PROGRESS IN OUR UNDERSTANDING OF COMETARY DUST TAILS

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I. INTRODUCTION

It is almost generally accepted that the essentially structureless and often significantly curved tails of comets are composed of sunlight-scattering solid particles of various sizes, ejected from the comet's nucleus by evaporating gases. Much less agreement has so far been achieved as to the character, composition, and size distribution of the particles.

The original version of the theory of cometary tails (Section II) followed the pattern of comparing a simple theoretical model with comet drawings based on visual observations, while modern versions (Sections III through VIII) utilize small-scale photographs of comets instead. Other techniques, complementing the photographic study of dust tails, include spectroscopy, broad-band photoelectric photometry, colorimetry, infrared photometry, and polarimetry. Major problems for these other techniques are the large extent of a cometary tail and its low surface brightness, which drops rapidly with increasing distance from the nucleus. Consequently, such observations often refer only to the brightest part of a tail, adjacent to the nucleus and/or coma, rather than to the tail as a whole.

Since the philosophy, covering the advantages as well as the limitations, of the various techniques employed is discussed in other review papers at this Colloquium, we shall avoid describing it here. We shall refer, however, to the results obtained by any technique in which the data are relevant to the theory of dust tails.

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II. THE MECHANICAL THEORY

The birth of the mechanical theory dates back to the 1835 apparition of periodic Comet Halley. The theory's fundamentals were worked out by Bessel (1836) in his attempt to explain the comet's observed structure. He derived equations of motion for particles ejected from a cometary nucleus and driven away from the sun by a repulsive force. This force, believed by Bessel to be caused by ether, was assumed to vary in inverse proportion to the square of heliocentric distance. It was not until more than 60 years later that the repulsive force was identified as solar radiation pressure (Arrhenius 1900; Schwarzschild 1901); this interpretation is now generally accepted.

Meanwhile, the mechanical theory was being improved by Bredikhin (Jaegermann 1903). He replaced Bessel's approximate equations of particle motion (expressed in terms of a power expansion, with the time elapsed since ejection used as the variable) by precise formulas for hyperbolic motion. The two, now very common terms describing dust tails – syndyne (or syndyname) and synchrone (or isochrone) – are also due to Bredikhin.

A syndyne is defined as the locus of particles leaving a cometary nucleus continuously and subject to radiation pressure of a particular magnitude. Each syndyne is thus determined by the acceleration $1 - \mu$ exerted by radiation pressure on the particles. When expressed in units of the solar gravitational attraction, $1 - \mu$ is related to the particle's radius a (cm) and its density ρ (g cm^{-3}) as follows:

$$1 - \mu = \frac{0.585 \times 10^{-4} Q_{rp}}{a\rho} \quad , \qquad (1)$$

where Q_{rp} is the scattering efficiency of the particle for radiation pressure.

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A synchrone is defined as the locus of particles subject to radiation pressure of all magnitudes and ejected from the nucleus at the same moment. Each synchrone is therefore determined by the instance of ejection, or by its "age" τ, i.e., by the time elapsed between ejection and observation.

The shape of a synchrone or a syndyne also depends slightly on the initial (ejection) velocity of the particles. However, since ejection velocities are relatively low (only a fraction of 1 km sec^{-1}), the synchrones and syndynes used in modern methods usually refer to an assumed zero ejection velocity, and the effect of the actual velocity is taken care of in a different way. On the assumption of a zero velocity of ejection, synchrones and syndynes can be calculated from the orbital elements of the comet once the values of τ and $1 - \mu$ are specified.

Bredikhin considered most tails to be syndynes. He determined $1 - \mu$ for a rather large number of comets and eventually organized his results into a classification of cometary tails. His type I tails are now identified with the plasma tails, and type II (and type III) tails, with the dust tails.

The mechanical theory was originally intended to cover all comet tails. However, the theory completely failed to explain the complicated structure of type I tails on comet photographs and was eventually replaced by Biermann's (1951) hypothesis of interaction between the comet plasma and the solar wind.

By the 1960s, serious doubts were expressed as to the validity of the mechanical theory even for type II tails: Most dust tails appeared to match neither a synchrone

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nor a syndyne; the tails were often found to point approximately midway between the prolonged radius vector and the orbit behind the comet; a dark band, observed to part tails of several comets into two branches, and described often as a "shadow of the nucleus," was much of a mystery, as was the occasional appearance of sunward-oriented tails; and the "synchronic" bands did not behave as they were supposed to according to the theory. Thus, the mechanical theory appeared to face a very bleak future.

III. THE FINSON-PROBSTEIN APPROACH

Eight years ago, Finson and Probstein (1966) published their preliminary model of dust comets. The motion of dust particles in the tail was treated as a hypersonic, collision-free, source flow. The particles, assumed to be subject to radiation pressure of a constant magnitude ($1 - \mu = \text{const}$), were allowed to leave the nucleus isotropically and continuously, though at variable rates. The emission process was described as the radial acceleration of dust outward from the nucleus by drag forces of the expanding gas in the circumnuclear region, where the dust and gas can be considered a two-phase, "dusty-gas" continuum and the problem can be solved by a fluid-dynamics approach. The ejection velocity of the dust particles is thus described as the terminal velocity from the point of view of fluid dynamics, but it becomes the initial velocity from the viewpoint of tail dynamics after the interaction between gas and dust has terminated. In their 1966 paper, Finson and Probstein approximated the ejection velocity by a Maxwellian distribution.

Their improved model (Finson and Probstein 1968a) has become the most powerful method of analyzing the dust tails of comets. It differs from the earlier version in

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two ways: It relaxes the postulation of a constant $1 - \mu$, thus accounting for a particle-size distribution; and it replaces the assumption of a Maxwellian distribution in particle ejection velocities by a functional dependence of velocity on particle size and density, following Probstein's (1968) fluid-dynamics approach. In this model, the terminal velocity of dust particles also depends on the ratio of the mass-flow rate of dust to the mass-flow rate of gas, on the nuclear radius, and on the properties of the gas.

With the three parametric functions – the size-density distribution of particles, their emission rate as a function of time, and their ejection velocity – established, the Finson-Probstein model determines the distribution of the surface density of particles in the tail, that is, the theoretical photometric profile of the tail.

In practice, the crucial – and the most intricate – part of the Finson-Probstein method is to reach the best possible agreement between the observed photometric profile of the comet's tail and a theoretical surface-density distribution by means of varying the three parametric functions by trial and error (Fig. 1). For a particular combination of these three functions, the corresponding surface-density distribution can be obtained either by calculating contributions from particles of various sizes ejected at times held constant and then integrating the results over all ejection times (synchrone approach) or by calculating contributions from particles of constant dimensions ejected at various times and then integrating over all particle sizes (syndyne approach).

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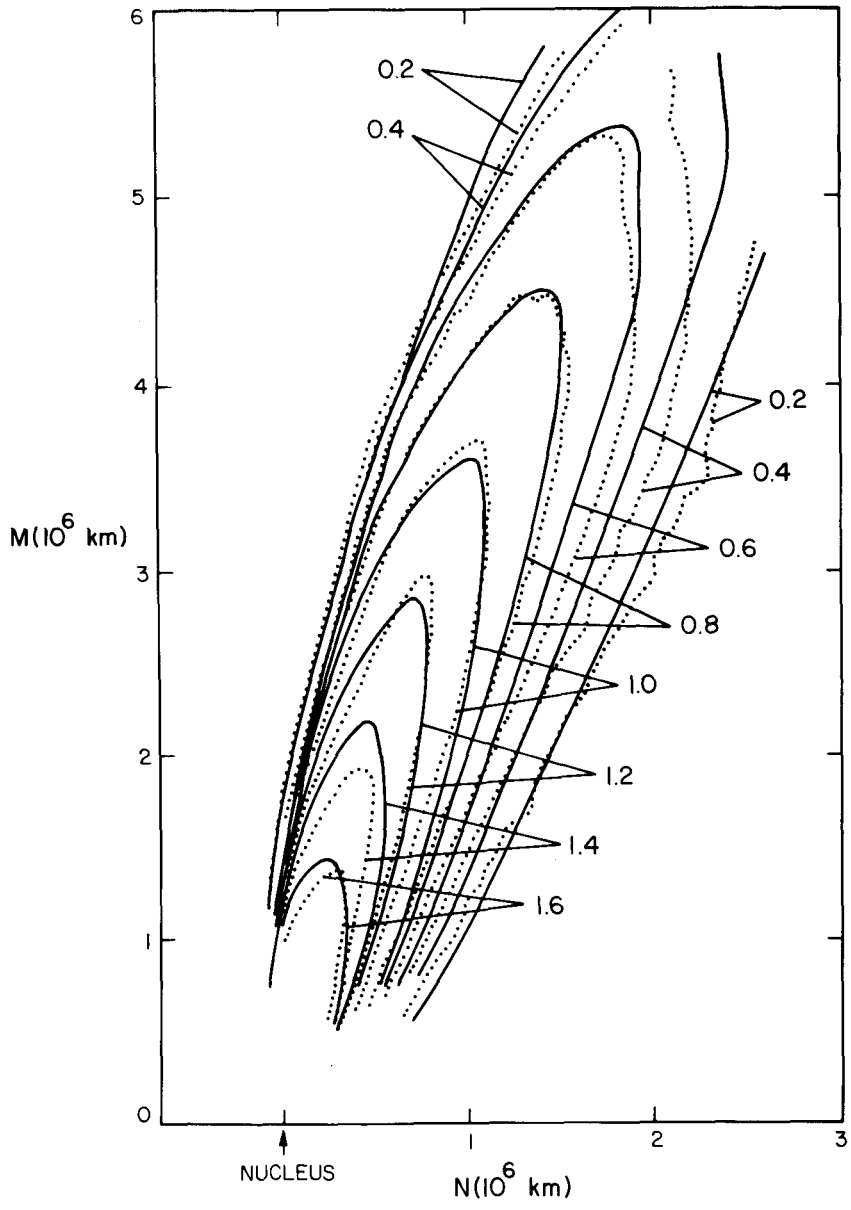

Fig. 1. Comparison of observed isophotes (dotted curves) with the theoretical density distribution (solid curves) for a photograph of Comet Bennett 1970 II taken on March 18, 1970. The numbers at individual pairs of curves indicate the logarithm of the relative surface density; M is the direction of the radius vector projected on the photographic plane; N is perpendicular to M in the direction of increasing right ascension (to the right). From Sekanina and Miller (1973).

