

ON THE ORIGIN OF STRIAE IN COMETARY DUST TAILS

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ABSTRACT

It has been argued by Sekanina that the so-called striae or pseudo-synchronic bands observed in the dust tails of several comets are a consequence of the sudden disruption of elongated or chainlike parent grains in the tail. Here we offer a specific mechanism for this disruption process, that is, electrostatic disruption following sudden charging to high electrostatic potentials. Assuming the grains to be prolate spheroids, we show that they can attain potentials in the range -60 V to -300 V when subject to energetic electron beams (1–10 keV). The energy source for these electrons is the interaction of the solar wind with the cometary ionosphere producing currents and associated electrostatic double layers. Calculation of the electrostatic tension in such charged spheroidal grains indicates that the vulnerable grains have tensile strength in the range 10^4 – 10^6 dyne cm^{-2} .

Subject headings: comets — Sun: solar wind

I. INTRODUCTION

There have been a number of important works describing the mechanical theory of dust tails of comets. The first quantitative analysis of the brightness distribution in the dust tail was presented by Finson and Probstein (1968*a, b*). This theory and later improvements (Hiroshi and Cai-pin 1977) have explained many of the observed dust tail phenomena including such rare phenomena as the extremely narrow sunward (anomalous) tail as displayed by comet Arend-Roland 1957III (Sekanina 1974). The matching of the observed and calculated brightness distributions has enabled these authors to determine the size distribution, emission rate, and initial velocities of the dust particles in comet Arend-Roland and in comet Bennett 1970II (Sekanina and Miller 1973).

Recently, Sekanina (1976*a, b*) has drawn attention to an interesting class of phenomena observed in the dust tail of several comets. These are the so-called striae or pseudo-synchronic bands which are seen as relatively straight structures intersecting the synchronic dust streamers (which originate in the nucleus) at angles which make them more nearly parallel to the Sun-comet radius vector. The first such comet identified was comet Donati 1858VI and the first photographed was 1910I. Other comets with striae are comets Mrkos 1957V, Seki-Lines 1962III, Bennett 1970II, and West 1976VI, which also displayed streamers (Sekanina 1980).

Sekanina (1976*a*) points out that, since the positional properties of the striae do not coincide with the expected properties of truly synchronic bands, they

cannot be composed of grains directly ejected from the nucleus as such. While Sekanina (1976*a*) has shown that, at least in some cases, the trajectories of gradually vaporizing grains could be made to coincide with the observed orientations of the striae, he considers this explanation as very unlikely due to the large distances ($> 10^6$ – 10^7 km) separating these from the nucleus.

Detailed calculations of the dynamical structure of the striae (16 in all) observed in the dust tail of comet West 1976VI have been reported by Sekanina and Farrell (1980) which seems to bear out Sekanina's (1976*a, b*) earlier suggestion that these are composed of the fragmentation products of friable dust particles ejected from the nucleus.

In this paper, we offer a suggestion for the mechanism responsible for the fragmentation of the grains.

II. THE NATURE OF THE PARENT GRAINS AND THEIR FRAGMENTS

Sekanina and Farrell (1980) also draw important conclusions regarding the physical nature of the fragments and their parent grains. In the first instance, they point out that fragments are subjected to repulsive accelerations (β) between 0.6 and 2.7 times the solar attraction per unit mass, which is strongly indicative of submicron sized absorbing particles. Dielectric grains are effectively excluded because the maximum value of β attainable by these are only about 0.6 (e.g., Schwehm and Rhode 1977).

The second important point made by the above authors is that the values of β of the parent grains of these fragments are only slightly lower than the average

for the fragments, indicating that the area-to-mass ratios of the parent and the fragment are nearly the same. This, of course, indicates that the parent grains are strongly nonspherical. While the above authors accept that needles, rods, or very thin disks satisfy the observation, they regard chainlike particles as the most attractive candidates since such linear aggregates are a common occurrence in grain condensation experiments in the laboratory under a variety of conditions.

