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INTERPLANETARY GAS. XXV. A SOLAR WIND AND INTERPLANETARY MAGNETIC FIELD INTERPRETATION OF COMETARY LIGHT OUTBURSTS

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ABSTRACT

Cometary brightness outbursts have been examined for possible relationships with, and causes in, the solar wind and interplanetary magnetic field (IMF). Two classes of outburst have been defined, both of which have plausible explanations in terms of a solar wind/IMF model. Class I flares are characterized by an increase of ionization in the head which strengthens the plasma tail shortly before a disconnection event (DE) occurs. The ionization surge is caused by electron jetting in the reconnecting current sheet which is produced by the passage of an interplanetary sector boundary. The time scale of ionization of CO is found to be $\sim 10^4$ s.

Class II outbursts involve the explosive release of gas and dust from the nucleus (in contrast to Class I, in which the brightening is *atmospheric* in nature); and in the cases of three flares in comet P/Tuttle-Giacobini-Kresak 1973b and comet P/Pons-Brooks 1883b, correlations with corotated high-speed streams and sector boundaries were found. The interpretation of these events is that the bombardment of the nucleus by disturbed solar wind triggers highly exothermic chemical reactions, as proposed by some previous workers.

Subject headings: comets — interplanetary medium — Sun: solar wind

I. INTRODUCTION

An understanding of the physical processes which govern the brightness of comets has long been a central goal of cometary study, and despite the progress witnessed during recent years, many questions remain unanswered.

Identification of the cause of light outbursts, and of ionization mechanisms, has been particularly notable for its lack of consensus agreement among workers in the field. This is not for want of ideas, however, as an examination of Figure 5 of Delsemme (1979) shows for the phenomenon of light outbursts. The same can also be said of the ionization question. For example, photoionization, solar-wind charge-exchange reactions, "internal" mechanisms (e.g., Ip and Mendis 1975, 1976), and gas-phase reactions (Oppenheimer 1975), have been proposed and all are more or less still under consideration today as possible ionization sources. Perhaps they all occur, but in different regions of a comet.

Despite the large uncertainties inherent in visual cometary photometry (instrumental factors, the human equation, etc.), it is clear that many comets undergo flaring activity; that is, they brighten by a magnitude or more (sometimes by 4–5 mag) on a time scale of about a day and then slowly decay to their original brightness. Vsekhsvyatskii (1966) has suggested that most comets (75%) during the years 1927–1963 exhibited flaring activity in various degrees. An interesting possibility is that comets are often discovered while they are flaring (Hughes 1975), and this was almost certainly the case for comet P/Holmes 1892h, for example (Bobrovnikoff 1943). A fine review of cometary outbursts has been given by Hughes (1975).

In a series of papers, Niedner, Rothe, and Brandt (1978, hereafter Paper XXII) and Niedner and Brandt (1978, hereafter Paper XXIII; 1979, hereafter Paper XXIV; 1980) proposed that the solar wind and interplanetary magnetic field control many of the rapid changes in cometary plasma tails, and most specifically, disconnection events (DEs) (Papers XXIII and XXIV), which were attributed to magnetic reconnection at sector boundary crossings. The magnetic field lines which thread the plasma tail are a source of stored energy in the *head* which can be released on a time scale of 0.5–1.0 days (Papers XXIII and XXIV), and it was suggested in Paper XXIII that reconnection *may* provide bursts of ionization and associated brightness increases at sector boundary crossings for comets with plasma tails.

The purpose of this paper is to explore further the plausibility of this concept, as well as to extend the discussion of possible solar-wind causes of cometary flaring to intrinsically faint, tailless objects such as P/Tuttle-Giacobini-Kresak 1973b, which underwent two huge flares in mid-1973.

II. TWO CLASSES OF COMETARY FLARES

Sudden brightness surges have been observed in comets of vastly different preoutburst appearance. A very coarse classification into two principal groups follows.

Class I.—The comet before the burst was at least moderately bright with a conspicuous plasma tail. Either visually or photographically, an outburst was detected in which both the head and plasma tail brightened significantly. Physically, the inference is that the rate of ion production in the head (specifically, that of CO^+, which dominates the visible light among ions) increased rapidly, loading the tail with enhanced cometary plasma. Comet Morehouse 1908c is the prototype (see § III).

Class II.—There was no (detectable) plasma tail before the burst; the comet was instead a very faint, diffuse object with perhaps a trace of central condensation (the photometric nucleus). The comet was presumably shining mostly by reflected sunlight. The burst commenced with the brightening of the central condensation (the so-called "stellar phase") and evolved with the slow radial expansion of a dust cloud. There may or may not have been a postoutburst plasma tail. The prototypes are comet P/Schwassmann-Wachmann (Roemer 1958) and, at smaller heliocentric distances ($r \approx 1$ AU), comet P/Tuttle-Giacobini-Kresak 1973b, which flared dramatically at least twice in 1973 (Kresak 1974).

In addition to providing a simple morphological distinction among flares, the classification scheme above may well represent an important physical dichotomy among comets. Namely, class I objects are thought to stand off the solar wind well away from the nucleus via the formation of a contact surface, whereas for the class II comets, the solar wind may actually impinge on the nucleus.