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In its full complexity, the Finson-Probstein model has so far been applied only to Comets Arend-Roland 1957 III (Finson and Probstein 1968b), Bennett 1970 II (Sekanina and Miller 1973), and, except for the absolute rate of the dust output, Seki-Lines 1962 III (Jambor 1973).

Some of the results found by Finson and Probstein for Arend-Roland and by Sekanina and Miller for Bennett are rather similar. The mass-flow rate of dust comes out to be of the order of 10^7 g sec^{-1}; the ratio of the mass-flow rate of dust to that of gas is about 1 for Arend-Roland and near 0.5 for Bennett. The corresponding production rate of the gas is of the same order of magnitude as that obtained by independent methods and suggests evaporation controlled by water snow. For Comet Bennett, direct measurements of the H and OH clouds around the nucleus give the production rate, which is in excellent agreement with the Sekanina-Miller result (Keller and Lillie 1974). Sekanina and Miller also solved for the radius of the nucleus of Comet Bennett and obtained 2.6 km.

The results for the particle sizes of the three comets differ. The optically important particle diameter (defined as the root-mean-square value of the particle-size distribution), at an assumed density of 1 g cm^{-3}, is 2.1 μm for Comet Bennett, 5.6 μm for Arend-Roland, and 14 μm for Seki-Lines. Since Finson and Probstein used the scattering efficiency for radiation pressure $Q_{rp} = 1$, whereas Sekanina and Miller assumed $Q_{rp} = 1.5$, the discrepancy between Arend-Roland and Bennett is actually even more substantial than indicated by the above figures. Indeed, Finson and Probstein

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terminated the $1 - \mu$ distribution at 0.55, while Sekanina and Miller found a fairly significant fraction of particles to have $1 - \mu \gg 1$. Jambor used a different type of distribution function, but its sharp peak at $1 - \mu = 0.005$ demonstrates the abundance in Seki-Lines of very large particles, consistently reflected in the optically important size.

As a whole, the Finson-Probstein method appears to give very reliable, astrophysically significant information about the dust and gas released from cometary nuclei. The practical application of the model, however, requires utmost caution and care. Since pure dust comets are rare, it is imperative that on photographs taken for dust-tail studies, the plasma tail be suppressed as much as possible. This can rather successfully be done by using red sensitive plates (such as 103aE, 103aF, or the new 098-02) combined with appropriate filters that cut off the shorter wavelengths (such as a Schott RG1). A few inconveniences inherent in the problem cannot be removed by this method, primarily those concerning the size-density distribution. First of all, no way exists to separate the particle size from its density and from the scattering efficiency for radiation pressure. Furthermore, the $1 - \mu$ distribution is essentially indeterminate for $1 - \mu \rightarrow 0$, i.e., for very large particles. These particles do not contribute appreciably to the photometric profile of regular dust tails. This indeterminacy may have a significant effect on the estimate of the mass-output rate of dust from the comet, but not on the optically important size. By contrast, the upper end of the $1 - \mu$ distribution is well established from the fit. Unfortunately, as long as no information is available on the optical properties of dust particles from independent studies, the sizes of the smallest particles are also poorly determined, not only

because of the effect of density, but also because at $1 - \mu \gtrsim 1$, the scattering efficiency Q_{rp} varies rather considerably within very narrow limits of particle sizes, the character of variations being a strong function of the particles' composition. And finally, the mass-flow rates of dust and gas are linearly proportional to the adopted Q_{rp} and inversely proportional to the reflectivity of the dust particles; the nuclear radius is also inversely proportional to the adopted particle reflectivity.

IV. THE ICY TAILS OF DISTANT COMETS

A noteworthy controversy developed after Osterbrock (1958) published the results of his photographic observations of two comets with perihelia near 4 a.u., Baade 1955 VI and Haro-Chavira 1956 I. A careful analysis of the orientations of their tail axes resulted in Osterbrock's conclusion that the nearly straight, structureless tails pointed approximately midway between the prolonged radius vector and the orbit behind the comet. This allegedly peculiar property of the tails was considered incompatible with the mechanical theory, and substantial modifications were proposed, the least vulnerable of them having been Belton's (1965, 1966) concept of the type II tails as a mixture of electrically charged dust particles and electrons whose motions were controlled by interplanetary plasma.

The importance of Osterbrock's discovery was emphasized by Roemer's (1962) remark that the "characteristic" tails displayed by Baade and Haro-Chavira are rather common among comets of large perihelion distances, and by Belton's (1965) finding that all type II tails show essentially the same orientation property regardless of heliocentric distance.

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Noticing the general similarity between the straight tails of distant comets and the theoretical synchrones, I recently undertook a study of the two comets, using a synchrone approach (considered but rejected in the past!) rather than the traditional syndyne approach (Sekanina 1973a). Application of the synchrone approach by no means implies that the tails of the distant comets are assumed to have been formed by ejection at a unique instant, since that approach can also be used advantageously to study the time span of continuous emission. My study showed that the tail dynamics were perfectly consistent with the mechanical theory, so that no additional forces – other than solar gravitational attraction and solar radiation pressure – need be considered to explain the strongly nonradial orientation of the tails. The calculations showed that the material ejected into the tail of Comet Baade was released from the nucleus essentially continuously from some 1500 to 200 days before perihelion, and the material ejected into the tail of Comet Haro-Chavira, from about 2000 to 300 days before perihelion (Fig. 2). The "age" of the tails is thus of the order of 1500 days, and the corresponding emission distances range between 5 and 15 a.u. from the sun! A slight curvature of the tails, noticed by Osterbrock, is due to the distribution of emission in time, with earlier emissions reaching farther away from the nucleus. It is believed that the activity continued even after the apparent cutoff time (i.e., 200 to 300 days before perihelion), though perhaps at a lower level, but that particles from the more recent emissions were still confined to the coma.

Analysis of the visible lengths of the two tails indicated that particles emitted from the comets must have been subjected to extremely low accelerations, not exceeding 1% of the solar gravitational attraction, and that therefore they were rather heavy particles, at least 0.01 cm in size. The implied significant deficit or, perhaps, total

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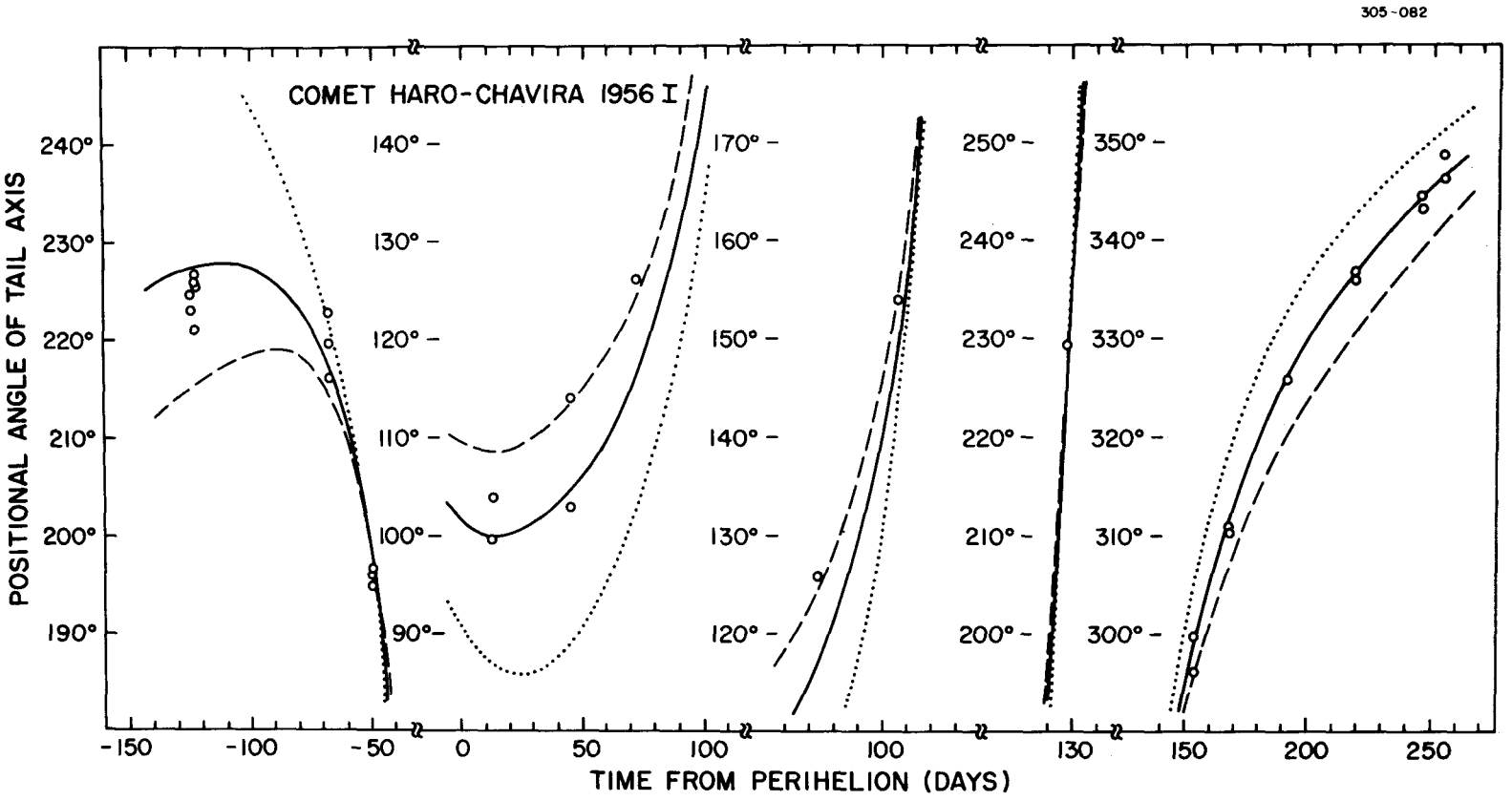