It is also worthwhile pointing out that while the cometary nucleus may very well contain grains of different shapes as well as sizes, those that are strongly nonspherical are most likely to be entrained by the drag of evaporating gases against the pull of the nuclear gravity. This is once again the effect of the area-to-mass ratio. For instance, a grain in the form of a prolate spheroid lying with its long axis parallel to the surface will be subjected to a gas drag which is $\lambda^{1/3}$ times that on a sphere of the same mass, where λ is the ratio of the long axis to the short axis. If λ is typically about 100 for long chainlike or rodlike grains, then the gas drag would be about 4.6 times that on a sphere of equal mass. Even if λ is only about 10, this drag ratio is still >2 . Consequently, it is reasonable to expect the dust tail to contain an overabundance of strongly nonspherical grains in proportion to approximately spherical ones.

III. THE GRAIN FRAGMENTATION MECHANISM

If we accept the view that the striae are indeed the result of fragmentation of parent grains far down the tail, the question arises as to the responsible mechanism. As a possible mechanism, Sekanina and Farrell (1980) have considered rotational bursting as a result of the uneven radiation pressure effect over the surface of an irregularly shaped body. This mechanism, which was proposed earlier (Paddack 1969; Paddack and Rhee 1975) as a general mechanism for the fragmentation of irregularly shaped interplanetary grains, may well be operative in cometary dust tails too. However, Sekanina and Farrell (1980) point out a difficulty with this hypothesis in that it requires that all the parent particles responsible for the formation of a discrete striae have the same torque factor (defined as a ratio of the linear torque arm to the maximum dimension of the grain), a condition which they find unlikely for all chainlike particles released during a single outburst from the nucleus. The only way out seen by the above authors is to speculate that the "background" dust tail is a smear of a large number of striae with the observed discrete ones corresponding to sharp peaks in the torque-factor distribution.

One cannot, therefore, entirely rule out the so-called "windmill" effect discussed above, as the mechanism responsible for the fragmentation of the parent grains,

although in view of the foregoing discussion it does not seem compelling.

In this paper, we propose an alternative mechanism, namely, electrostatic disruption of parent grains charged to moderately high potentials.

Electrostatic disruption of lunar dust particles has been proposed by Rhee (1976) with regard to the question of dust transport on the lunar surface. More recently, Fechtig, Grun, and Morfill (1979) have explained certain micrometeorite swarms in the terrestrial environment as electrostatic disruption products of larger interplanetary grains traversing the Earth's auroral regions, and Mendis (1979) and Hill and Mendis (1979, 1980) have proposed a similar mechanism to explain the observed micrometeoroid dust distribution within the magnetosphere of Jupiter.

In all these instances, however, energetic plasma (of at least a few hundred eV or more) is required to charge up the grains to sufficiently high potentials to disrupt the grains. The thermal plasma in the comet tail is, however, unlikely to have energies greater than 50 eV at most, while the thermal energy of the solar wind plasma itself does not amount to more than about 10–80 eV, even during disturbed times. On the other hand, there are good reasons to expect the existence of energetic nonthermal plasma in the cometary plasma tail. It has been pointed out by Ip and Mendis (1976) that the interaction of the solar wind with the cometary ionosphere causes large currents to flow both in the plasma tail and the ionosphere, with the current carrying electrons and ions in the cross-tail neutral sheet being energized to about 1–10 keV, possibly across an electrostatic double layer where the total voltage drop in the circuit is localized (see, e.g., Alfvén 1979). This cross-tail current will close in a double solenoidal fashion across the cometary tail plasma and the solar wind. Also, due to the highly inhomogeneous and filamentary nature of the cometary tail plasma, it is likely that this current will close along a system of thin sheets and filaments. Consequently, any cometary dust grain passing through one of these sheets or filaments in the vicinity of such a double layer would be subjected to a unidirectional flux of energetic (keV) electrons, which are the principal carriers of the current. The observed positions of the grain fragmentation events in comet West 1976VI at distances of 2×10^5 – 4×10^6 km from the radius vector (Sekanina 1979, private communication) are entirely reconcilable with this process. We consider the charging of these grains in § IV.