The critical ion density needed to stand off the streaming solar wind is

$$n_{i,c} = \frac{n_p V_p^2}{\langle \mu \rangle V_i^2}, \qquad (1)$$

where n_p and V_p are the solar-wind proton number density and bulk speed, V_i is the ion outflow velocity (with respect to the nucleus), and $\langle \mu \rangle$ is the mean molecular weight. Average solar-wind conditions at 1 AU are $n_p = 10$ cm^{-3} and $V_p = 400$ km s^{-1}, and the appropriate cometary parameters are $\langle \mu \rangle = 28$ (for CO^+) and $V_i \approx 1$ km s^{-1}, which result in $n_{i,c} = 5.7 \times 10^4$ cm^{-3}. It follows that the ion production rate (at 1 AU) is $Q_i \approx 7.2 \times 10^{10} r_c^2$ s^{-1}, where r_c is the distance to the contact surface. Ionization which takes place outside r_c is not included in Q_i.

For bright comets with $Q_i = 10^{28} - 10^{29}$ s^{-1} (e.g., comet Morehouse 1908c and comet P/Halley 1909c), $r_c = 3.7 \times 10^3 - 1.2 \times 10^4$ km. The implied ionization time scale is thus $\tau \approx 10^4$ s, and this is several orders of magnitude faster than that caused by photoionization ($\sim 10^6$ s), for example. The disparity prompted Wurm (1961), who deduced $\tau \leq 10^3 - 10^4$ s from short-exposure photographs, to argue for an "internal source" of ionization. Gas-phase reactions in the collision zone surrounding the nucleus (Oppenheimer 1975) may possibly provide the answer, whereas Ip and Mendis (1975, 1976) have discussed the ionizing role provided by the sporadic discharge of the cross-tail electric current through the coma.

For relatively inactive, gas-poor periodic comets, Q_i may not be large enough to stop the solar wind effectively. Spectroscopic observations of the ionic component of such comets (and, specifically, production rates) are almost completely lacking (Delsemme and Combi 1976), but an indirect argument can perhaps be made using the neutral coma observations which do exist. A'Hearn, Millis, and Birch (1979), for example, determined Q(CN) and $Q(C_2)$ in comets P/d'Arrest, P/Grigg-Skjellerup, P/Encke, and P/Chernykh. The average production rate (near 1 AU) was $Q(\text{CN}) \approx 0.5\, Q(C_2) \approx 1.8 \times 10^{25}$ s^{-1}. We will assume for the sake of illustration that the total gas production rate is $Q_n \approx 5 \times 10^{26}$ s^{-1} [$\sim 25\, Q$(CN)] and that the ion density a distance r from the nucleus is related to the decay of the neutrals via

$$n_i(r) \approx Q_n (1 - e^{-r/V_i \tau}) / 4\pi r^2 V_i,$$

where τ is a typical time scale of ionization for the neutrals. On the assumption that $\tau \approx 10^4$ s, we find that $n_i = n_{i,c} = 5.7 \times 10^4$ cm^{-3} (see eq. [1]), when $r = r_c = 70$ km. Such a contact surface would actually be within one solar-wind proton gyroradius of the nucleus (85 km for $V_p = 400$ km s^{-1} and a compressed magnetic field of 50 γ), and the extent to which the nucleus would be screened from the incident solar wind is therefore highly questionable.

This discussion is not intended to be completely rigorous, but it nonetheless seems certain that as the gas production is decreased, a threshold is reached at which the solar wind has direct access to the nucleus. We propose as a working hypothesis that our two classes of flares may straddle this threshold. Thus, if the solar wind is (at least sometimes) the root cause of both kinds of flaring, then we suggest that in class I the seat of the disturbance is in the ionosphere, whereas in class II the outburst takes place on the nuclear surface. We are of course aware of the possibility that a sudden increase in the sublimation rate of a bright comet can (and probably does, on occasion) manifest itself as a class I flare as defined above.

III. CLASS I FLARES

a) *Comet Morehouse* 1908*c*

Comet Morehouse 1908c is in many respects one of the two or three most important and unusual comets of this century. The plasma tail was known to undergo remarkable disturbances (e.g., Barnard 1908*a*, *b*, 1909), even at rather large heliocentric distances ($r \approx 2$ AU), the apparent brightness of the comet varied rapidly (Barnard 1908c), and the spectrum was almost completely composed of molecular band emissions (Frost and Parkhurst 1909).

Barnard (1908*c*) described naked-eye observations of the comet which strongly imply that light outbursts took place in the head and tail on about 1908 October 14 and 29 (the comet may also have brightened near October 21). It is important to note that this is not simply our interpretation: Barnard himself was convinced that the comet had brightened rapidly. There is no quantitative data on the amplitude of these brightness increases, as Barnard's descriptions consist simply of qualitative night-to-night comparisons. For example, he could see (with the naked eye) the comet and a short tail on October 14 and 15, but on the 17th it was not visible even though the observing conditions were nearly identical (it is implicit in Barnard's writings that the comet brightened between the 13th and the 14th). Similarly, the comet was extremely prominent and conspicuous on October 29, but faint and indistinct on the 28th and 30th.

The October 14 and 29 light outbursts described by E. E. Barnard are associated with *disconnections of the cometary plasma tail*, which are thought to be caused by magnetic reconnection in the cometary ionosphere at sector boundary crossings (Paper XXIII). A high-speed stream model has been proposed by Ip and Mendis (1978), but the original sector boundary model was subsequently defended and strengthened in Paper XXIV, and we will accept this model in the discussions which follow.

