Anisotropic distribution of active areas on the nuclear surface can significantly contribute to this phenomenon and also appears to be the most promising explanation for a sharply bounded envelope around the nuclear condensation, another characteristic of the distant comets.

5. The Antitail of Comet Kohoutek 1973f: A Prediction and Its Confirmation

This comet was predicted to develop an antitail, i.e., a sunward oriented dust tail, shortly after its perihelion passage on December 28, 1973, and the possibility of its detection by the Skylab astronauts was suggested. This prediction was remarkably confirmed by the Skylab crew's reports; the antitail was later also noticed by many ground-based observers and became the subject of several major studies. The general projection conditions for the appearance of an antitail have been formulated and can from now on be applied to any comet's apparition.

6. Investigation of the Antitail of Comet Kohoutek

A preliminary analysis of the observations of the antitail has led to a relatively flat particle-size distribibition function and to an emission rate depending inversely on the 3rd or 4th power of heliocentric distance. A more quantitative study, based on photometric analysis of ground-based photographs, has shown that the flat size distribution is most probably due to dust-particle evaporation near perihelion. The total vaporization loss in particle diameter is estimated at about 100 microns in the antitail and it is suggested that the typical latent heat of vaporization of the dust amounted to between 40 and 45 kcal/mole at the blackbody approximation. Sodium, evaporating from dust particles, is believed to have contributed significantly to the brightness of the antitail at small heliocentric distances.

7. The Dynamics of Vaporizing Dust Particles

The indication of the presence of appreciably vaporizing particles in the antitail of Comet Kohoutek instigated an investigation of the dynamics of such particles. The heliocentric motion of a vaporizing particle near the sun has been modeled on some simplifying assumptions, taking into account the radiation pressure and the Poynting-Robertson (P-R) effect, assisted by an effect due to solar-wind sputtering. The P-R effect is known to cause small dust particles in interplanetary space to spiral in toward the sun. Surface evaporation of such particles must increase progressively with time and their size is being reduced accordingly. It is shown that when the rate of evaporation is no longer negligibly low, it induces on the particle a measurable dynamical effect, which is associated with the implied variations in the magnitude of solar radiation pressure relative to solar attraction. By gradually reducing solar attraction, the particle evaporation tends to increase the orbit dimensions, thus acting against P-R. The P-R inward spiraling, far exceeding the dynamical effect from evaporation at larger heliocentric distances, slows gradually down as the particle approaches the sun, and virtually ceases when the critical distance is reached, where the two forces approximately balance each other. Then the perihelion distance stabilizes, while the eccentricity starts increasing very rapidly until the particle is swept out of the solar system. This, in brief, is the orbital evolution of a vaporizing particle in the absence of other potentially important but rather poorly known processes, such as particle collisions, rotational bursting, electric charging and interactions with the solar wind and with the interplanetary magnetic field. Low emissivity can in fact lead to the particle's complete evaporation before its expulsion from the solar system.

8. Statistical Investigation of the Anomalous Tails (Antitails) of Comets

A cometary tail consisting of dust particles, whose diameters are mostly in the submillimeter and millimeter size ranges, is termed anomalous, when its apparent direction in the sky diverges considerably from the projected anti-solar direction. In space the anomalous tail is essentially a thin sheet of cometary debris confined to the orbit plane of the comet and located on the outside of the orbit and well behind the sun-comet direction. When the earth is crossing the orbit plane of the comet, the edge-on projection causes the anomalous tail to point exactly sunward and to adopt, typically, a spike-like appearance. The conditions of projection for observing an anomalous tail at and around the time of crossing were formulated, and subsequently applied to list comets with favorable circumstances for displaying such anomalous tails. Since the production rate of dust is never known beforehand, it is always only the favorable observing situation and not the actual presence of the anomalous tail that can be predicted. An extensive search was undertaken for reports on observations of the expected anomalous tails, among both the nearly-parabolic and the short-period comets. It was found that of the nearly-parabolic comets that could have been observed to exhibit an anomalous tail, every fifth comet was reported to have done so. The appearance of anomalous tails of the nearly-parabolic comets correlates strongly with apehlion distance, moderately with intrinsic brightness and spectrum, and possibly also with some other comet characteristics. These conclusions clearly have ramifications in the predictions of anomalous tails for the future nearly-parabolic comets.