IV. CHARGING OF ELONGATED GRAINS

The electrical charging of small spherical grains in the Jovian magnetosphere under the condition that their radii are much less than the Debye length (λ_D) has already been considered (Hill and Mendis 1979). Here we extend the analysis to elongated grains, which

we consider for mathematical tractability as prolate spheroids. Here too, λ_D is much greater than the major axis (2a), which makes the potential effectively Coulomb. As before, the important charging currents to the grain are the electron current (I_e), the ion current (I_i), and the photoemission current (I_p), while the field emission would be of crucial importance only if the semiminor axis $< 0.15 \mu\text{m}$. Assuming a unidirectional flux of energetic electrons near an electrostatic double layer against a background of omnidirectional flux of thermal ions, which would produce a negative grain potential, we have

$$I_e = \frac{n_e e \alpha_e A}{2\sqrt{\pi}} \exp(-|V|e/kT_e), \quad (1)$$

where

$$\alpha_e = (2kT_e/m_e)^{1/2},$$

$$A = 4\pi\lambda b^2, \quad (2)$$

and b is the semiminor axis, V is the surface potential, and $\lambda = a/b$. Also

$$I_i = \frac{4n_i e \alpha_i A}{2\sqrt{\pi}} (1 + |V|e/kT_i), \quad (3)$$

where

$$\alpha_i = (2kT_i/m_i)^{1/2}. \quad (4)$$

Finally

$$I_p = A e f_p \phi, \quad (5)$$

and

$$f_p \phi = f_{p\oplus}/d^2 \approx \frac{3 \times 10^{10}}{d^2} \chi \text{ cm}^{-2} \text{ s}^{-1}, \quad (6)$$

where d is the heliocentric distance of the comet in AU and $\chi = 0.1$ for carbonaceous material (and presumably also cometary dust) (see Hill and Mendis 1979).

In the following analysis, we will assume that the plasma has three populations: low-energy ions and low- and high-energy electrons. The low-energy components are $n_e = 250 \text{ cm}^{-3}$, $kT_e = 50.0 \text{ eV}$; $n_i = 500 \text{ cm}^{-3}$, $kT_i = 50$; while the energetic electron component has $n_e = 250 \text{ cm}^{-3}$, $kT_e = 3 \text{ keV}$. Also the value of d at fragmentation varied from about 0.23 AU to 0.28 AU for the 16 striae in comet West 1976VI. Here we will assume that $d = 0.25 \text{ AU}$.

The charging rate of the grain is then given by

$$\frac{dQ}{dt} = I_e - I_i - I_p, \quad (7)$$

where for a prolate spheroidal grain (Jeans 1927)

$$Q = \frac{2bV(\lambda^2 - 1)^{1/2}}{\ln \left[\frac{\lambda + (\lambda^2 - 1)^{1/2}}{\lambda - (\lambda^2 - 1)^{1/2}} \right]}. \quad (8)$$

Taking $b = 0.2 \mu\text{m}$ as the solution of equation (7), giving $|V|$ as a function of t for values of the parameter λ varying from 1 to 50 is shown in Figure 1. It is seen that all the grains tend to achieve a quasi-equilibrium potential of about -130 V , with the larger grains ($\lambda = 50$) attaining this value in about 30 seconds.

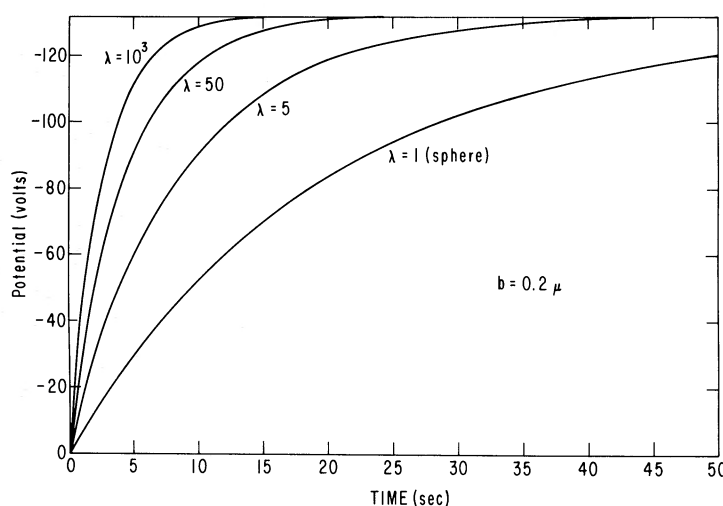


FIG. 1.—Time variation of the grain potentials when the grain is subjected to energetic electrons ($kT = 3 \text{ keV}$, $n_e = 250 \text{ cm}^{-3}$), thermal plasma ($kT = 50 \text{ eV}$, $n_e = 250 \text{ cm}^{-3}$, $n_i = 500 \text{ cm}^{-3}$), and solar radiation at 0.25 AU. The grain is modeled as a prolate spheroid with semiminor axis $b = 0.2 \mu\text{m}$ and major-to-minor axis ratio (λ) between 1 and 10^3 .

