THE PHYSICS OF COMET TAILS[1]

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Introduction

Comets are among the least massive and most intriguing objects subject to astronomical scrutiny and investigation, and they are the object of ever increasing interest and physical study. A significant part of this new effort stems from the fact that comets act as natural probes of the interplanetary plasma or solar wind, and potentially contain a large amount of information that is difficult to obtain directly through space probes (such as properties away from the plane of the ecliptic). In addition, the comets (type I) provide a valuable supplement to our natural plasma physics laboratory already found in the corona and solar wind. It seems that a magnetohydrodynamic model will be required, to give a proper explanation of type I comet tails.

While this review, strictly speaking, is concerned only with comet tails, it is impossible to discuss them without giving a reasonable idea of a total comet model. The comet nucleus is presumed to be a solid body with a radius in the range 1 to 10 km (Roemer 1966); masses of comet nuclei are very uncertain, but values of $\sim 10^{16}$ to 10^{21} g are found in the literature. The nucleus is thought to correspond to Whipple's (e.g., 1963) "icy-conglomerate" model wherein the nucleus consists of relatively complex parent compounds (possibly H_2O, NH_3, CH_4, CO_2, C_2N_2, etc.) which sublimate in vacuum at temperatures of a few hundred ° K and when dissociated provide the daughter molecules observed in cometary spectra. Meteoric material of a wide size range is interspersed throughout the ices. The nucleus is required to have considerable cohesiveness to avoid gravitational breakup and an inhomogeneous structure for outbursts, apparent features, etc. Calculations for a model nucleus (Hübner 1965) indicate a surface temperature in the range 150–250° K. Finally, the total mass loss from a large comet during a perihelion passage has been estimated at 1 per cent of the total mass; this mass must come from the nucleus.

The coma is composed of meteoric dust and neutral molecules in an essentially spherical volume centered on the nucleus; these constituents appear to be moving away from the nucleus with velocities of about 0.5 km/sec [estimated from concentric expanding rings or halos from comet Halley (Bobrovinikoff 1931)]. The coma can be detected out to distances of 10^5 to 10^6 km from the nucleus. The molecules CN, CH, NH, OH, C_3, and NH_2 have been identified spectroscopically (Rosen, Swings & Houziaux 1957; Arpigny 1965); this list may well be seriously incomplete because the observations are limited to the visible spectrum. Rocket or satellite observations (above the atmo-

[1] The survey of literature for this review was concluded November 15, 1967.

sphere) would remove this rather serious uncertainty. If the velocity is constant and photodissociation unimportant, the space density varies as r^{-2} and the surface brightness as r^{-1} (provided that the opacity is small); this latter variation is approximately observed. Typical estimates for the total gas density are 10^{12}-10^{14} molecules/cm^3 near the nucleus and 10^2–10^4 molecules /cm^3 near the outer boundary.

The coma is visible during most of a perihelion passage of a comet. It is apparently quite small at distances of 4 a.u. or greater; a maximum size appears to be obtained at 1.5–2.0 a.u. together with a "contraction of the coma" as the comet approaches the Sun (e.g., Sekanina 1966). The various molecules appear in a sequence as the comet approaches the Sun. The CN bands appear when the comet is near 3 a.u. and near 2 a.u., C_3 and NH_2 appear. With closer approach, C_2, CH, OH, and NH appear.

The third basic structural element of a comet is the tail. Comet tails, the subject of this review, are most spectacular, reaching up to 10^8 km or 1 a.u. in length. The type I tails are composed of ionized molecules with CO^+ predominant and a contribution from N_2^+, CO_2,$^+$ CH^+, and OH^+. These species have been identified spectroscopically; the list may well be incomplete because of the limited spectral range currently available. The ionized species usually appear only when the comet is within 2 a.u. of the Sun; a notable exception is comet Humason 1961e which showed CO^+ emission at 5 a.u. and beyond (Dossin 1966). Type I tails are straight (or have only a very small curvature) and, to a first approximation, point away from the Sun. Considerable filamentary structure exists in the form of tail rays which tend to be arranged symmetrically about the tail axis and which turn in time towards the tail axis. Typical densities of CO^+ are in the range 10^2–10^3 molecules /cm^3. The tail streamers are quite thin with radii of some 3000–4000 km or less, and the entire type I tail typically has a width of only 10^5–10^6 km. Additional fine structure in type I tails is found as knots of bright material or kinks in the streamer structures. These are of considerable interest in studies of accelerations which led Biermann (1951, 1953) to the concept of a solar wind.

Type II tails are strongly curved and their lengths are some 10^7 km, generally somewhat shorter than type I tails. These tails are broad, and rarely contain extensive fine structure. The spectrum of type II tails is a reflected solar spectrum and thus the type II tails are undoubtedly composed primarily of dust. Photometric and polarimetric studies (e.g., Liller 1960; Donn, Powell & Remy-Battiau 1967 and references contained therein) indicate typical dimensions $\sim 1\ \mu$; such sizes are also compatible with the observed tail curvatures.

The two types of tails are not mutually exclusive as is well shown in the case of comet Mrkos (1957d; see Figure 1). However, examples of essentially pure type I and type II comet tails are known.

In this review, the gross tail structure and orientation will serve as the focal point of our discussion. Rationale for this approach stems from the

FIG. 1. Photograph of comet Mrkos (1957d) clearly showing a type I (plasma) and a type II (dust) tail. Courtesy of Mount Wilson and Palomar Observatories.

author's personal interest, recent advances in this area, and the fact that the understanding of the basic forms of comet tails is essential to a physical theory of comet tails. The reader who is not familiar with the physics of comets or comet tails may welcome a few standard references. These are Bobrovnikoff (1951), Wurm (1959), and the book by Richter (1963). The 4th and 13th *Liège International Astrophysical Symposia*, held in 1952 and

1965, were devoted to comets; the *Proceedings* were published in 1953 and 1966. Volume IV of the Solar System Series (University of Chicago Press) entitled *The Moon, Meteorites, and Comets*, edited by B. M. Middlehurst and G. P. Kuiper, contains several review articles on comets. Finally, a discussion of comets is contained in the text by Brandt & Hodge (1964). All of these publications are somewhat out of date.