The disconnection event (DE) in mid-October is one of the most prominent of known cases. It displayed maximum visibility on October 15 and is well shown in Figure 1. Barnard calculated a disconnection time of October 15.1 GMT under the assumption of a constant recession velocity. Actually, it is more likely that the receding tail accelerated from an initial speed of $V_0 \approx 20$ km s^{-1} to the velocity measured by Barnard, and the resulting disconnection time is October 14.8 (Niedner 1980*a*).

The time required for a sector boundary traversal to dissipate the magnetic fields hung up in the ionosphere is thought to be 0.5–1.0 days (Paper XXIV), and thus the inferred time of sector boundary encounter for the DE in Figure 1 is in the range October 13.8–14.3 GMT. Barnard's naked eye observations of a bright comet on October 14 were made at ~ October 14.6, that is, *during the time that magnetic reconnection was probably occurring in the head*.

Further evidence that the light outburst of October 14 was physically related to the disconnection first seen on October 15 is contained in Barnard's (1908*b*) description of photographs taken on October 14: "The photograph of October 14 shows that the comet at that time was becoming very active. *It was throwing off volumes of matter which made the tail very strong*, with heavy irregularities in it. This activity culminated in the convulsion that 12 hours later threw off the great masses seen on the photograph of October 15" (italics supplied).

The DE associated with the October 29 brightening is not so conspicuous as that on the 15th (Fig. 1), but Niedner and Brandt (1980) have presented evidence that a DE did actually take place on the 29th and manifested itself in the distorted appearance of the tail on October 30 which appears in Barnard (1908*b*). The inferred time of sector boundary encounter is late on October 28 or early on the 29th. Thus, once again, the brightness surge falls in the time interval during which magnetic reconnection was probably occurring.

It is possible that Denning (1908) observed a brightness flare which was associated with the September 30 DE described by Barnard (1908*a*). It is not known, however, how many of comet Morehouse's other DEs (see Table 1, Paper XXIII) were accompanied by major brightness surges.

b) *Class I Flares in Other Comets*

It is not surprising that data pertaining to the *large-scale* brightness of a class I flaring comet are very abundant for comet Morehouse 1908c. On the one hand, the many anomalous properties of this object ensured that it would be observed frequently at many observatories, and second, at a heliolatitude of ~45° for much of late 1908 it was a high-declination object which was visible for many hours each night.

The extent to which comets other than Morehouse show brightness enhancements (in the head and tail) immediately preceding a DE is not known. It is the writer's impression, however, from an examination of many (uncalibrated) photographs, that DE-associated brightenings are not rare. The 1974 January 20 DE in comet Kohoutek 1973f, for example, was discussed in exactly this context in Paper XXIII. A DE is not known for comet Alcock 1963b on 1963 May 29, perhaps due to a lack of published photographs near that date, but a 2.5 mag burst in this relatively bright comet did take place at the time of a corotated sector boundary (Niedner 1980*b*). The comet's heliographic latitude at the time was only 12°.6.

Perhaps the most compelling evidence comes from realizing that the plasma tails of *many* comets show a