V. ELECTROSTATIC DISRUPTION OF ELONGATED GRAINS

As first pointed out by Öpik (1956), an important consequence of grain charging is their possible disruption due to the mutual electrostatic repulsion of the surface charges. As a result, it has been shown that a spherical grain of given tensile strength and surface potential would disrupt if its radius is less than some critical value R_c (Rhee 1976; see also, Mendis 1979). Here we will derive a similar result for the elongated cometary grains, idealized as prolate spheroids.

When a prolate spheroid is freely charged to a surface potential V the surface charge σ distributes in such a way that (Jeans 1927)

$$\sigma = \frac{pQ}{4\pi\lambda b^3}, \quad (9)$$

where p is the length of the normal from the center of the spheroid to the tangent plane at the point in question. The electrostatic force causing the grain to disrupt may be computed by considering it to be divided into two equal hemispheroids by a plane through the center normal to the long axis. Then if we divide these into strips by planes normal to the long axis, it is easy to show that this force of electrostatic repulsion between two elemental strips at algebraic distances x and x' from the center (see Fig. 2) is given by

$$dF_e(\theta', \theta; V, b, \lambda) d\theta' d\theta = \frac{dq' dq(x' - x)}{2\pi} \times \int_0^{2\pi} \frac{d\phi}{[(x' - x)^2 + \rho'^2 + \rho^2 - 2\rho'\rho \cos \phi]^{3/2}}, \quad (10)$$

where the charge dq on the elemental strip (at distance x from the center) is given by

$$dq = \frac{prQ}{2\lambda b^3} \left[r^2 + \left(\frac{dr}{d\theta} \right)^2 \right]^{1/2} \sin \theta d\theta, \quad (11)$$

with

$$x = r \cos \theta, \quad \rho = r \sin \theta, \quad (12)$$

$$r = \lambda b (\cos^2 \theta + \lambda^2 \sin^2 \theta)^{-1/2} \quad (13)$$

and

$$p = \lambda b \left(\frac{\cos^2 \theta + \lambda^2 \sin^2 \theta}{\cos^2 \theta + \lambda^4 \sin^2 \theta} \right)^{1/2}. \quad (14)$$

Similar expressions hold for the superscripted terms. The integral in equation (10) can be evaluated using equation (3.682) in Gradshteyn and Ryzhik (1965). The force of the electrostatic repulsion between the two hemispheroids is then given by

$$F_e(V, b, \lambda) = \int_0^{\pi/2} \int_0^{\pi} dF_e(\theta', \theta; V, B, \lambda) d\theta d\theta'. \quad (15)$$

For a given value of λ and a given surface potential V the grain would electrostatically disrupt if b is less than some critical value b_c . Equation (15) is evaluated numerically and the solution is exhibited in Figure 3, where it is seen that the electrostatic tension varies approximately as $\lambda^{-1/3}$. The critical radius, b_c (in microns), is then approximately