Type I Tails

Orientations.—The presence of the solar wind in interplanetary space is of prime importance for the physics of type I comet tails; details of the physical properties of the solar wind are given by N. F. Ness in this volume. Briefly, the solar wind near the Earth is essentially a completely ionized plasma (predominantly protons and electrons) moving approximately radially with typical velocities of 300–500 km/sec. The number densities are in the range 1–10 particles/cm^3 and the temperature is of the order of 10^5 °K. The quiet-time magnetic field is about 5 γ (5×10^{-5} G) and is "frozen-in" to the expanding plasma. Higher fields are found during disturbed periods. Considerable fine structure exists in the field, and the general orientation of the field direction makes an average angle of 45° with the radius vector.

In his basic paper, Biermann (1951) cited as evidence for the existence of the solar corpuscular radiation the fact that the orientations of type I comet tails lagged a few degrees behind the radius vector. The interpretation was made on the basis of dynamical aberration or the direction of the interplanetary plasma as seen by a hypothetical observer riding on the comet; the evidence then available was the pioneering study of the orientations of type I tails by Hoffmeister (1943). These types of studies have been actively pursued by Belton & Brandt (1966), Pflug (1966), Brandt (1967), and Brandt & Heise (1968) as a means of delineating the gross velocity field of the solar wind. Conversely, since the dynamical-aberration hypothesis seems established and the basic properties of the solar wind velocities are known, the data collected can be used to produce a picture of the orientations of ionic comet tails.

A catalogue of information relating to comet-tail orientations (both type I and type II) has been produced by Belton & Brandt (1966). Original measurements of plates and prints, as well as published data, have been analyzed to produce a basic body of information for some 1600 individual observations of 60 different comets. The observational data consist of the position angle θ of the tail axis on the plane of the sky; also calculated are the position angle ϕ of the prolonged radius vector and the position angle ψ of the tangent to the comet's orbital path prolonged backward along the orbit. These quantities, together with the orbital properties of the comet and the geometrical circumstances, can be utilized to produce the orientation of the tail in the comet's orbital plane, assuming that it lies in the plane. This assumption has been verified on the average for comet Daniel 1907d (type I tail) by Mammano & Wurm (1965), and by Belton (1965) for the type II tails of comets Haro-Chavira (1954k), Arend-Roland (1956h), and Wilson-Hubbard (1961d) on individual days when the Earth passed through the plane of the comet's orbit. Note that the type I structure in the tail of comet Arend-Roland was close to the plane of the comet's orbit on April 25, 1957 when the Earth was also in this plane; see the photograph reproduced by Wurm (1963, Figure 4). The geometrical situation is resolved to yield the aberration angle ϵ which is measured positive in the direction opposite the comet's velocity V. If we resolve the solar wind velocity into a radial component w_r and an azimuthal component w_ϕ (measured positive in the sense of the solar rotation), the aberration angle for a comet near the solar equator is given by

$$\tan \epsilon = \frac{V \sin \gamma - w_\phi \cos i'}{w_r - V \cos \gamma} \qquad 1.$$

where i' is the inclination of the comet's orbit to the plane of the solar equator, γ is the angle between the radius vector and the direction of V, and thus $V \sin \gamma$ is the comet's velocity perpendicular to the radius vector.

We may inspect Equation 1 to predict the properties of the type I tails. The average $V \sin \gamma$ is approximately 33 km/sec, and 450 km/sec is a reasonable average value for w_r; hence the average ϵ should be about 5°. If a substantial w_ϕ exists, it would show up as a systematic difference in the mean aberration angles for direct versus retrograde comets because $\cos i'$ changes sign. For w_ϕ of approximately 8 km/sec (at 1 a.u.), the mean aberration angles should differ by approximately 2° with the retrograde value being the larger. Note that while the w_ϕ value of about 8 km/sec was first derived from studies of ionic comet tails (Brandt 1966, 1967; Brandt & Heise 1968), it has been independently confirmed by direct space-probe measurements (Strong, Asbridge, Bame & Hundhausen 1967). Finally, if the solar wind direction shows a dispersion of about 5° about its mean direction, as has been observed by Strong et al. (1967) and by Wolfe, Silva, McKibbin & Matson (1966), the aberration angles should show a dispersion of the same amount which cannot be removed by a straightforward variation of the quantities in Equation 1 or by errors of reduction.

The observational results for some 600 individual observations of type I tails contained in the catalogue of Belton & Brandt (1966), as discussed by Brandt & Heise (1968), are shown in Figure 2; all the features expected are clearly discernible. The overall sample has an $\langle\epsilon\rangle$ of 4°.7 while the retrograde and direct comets considered separately have $\langle\epsilon\rangle_R = 3°.7$ and $\langle\epsilon\rangle_D = 5°.5$ (respectively). Thus, the aberration effects due to the radial and azimuthal components of the solar wind are quite apparent. The rms dispersion about $\langle\epsilon\rangle$ for the entire sample is 4°.7. The mean is virtually unchanged if direct and retrograde comets are considered separately. The effects of errors and straightforward variations of the quantities in Equation 1 are considered by assuming that they are all independent and, hence, add in the square. Generous estimates of errors and variations related to Equation 1 leave an inherent