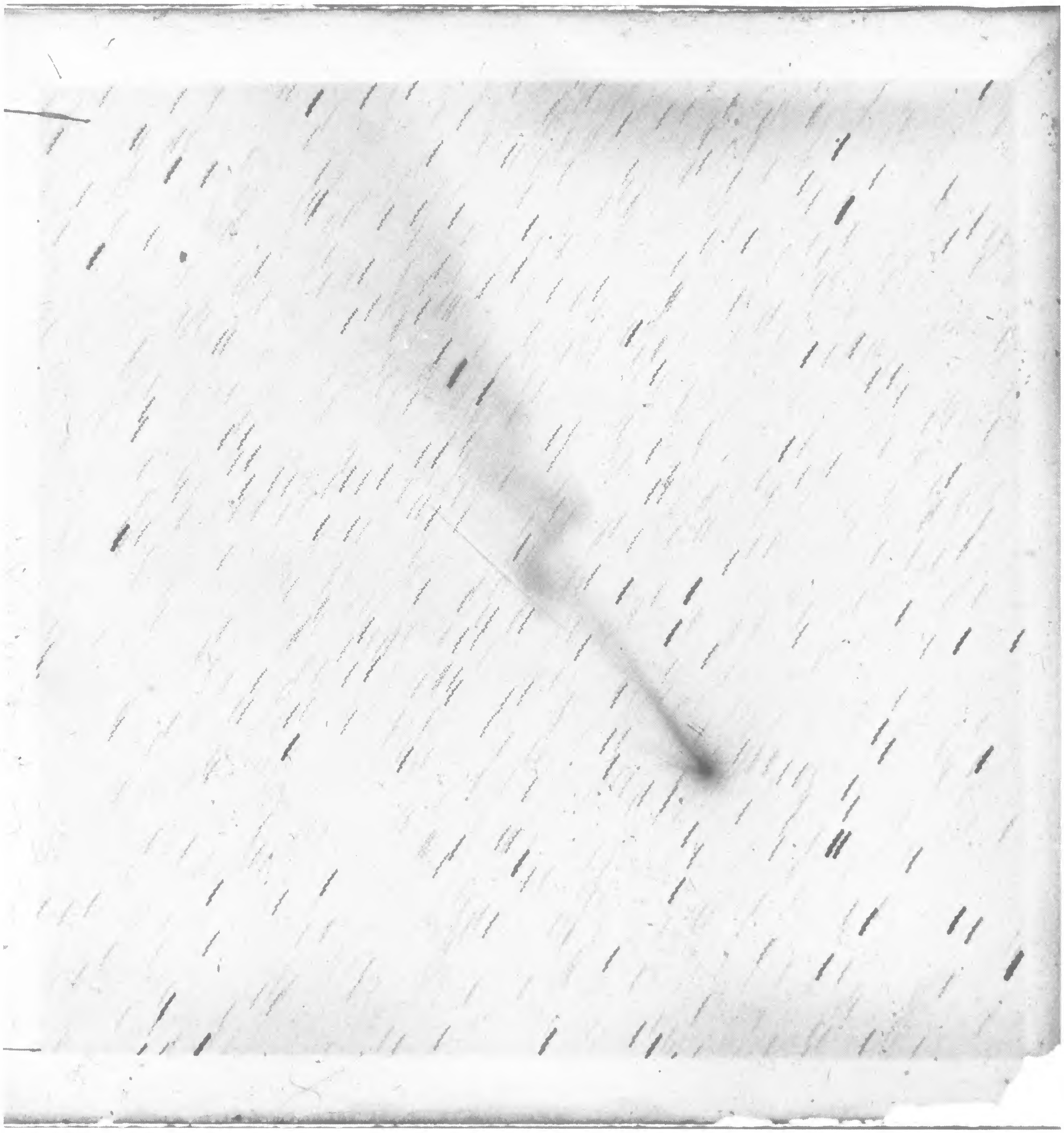

FIG. 1.—Comet Morehouse 1908c on 1908 October 15, 13^h00^m–14^h00^m GMT. The photograph shows one of the most spectacular of all known plasma-tail disconnection events (DEs) (Indiana University photograph).

repeating, cyclic morphology (Paper XXIV; Niedner and Brandt 1980). The pattern was first recognized in comet Morehouse (Astronomer Royal 1908): "The stage of maximum activity is now reached, and *larger quantities of matter appear to be expelled from the head and then driven back, forming a bright wavy tail*, the streamers being no longer straight, but greatly disturbed. This *bright tail* then appears to be driven off and the stage of quiescence follows" (italics supplied).

We suggest that not only the Astronomer Royal's statements about plasma tail *morphology*, but also his conclusions about *brightness enhancements* ("bright tail"), may be general from comet to comet.

c) A Reconnection Model of Class I Flares

Figure 2 shows the reconnection geometry which will be used in the following discussion. The quantity z^* is the half-width of the diffusion region, which also will be taken as the approximate half-width of the reconnecting current sheet. The length of the diffusion region is denoted by x^*.

It is assumed that, due to the forcing of the reconnection by the solar wind, a current sheet instability operates which enhances the resistivity above classical values and speeds up the reconnection rate. An initial analysis (Ionson, Niedner, and Brandt 1980) shows that the observed reconnection time scale of $\tau_{rec}=0.5-1.0$ days requires anomalous transport processes.

We assume that a typical anomalous resistivity in the cometary ionosphere is that provided by the ion-acoustic instability, *although we do not claim here that this instability is necessarily the one most likely to be triggered in the current sheet configuration under discussion*. For an assumed merging Mach number of $V/V_A=0.1$, we have (Smith 1977)

$$z^* \approx \lambda_A = (2.4\times 10^3)/B, \qquad (2)$$

where λ_A is the characteristic resistive length for the assumed instability. The quiet-time stagnation magnetic field at 1 AU determined by pressure balance with the solar wind is $B_{st}\approx 60\gamma$ (Paper XXIV). At a sector boundary crossing, the comet can be expected to be embedded in a high-speed stream compression region, where the solar-wind kinetic pressure is enhanced

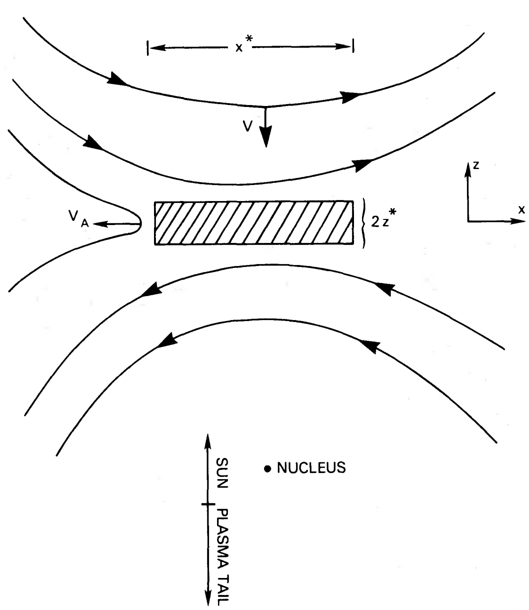

FIG. 2.—A possible geometry of reconnecting magnetic fields in the cometary ionosphere during the predisconnection phase of a DE. The hatched rectangle is the diffusion region.

5–7 times above quiet values. Hence $B\approx\sqrt{5}\ B_{st}\approx 150\gamma$, which results in $z^*=1.6\times 10^6$ cm.

From Maxwell's equations,

$$\nabla\times \boldsymbol{B}=4\pi \boldsymbol{j}/c\approx \hat{j}B/z^*, \qquad (3)$$

where $\hat{j}$ is the unit vector in the y-direction. Note that the current $\boldsymbol{j}$ is directed in the y-direction, i.e., out of the plane of Figure 2. If energetic and intense enough, this current could be an ionization source of CO, say, via electron impact. The flux of electrons is

$$f=|\boldsymbol{j}|/e=\frac{Bc}{4\pi z^* e}=4.7\times 10^9\ \text{cm}^{-2}\text{s}^{-1}, \qquad (4)$$

and the time scale of CO ionization is (Ip and Mendis 1975; Ip 1979)

$$\tau=\frac{1}{f\sigma N}, \qquad (5)$$

where σ is the ionization cross section of CO due to electron impact and N is the average number of ionizations per current electron, i.e., $N=\langle E_e\rangle/I_{CO}$, where $I_{CO}=14.1$ eV (Massey and Burhop 1952).