Fig. 2. Orientation of the tail of Comet Haro-Chavira 1956 I versus time. Circles: observations; dashed curve: synchrone corresponding to the emission time 2000 days before perihelion; solid curve: synchrone emitted 500 days before perihelion; dotted curve: synchrone emitted 200 days before perihelion.

lack of particles smaller than ≈0.01 cm in size contradicts all known comet-related particle-size distributions, except for the distribution of grains of solid hydrate of methane, studied in the laboratory by Delsemme and Wenger (1970). It should be pointed out that our lines of evidence cannot actually distinguish solid-hydrate grains from pure water-snow or frost grains of the same size-density distribution, and that the solid hydrates are preferred primarily for the reasons given by Delsemme and his collaborators (Delsemme and Miller 1970, 1971a, b; Delsemme and Wenger 1970). Since the dissociation of solid hydrates is determined by the evaporation of the icy lattice, the vaporization lifetimes of water-frost and solid-hydrate grains are practically identical; they were shown to be virtually infinite at heliocentric distances over 4 a.u. and can be rather long (for high-reflectivity grains) even at distances near 2 a.u. from the sun.

Examination of tail-orientation data of all comets with perihelia beyond 2.2 a.u. (Sekanina 1974a) largely confirms the conclusions from the study of Comets Baade and Haro-Chavira. The tail age, however, appears to be correlated with the perihelion distance, becoming shorter for comets with perihelia between 2.2 and ~3 a.u. (Fig. 3). This effect is attributed to an increase in the vaporization rate of water snow at heliocentric distances below 3 a.u., and therefore to a higher disintegration rate of icy grains or grains of solid hydrates.

The dynamical evidence thus appears to point unambiguously to the conclusion that the "characteristic" tails of the distant comets are indeed composed of water-frost or solid-hydrate grains. A small body of available spectroscopic evidence is also consistent with this hypothesis: Large-q comets – with the notable exception of Comet

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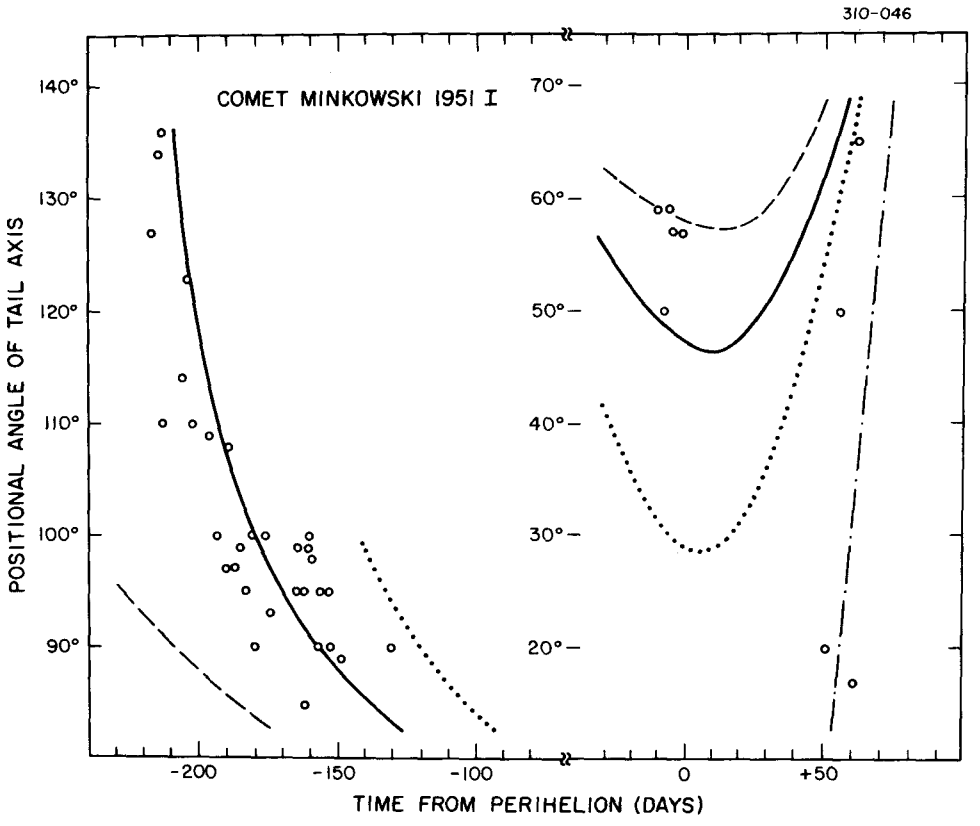

Fig. 3. Orientation of the tail of Comet Minkowski 1951 I versus time. Circles: observations; dashed curve: synchrone corresponding to the emission time 500 days before perihelion; solid curve: synchrone emitted 250 days before perihelion; dotted curve: synchrone emitted 150 days before perihelion; dotted-and-dashed curve: synchrone emitted at perihelion.

Humason 1962 VIII – have continua much stronger than molecular emissions, and in some comets, emissions are missing entirely. Obviously, the light of distant comets is mostly due to reflection of solar light. Spectrophotometric evidence, though inconclusive, possibly suggests that the grains might be "dirty," i.e., contaminated by impurities of fine dust. The concept of such dirty grains would explain the observed discrepancy between the size distribution of solid material in comet tails at large heliocentric distances and that at moderate to small distances: Micron and submicron dust particles bound to icy grains far from the sun are set free at moderate heliocentric distances when the grains start disintegrating by evaporation. Recent observations of Comet Kohoutek 1973f at nearly 2 a.u. from the sun by Rieke and Lee (1974) give some support to this hypothesis.

The proposed icy-tail hypothesis is also reasonably compatible with some other observed properties of the distant comets, such as the following: nearly parallel-sided tails, a sharply bounded envelope around the nuclear condensation, a high correlation between the appearance of the "characteristic" tail and the large perihelion distance, and occasional fan activity (Roemer 1962). However, an important implication of the hypothesis is that substances considerably more volatile than water snow are also required to be present in cometary nuclei in appreciable amounts in order to supply the necessary momentum to lift the icy grains of the inferred sizes into the tail at large distances from the sun.

It is appropriate to note here that the presence of icy grains in the coma at moderate heliocentric distances had been anticipated by Delsemme and Miller (1971a). They showed that the brightness gradient of a photometric profile of the continuum in

the coma, which progressively increases with distance from the nucleus to very large values [such as observed by O'Dell (1961) for Comet 1960 II], implies the existence of a halo of decaying icy grains. At distances comparable to the earth–sun distance, the vaporization lifetime of such grains is rather short; they evaporate completely while they are still within the coma.

V. SPLIT TAILS

A rather peculiar feature was detected both visually and photographically in the tails of quite a few comets. It can generally be described as a dark gap or band extending from the nucleus essentially along the tail's axis far into the tail, thus giving the impression that the tail is divided into two branches. The feature is often nicknamed the "shadow of the nucleus" in the literature, although such an interpretation is physically entirely unacceptable.

Brief examination of the reported appearances of split tails suggests that they were observed only in comets with small perihelion distances and, as a rule, after perihelion. The feature seems to be associated with dust tails, although a few cases of split plasma tails are not completely ruled out. Among the comets displaying a split tail, the best known are 1858 VI, 1882 II, 1910 I, 1962 III, and 1973f.

Until recently, the cause of a split tail had not been clear. Jambor's (1973) study of Comet Seki-Lines 1962 III gave a very straightforward and simple answer: The synchrones, corresponding in this case to particle emissions some 11 to 16 hours after perihelion, were missing – practically no dust was produced during the 5 hours.

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The split tail is thus understood, but the cause for the missing synchrones must be explained. Jambor considered the possibility of complete evaporation of small particles and a reduction in size of the large ones due to intense solar heating. While not denying the presence of particle evaporation at such small heliocentric distances (Section VIII), we note that it is not selective, unless we are willing to accept that the particles emitted during the 5 hours were completely different in composition from those emitted at other times, notably earlier. In other words, this interpretation fails to explain why the particles that had been emitted before the critical interval of the 5 hours – and therefore were exposed to solar heating for a longer period of time – did not evaporate, too. In fact, the dust emission rate, derived from the presence of particles in the tail, shows a sharp peak right at perihelion, 11 hours before the sudden drop in the production commenced.

My guess is that the inferred drop in the rate of particle release from the nucleus of Seki-Lines is real. Subsequent to a sharp peak in the production rate of the dust (which itself must presumably have been triggered by an outburst in the nucleus), the sudden drop in the dust output should be associated with a rapid decrease in the vaporization flux from the comet's surface. The implied sink in the impinging energy is apparently caused by a high opacity for solar radiation of the dusty atmosphere, oversaturated by particles from the preceding flareup. Now, as the vaporization flux from the surface drops, an imbalance arises in the atmosphere between the high escape rate of the particles into space and the very low input rate of fresh dust from the underexposed nucleus. Consequently, the atmosphere is rapidly cleared out of the excess of dust particles, its opacity therefore drops, and the vaporization flux and production of dust from the nucleus increase to restore the equilibrium levels again.