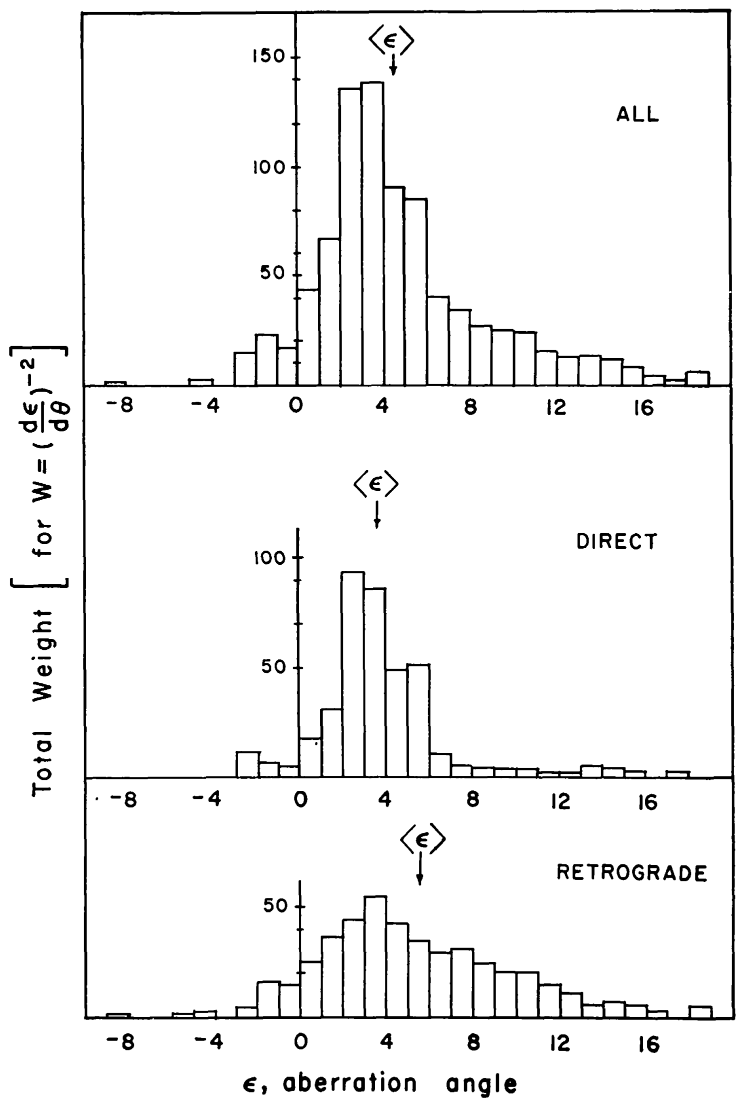

FIG. 2. The distribution of aberration angles of type I comet tails according to data presented by Brandt & Heise (1968). Aberration effects due to the radial and azimuthal components of the solar wind as well as the dispersion are clearly shown; see text for discussion.

rms dispersion of about 4°, in excellent agreement with the results obtained from space probes. Thus the aberration picture is confirmed in every respect and the ionic comet tails qualify as extremely good natural wind-socks in the expanding solar plasma.

The aberration picture can be checked in one additional way. Axford, Dessler & Gottlieb (1963) have given convincing physical arguments for a lower bound to the solar wind velocity $\sim 10^2$ km/sec. This can best be found in the comet data by using a function which removes the angle γ from the consideration. Osterbrock (1958) introduced the parameter

$$h = \sin(\gamma + \epsilon) \csc \epsilon \qquad 2.$$

such that

$$|w| = |V|h \quad 3.$$

Here w is assumed radial and V is the total velocity of the comet. Since $|V|$ is a slowly varying function, we expect a minimum value for h; this was first found by Belton (1965) and is clearly shown in his Figure 5 where $h \geq 4$. Essentially the same value is found for a much larger sample by Brandt (1967) and Brandt & Heise (1968) who find a minimum solar wind velocity of about 200 km/sec. Again, the aberration theory is confirmed.

Note that the detailed nature of the interaction is not specified. All that is required is that the tail be symmetrical near the head with respect to the local wind direction, much as for the geomagnetic tail; the analogy between comet tails and the geomagnetic tail has been suggested by Brandt (1962b) and by Ness & Donn (1966).

A possible complication concerns the assumption that the tail lies in the plane of the comet's orbit, at least on the average. The available checks (cited above) and the nature of our results indicate that this assumption is approximately true. However, even a small systematic departure (which may exist) or other unexpected effects could influence the results presented above.

An unresolved problem concerning the orientation of type I comets is the case of the "wagging tail" of comet Burnham (1959k) studied by Malaise (1963). Ness & Donn (1966) have proposed an alternate interpretation in which the apparent periodicity is due to the turning of individual tail rays to the axis with a spacing of a few days. The manner in which such a phenomenon could fit the observations is shown in Figure 7 of Ness & Donn (1966). However, Belton (1967) finds that additional observations of ϵ not available to Malaise tend to fill out and extend the quasi-sinusoidal variation suggested by him. Thus, this tail appears to "wag"! This could imply a distinctly structured nucleus (Brandt 1962b), or directed plasma emission, or both. Also possible is a significant departure of this tail from the plane of the comet's orbit. Despite the new evidence concerning the orientations of comet Burnham, the ideas of Ness & Donn (1966) are still of considerable interest in explaining cometary fine structure.