The computation of N requires a complete model of the cometary ionosphere which takes into account all of the heating and cooling mechanisms of electrons, and this lies beyond the scope of the present paper. However, Beard (1965, 1966) has proposed that the greater penetration of solar-wind protons (vis à vis electrons) into the comet creates a charge separation electric field which essentially accelerates the electrons up to the proton streaming energy of the solar wind. A 400 km s^{-1} proton has $E\approx 1$ keV and thus $N\approx 70$ under these circumstances.

Note that it is exactly at sector boundary crossings that Beard's process would deposit energetic (keV) electrons into the deepest layers of the coma (at the contact surface at and near the moment of tail disconnection). During quiet times, in contrast, the "magnetosheath" is saturated with magnetic fields and the solar wind may not have access to the inner ionosphere (Paper XXIV).

The CO ionization cross section appropriate for keV electrons is $\sigma=10^{-16}$ cm^{-2} (Massey and Burhop 1952; McDaniel 1964), and as a result, equation (5) yields $\tau=3\times 10^4$ s. This value is not only almost two orders of magnitude smaller than the time scale for photoionization, but it is comparable to that derived by Ip and Mendis (1975, 1976) for a discharge of the cross-tail electric current through the inner coma. It thus seems promising that reconnecting current sheets on the sunward side of the ionsphere can produce ionization "bursts" at sector boundary crossings.

Equations (3)–(5) neglect the "thermal flux" of electrons, which is likely to be important under the set of assumed conditions. Namely, if we replace the f in equation (4) with

$$f=n_e\sqrt{2kT_e/m_e}$$

and substitute this into equation (5) (with $n_e \approx 10^2$ cm^{-3}), we find that $\tau \approx 10^3$ s. Thus the ionization associated with strictly thermal motions of the hot electrons *may* be as fast or faster than that caused by electron jetting in the current sheet. However, the electron density, which we assumed was $n_e = 10^2$ cm^{-3}, is highly uncertain. Owing to the presumed high energy state of the electron gas ($kT_e = 1$ keV), the densities may be very much less ($n_e = 0.1-1$ cm^{-3}, in analogy with hot plasma in the Earth's magnetotail; see Frank, Ackerson, and Lepping 1976), which would tend to increase the ionization time scale.

It is important to consider the energy budget of the flare process. A useful energy yardstick is that energy E_0 required to, say, double the ionization rate of CO for 0.5 days in a bright comet like P/Halley. Wurm (1963) calculated $Q(CO^+) = 10^{28}$ s^{-1} for this comet, and so the total energy required is $E_0 = Q\Delta t I_{CO} = 9.8 \times 10^{21}$ ergs. The solar wind is probably disturbed over a scale length of 10^6 km (Mendis and Ip 1977; Brandt and Mendis 1979), and it is perhaps reasonable that the scale size of compressed magnetic fields ($\langle B \rangle = 50\gamma$) is $\sim 10^5$ km (Paper XXIV). The magnetic energy available for electron heating and resultant ionization is thus $(B^2/8\pi)V = 10^{22}$ ergs, which is of the order of E_0. It must be noted, however, that the *actual* magnetic energy dissipated will be much smaller if the length of the diffusion region x^* (Fig. 1) is $\ll 10^5$ km.

Any deficiency in the stored magnetic field to heat electrons is probably made up for by the solar wind flow into the coma. For example, the total streaming energy possessed by a solar-wind cylinder of radius 10^5 km, density $n_p = 10$ cm^{-3}, and length 0.5 days (expressed in flow time), is $1/2\ n_p m_p V_p^3 \pi r^2 \Delta t = 7.3 \times 10^{24}$ ergs, which is almost three orders of magnitude greater than E_0. Thus the combination of magnetic field and solar-wind streaming energies is enough to power the ionization burst if the energy transfer is even reasonably efficient.

Our treatment of the ionizing effect of magnetic reconnection in the cometary ionosphere has admittedly been somewhat qualitative. Factors not discussed, for example, are (1) the (probably) enhanced role of charge-exchange reactions (e.g., $p + CO \rightarrow CO^+ + H$) when the solar wind penetrates deeper into the ionosphere as the captured magnetic fields are stripped away during a DE, (2) the cooling mechanisms of electrons, and (3) the competition between ionization and other (e.g., dissociation) processes. Nonetheless, the simple discussion does lend plausibility to the idea that magnetic reconnection is an effective ionization source in bright comets.

Several of the ideas presented here, such as ionizing electron currents, multiple ionizations per electron, etc., are similar in spirit to those presented by Ip and Mendis (1975, 1976) and by Ip (1979), but with one very important difference: the ionizing source in our model is located *in the head, where the ions are created*, and it is controlled directly by conditions in the incident solar wind (namely, sector boundaries). This is *not* to say that the sporadic auroral discharge model of Ip and Mendis (1975, 1976) never operates; it may well be an occasionally important ionization mechanism, but it cannot explain in any obvious fashion the correlation between brightness outbursts and DEs (§ III*a*, *b*).