A self-regulation mechanism of this type, turned on by a precipitous growth in the production rate of dust, might also have been operative in Comet Bennett. Although no shadow of the nucleus was reported for this comet, Sekanina and Miller (1973) found that a steep continuous increase in the emission rate of dust culminated in a sudden drop by a factor of 2, between 17 and 10 days before perihelion. On the other hand, Finson and Probstein (1968b), who detected an outburst in Arend-Roland about 6 days before perihelion, found no evidence for any subsequent drop much below the pre-explosion level of the dust emission flux.

VI. ANOMALOUS TAILS OF COMETS (ANTITAILS)

Significant lagging of early emissions behind the radius vector, combined with a special sun–earth–comet configuration, can account for an occasional appearance, primarily after perihelion, of a flat, sunward, "anomalous" tail (antitail). Physically and dynamically, there is nothing anomalous about these tails. However, they contain only large particles (usually in the range 0.01 to 0.1 cm in size – see below), whose low velocities relative to the nucleus prevent them from getting dispersed far away from the comet even after long flight times. These particles are comparable in size to meteoroids that produce radio meteors.

A great deal of information on anomalous tails can be learned from the distribution and structural details of synchrones. Actually, analysis of a synchrone diagram is sufficient for the understanding of the nature and basic properties of the anomalous tails (Sekanina 1974b).

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An example of a synchrone diagram for Comet Arend-Roland is exhibited in Fig. 4, in which the projection of synchrones (and syndynes) onto the sky is complemented by their projection in the orbit plane of the comet unforeshortened by perspective. The arrow pointing to the earth's position on the right-hand side indicates that, to a terrestrial observer, all synchrones older than about 30 days project in the general direction of the sun, while the younger ones project in the other direction. This, indeed, is the picture shown on the left-hand side. A direct comparison of the latter diagram with photographs taken at approximately the same time reveals that the main body of the anomalous tail was formed by preperihelion emissions only. From diagrams similar to the one shown on the left of Fig. 4, Finson and Probstein (1968b) estimated that the antitail of this comet was made up of material emitted 5 to 9 weeks before perihelion.

The left panel of Fig. 4 indicates a considerable pileup of very old synchrones, as well as some crowding of very young ones. This effect is largely due to projection, but, as demonstrated by the orbit-plane view, real variations in the density of synchrones do occur – in particular, old synchrones indeed tend to pile up on top of each other. Also, they actually turn to the sunward side, so that the term "sunward" does not necessarily refer only to the tail's projected property. The pileup of synchrones toward the earliest ejection times readily explains another peculiarity of the sunward tail: its sharp edge on the side toward the radius vector and its fuzzy edge on the outer side.

In contrast to the crowding of synchrones of extreme ages, synchrones of intermediate age (i.e., those in Fig. 4 pointing essentially toward the earth) are greatly thinned out by projection. This is why the tail in the sky looks as if it is split into main and sunward branches.

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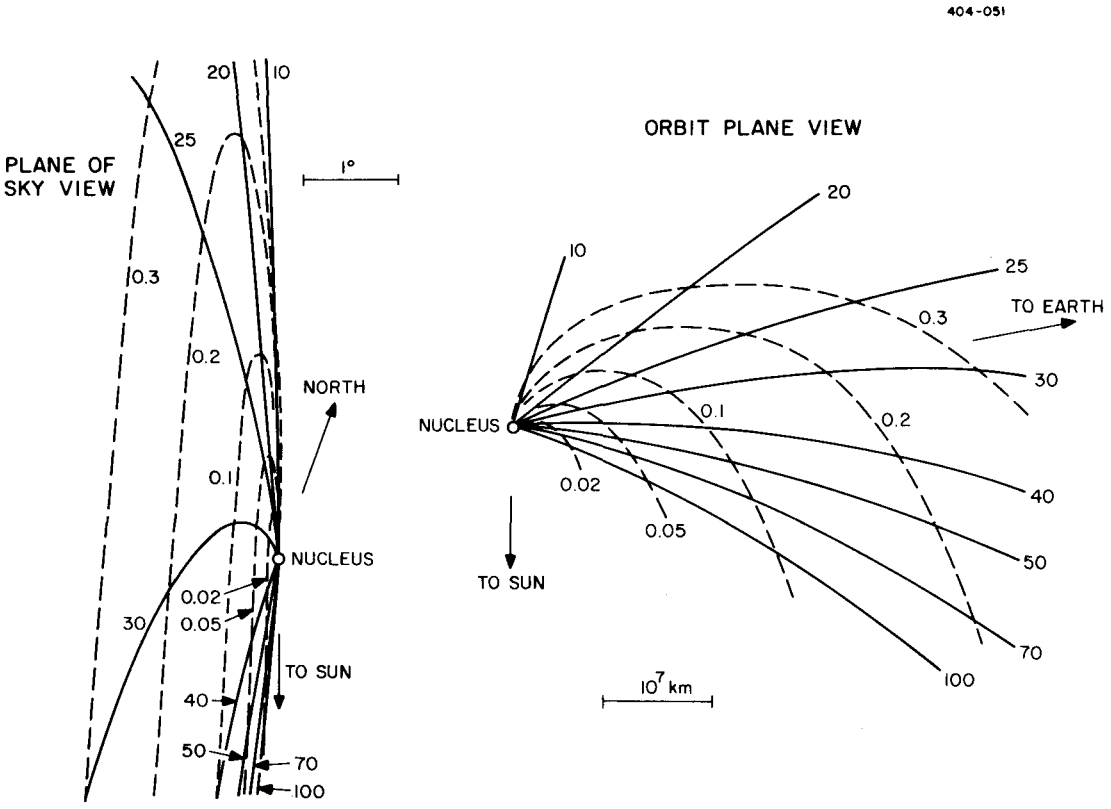

Fig. 4. A synchrone/syndyne diagram for the dust tail of Comet Arend-Roland 1957 III on April 28.0 UT, 1957, as projected onto the plane of sky (left) and as viewed in the orbit plane (right). Solid curves are synchrones, defined by their age (in days); dashed curves are syndynes, defined by the acceleration ratio of radiation pressure to solar gravity, $1 - \mu$.

The exceptionally narrow width of the sunward spike of Comet Arend-Roland during the earth's passage through the comet's nodal line indicates an ejection velocity normal to the orbit plane of less than 3 m sec^{-1}. Although the outward component of the ejection velocity should have been somewhat greater, it could not amount to more than a few percent of the relative velocity acquired by the particles from their acceleration by radiation pressure.

Finally, we note from Fig. 4 that the visible portion of the anomalous tail consists of particles significantly heavier than those in the main tail, with particle size increasing toward both the sharp edge and the nucleus. Whereas the optically important particles of the regular tail of Comet Arend-Roland, according to Finson and Probstein (1968b), were about 6 μm in diameter (at an assumed density of 1 g cm^{-3}), the anomalous tail contained particles of submillimeter and perhaps even millimeter size.

The behavior of the anomalous tail of Arend-Roland is rather representative of this type of tail in general. The conditions under which antitails can be observed from the earth can be formulated as follows:

(1) The earth must be in or at least fairly near the orbit plane of the comet to allow the edgewise or near-edgewise perspective. The "in" condition is absolutely necessary for the appearance of the narrow ray. If only the "near" condition is satisfied, the anomalous tail cannot point exactly sunward. For a comet of arbitrary inclination, this condition can be satisfied only for several days twice a year, but for a low-inclination comet, the near condition can hold for quite an extensive period of time.

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(2) The earth (or, more precisely, its projected position onto the comet's orbit plane) must be located either within the sector defined by the prolonged radius vector and the synchrone of the earliest detectable emission (position E_1 in Fig. 5) or within the sector defined by the above two directions turned 180° (E_2). In the former case, the tail points in the general direction of the earth, the earth's atmosphere actually being bombarded by the comet's debris; and in the latter, it points away from the earth. If the earth is very near the prolonged radius vector (E_3) or very near the sunward direction (E_4), the comet is likely to display only a sunward tail, since the very young emissions – the only ones that project away from the sun, as seen from the earth – may not yet be well developed into a regular tail and their actual length is drastically shortened by projection.

(3) The preceding point also implies that the probability of seeing an anomalous tail from the earth increases statistically with the sector angle, which is identical to the lag angle of the apparent-onset synchrone. Since the lag angle increases with the true anomaly of the time of observation, the probability of seeing an anomalous tail is very small before perihelion but enhances considerably after perihelion.

(4) Finally, it is, of course, essential that a reasonably high level of dust-emission activity, particularly in the range of heavy particles, have been reached by the comet a sufficiently long time before perihelion.

Except for point (4), the conditions are geometrical in character. Consequently, if there are indications that the last point is likely to be satisfied (a "dusty" comet), the appearance of the anomalous tail can be rather straightforwardly predicted (Sekanina 1974b).