Fine structure.—Two classes of structures require discussion—filaments and the tail knots or kinks. The basic filamentary structure appears to be compelling evidence for magnetic fields in comet tails. Filamentary structure in the tail away from the head is shown in Figure 1 for comet Mrkos (1957d) and in Figure 3 in the vicinity of the head for comet Halley (1909c). We have mentioned that typical radii for the tail rays are some 3000–4000 km and note that Maffei & Wurm (1961) have measured 2000 km for comet Burnham (1959k) which passed rather close ($\simeq$0.2 a.u.) to the Earth. For thermal velocities, the CO^+ ions would traverse the ray in a few hours even for a temperature $\sim$1° K. This temperature for the tail ions is clearly ridiculous. The difficulty vanishes if the radii are interpreted as being approximately the size of the Larmor radius for the CO^+ ions from the formula $r_L = V_\perp m/qB$

FIG. 3. Photograph of comet Halley (1909c) showing the structure of filaments near the head. Courtesy of Mount Wilson and Palomar Observatories.

where $V_\perp$ is the velocity of the ion perpendicular to the field, m is the ionic mass, q is the charge (emu), and B is the field in gauss. If $V_\perp$ is the thermal speed for 10^4 °K and B is comparable to the quiet interplanetary field near the Earth of 5 γ, $r_L \sim 10^2$ km. Any reasonable parameters will always keep r_L less than the presently accepted streamer size.

Wallis (1967) has challenged this interpretation and has given calculations explaining the stability and extreme straightness of the tail rays as due to the hypersonic nature of the flow rather than to a cometary magnetic field. However, it seems that this picture does not apply to the complex evolution of tail rays and their turning to the axis in the manner of a "folding umbrella" as described by Marochnik (1964); see Figures 4 and 5 for the complex structure near the nucleus and Figure 3 for the structure in the head. Moreover, the observed motions of kinks in the streamers and the observed helical structures [which resemble the forms found in force-free magnetic fields (R. Lüst & Schlüter 1954)] argue strongly for the influence and importance of magnetic fields in the tail structure; see especially the results presented by Rh. Lüst (1962) and by Biermann & Rh. Lüst (1966).

In principle, cometary magnetic fields might be derived from studies of the sodium D_2 emission line (Hyder 1965). However, Chamberlain (1967) has shown that the cometary fields would have to be orders of magnitude higher than those expected, to produce any spectroscopic effects.

The problem of the accelerations of structural details in comet tails (such as knots and kinks) is one of the most vexing in the area of cometary physics. These features can be followed for a period of a few hours or, in exceptional cases, of a few days. Such observations yield the position of the feature along the tail as a function of time, and, if one assumes that actual material motions are involved, the velocities and accelerations can be calculated; a table of references to such calculations has been given by Biermann & Rh. Lüst (1963, Table I). Typical velocities are $\sim$10–100 km/sec. Accelerations are generally measured in terms of the quantity (1-μ) which is the extra outward acceleration in units of the local solar gravity; thus the "extra force" is as-

FIG. 4. Photograph of the head region of comet Morehouse (1908c) showing the form of the CO^+ emission near the nucleus. Greenwich plate, reproduced by K. Wurm. Courtesy of J. Rahe.

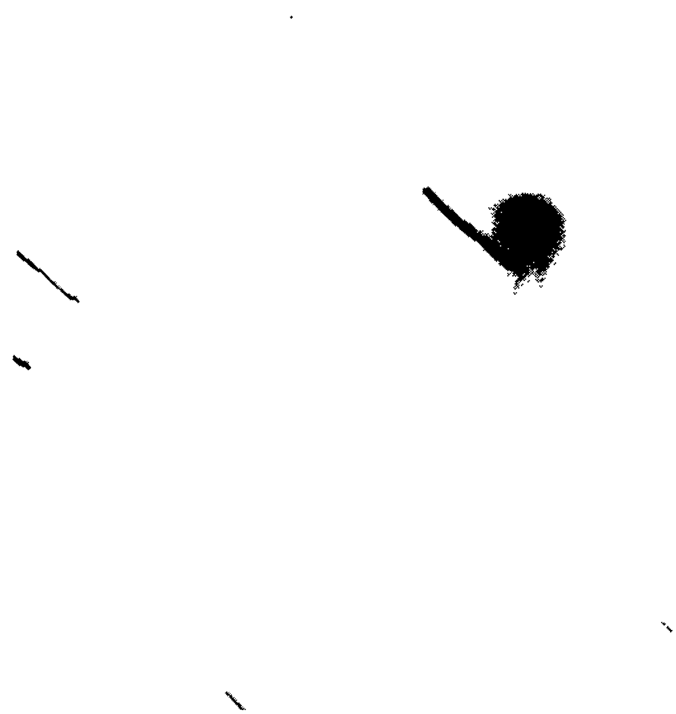

FIG. 5. The head region of comet Morehouse showing further structure and extension of CO^+ filaments. Greenwich plate, reproduced by K. Wurm. Courtesy of J. Rahe.

sumed to vary as the inverse square. Typical values of $(1-\mu)$ are $\simeq 100$; the lower values are found in the inner part of the tail and the higher values are found in outer rays close to the head. If the accelerations are real, the inner rays seem to be shielded from the accelerating force by the outer rays or the nucleus. For some time now, it has been apparent that radiation pressure is insufficient to produce the observed accelerations of CO^+ clouds (e.g., Wurm 1963) by three orders of magnitude, although radiation is an attractive mechanism because it can penetrate the cometary atmosphere with relative ease.

Thus, Biermann (1951, 1953) suggested that the accelerations are caused by an interaction with a plasma flow (possibly magnetized) from the Sun. This suggestion has been discussed at some length through the years (see e.g. Biermann & Rh. Lüst 1963) and it is clear that solar wind contains sufficient momentum and that the imbedded magnetic field would provide efficient coupling. However, it is not at all clear that the solar wind has sufficient access to the tail knots, particularly those well within the tail. Hence, it may be worthwhile to consider briefly two alternatives in which the solar wind is the "ultimate cause" but does not act directly on the tail condensations. The picture of the turning of the rays to the tail according to Marochnik's (1964) "folding umbrella" analogy is suggestive of a picture in which the solar wind pushes on the outer magnetic tubes forming the tail streamers and thus compresses the ensemble of streamers into a smaller cross-sectional area as one moves away from the head. Blobs of CO^+ ions could then derive their accelerations from Schlüter's (1950) "melon seed" mechanism. This reviewer has not seen this suggestion in the literature.