IV. CLASS II FLARES

a) *Comet P/Tuttle-Giacobini-Kresak* 1973*b*

This comet probably holds the distinction of having the two largest-amplitude flares ever recorded in a comet (Hughes 1975). Figure 3, a light curve constructed by Kresak (1974), shows that on about 1973 May 25.0 and July 5.0 (Kresak's estimates), the comet flared by ~9 mag from 13–14 mag to naked eye brightness. Thus the comet twice brightened by a factor of several thousand.

Of Kresak's estimated flare onset times, the first is probably more accurate since a data point exists on the rising branch of the light curve. For the July flare, however, Kresak simply assumed that the rise to maximum light on ~ July 7.0 took 2 days. This is certainly not an unreasonable assumption, but it bears noting, and it will be important for what follows, that other interpretations are possible.

Inspection of the July 6.9 UT photograph presented in Kresak (1974) (taken by Antal at the Skalnate Pleso Observatory) shows that the comet at that time had a sharply terminated border and was very circular in shape. Kresak drew essentially the same conclusions from an isophotal analysis of the original plate. The radius as measured by Kresak was 55,000 km.

Barnard (1893) gave almost exactly the same description of comet P/Holmes 1892h on 1893 January 16, when the comet was in the *initial phase* of a prominent outburst. Barnard actually watched at the telescope what he called "the development of the nucleus" (the "stellar phase" of an outburst). The developing nucleus was *yellow* and was embedded in the center of a bright, "perfectly round," and sharply-bounded disk of light which Barnard said was *greenish blue*. This bright disk, which existed before the "nucleus" was plainly visible, was expanding at a rate of $V \approx 1.4$ km s^{-1} from an initial radius of ~25,000 km, judging from Barnard's angular measurements. By its color and by its expansion velocity, the sharply defined disk must have been gaseous in composition, and it probably formed the outermost distribution of material ejected from the nucleus some 5 hours before Barnard's first observation.

Our point here is simply this. If, in analogy with Barnard's observation of comet P/Holmes in 1893, the

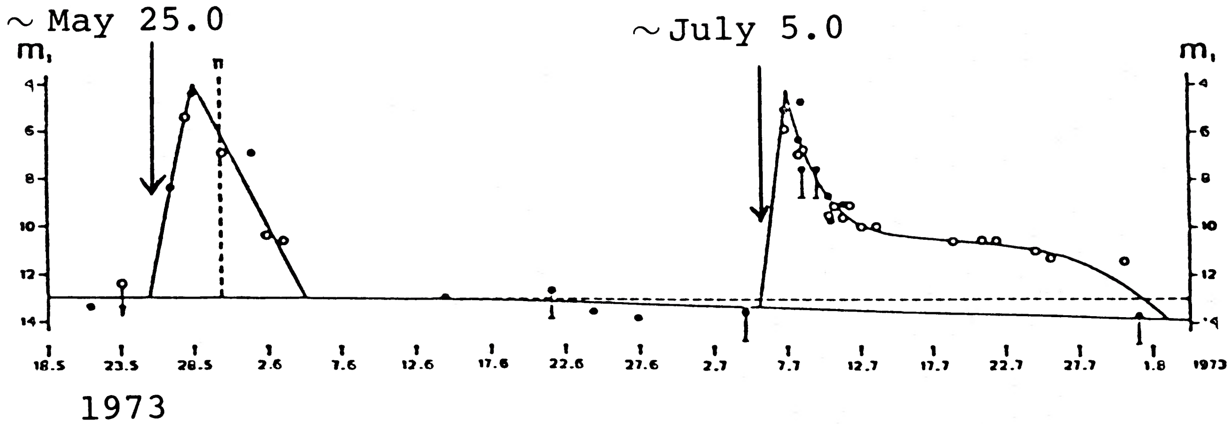

FIG. 3.—The light curve of comet P/Tuttle-Giacobini-Kresak 1973b during mid-1973 (after Kresak 1974). Hollow circles refer to visual observations; filled circles denote magnitudes determined photographically. Major brightness flares erupted on ~ May 25.0 and ~ July 5.0.

bright 55,000 km (radius) disk of P/Tuttle-Giacobini-Kresak on 1973 July 6.9 was composed of gas expanding at ~1 km s^{-1}, then the onset time of the outburst *might* have been only 12–15 hours before the time of the observation (and not two days), i.e., $t_0 \approx$July 6.3. This is a matter of speculation, of course, but it is by no means physically implausible.

We searched King's (1977) atlas of near-Earth solar-wind and interplanetary magnetic field (IMF) conditions for correlations with the outbursts of the comet, and the results are truly exciting. Figure 4 shows that the sector boundaries observed at Earth on 1973 May 27.9 and July 8.6 corotate to May 25.3 and July 6.4 at the comet (the X's). These arrival times, computed on the assumption of north-south running boundaries and associated solar-wind velocities of 350 km s^{-1}, are very close to the estimated outburst onset times, especially if $t_0 \approx$July 6.3 is adopted for the second burst. Note that the heliographic latitudes of the comet, $b = +1\overset{\circ}{.}5$ and $+11\overset{\circ}{.}1$, were very small and hence favorable for correlating events at the comet with solar-wind structures observed at Earth. It should be noted that Golubev (1978) has also pointed out the associations between the outbursts of this comet and the sector boundaries mentioned above.

The reader is referred to Kresak (1974) for a more complete discussion of the observed characteristics of these outbursts.