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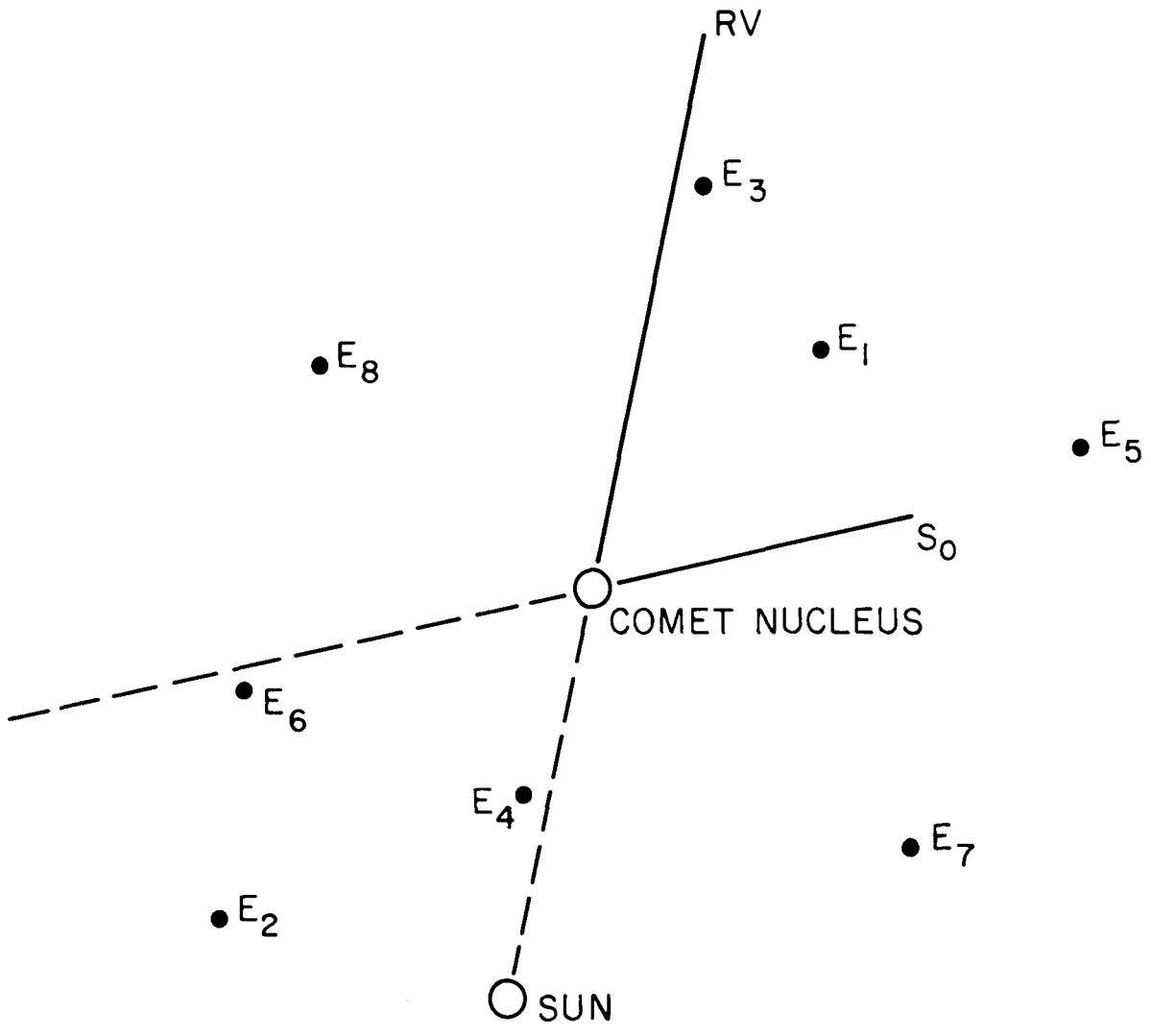

Fig. 5. Visibility conditions for an anomalous tail. Dust particles fill a flat sector between the synchrone S_0 (drawn schematically as a straight line) of the earliest detectable dust emission and the radius vector RV. When the earth is in the general area of E_1 or E_2, the comet displays, in projection onto the sky, a regular tail as well as a sunward tail. When the earth is near E_3 or E_4, the comet may display only a sunward tail. When the earth is around E_5 or E_6, the sunward tail may become difficult to detect. No sunward tail can be seen when the earth is in the general area of E_7 or E_8.

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Historically, the term anomalous tail was not always used to describe the type of phenomena we deal with here. Harding (1824) and Olbers (1824) were probably the first to use the term, but Bredikhin (Jaegermann 1903) distinguished two types of anomalous tails. The tails of interest to us were called pseudo-anomalous by him; he considered "genuine" anomalous tails to be composed of heavy particles, moving toward the sun and subjected to no repulsive force. He concluded that such particle formations must move ahead of the comet and inside its orbit. Interpreting the descriptions of some of the reported sunward extensions as genuine anomalous tails, Bredikhin derived particle-ejection velocities of the order of 1 km sec^{-1}. For heavy particles subjected to no repulsive acceleration, such velocities are at least 2 orders of magnitude too high. There is no way to escape the conclusion that Bredikhin's assumptions were, in this respect, incorrect. It appears that his genuine anomalous tails can readily be identified either with gas jets or with unidirectional emissions of fine dust particles that have ejection velocities comparable to the thermal velocity of sublimating gases but that are subjected to substantial repulsive accelerations due to radiation pressure.

By contrast, anomalous tails as we define them behave in complete agreement with the equations of motion of relatively heavy particles. Yet it is the initial ejection velocity, and not the repulsive force, that can be neglected at only a minor loss of accuracy. These antitails are rather massive formations and might pose a real hazard for space missions to comets. Fortunately, since their dynamics are now well understood, it is not difficult, in principle, to avoid such a hazard. An antitail is essentially a two-dimensional formation located in the comet's orbit plane, so spacecraft are safe when kept away from the orbit plane. Hazards from the antitail could also be avoided

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when spacecraft are guided slightly ahead of the comet and inside its trajectory. Finally, the known short-period comets, to which early space missions are planned, currently appear not to display anomalous tails (Section VII).

VII. STATISTICS OF APPEARANCES OF ANOMALOUS TAILS

The geometrical visibility conditions for anomalous tails were used to list the comets that should have displayed a sunward tail around the time of the earth's passage through the orbit plane (Sekanina, unpublished). A computer program executing the conditions has been applied to an updated card file of the Catalogue of Cometary Orbits (courtesy of B. G. Marsden), starting with the comets of 1737. Excluded were comets observed at elongations exceeding 135° and distances larger than 2 a.u. from the sun.

Forty-six comets with revolution periods exceeding 200 years were found to have had favorable visibility conditions (satisfied within, or not more than 5 days outside, the period of observation), when dust production was allowed to commence at 2 a.u. from the sun on the incoming branch of the orbit. When this condition was relaxed to 4 a.u., the number of eligible comets increased to 69. An extensive search of the literature revealed, however, that a sunward tail was actually observed only in the following eight comets: 1823 (Harding 1824; Olbers 1824; von Biela 1824; Hansen 1824), 1844 III (Waterston 1845; Maclear 1845), 1895 IV (Fric and Fric 1896), 1937 IV (Jeffers and Adams 1938; Van Biesbroeck 1938), 1954 VIII (Van Biesbroeck 1957; Waterfield 1954; Kresák and Vozárová 1954), 1957 III (many observations; see, e.g., Whipple 1957a, b; Larsson-Leander 1957) 1961 V (several observations; see, e.g., Porter 1962) and 1969 IX (Miller et al. 1971).

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In all eight cases, the earth passed through the nodal line after the comet's perihelion, the time lag being 4 to 54 days. Comets 1957 III and 1961 V were the only ones whose tails pointed at the critical time in the general direction of the earth; the others were directed away.

Five of the eight comets - 1823, 1844 III, 1957 III, 1961 V, and 1969 IX - exhibited a double-tail appearance with the antitail no brighter than the main tail. In the case of 1954 VIII, only a sunward tail was observed by Van Biesbroeck and Waterfield, but a "faint prolongation" away from the sun, in addition to the brighter antitail, was reported by Kresák and Vozárová. The other two comets, 1895 IV and 1937 IV, displayed only a sunward tail. Three of the eight events were affected by unfavorable circumstances: The moon interfered in the case of 1844 III, while 1954 VIII and 1961 V were not discovered until about 2 days after the earth's passage through the node. Comet 1961 V was also at a very small angular distance from the sun.

The presence of the antitail is correlated, to some extent, with orbital evidence. Except for 1937 IV, all the comets had perihelion distances less than 0.7 a.u. Four seem to have come from the Oort (1950) cloud (1895 IV, 1937 IV, 1954 VIII, and 1957 III), while 1969 IX is a "fairly new" comet in the Oort-Schmidt (1951) terminology. The original orbit of 1823 is indeterminate, whereas 1844 III and 1961 V appear to be the only two "old" comets (in the Oort-Schmidt sense). Comet Kohoutek 1973f was not among the candidates, because the antitail conditions were not satisfied during the earth's passage through the nodal line on December 10, 1973. The "near" condition was not examined at all.

Of the candidates for which no antitails were reported, at least two dozen were observed extensively enough during the critical period around the nodal passage that we can be reasonably sure that the absence of the antitail indeed indicates insufficient

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or no production of heavy particles from these comets at large distances Among others, this group covers two sun grazers (1843 I and 1963 V) plus Comets 1840 IV, 1853 II, 1858 VI, 1861 II, 1881 III, 1931 III, 1941 II, 1959 IV, 1963 I, and 1963 III. Many of them have revolution periods in the general range of several hundred to several thousand years, which appears to suggest that antitails, by and large, are not displayed by old comets. Observations during the critical periods for at least a dozen comets were severely affected by moonlight, and the rest of the condidates were poorly observed for other reasons.

A similar list of candidates was produced for short-period comets (with revolution periods shorter than 200 years). The list shows that if the short-period comets were currently emitting large amounts of heavy particles, anomalous tails should have been plentiful. With an assumed onset of dust production at 2 a.u. before perihelion, 20 more-than-one-apparition and 3 one-apparition comets should have displayed anomalous tails, 8 of the 20 on two or more occasions. If the condition is relaxed to 4 a.u., the figures become 28, 6, and 17, respectively. If, on the other hand, the condition is severed and dust production is assumed to commence at perihelion, 11 more-than-one-apparition comets should have displayed anomalous tails – 2 of them on two occasions – and no one-apparition comets.

Since most short-period comets have low inclinations, excellent prospects exist, statistically, for favorable visibility conditions for detecting antitails outside the critical times of nodal passages as well (the "near" condition in Section VI). As with the nearly parabolic comets, such configurations were not examined.

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An extensive search in the literature for observations of antitails of short-period comets gave a completely negative result. Well-established associations of meteor streams with many short-period comets appear difficult to reconcile with the absence of anomalous tails. While it is possible that an element of proper timing is all that is responsible for the contradiction, more work remains to be done on this problem.

VIII. THE ANTITAIL OF COMET KOHOUTEK 1973f, AND THE "SYNCHRONIC" BANDS: EVIDENCE FOR VAPORIZATION AND FRAGMENTATION OF COMETARY PARTICLES?