$$b_c \approx 9.4 |V| \lambda^{-1/6} F_e^{-1/2}, \quad (16)$$

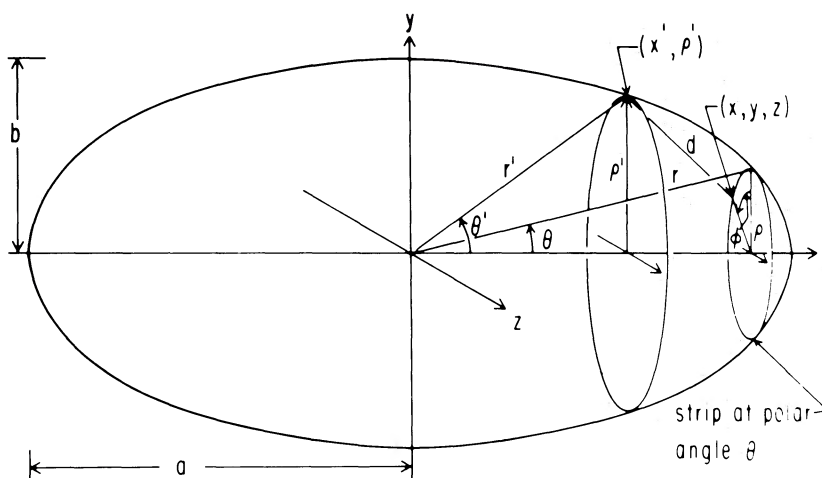


FIG. 2.—Specification of the coordinates used in evaluating the electrostatic stress in a charged prolate spheroid.

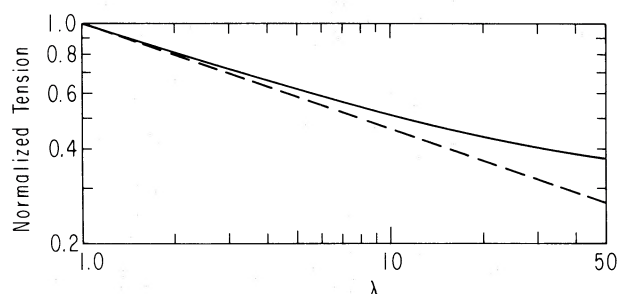


FIG. 3.—Electrostatic tension at the center of a charged conducting prolate spheroid is shown by the solid line. The dashed line corresponds to a $\lambda^{-1/3}$ power law which closely approximates the exact solution for moderate values of λ .

where F_t is the tensile strength of the grain. The tensile strength of cometary material is, of course, quite uncertain, but values as small as 10^3 dyne cm^{-2} (Sekanina 1977) as well as larger values, 10^4 – 10^6 dyne cm^{-2} (Öpik 1956) and 10^3 – 10^7 dyne cm^{-2} (Whipple 1963) have been quoted in the literature for the tensile strength of the cometary nucleus. We will consider the range for F_t of 10^4 – 10^7 dyne cm^{-2} . The critical semiminor axis for different tensile strengths in this range and varying electrostatic potentials against disruption are shown in Figure 4, by the diagonal lines. The limiting values for grain discharge by field emission are also indicated. The stable regions are above the respective lines. Three lines corresponding to the axis ratios of 1, 10, and 50 are shown for dust balls ($F_t = 10^4$ dyne cm^{-2}) and for “cometary” material ($F_t = 10^6$ dyne cm^{-2}). The equilibrium potentials that could be reached in the absence of disruption in the four different environments, namely: (a) the thermal plasma and solar radiation (+6 V); (b) with the addition of 1 keV energetic electrons (−63 V); (c) with the addition of 3 keV energetic electrons (−132 V); and (d) with the addition of 10 keV energetic electrons (−300 V) are shown by the vertical lines. The charging of a parent grain of striae material ($b = 0.2 \mu\text{m}$) to beyond Φ (solar radiation) without disruption requires that $F_t \approx 8 \times 10^4$ dyne cm^{-2} when $\lambda = 1$ and that $F_t \approx 2 \times 10^4$ dyne cm^{-2} when $\lambda = 50$. If we take the energy of the beam electrons to be 3 keV as the most likely value, then such a grain can reach the equilibrium potential without disruption only if $F_t \gtrsim 4 \times 10^7$ dyne cm^{-2} when $\lambda = 1$, and if $F_t \gtrsim 10^7$ dyne cm^{-2} when $\lambda = 50$. The slow convergence of our integral (eq. [15]) for large values of λ made the numerical calculation impractical beyond about $\lambda = 50$. However, it can be shown that for large values of λ the tension at the center of a prolate spheroid may be estimated by replacing it with an open ended cylinder having a uniform surface charge distribution and the same total charge as the spheroid. Using this cylinder model we have calculated that when $\lambda = 5 \times 10^4$ (corre-

sponding to a 1 cm needle), $F_t \gtrsim 2 \times 10^6$ dyne cm^{-2} . Even when λ is as large as 10^6 (corresponding to a 20 cm needle), F_t is still $\gtrsim 10^6$ dyne cm^{-2} . The shaded region brackets the disruption parameters for the range of observed grain sizes.