The second alternative is to abandon the idea that the condensations are material motions; perhaps they are wave motions or patterns of excitation produced by irregularities in the solar wind. Ness & Donn (1966) find that the velocities needed could result from Alfvén waves [$V_A = B/(4\pi\rho)^{1/2}$] for tail fields $\sim 40\ \gamma$; it is not immediately clear how the field and density could vary to produce an apparent acceleration. However, Coppi, Laval & Pellat (1966) point out (in connection with the geomagnetic tail) that annihilation of magnetic field across the neutral sheet can produce waves and particle acceleration.

Overall structure and theory.—A successful theory of type I comet tails must explain the rather efficient production of the CO^+ and other ions and their confinement to specific locations with respect to the cometary nucleus. The overall interaction is quite complex and no truly definitive picture exists, although an encouraging start is the hydrodynamical model of Biermann, Brosowski & Schmidt (1967).

The structure of the CO^+ emission near the nucleus is clearly shown in Figure 4 and 5 which are from Professor K. Wurm's reproductions of the Greenwich Plates of comet Morehouse (1908c), courtesy of Dr. J. Rahe. As noted by Wurm (1962), the CO^+ emission originates in a small volume very near the nucleus on the sunward side and extends into the tail streamers. Initially, the "jet" of tail material points towards the Sun (Rahe 1968, Rahe & Donn 1968); the jets have lifetimes of about one day and during this time lengthen and turn to the tail axis. Rahe and Rahe & Donn estimate that the ionization of tail plasma on the sunward side is confined within 1000 km of the nucleus. The travel times involved in such distances (at about 0.5 km /sec for the neutral molecules) and transient phenomena imply ionization time scales of 10^3–10^4 sec for production of CO^+. The direct mechanisms such as photoionization (Wurm 1961) and charge exchange (Biermann & Trefftz 1964) give time scales $\sim 10^6$ sec, hence the ionization mechanism is not well understood. The unusual comet Humason not only showed strong CO^+ emission at distances of 5 a.u., but also displayed structural pecularities and a variety of form which will serve as a severe challenge to any theory of the solar wind-comet interaction; see, for example, the photographs presented by Van Biesbroeck (1962) and Guigay (1966a).

The basic form of the comet-solar wind plasma interaction was suggested by Alfvén (1957); on his picture, the frozen-in field lines of the solar wind plasma capture the cometary ions (produced by photoionization and charge exchange) onto the field lines (recall the extremely small Larmor radii quoted above). This slows down the plasma in the vicinity of the head and causes the field lines to wrap around and turn to the tail axis. Axford (1964) noted that a shock transition (analogous to the Earth's standing bow shock) would occur. The partial thermalization achieved produces a source of energetic electrons which could be the ionizing agent. Beard (1966), on the other hand, points out that protons penetrate farther into the slower, compressed field ahead and a charge separation is created. This can produce energetic electrons for ionization, etc. Ness & Donn (1966) modified Alfvén's picture to include capture of neutral sheets known to exist in the interplanetary plasma as a result of the magnetic sector structure (Ness & Wilcox 1964); such neutral sheets are regions of higher density which are necessary to separate the fields of opposite polarity. The neutral sheets in the solar plasma would encounter a comet at a frequency of about one per week and could, in principle, account for the periodicities found by Malaise (1963) for the case of comet Burnham (1959k); see above for a discussion of the orientation of this comet tail.

The literature on the subject of the comet-solar wind interaction is large and the reader is referred to the paper by Biermann, Brosowski & Schmidt (1967) where extensive references are given. We now briefly describe their hydrodynamic model. It is taken to be axisymmetric and applies only to the sunward side. The cometary nucleus is taken to be a source of a flow of neutral molecules which do not interact with the solar or cometary plasma until they are ionized; then they are quickly accelerated to the mean velocity of the surrounding plasma through the frozen-in field (recall the small value of the Larmor radius quoted above for the cometary ions). Thus in the equations describing the motion of the plasma, mass is not conserved. In these first calculations, photoionization is considered as the only mechanism for ionization. A detached shock develops when the mean molecular weight has increased (because of the added cometary ions) by a small amount corresponding to an addition of CO^+ ions in the amount 1 per cent by number. The standoff distance for the shock is about 10^6 km sec as would be expected, because this is roughly the distance traveled by the neutral molecules (emitted at velocities $\sim$1 km/sec) before photoionization becomes significant. The solution also shows a stagnation point at distances of about 10^5 km which delineates the contact discontinuity separating the pure cometary plasma inside from the mixed plasma outside. Note, for example, that the cometary plasma extends much farther towards the Sun than the observations appear to allow.[2] The authors stress the preliminary nature of this model, and the inclusion of further details such as other ionization mechanisms is currently in progress. However, this work has already illustrated the potential importance of the hydrodynamical approach to comet models, and indicates that comets may interrupt the solar wind flow over dimensions larger than the currently accepted coma sizes.

While many groups pursue the problem from the theoretical viewpoint,

[2] However, Rh. Lüst (1967) has studied "envelope" structures in the coma of comet Morehouse; these might be the contact surface in the theory by Biermann, Brosowski & Schmidt.

three experimental approaches may yield results. First, the subject of rendezvousing a deep space probe with a comet has been discussed for years (e.g., Corben 1962; Roberts, Narin & Pierce 1966). Direct measurements of densities, velocities, field strengths, etc. could drastically alter our ideas concerning cometary physics. Second, there is the possibility of creating an artificial comet whose properties could be studied, but with the tremendous advantage of detailed knowledge pertaining to the state and composition of the original material (see, for example, Biermann, R. Lüst, Rh. Lüst & Schmidt 1961; Shklovskii 1961; and Biermann & R. Lüst 1966). Third, phenomena resembling comet tails have been simulated in the laboratory (Danielson 1966). While such experiments are potentially quite valuable, one should bear in mind the unrewarding experience of auroral investigators regarding laboratory simulation through terrella experiments.