The antitail of Comet Kohoutek, the first that was predicted (Sekanina 1973b), is currently under intensive study. A number of ground-based observations, including the first infrared measurements of an antitail (Ney 1974), were complemented by remarkable observations from outer space (Gibson 1974). At least two preliminary models have so far been proposed (Gary and O'Dell 1974; Sekanina 1974c).

My working model, based on the Finson-Probstein theory for the case of small emission velocities, has been fitted to semiquantitative descriptions of the antitail by various observers, including the Skylab III astronauts. The model shows that the main body of the antitail was made up entirely of material shed by the comet before perihelion. The particles ranged mostly between 0.1 and 1 mm in size, and their differential mass distribution, $m^{-s}\,dm$, was tentatively approximated by $s \simeq 1.4$. This value of the population index s is substantially lower than the commonly accepted $s \gtrsim 2$, derived from various radio-meteor studies, and implies a rather strong relative excess of heavy particles, in which practically all the mass of the antitail was concentrated. The excess of large particles has been interpreted as an indication of a severe evaporation effect. Indeed, a cloud of particles of specific composition, ejected from

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a cometary nucleus and later undergoing evaporation as a result of exposure to intense solar heating, will have its particle-size distribution substantially modified. Because evaporation reduces the radii of the particles in such a cloud by the same amount, Δa, independent of their dimensions, particles with original radii, a, smaller than Δa do, of course, sublimate out completely. Larger particles, whose original size distribution was governed by a law of the type $a^{-u}\,da$ ($u = \text{const}$), are reduced in size to $b = a - \Delta a$, and the logarithmic slope t of their postexposure distribution varies with b and is related to its preexposure equivalent u by

$$t(b) = \frac{u}{1 + (\Delta a/b)} \quad . \tag{2}$$

Since $t = 3s - 2$, the observed (i.e., postperihelion and, therefore, postexposure) particle-size distribution in the antitail has $t \simeq 2.2$ for $b \approx 0.1$ to 1 mm. Taking, further, a population index of $2 \lesssim s_0 \lesssim 7/3$ and, hence, $4 \lesssim u \lesssim 5$ for the original (preexposure) particle distribution, we find $0.8 \lesssim \Delta a/b \lesssim 1.3$. Thus, a rough assessment of the evaporation effect suggests that the total loss in radius of the particles in the antitail of Comet Kohoutek appears to be comparable to typical postexposure particle sizes, i.e., some 0.1 to 1 mm.

This approximate result has now been checked by Sekanina et al. (1975). From the progressively increasing gradient of the radial photometric profiles of the antitail, it is found that t is, indeed, variable and fits Eq. (2). After substituting from Eq. (1), Eq. (2) can be written in the form

$$\frac{1}{t} = \frac{1}{u} + Q\,(1 - \mu) \quad , \tag{3}$$

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where Q is a constant determined by u and Δa. The plot of 1/t versus $1 - \mu$, reproduced here in Fig. 6, gives 1/u and Q as the ordinate at $1 - \mu = 0$ and the slope of the fitted straight line, respectively. The numerical results of Sekanina et al. put the evaporation loss in particle diameter at about 0.12 mm and give $u \simeq 4.8$, i.e., the original population index of the particle mass distribution $s_0 \simeq 2.3$. The derived evaporation loss rate implies an apparent latent heat of vaporization of the particle material (defined as the product of the actual latent heat and of the fourth root of the ratio between the particles' emissivity for reradiation and their absorptivity for solar radiation) of about 46 kcal $mole^{-1}$, very close to the estimate of the preliminary study (Sekanina 1974c). However, an uncertainty remains in the above determinations because the effect of evaporation on the particles' motions, i.e., the change in the magnitude of radiation pressure, has not been taken into account. The improved model of the antitail therefore requires a study of non-Keplerian motions of dust particles (variable $1 - \mu$).

While dust tails are usually structureless, this was certainly not the case with such comets as 1858 VI, 1901 I, 1910 I, 1957 V, and 1965 VIII. Well-developed systems of several nearly parallel bright bands, streaking across the broad, strongly curved "background" tail, are particularly clearly seen on the photographs of 1910 I and 1957 V (Lampland 1912; McClure and Liller 1958).

Bredikhin (Jaegermann 1903) noticed that the bands essentially coincide in orientation with synchrones and concluded that they are the result of discrete ejections into the tail of a large number of dust particles of various sizes. The bands became known generally as "synchronic" bands.

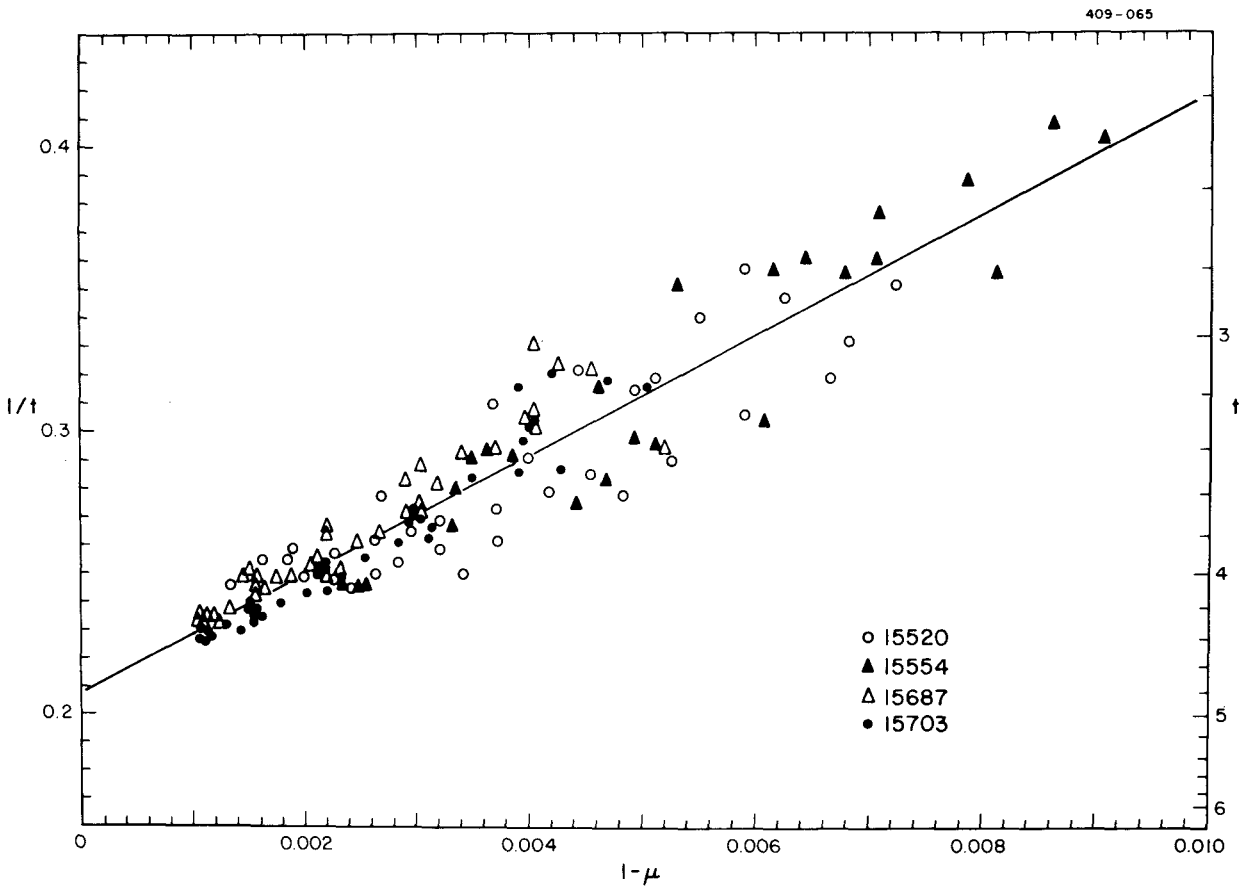

Fig. 6. Plot of particle acceleration 1 - μ versus the logarithmic gradient t of the size distribution of vaporizing particles in the antitail of Comet Kohoutek 1973f. The four types of symbols indicate the plates from which the data were derived. From Sekanina et al. (1974).

Vsekhsvyatsky (1959), however, pointed out that available photographs of the synchronic bands demonstrate a systematic deviation between the orientation of the bands and that of the theoretical synchrones. The bands always make a smaller angle with the prolonged radius vector and, when extended to intersect the radius vector, often meet on the sunward side of the nucleus (which the theoretical synchrones never do). Although Vsekhsvyatsky gave three more arguments against the interpretation of the synchronic bands in terms of discrete ejections of dust, we find the orientation problem to be the strongest point of his criticism and the only crucial objection to the laws of the mechanical theory.

The way the bands deviate from the respective synchrones gives the impression that each particle in the band is subjected to a repulsive acceleration $1 - \mu$ that gradually increases toward the far end of the band. If correct, this hypothesis implies the presence of vaporizing particles.

Some properties of vaporizing dust particles were studied by Huebner (1970). He showed that the vaporization rate of materials with high latent heats of vaporization increases very steeply with decreasing heliocentric distances; he suggested that, as a result of grain vaporization, a dust tail of a sun-grazing comet might completely disappear shortly before perihelion, with atoms ionized to form a plasma tail. Jambor (1973) pointed out that, indeed, the whole visible tail of the sun-grazing Comet Ikeya-Seki 1965 VIII, on a plate taken 9 days after perihelion, was due to emissions subsequent to perihelion. Similarly, I have found that the tail of another sun grazer, 1887 I, was a synchrone ejected 5.5 hours after perihelion (Sekanina 1973c). Spectroscopic data were also interpreted in terms of vaporizing particles (Spinrad and Miner 1968).