A total of 168 predicted returns, between the years 1976 and 2000, of 53 short-period comets with perihelion distances less than 2 A.U. have been studied. It turns out that opportunities to observe antitails edge-on will be extremely rare. The examination of prospects of the detection of anomalous tails under the broad-side projection has suggested favorable geometrical conditions for 22 returns of 12 short-period comets between 1976 and 2000, but the general observing conditions should almost invariably be troubled by the excessive faintness of these comets. Nevertheless, a coordinated search has led to positive results on two occasions (Sec. 9).

9. Anomalous Tails of Periodic Comets d'Arrest and Encke

The predicted anomalous tail of Periodic Comet d'Arrest was photographed and photometrically studied. Particle dimensions span a few orders of magnitude, the mean size being in the general range of 0.01 to 0.1 cm depending on the assumed bulk density. The product of the particle albedo and of the mass production rate of meteoroids that remain gravitationally bound to the solar system is found to be about 3000 g sec^{-1} at the time of maximum activity and some 200 g sec^{-1} when averaged over the comet's revolution period. The ice content of the meteoroids is likely to be insignificant. For any reasonable value of the particle albedo and on the assumption that the dust-producing capability of Comet d'Arrest is near the average for a short-period comet, the present results suggest that the short-period comets do not supply enough mass to maintain the self-destructive interplanetary cloud of dust in steady state. The same conclusion has also been reached from a similar study of a photograph of the anomalous tail of Periodic Comet Encke.

10. Discrete Bursts of Dust in the Tail of Comet West 1976 VI

Analysis of four small-scale photographs of Comet West offers evidence of five discrete bursts of dust from the comet's nucleus from six days before perihelion to three days after it. An additional study of prints of several photographs taken at the Lowell Observatory increased the number of identified bursts to 12, spanning a total of 17 days. The images of the comet on the photographs were computer-enhanced to increase the contrast of the fine structure. The timing of two of the bursts suggests very strongly that they accompanied the two breakup events that gave birth to the companion nuclei D and B. The primary breakup, on 19 February, also coincides with a 2-magnitude surge in the comet's brightness. Some of the other dust bursts might be correlated with less conspicuous flare-ups observed in both the visual brightness and the thermal emission of the comet. A distinct intensity discontinuity makes up the trailing boundary of the main body of the dust tail. When the observed position of the discontinuity is corrected for an effect of particle-expulsion velocity, it is found to correspond to dust expelled from the comet exactly at perihelion. It is suggested that because of its timing, the intensity discontinuity could be a product of particle evaporation sharply peaked at perihelion.

11. The Striated Dust Tail of Comet West 1976 VI as a Particle Fragmentation Phenomenon

The motions of 16 striae in the dust tail of Comet West have been successfully fitted on four small-scale photographs taken on four consecutive nights. Our model assumes that the striae are the result of the ejection of dust particles that subsequently fragment in the tail. The particles responsible for the formation of a discrete stria must be emitted simultaneously, be subjected to the same repulsive acceleration in the tail, and break up simultaneously. The results of the analysis indicate a strong correlation between the ejection times and the times of known explosive events. The repulsive accelerations of the fragments are found to be between 0.6 and 2.7 times the solar attraction, indicating submicron-sized absorbing particles. We also find that the repulsive accelerations of parent particles are only slightly smaller than those of their fragments, and therefore highly nonspherical shapes of parents. Complex, tenuously bonded, chain-like aggregates of submicron-sized grains would satisfy these conditions. The mass of dust in an average stria is estimated to be about 10^9 g. There was no measurable effect from the Lorentz force indicating an upper limit of a few volts for the electric charge of the fragments. We consider rotational bursting caused by a "windmill" effect of radiation pressure to be a possible fragmentation mechanism. Application of a simple chain-particle model suggests the existence of discrete particle types.

12. Anisotropic Emission from Comets

Conspicous anisotropy in the outgassing from comets, especially from short-period ones, appears to be the factor responsible for a frequent occurence of a fan-shaped coma, extending in the general direction of the sun. It is proposed that the pattern of deviations from the sunward direction contains information on the orientation of the spin axis and on the time lag in the sublimation process, which in turn provides insight into the nature of the nuclear surface. A simple model of a spherical rotating nucleus is formulated and a trial-and-error technique devised to determine the axis-orientation constants and a lag angle, a measure of the time lag in units of the rotation period. The results of application of this method to periodic comets Encke, Tempel 2, Borelly and Schwassmann-Wachmann 3 are presented. It is shown that the sense of rotation determined in this fashion is consistent with the results established for three of the four comets from the transverse component of the nongravitational force affecting their orbital motions. It is found that in general the time lag is strongly time dependent and that lag angles approaching 90° are rather common near perihelion, suggesting a complex surface structure that involves an insulating crust of dust of variable thickness and strength. These results are compared with the observed light curves of the four comets and with the calculated distributions of integrated insolation at the nuclear surface as functions of the cometocentric latitude and time. Noticed is some tendency of the comets to turn their spin axes to the sun near perihelion and to replace, on the outbound leg of orbit, the established fan-orientation pattern by a "late"-tail pattern indicative of old, slowly accelerated particles. It is shown that the motion of P/Schwassmann-Wachmann 3 has been affected by a secular deceleration. This prediction was indeed confirmed, when in 1979 the comet passed through perihelion several weeks later than the orbital elements based on the assumption of purely gravitational motion had indicated.