It is seen that for any reasonable values of the dust cross section, sudden disruptions due to the above process occurs only if the tensile strength of the parent grains $\gtrsim 10^4$ dyne cm^{-2} . If the tensile strength were smaller, the dust would disrupt soon after leaving the nucleus, due to attaining a potential of about +6 V in the solar radiation field attenuated by the cometary thermal plasma. It should be noted, in passing, that this lower limit on the tensile strength is very much larger than the one set by the requirement that the grains are not disrupted by the effects of gas drag when being lifted off the cometary surface. This latter is not likely to exceed a few dyne cm^{-2} for any reasonable heliocentric distance if the dominant volatile species in the nucleus is H_2O . On the other hand, it is also seen that if the tensile strength of the grains $\gtrsim 10^6$ dyne cm^{-2} , electrostatic disruption will not occur even with the enhanced potentials reached when subject to the energetic beams. These grains will remain in the normal dust streamers. Consequently, if electrostatic disruption due to sporadic charging is the process responsible for the striae, it implies that the tensile strength of the parent grains must lie in the range $\sim 10^4$ – 10^6 dyne cm^{-2} .

VI. CONCLUSION

In this paper, we have described a mechanism which may explain the observed striae in cometary dust tails. Several features which are explained include the sudden disruption of a large number of dust grains within a few hours. If the current discharge which we suggest arises from an electrostatic double layer similar to those associated with auroral displays, we expect the energetic electrons to be localized within about one mean free path length l of the double layer (Alfvén, 1979; Andersson *et al.* 1969). If we take $n \approx 10^3$ dyne cm^{-3} , $l \approx 5 \times 10^5$ km (if n is 10^2 cm^{-3} , $l \approx 5 \times 10^6$ km). We therefore expect the dust disruption to occur within about 5×10^5 – 5×10^6 km of the double layer that energizes the beam. The double layer itself could be formed anywhere within the plasma tail fan although it is most likely to form at the edges of the plasma streamers where the plasma density suddenly decreases causing a sudden impedance to the electric current, which closes across them. The outermost plasma streamers that can be seen in the numerous photographs of comet West exhibited in the paper by Sekanina (1976b) show them to be at no more than about 10° to the plasma tail axis. But at distances of $\approx 5 \times 10^6$ km down the plasma tail axis this would