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Obviously, plenty of circumstantial evidence exists for the presence of appreciably vaporizing dust particles in the tails of comets with small perihelion distances. However, nothing appears to have been done – to my knowledge – on actual calculations of the trajectories of such vaporizing particles. The analytical approach is clearly unfeasible because of the complex form in which the central force varies with time (caused by the variable vaporization rate of the particles). I recently developed a numerical method of computing the motion of a vaporizing particle, based on an iterative adjustment of the particle's orbital elements to its changing dimensions (and, therefore, to its acceleration). Since the particle's motion is restricted to the comet's orbit plane, the particle's orbit differs from that of the comet in only four elements: the eccentricity e, the semimajor axis a, the perihelion angle α (i.e., the angle subtended by the lines of apsides of the particle's and the comet's orbits), and a time constant (such as the moment of perihelion passage T).

A particle of known size, density, and scattering efficiency for radiation pressure is assumed to be ejected at a zero initial velocity from the nucleus at a time t_0. The repulsive acceleration $(1 - \mu)_0$ by radiation pressure is determined by Eq. (1). The four elements of the particle's orbit at t_0 are then calculated from $(1 - \mu)_0$ and from the comet's orbital elements by applying the two conditions of coincidence between the radial (distance from the sun) as well as transverse (true anomaly) coordinates of the particle and those of the comet at t_0, plus the similar two conditions of coincidence of their velocity components at t_0. With these elements, e_0, a_0, α_0, and T_0 [and with $(1 - \mu)_0$], the particle's motion is run until a time t_1. Simultaneously, the loss in the radius of the particle due to its evaporation between t_0 and t_1 is derived from the equations of an adopted physical model [see Eq. (4) below, for example],

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and the new acceleration $(1 - \mu)_1$ is calculated from Eq. (1). Four conditions of coincidence in position and velocity at t_1 plus $(1 - \mu)_0$ and $(1 - \mu)_1$ then serve to determine new orbital elements of the particle at $t_1 - e_1$, a_1, α_1, and T_1 – from the preceding elements. The particle's motion is then run to a time t_2, etc., until the time of observation. The iteration intervals, $t_{i+1} - t_i$, must, of course, be kept very short to prevent an accumulation of errors. In practice, it is advisable to adjust the step in time by simultaneously checking the sequence of steps in $1 - \mu$, to avoid a large step in either quantity. The method is programed to work for both short-period and nearly parabolic comets; it also allows $1 - \mu > 1$ (negative attraction).

Although calculations of this type have just commenced, we can present, in Fig. 7, the first positive (though very preliminary) result of analysis of one of the synchronic bands in the tail of Comet Mrkos 1957 V. The orientation of band No. 3 (Vsekhsvyatsky 1959) is compared in the figure with the best matching nonvaporization synchrone (of age 8 days) and with a much more nearly coinciding vaporization synchrone (age 12 days), the latter corresponding to particles with a vaporization rate controlled by the law

$$Z = A \exp [1.80 \times L(1 - \sqrt{r})] \quad , \tag{4}$$

where $A = 10^{-17}$ g cm^{-2} sec^{-1} and the apparent latent heat of vaporization $L = 30$ kcal mole^{-1}.

The first results of our dynamical experimenting with vaporizing particles have proved rather successful. However, since vaporization implies a gradual loss of luminosity on account of the decreasing scattering

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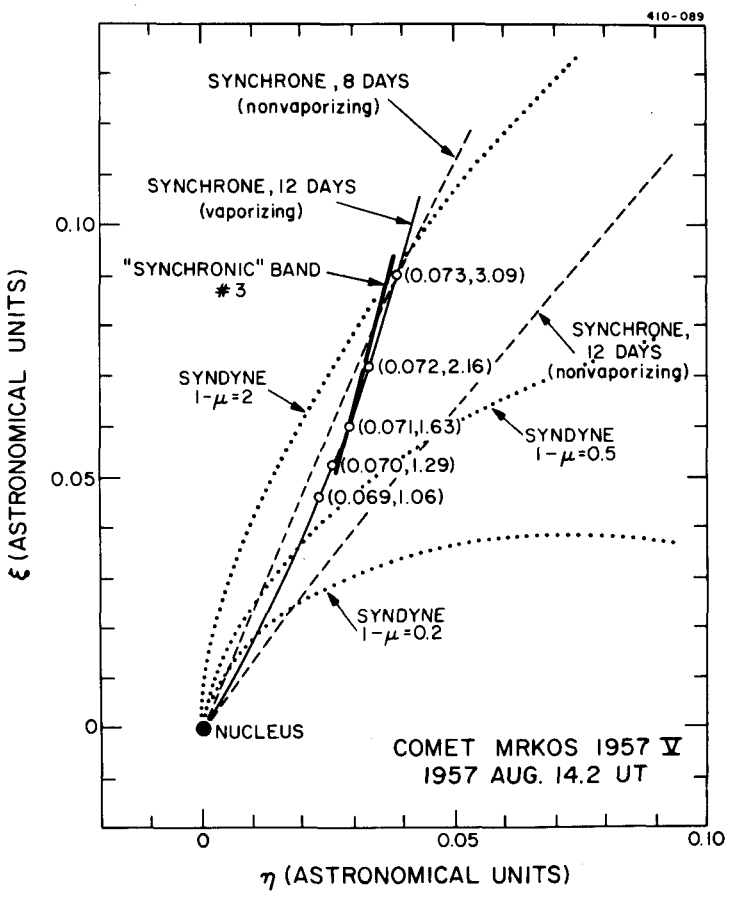

Fig. 7. Motions of vaporizing dust particles in the tail of Comet Mrkos 1957 V. The orientation of the observed "synchronic" band #3 (thick line) on a plate exposed by A. McClure (Vsekhsvyatsky 1959) is compared with a synchrone, 12 days old, of vaporizing dust particles (thin solid curve) of apparent latent heat of vaporization of 30 kcal mole^{-1}. The projection is in the orbit plane. The $+\xi$ axis points away from the sun, and the $+\eta$ axis, behind the comet. The five open circles indicate the locations of particles of specified repulsive accelerations $1 - \mu$ at the times of ejection (first figure in parentheses) and observation (second figure). Note that the observed extent of the band corresponds to a very narrow interval of $1 - \mu$ at ejection (of about 0.003). Note also that the synchrone of the vaporizing particles is concave toward the prolonged radius vector, while the synchrones of nonvaporizing particles (dashed curves) are convex. A few syndynes of nonvaporizing particles (dotted curves) are also plotted.

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(or reflecting) power of the particles, the interpretation of the synchronic bands in terms of vaporizing particles is problematic from the photometric viewpoint: a synchronic band is much brighter than the ambient "background" tail, while the space between the band and the nucleus is usually almost nonluminous, as though the band emanated from "nothing". To explain both the dynamical and photometric effects, we are in need of a mechanism that would provide an increase in the acceleration (i.e., a drop in the particle size) as well as an increase in the brightness (i.e., an increase in the total scattering or reflecting surface) of the particles in the bands. The mechanism that does just that is fragmentation. Simple calculation shows that fragmentation of a particle into N fragments of equal size would increase the $1-\mu$ of the fragments as well as their total scattering surface, compared to the corresponding figures for the parent particle, by a factor of $N^{1/3}$, i.e., in proportion to the ratio between the linear dimensions of the parent and those of a fragment.

In practice, of course, the fragments have a certain size distribution; the limiting values of $1-\mu$ of the fragments define the length of the band. The position of the band in the tail at any particular moment depends on three quantities, namely, the time of ejection of the parent particles, their size and the time of fragmentation. However, since the band's position is defined only by two parameters, the three quantities cannot all be unequivocally determined from the band's single observation. The orientation of the band (i.e., its slope $d\eta/d\xi$ in Fig. 9), however, is primarily a function of the time of fragmentation, which thus can be fixed fairly precisely. As an example, we list in Table I six sets of parameters of the synchronic band No. 3 in

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Fig. 9, all of which fit equally well (perfectly) its observed position. Note that while the time of fragmentation comes out indeed practically the same in each of the six cases of Table I, the time of ejection is highly correlated with $(1-\mu)_{par}$, the $1-\mu$ value of the parent particles. Only an upper limit can be established for $(1-\mu)_{par}$ from the obvious condition that the dimensions of the parent particle must be larger than those of any of its fragments. Of course, this also sets a limit on the time of ejection. In the case of the synchronic band No. 3 $(1-\mu)_{par} < 0.75$, and the ejection must have taken place earlier than 3.6 days after perihelion (i.e., before August 5.0 UT, 1957; by contrast the fragmentation occurred on about August 9.1 UT).

Since the range of the particle sizes of the fragments, assessed from the range of their $1-\mu$ values, is rather narrow, the number of fragments per parent particle does not significantly depend on their size-distribution law. However, it does depend crucially on the variations, with the particle size, in the scattering efficiency for radiation pressure, which are practically unknown, because neither the composition nor the shape of the fragments are known. It is therefore believed that only order-of-magnitude estimates can be given for the number of fragments per parent particle, such as those listed in Table I.