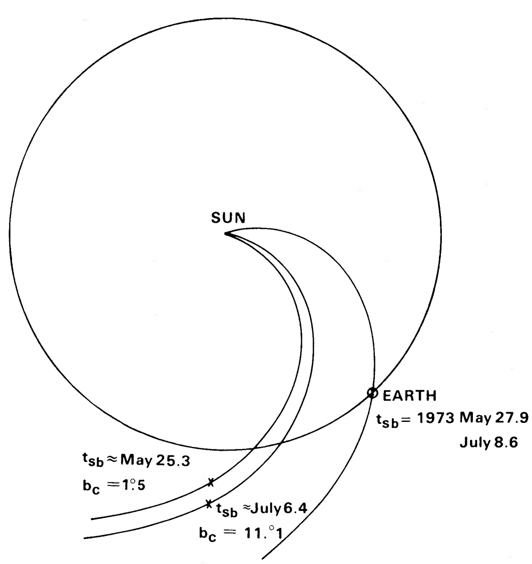

FIG. 4.—Earth-Sun-comet geometry for the times of outburst of comet P/Tuttle-Giacobini-Kresak. The sector boundaries observed at Earth on 1973 May 27 and July 8 corotate to the comet (*crosses*) at times very near the onsets of the bursts. Note the low latitudes of the comet at the times of both outbursts.

b) *Class II Flaring in Other Comets*

There are certainly other examples of class II flaring objects which are well known, but it goes almost without saying that none of them possess the extremely favorable Earth - Sun - comet geometry of comet P/Tuttle-Giacobini-Kresak (§ IVa, above). Comet P/Schwassmann-Wachmann, for example, undergoes at least several spectacular outbursts each year, but at an average solar distance of $\sim$6 AU, it is difficult to associate the activity with near-Earth solar-wind conditions or with geomagnetic activity. Richter (1954), however, has claimed that the outbursts of this comet are associated with geomagnetic storms.

Comet P/Pons-Brooks, as a result of extensive flaring activity in 1883–1884, is perhaps the second most well-known flaring comet after comet P/Schwassmann-Wachmann. Outbursts took place on 1883 September 22 and October 15 (Chandler 1883) at heliographic latitudes in excess of 75°, and hence no conclusions about associations with geomagnetic activity are really feasible; but a burst on 1884 January 1 (Richter 1949) occurred at $\sim+25°$ which does look promising in this context.

The comet at the time of this outburst had a heliocentric distance of $r=0.9$ AU and it lagged the Earth in solar longitude by 30°. The *aa* geomagnetic index (Mayaud 1972; also see Paper XXIII) shows that on 1883 October 14, November 10, and December 7, the Earth was on the leading edge of a pronounced recurring geomagnetic storm, or high-speed stream. The *aa* indices do not delineate the stream sharply on its next (January) passage, but there is a suggestion of its leading edge on $\sim$1884 January 3 (= December 7+27 days). Accepting January 3.5 as the approximate date of any associated sector boundary at Earth, the corotated arrival time at the comet is January 1.0 if a solar-wind speed of 350 km s^{-1} is used, and this coincides with the day of the outburst.

The statistical sample of class II flares discussed above is rather small, but it does suggest a possible relationship between these flares and geomagnetic activity, solar-wind streams, and sector boundaries. Similar positive correlations between outburst activity and geomagnetic storms have been reported by Maris and Hulbert (1929) and by Andrienko *et al.* (1972).

c) *Mechanisms of Class II Flares*

The response of a cometary nucleus to bombardment by the solar wind is probably one of the least-known properties of a comet; thus the remarks in this section are highly speculative.

One conclusion which *is* well established, however, is that if the solar wind is in some way the cause of class II outbursts, then it can only perform the role of "trigger." For example, the average kinetic energy of an expanding dust halo *alone* is $\sim10^{20}$ ergs (Whitney 1955), and this is almost five orders of magnitude larger than the solar-wind kinetic energy incident on a nucleus of 1 km radius during, say, 0.5 days. The appropriateness of this time scale is that it is roughly the half-width of a high-speed stream compression region, a typical solar-wind feature.

Solar-wind models of class II outbursts have come to be rejected in the past also because the energy flux of the solar wind is some six orders of magnitude less than that of sunlight. However, as pointed out by Donn and Urey (1956), keV protons might be more effective than electromagnetic radiation in triggering chemical explosions. This concept would seem to open up a wide range of possible models in which energetic particles simply act as a trigger of some highly exothermic reaction on the nuclear surface, thereby releasing the large quantities of dust (and gas) which have been observed. Obviously, the occurrence probability of such reactions is greater when the solar wind is disturbed.

The role of sector boundaries—which are central to the class I phenomenon (via electron jetting and deep penetration of the solar wind into the coma)—is unclear for class II objects because the correlations between the outbursts of comet P/Tuttle-Giacobini-Kresak and sector boundaries also constitute correlations with high-speed stream compression regions. If there is no quiet-time field capture for class II objects, then it is highly likely that the presence of a sector boundary on the stream leading edge is only incidental, any solar-wind cause of the outburst being simply due to the usual increase in particle flux, etc., in the stream (or flare).

On the other hand, if the comet produces enough ions to decelerate the incident solar wind somewhat, resulting in the formation of a small ($10-10^2$ km) magnetosheath very close to the nucleus, then perhaps the sector boundary does play a major role by reconnecting away the magnetic fields and allowing the solar wind (greater) access to the nucleus, whereupon the explosive chemical reactions proposed above have a much increased chance of occurring. Or, the reconnection process may itself beam energetic particles down on the nucleus. Unfortunately, there is almost no observational data which can be brought to bear on the problem of physical conditions so near the nucleus.