Type II Tails

Orientations and structure.—Type II tails appear to be rather different from type I tails in terms of the governing physical processes. This is not unexpected because the type II tails are composed of dust particles with dimensions $\sim 1\ \mu$. Strongly curved dust tails are occasionally called type III tails; there seems to be no fundamental physical difference between type II and type III and the latter will not be considered separately. These views are widely, but not universally, held; Levin (1966) holds that type II tails are composed of neutral molecules and reserves type III for straight, synchronic formations caused by discrete outbursts of material. In addition, we do not discuss anomalous or sunward spikes such as the one displayed by comet Arend-Roland (see Öpik 1958).

Mixed comets (having both type I and type II tails) are a problem somewhat apart. Belton, Brandt & Hodge (1963) noticed that the type I and type II tails of comet Mrkos (1957d) were tangent near the nucleus, particularly when viewed on plates obtained with short exposure. The phenomenon seems widespread (although exceptions, such as comet Perrine 1895c, are known) and apparently results from a drag force exerted on the dust particles by the plasma in the type I tail (Notni 1964; Belton 1964, 1965). The two types of tails apparently become decoupled within 10^6 km of the nucleus (comet Mrkos).

The fundamental problem for the orientations of type II comet tails concerns primarily the pure type II of which only a handful are shown. Over a hundred years ago, Bessel (1836) obtained the equations for tails formed by a repulsive force such as solar radiation pressure; Bredichin (see Jaegermann 1903) refined the theory around the turn of the century. The basic parameter of the Bessel-Bredichin theory is the quantity $(1\text{-}\mu)$ which is the excess outward force in units of the local solar gravity. Orbits of the ejected particles in the ξ–η coordinate system (with origin in the head of the comet, see Figure 6) can be calculated as a function of the initial conditions, $(1\text{-}\mu)$, and time. These equations can be combined to predict the apparent forms of

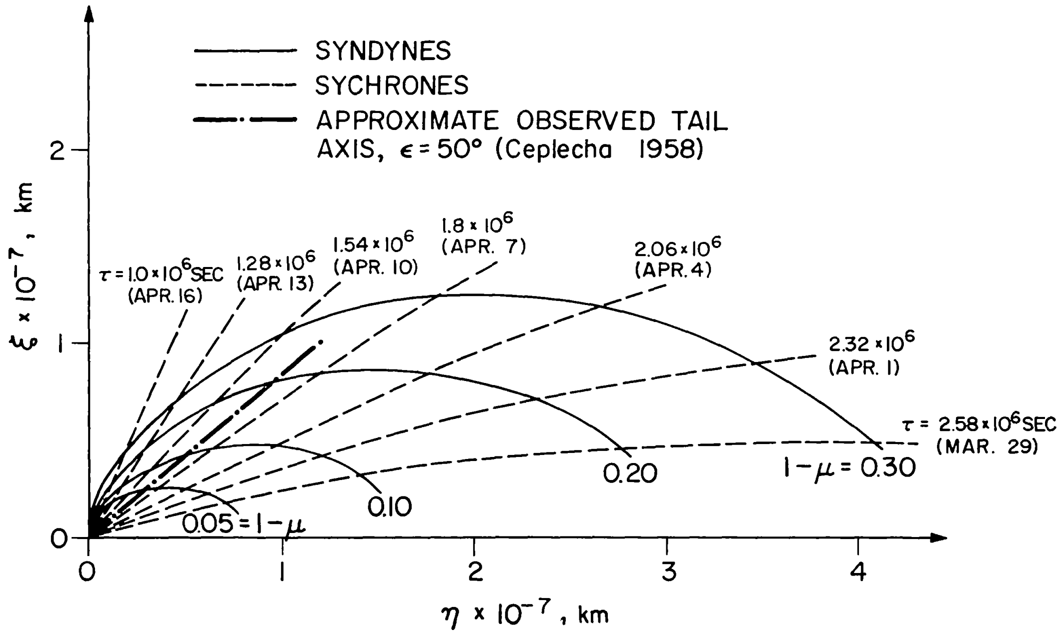

FIG. 6. The observed orientation of the tail of comet Arend-Roland on April 27, 1957 and a comparison with the standard syndynes and complete synchrones. The ξ axis is in the direction of the prolonged radius vector and the η axis is in the direction opposed to the comet's motion; the ξ-η axes lie in the plane of the comet's orbit. The dates for the synchrones are for the time of dust emission necessary to produce a tail in the given location on the date of observation. Courtesy of M. Finson & R. F. Probstein (1967).

comet tails. A syndyname is the locus of points of particles with a given (1-μ) which are emitted continuously. It is tangent to the radial direction at the head and lags the radius vector in the direction opposite to the comet's motion. A complete synchrone consists of a group of particles of all sizes and hence, in principle, all (1-μ) emitted at one time; the locus occupied by these particles can be nonradial and lags behind the radius with an angle that increases with time. Examples are shown in Figure 6. Modern discussions of the Bessel-Bredichin theory assume radiation pressure to be the repulsive force.