The outlined hypothesis of particle fragmentation in cometary tails adopts that a particular synchronic band is composed of fragments, whose parent particles had a certain $1-\mu$ acceleration, were simultaneously ejected from the nucleus and later, also at the same time, crumbled into fragments. If the first condition is relaxed to allow a multiple-peak distribution of sizes of

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Table I

Synchronic band No. 3 in the tail of Comet Mrkos, interpreted in terms of particle fragmentation

(Time of observation: 12.7 days after perihelion)

	Time of ejection of parent particles from comet (days from perihelion)					
	+3	+2	0	-3	-7	-12
Age of parent particles (days)	9.7	10.7	12.7	15.7	19.7	24.7
$1-\mu$ of parent particles	0.55	0.35	0.17	0.077	0.040	0.026
Diameter of parent particles (microns) at density 1 g cm^{-3} and scattering efficiency $Q_{rp}=1$	2.1	3.3	6.9	15	29	45
Time of fragmentation (days from perihelion)	+7.6	+7.6	+7.6	+7.6	+7.7	+7.8
Age of parent particles at time of fragmentation (days)	4.6	5.6	7.6	10.6	14.7	19.8
Age of fragments (days)	5.1	5.1	5.1	5.1	5.0	4.9
Range in $1-\mu$ of fragments	1.0 - 3.6	1.3 - 3.9	1.7 - 4.3	2.1 - 4.6	2.4 - 5.1	2.7 - 5.4
Estimated number of fragments per parent particle	$10^1 - 10^2$	$10^2 - 10^3$	$10^3 - 10^4$	$10^4 - 10^5$	$10^5 - 10^6$	$10^6 - 10^7$

the parent particles, the result is a system of practically parallel synchronic bands. Such a property of band systems has actually been observed in the tails of a few comets. It permits to improve the determinacy of the three fragmentation parameters and so does the identification of the same synchronic bands on photographs taken on two or more consecutive days.

One can also think of multiple fragmentation of cometary particles. Mathematically this case is tractable with the same ease as the problem of simple fragmentation, and I have a computer program handling the corresponding particle dynamics. At present, however, there does not seem to be any clear observational evidence for multiple fragmentation of particles in the cometary tails.

Incidental to the problem of the motions of particles subject to vaporization and/or fragmentation is that the term syndyne becomes ambiguous or meaningless and should not be used unless it is redefined.

IX. REMARKS ON RELATED RESEARCH. FUTURE WORK

The preceding sections have demonstrated that the explanation of all the major features observed in the dust tails of comets is within the reach of the mechanical theory, in spite of the fact that the original ideas of Bessel and Bredikhin required considerable revisions. We wish to stress, however, that while we claim that no additional forces – other than solar gravitational attraction and solar radiation pressure – need be considered to explain the observed motions of dust particles in cometary tails (after their lifting into the coma by molecular drag), we do not deny that the particles are also subject to other, though much smaller, forces. Credence should be given at this point to at least two studies that appear to show a potential presence of detectable forces in the dust tails ignored by the mechanical theory. Belton (1965, 1966) noted that in comets where both prominent plasma and dust tails are present, their orientations near the nucleus appear to coincide, thus perhaps suggesting that an important interaction

may occur between the dust and plasma in certain cases. Along a different line of reasoning, Harwit and Vanýsek (1971) suggested that an alignment of the angular-momentum axes of dust grains may result in cometary tails from bombardment by solar protons and in cometary heads from the drag by outgoing gas from the nucleus. An indication of such a phenomenon was indeed detected by Clarke (1971) in his polarization measurements of Bennett 1970 II.

Unfortunately, many fundamental properties of the dust tails are still known with only a rather unsatisfactory precision, the uncertainties in particle size and composition being perhaps the most severe. In spite of the accomplishments of the Finson-Probstein method, we do not know what the particles are made of. Numerous investigations were undertaken in the past to attack the problem from another direction, often by comparing the distribution of energy in the continuous spectrum of a comet's head or tail with theoretical curves for light scattering by small particles based on the Mie theory (e.g., Liller 1960; Remy-Battiau 1964). O'Dell (1974) compared the results of three different methods of particle-size determination applied to Comet Bennett, yet he found an uncertainty of at least a half an order of magnitude in the value of the minimum particle size.

Infrared observations represent another line of attack. Maas et al. (1970) found that the infrared radiation from Comet Bennett indicated effective temperatures significantly higher than the expected blackbody temperature in the 2- to 20-μm region and that a strong emission feature existed near 10 μm, which was interpreted as due to silicate grains. Extending his multichannel photometry between 0.55 and 18 μm to Comets 1973f, 1974b, and P/Encke, Ney (1974) recently confirmed the excessive

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temperature [detected also by Becklin and Westphal (1966) in Comet Ikeya-Seki 1965 VIII] as well as the silicate signature. He was also able to set a lower limit (from the absence of Rayleigh scattering) and an upper limit (from the opacity of silicate material) to the average particle size: 0.2 and 2 μm, respectively. However, the antitail of 1973f showed neither excessive temperatures nor any silicate signature, and Ney concluded – in complete agreement with my independent finding (Sekanina 1974c) – that the antitail particles must have been definitely larger than 10 μm in diameter.

The field where infrared data would be of invaluable assistance to the theory is the study of the tails of distant comets. Present infrared techniques may not yet be sensitive enough to pick up the faint images of the comets at large heliocentric distances, but Rieke and Lee's (1974) observations, in the wavelength range 10 to 20 μm, of Comet Kohoutek at distances of almost 2 a.u. hold out hopes for the future. Further progress in the study of icy grains in the tails also depends on better knowledge of the optical properties of snows. At present, laboratory data on water snow are rather fragmentary, and those on other snows of interest – such as solid hydrates – are virtually nonexistent.

More work is needed on the anomalous tails of short-period comets, as well as on the apparent absence of a correlation between them and meteor streams. We would consider the possibility of predicting future favorable visibility conditions for antitails of short-period comets to facilitate a reasonably efficient observational program, if interest is expressed in pursuing such a search. In any case, we plan to make routine predictions of expected antitail appearances for bright, nearly parabolic comets.

The nature and properties of vaporizing dust particles in cometary tails probably constitute the most intricate problem ahead. Work is in progress on the antitail of Kohoutek 1973f and on the synchronic bands in Mrkos 1957 V – the two instances where the presence of vaporizing particles now appears to show up rather convincingly. A comparative study of the antitails of Comets Kohoutek and Arend-Roland is intended for the near future. The two best comets for a systematic study of the synchronic bands – in addition to 1957 V – are 1965 VIII and 1910 I. Concerning the latter, a discrepancy exists between Orlov's (1945) and Vsekhsvyatsky's (1959) comparison fits of the synchronic bands, and this needs clarification.

A purely mechanical approach is also used by Jambor (1974) to point out that there might be problems in reconciling existing models of the zodiacal cloud with the mechanism of dust contribution from short-period comets, in terms of both the amount of dust that can be supplied and particle sizes. A more comprehensive study is clearly necessary.

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DISCUSSION

P. M. Millman: In reference to Dr. Sekanina's suggestion that the tensile strength of the dust in comet tails may break down at certain sizes in their evaporization, it should be noted that evidence from various types of observation of the interplanetary medium suggests that there is a tendency for micrometeoroids to break into certain preferred sizes in various size regimes.

Z. Sekanina: I'm of course glad to hear that.

E. Gerard: Did you study what the effect of the rotation of the nucleus may be if you have anisotropic dust emission and could this affect the dust tail curvature?

Z. Sekanina: I don't want to go into details, but the basically correct answer is that it would not affect the curvature.

D. A. Mendis: A modification of the mechanical theory could be produced by the charging of the grains. With small grains in the typical environment of the tail it is not difficult to charge them to large potentials and if magnetic fields in the tail are of the order of 100—1000γ it may be possible to explain the helical features seen in the dust tail of comet Ikeya-Seki.

Z. Sekanina: This is, of course, one of the objections that has been raised in the past. My reply to that is, if you come up with a quantitative picture and you get better agreement than I get with other sources, I am going to accept it. So far, nobody has come up with a sufficiently precise quantitative picture.

B. Jambor: I am anxious to see the applicability of the "vaporizing particle" variation of the Finson-Probstein theory shown by Dr. Sekanina to Comet Ikeya-Seki. In this case the features appear only far away in the tail in the zone where particles of $1-\mu > 1$ are found, showing that only small particles are involved, the larger ones do not seem to vaporize. Vaporization and reduction of radius should be accompanied by charging and therefore plasma effects are to be expected. If no such effects are observed, one should almost necessarily ask: "why?"

Z. Sekanina: Yes. There is a complete lack of sufficiently precise theory that explain the observations by including other forces. If this problem were overcome, I would be willing to accept such a theory but so far, nothing great has happened.

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W. F. Huebner: What is the significance of the value of 0.585 for the density? Is this an effective value, or are you assuming spherical particles?

Z. Sekanina: This number is only a mathematical exercise. We generally work with 1 minus mu, and if we want to talk about particle radii, we have to assume the density. Of course, in the case of vaporization we are very lucky because what we actually get is the change in the size multiplied by the density, so that a only problem would arise only if the density of the particle changes. I use $Q_{RP}=1$ everywhere in the calculation and I use latent heat of vaporization=30 Kcal/mole.

W. F. Huebner: If the dust particles vaporize under the effect of solar radiation, then the released atoms may get ionized, either by radiation or by charge exchange. The Los Alamos Vela satellite group can look at the ionic charge-to-mass ratio, e.g., they have detected various isotopes of iron coming from the solar abundances. Is there any possibility of looking for released cometary ions in the Vela satellite data; what date might be the most appropriate to look for?

Z. Sekanina: The dates would be specific for various comets.

H. Keller: The orbital positions of satellites were checked by M. Dryer at NOAA Boulder to determine whether they were favorable for detection of cometary ion in Kohoutek. They were not.

Does Comet Ikeya-Seki also show evaporation of dust?

The observations of the fast increase in the tail length of Kohoutek after perihelion by the astronauts on Skylab may support the evaporation of particles, since large values of $1-\mu$ ($\geqslant 10$) were necessary as explanation (not taking evaporation into account).

Z. Sekanina: Yes. I haven't done the quantitative analysis but I know that this may be the case.

E. Grün: I do not agree with Dr. Sekanina's statement that the probability of detecting particles by in-situ dust experiments is very low. Trajectories of dust particles can always be found — by varying the emission time and the size of particles — such that these particles are at the same place in space as the in-situ detector during its penetration through the orbital plane of the comet. The probability of detection is really dependent on how abundant these particles are. Our group will continue looking for more evidence of dust-particles released from comets using our dust detector on Helios A.

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Z. Sekanina: I haven't done a quantitative analysis but I think it's a good idea to try this experiment.

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