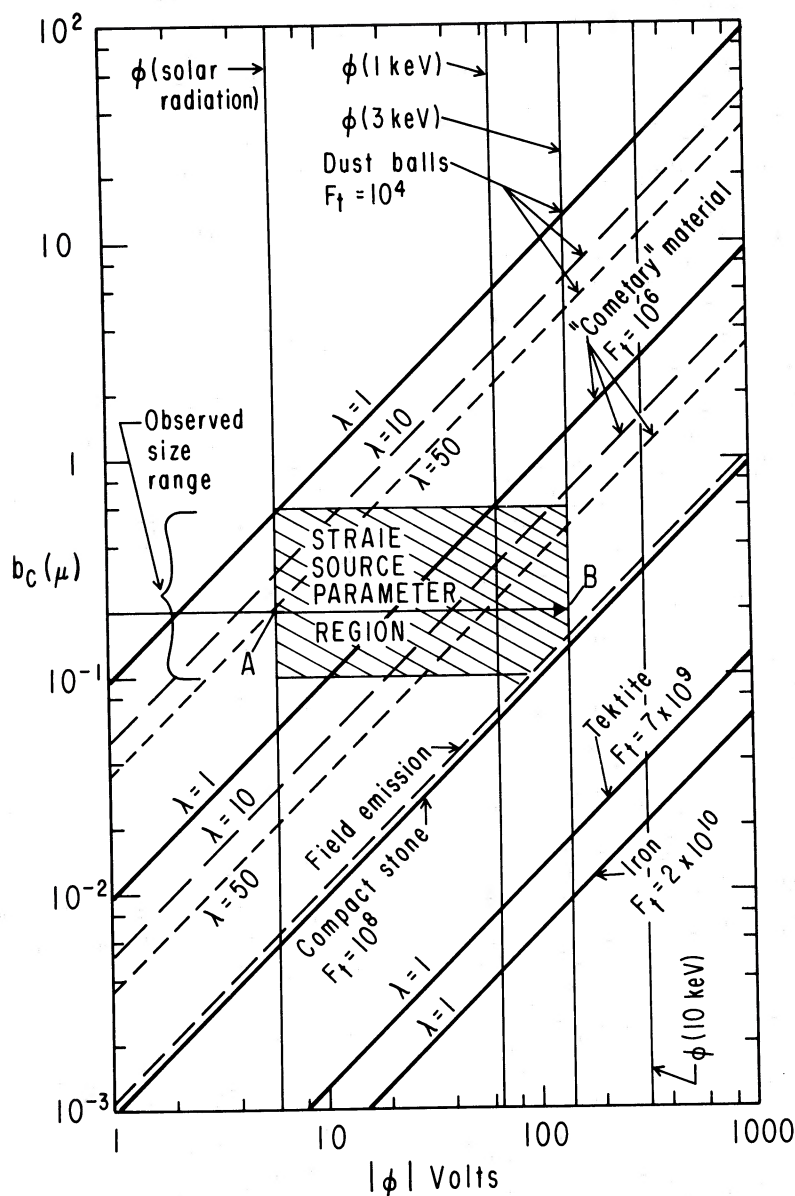


FIG. 4.—Critical semiminor axis for spheroidal grains of different tensile strengths and varying electrostatic potentials against electrostatic disruption are shown by the diagonal lines. The limiting values for grain discharge by field emission are also indicated. The stable regions are above the respective lines. Three lines corresponding to axis ratios of 1, 10, and 50 are shown for dust balls ($F_t = 10^4$ dyne cm^{-2}) and for "cometary" material ($F_t = 10^6$ dyne cm^{-2}). Vertical lines represent equilibrium potentials in (a) thermal plasma and solar radiation (+6 V), (b) with the addition of 1 keV energetic electrons (−63 V), (c) with the addition of 3 keV energetic electrons (−132 V), and (d) with the addition of 10 keV energetic electrons (−300 V). The charging of a parent grain of striae material ($b = 0.2 \mu\text{m}$) to beyond Φ (solar radiation) without disruption (point A) requires approximately $F_t = 8 \times 10^4$ dyne cm^{-2} , $\lambda = 1$; or $F_t = 2 \times 10^4$ dyne, $\lambda = 50$. For the grain to reach the equilibrium potential of −132 V without disruption requires $F_t > 4 \times 10^7$ dyne cm^{-2} , $\lambda = 1$; or 10^7 dyne cm^{-2} , $\lambda = 50$. The shaded region allows determination of disruption parameters for the range of observed sizes.

correspond to a transverse displacement of $\approx 10^6$ km. Furthermore, both the dust tail and the plasma tail axes are on the same side of the Sun-comet radius vector. Consequently, the distances from the plasma tail axis to the fragmentation events are less than the distances (2×10^5 – 4×10^6 km) given by Sekanina since these are measured from the radius vector. Taking all these into consideration and also recognizing the order of magnitude nature of our distance estimates, we find that our expectation of the locations of dust disruption events are not incompatible with those given by Sekanina, including the largest distance of 4×10^6 km.

The detailed calculations of the tension in the chain-like dust grains have shown it to be only moderately dependent on the length of the grain. In fact, to a good approximation the tension has the same form as that for a sphere with a correction factor involving the third root of a/b . Thus, the details of the geometry are less important to the disruption process than the dust cross section, tensile strength and the plasma and radiative environment.

Finally, if electrostatic disruption due to sporadic charging is the process responsible for the striae, it

implies that the tensile strength of the parent grains must lie in the range $\sim 10^4$ – 10^6 dyne cm^{-2} . Those with tensile strength $\lesssim 10^4$ dyne cm^{-2} disrupt soon after leaving the nucleus due to the charging in the solar radiation field attenuated by the cometary thermal plasma. Those with tensile strength $\gtrsim 10^6$ dyne cm^{-2} will not be disrupted even when subject to charging by the energetic plasma beams. They are not parent grains that produce the striae fragments. They would merely populate the normal dust tail streamers.

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