The syndynames of the Bessel-Bredichin theory were generally considered adequate explanations for type II tails until about 10 years ago. Osterbrock (1958) published a detailed study of the tail orientations of comets Baade (1954h) and Haro-Chavira (1954k). The tails were smooth, straight and were oriented such that $\epsilon \approx 45°$, or in terms of Osterbrock's parameter, $h \approx 1$. Similar results for distant comets were obtained by Beyer (1955). Walker's (1958) photoelectric and spectroscopic observations of comet Baade clearly indicated a dust or type II tail. These comets were both observed between 4 and 5 a.u. and hence this atypical orientation was considered to be a "problem of the distant comets." Ordinary, "well-behaved" type II comets observed at distances nearer the Sun "showed" the approximately radial orientation predicted by the Bessel-Bredichin theory (see below). Among the possible alternatives was the postulation of a drag force on the tail particles caused by the ambient material (Osterbrock 1958); this would necessitate a stopping of the solar wind interior to 4 a.u. (Brandt 1962a).

The interplanetary drag hypothesis was demolished by Belton (1965) who showed that pure type II tails displayed the property $h \approx 1$ independent of heliocentric distance. Mixed comet tails (as discussed near the beginning of this section) usually have the orientation of the type II tail strongly influenced by the type I tail near the head, which causes the near-radial orientation in these cases. Belton found that *pure* type II comet tails were rather rare. The data collected by Belton & Brandt (1966) indicated that about 18 per cent of comets are pure type II. Some discrepancy exists concerning this figure. Antrack, Biermann & Rh. Lüst (1964) find 67 per cent for pure type II tails, whereas Orlov (1958) finds 22 per cent. The difference may result from different sources for the tail-type classification, and serves to illustrate the difficulty in assigning a correct tail type.

Comet Arend-Roland (1956h) was a bright comet with a well-developed type II tail and photometric observations (Ceplecha 1958). Orientation of the type II tail appears "normal" with h largely ~ 1 (Belton 1965, Belton & Brandt 1966). Any acceptable theory of dust tails must at least account for this. Guigay (1960) suggested that the tail orientations could be explained by a complete synchrone due to an outburst of dust emission near perihelion (April 8, 1957); while this suggestion fits some of the data, it clearly does not fit all of the data. This hypothesis will reappear below in modified form.

Belton (1965) concluded that the traditional Bessel-Bredichin or mechanical theory was inadequate for type II tails and suggested (Belton 1966a) the possibility of a gross plasma interaction. The dust particles acquire a positive charge essentially due to the photoelectric effect. The charged dust particles show little reaction to the magnetic field convected by the solar wind because of their low charge-to-mass ratio; however, the electrons from the dust particles *tend* to be whisked away rather quickly by the magnetized solar plasma. This process would set up an electric field which would transfer momentum to the "dust ions" in a manner rather similar to the original mechanism suggested by Biermann (1951) for the acceleration of the tail condensations. Details of this mechanism are unavailable, but the idea of possible collective interactions receives support from observed fine structure in the brighter type II tails.

Finson & Probstein (1967) and Probstein (1967) have presented the results of a massive attack on the forms of type II comet tails. Since it has been pointed out by Jackson & Donn (1966) that continuum fluid dynamics is valid near the nucleus by virtue of the short kinetic mean free path, Probstein (1967) considers the problem of the expansion of a two-phase "dusty gas." The dust coupling to the gas is computed using standard free-molecular drag coefficients. The solution contains a sonic or critical point at which there is a transition from the subsonic solution valid toward the nucleus to the supersonic solution valid away from the nucleus; this pattern is remarkably similar to the flow in the solar wind (Parker 1958, Clauser 1960, Dessler 1967). The terminal velocity is reached within some 20 radii of the nucleus (corresponding to distances of 20 to 100 km); for a surface temperature of 200° K, the dust ejection velocities of ≈ 0.3 km/sec required by the widths of dust tails (and by detailed comparison with observations of comet Arend-Roland) are easily reproduced with reasonable values of the flow parameters. Because the terminal velocities are reached within such small distances, the dust emanates from a point source so far as calculations of the tail structure are concerned.

Finson & Probstein (1967) have studied the dust tail of comet Arend-Roland using the "inner solution," described above, as the initial values in a Bessel-Bredichin solution with radiation pressure. However, we have indicated that neither the standard syndyname nor a complete synchrone solution can fit the observations. Finson & Probstein find the remarkable result that superposition of synchrones broadened by this initial velocity and having a varying dust ejection rate can fit the observations; perhaps "modified synchrone hypothesis" is a name which adequately describes this new suggestion.[3] The amount of light scattered by the particles in the superposed solutions is calculated and the surface brightness compared with Ceplecha's (1958) observations in Figure 7; the agreement is very striking. The key to this solution lies in the form of the dust-emission rate with time; this quantity reaches a maximum before perihelion and declines after perihelion. Hence, if the answer suggested by Finson & Probstein (1967) for comet Arend-Roland is general, then apparently an asymmetrical dust emission with respect to perihelion is required with an increased rate prior to perihelion. This is certainly *not* in conflict with the evidence available; for example, Oort & Schmidt (1951) have noted that comets approaching the Sun for the first time have strong dust components of their spectrum. In addition, the inferred gas and dust-emission rates as well as the typical particle size ($\sim 1\ \mu$) are entirely compatible with the results of other studies. Finson & Probstein have briefly considered the case of comet Van Gent (1941d) and find rough agreement with the observed tail orientation if the dust emission occurred almost entirely before perihelion.

The "modified synchrone" hypothesis merits serious consideration. At present, it suffers from the fact that it has been applied in detail only to one comet, Arend-Roland. In addition, this comet had a substantial type I tail or structure during at least part of the last perihelion passage (Porter 1957, Maffei 1961); this structure is clearly shown in the Mount Wilson photograph of comet Arend-Roland included as Figure 5 of Finson & Probstein (1967). Finally, it is not clear that the Finson-Probstein model applies to a tail which has an essentially constant orientation over a long period of time.

[3] This reviewer finds the "modified synchrone" description easier to visualize than a "modified syndyname" description. Finson & Probstein (1967) note that they are equivalent. The structure results from a continuous but peaked variation with time of the dust-emission rate.