It seems obvious, in view of the relative paucity of reported major outbursts, that the probability for chemical explosions is rather low, even under the most favorable conditions. In other words, the ratio of stream/sector boundary passages to (major) outbursts is very high. For example, comet P/Tuttle-Giacobini-Kresak must certainly have encountered many sector boundaries and high-speed streams since its discovery in 1858, and yet, according to Kresak (1974), no large brightness variations were reported prior to 1973.

Comet P/Schwassmann-Wachmann, for many years considered a unique comet, may, like comet Morehouse, simply display more exaggerated forms of the dynamic behavior exhibited by many comets. This may in part derive from its inferred large size (radius $\approx$70 km; Whitney 1955), but perhaps also from an exciting property of the solar wind which was discovered during the flights of *Pioneers 10* and *11*. McDonald *et al.* (1975) found that *corotating* streams of energetic (MeV) protons, which were known during the early years of solar-wind research by satellites (e.g., Bryant *et al.* 1965; Wilcox and Ness 1965), do not show the expected $1/r^2$ falloff in particle fluxes. In fact, the streams at $\sim$4 AU were regularly found to be $\sim$20 times as intense as the energetic particle streams at 1 AU. The inference is that some *interplanetary* process, perhaps the stream-stream interaction, accelerates the particles beyond 1 AU (McDonald *et al.* 1975; Barnes and Simpson 1976). The importance here is that, if such energetic nucleon streams are at all effective in producing class II outbursts, then they would be *most* effective out past 4–5 AU, which is exactly the region of interplanetary space traversed by comet P/Schwassmann-Wachmann. The problem merits further study.

V. DISCUSSION

A comparison of the ideas proposed here with the many other outburst models which exist (see Fig. 5 of Delsemme 1979) could be the subject of an entire paper (due to the large number of models), and no such exercise will be attempted here. A few general comments are appropriate, however.

The proposal that class II flares might be caused by solar-wind features is certainly not new to this investigation. Richter (1954), Donn and Urey (1956), Vsekhsvyatskii (1966), and Eviatar, Joseph, and Dryer (1970) have all put forward solar-wind or high-speed stream models (none have discussed the possible role of sector boundaries). Perhaps the major contribution of the present paper in this regard is the addition of the two 1973 events in comet P/Tuttle-Giacobini-Kresak to the body of evidence for such a picture. These huge flares were closely correlated with corotated sector boundaries and high-speed streams, and the geometrical circumstances were exceptionally favorable. A detailed understanding of the manner in which sector boundaries and/or high-speed streams could trigger chemical reactions on the nuclear surface is not yet at hand, however, despite previous suggestions. Much more work is needed in this area.

It was suggested that the frequent outburst activity in comet P/Schwassmann-Wachmann may be related to the intense fluxes (relative to those at 1 AU) of energetic nucleon streams which occur out near (and presumably past) 4–5 AU. Discussions of cosmic-ray effects on the chemistry of the surface layers of a nucleus have been presented by Shul'man (1972), Donn (1976), and Whipple (1977).

The sector boundary/reconnection mechanism proposed for class I flares is new, and because it invokes increased ionization as the reason for the light outburst, it is an addition as much to the list of proposed ionization mechanisms as to the list of outburst models. The key point is that the time scales for ionization (of CO) computed by Ip and Mendis (1975, 1976) for disruption of the tail current sheet are no smaller than the time scales computed here for reconnecting current sheets *in the head*. The principal differences between the models are two-fold: (1) the locations of the ionizing sources are different (head vs. tail), and (2) one mechanism (present paper) couples directly to external solar-wind conditions, whereas the other one (Ip and Mendis 1975, 1976) does not. It is the writer's view that neither mechanism is preferable to the other: both may be operable in bright comets.

VI. CONCLUSIONS

Cometary light outbursts, after being classified into two groups based on their preoutburst appearance, were examined for possible relationships with solar-wind and interplanetary magnetic field structures, and the results were as follows.

1. Class I bursts, in which the comet was a bright object with a plasma tail before the event, precede and accompany disconnection events (DEs) of the plasma tail. The brightening consists of the generation in the head of enhanced amounts of cometary ions (e.g., CO^+) and their injection into the tail shortly before it disconnects. A simple model shows that the $(\nabla \times \mathbf{B})$-driven electron jets in the reconnecting current sheet create time scales of ionization of CO which are (a) several orders of magnitude faster than photoionization and (b) comparable to the time scale computed by Ip and Mendis (1975, 1976) for an auroral discharge of the cross-tail current through the coma. Thus sector boundary crossings are suggested capable of providing "bursts" of ionization for class I flaring objects.

2. Class II outbursts, in which gas and dust are (presumably) explosively released from the nuclear surface, are associated with sector boundaries and high-speed streams for the few cases we were able to examine. In particular, the two 1973 outbursts in comet P/Tuttle-Giacobini-Kresak occurred very near the ecliptic plane, and their associations with sector boundaries and streams is almost beyond doubt. The results give added plausibility to the idea that keV solar-wind protons impinging on the cometary nucleus may be able to trigger explosive chemical reactions. Comet P/Schwassmann-Wachmann may be a special case in which large heliocentric distances ($r \approx 6$ AU) actually increase the chance of outburst activity due to the observed steepening of corotating streams of energetic (MeV) nucleons with increasing heliocentric distance.

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