13. Precession of Periodic Comet Encke

For the purpose of testing whether the nucleus of Comet Encke has been precessing over the past 200 years, a problem studied recently by Whipple and Sekanina under another NASA Grant, a number of reports on the orientations of the comet's fan-shaped coma between 1805 and 1905 have been collected and the method for the rotation-axis determination, developed under the present Grant (Sec. 12), applied. The results clearly demonstrate that the observed fan orientation is consistent with the precessing nucleus.

14. Split Comets

A dynamical study of the split comets has been supported by another NASA Grant. However, a new, successful approach, which was formulated, was based on a recognized similarity in the dynamical effects of the differential nongravitational force and of the radiation pressure. The formulation, developed for the motions of dust particles in the tail under the present Grant, could therefore rather straightforwardly be applied to the problem of the split comets.

15. Dissipating Comets

There is a small class of comets that have dissipated literally before the eyes of observers, on a typical time scale of a few weeks. This development is characterized by the following circumstances: (a) the comet may be quite bright until the fading suddenly sets in; (b) the accelerated brightness decrease is always accompanied by a progressive expansion of the apparent dimensions of the coma and results in a dramatic drop in the surface brightness, terminating in the object's complete disappearance; (c) in the advanced phase an elongation of the coma becomes rapidly prominent and a tail usually survives till the very end; (d) in some cases there is evidence that the comet had suffered an outburst (possibly more than one) many weeks or months before its extinction; (e) a possibility exists that the discovery of at least some of these objects does occur shortly following an outburst and is facilitated, if not prompted, by a flare-up entailed by the outburst. Comet Ensor, 1926 III, which disintegrated more than two months after perihelion, is shown to have undergone an outburst about two weeks before perihelion. Most of the dissipating comets disappeared around or before perihelion. It is argued that the sequence of events experienced by the dissipating comets is strongly reminiscent of the behavior of short-lived fragments of the split comets.

16. Evolution of Dust Jets in Periodic Comet Swift-Tuttle

This investigation, near completion at the present time, offers a complete interpretation of the jet, envelopes, and tail development in terms of dust emissions from discrete active areas on the rotating nucleus. It also provides quantitative information on the rotational properties of the comet; on the surface distribution and lifetime of the active areas; on the gas emission variations with time; on the mode of emission; on the time lag in sublimation versus the sun's altitude above the local horizon; and on the relation between the ejection particle velocity and the particle acceleration from radiation pressure. The method thus offers information on the gross morphology of the surface layer of the nucleus, on the nature of dust, and on the character of cometary activity.

17. Relation to the Space Exploration of Comets

Knowledge acquired through this research has found considerable application in strategy planning of cometary missions. Information supplied by this project was used in the deliberations of the NASA sponsored Comet Science Working Group; to study spacecraft operations of a rendezvous mission; and to propose a conceptual design of the dust-hazard shield for a spacecraft to flythrough Comet Halley.

18. Invited Papers and Reviews

A number of the papers in the attached list of publications have been written or presented upon request. These are mostly reviews of the progress in the field, sometimes with the emphasis on a specific problem. These are marked in the following list by an asterisk preceding the entry.

Acknowledgment

I appreciate it very much that NASA has given me the oppor-

tunity and support to conduct this research. It has been a very productive period in my scientific career at the Smithsonian Astrophysical Observatory and I look forward to continuing the cometary research at the Jet Propulsion Laboratory in Pasadena, California.

List of Publications Supported by the Grant

1. Sekanina, Z. and Miller, F. D. (1973). Comet Bennett 1970 II. Science, vol. 179, pp. 565-567.

2. Sekanina, Z. (1973). Existence of icy comet tails at large distances from the sun. Astrophys. Lett., vol. 14, pp. 175-180.

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4. Sekanina, Z. (1974). The prediction of anomalous tails of comets. Sky and Tel., vol. 47, pp. 374-377.

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