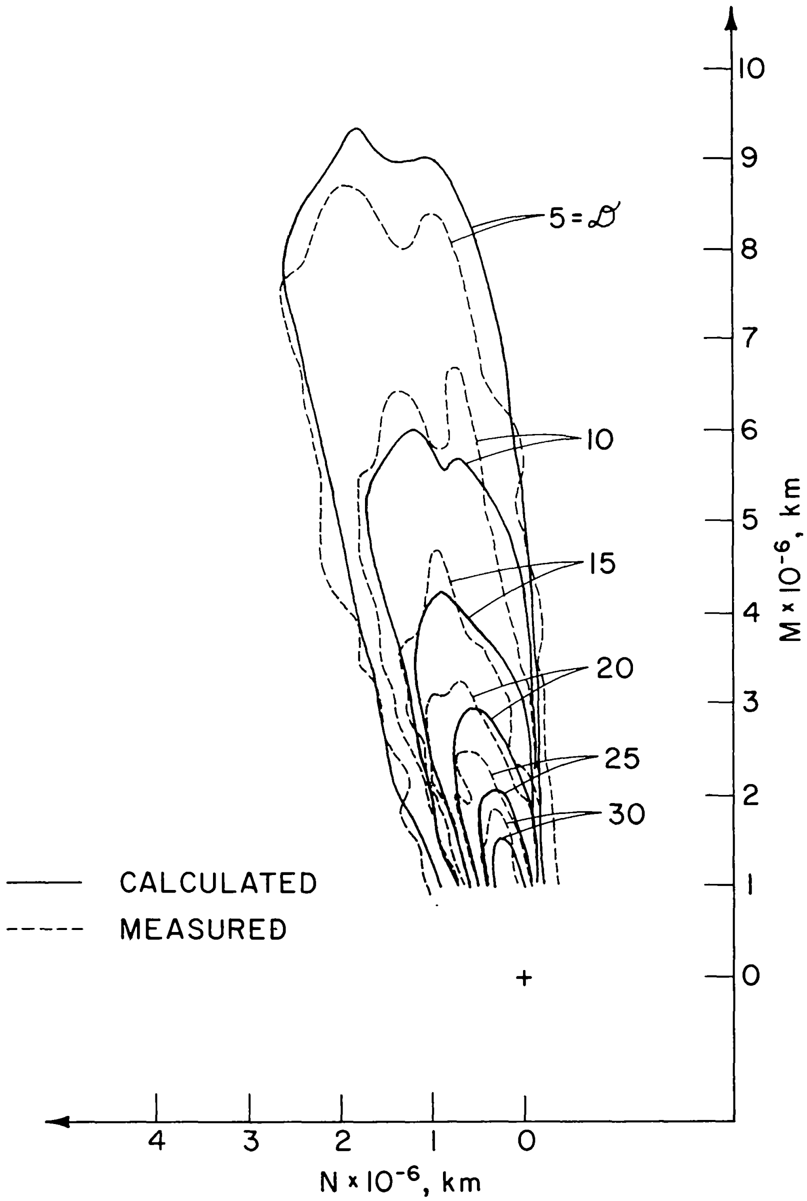

FIG. 7. A comparison of observed (Ceplecha 1958) and computed isophotes for comet Arend-Roland on May 29, 1957. The *M-N* axes are in the plane of the sky with *M* the apparent radial direction. The length scales are computed as the product of the angular distance times the Earth-comet separation. Courtesy of M. L. Finson & R. F. Probstein (1967).

Such is the case for comet Haro-Chavira (1954k) which had $h \approx 1$ for about one year as the comet moved from 4.21 a.u. to perihelion at 4.07 a.u. and back to 4.60 a.u. All of these possible objections can be removed by additional study and application of the "modified synchrone" hypothesis to other comets.

Fine structure.—Type II comet tails are often described as smooth and featureless, but this is not strictly true. The most common feature is the "synchronic band" structure observed as striations toward the end of the tail;

FIG. 8. Photograph of comet Ikeya-Seki (1965) on October 30, 1965, clearly showing fine structure; see text for discussion. Courtesy of M. J. S. Belton.

this phenomena is discussed by Vseksviatsky (1959) and has now been observed in five comets (see also Belton 1964, 1965, 1966a,b; Notni 1964, 1966). The effect is clearly shown in Figure 8 of Belton (1966b). There is a consensus among these authors that the Bessel-Bredichin or mechanical theory based on radiation pressure is inadequate and that the explanation may be some sort of electromagnetic or magnetohydrodynamic force (perhaps as wave phenomena).

The sun-grazing comet Ikeya-Seki (1965f) showed considerable fine structure, and spectroscopic observations have failed to detect any CO^+ emission; it is presumably a type II tail and the orientation of the tail shows $h \approx 1$ (Belton 1967). A color photograph of comet Ikeya-Seki by Dr. C. R. Lynds shows a yellow tail with no trace of the intense blue which is characteristic of CO^+ emission and which, for example, is easily visible on the Mount Wilson and Palomar Observatory color photograph of comet Humason. This fact supports the identification as a type II tail.[4] Figure 8 shows this fine structure in the tail of comet Ikeya-Seki. This phenomenon is currently unexplained. It would be interesting to see if the kind of calculations performed by Finson & Probstein (1967) can explain such fine structure and the "synchronic bands" or if other (and possibly magnetohydrodynamic) forces must be invoked.

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[4] Guigay (1966b) has performed a dynamical aberration analysis (of the kind discussed above in connection with the type I comet tails) on the tail of comet Ikeya-Seki. Since this comet passed within a few solar radii of the Sun, such analysis, in principle, contains information about the solar wind velocity very near the Sun. Such an analysis is normally inappropriate for a type II tail although the extremely close approach to the Sun could conceivably alter the situation for comet Ikeya-Seki.

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