

COMET WEST 1976 VI: DISCRETE BURSTS OF DUST, SPLIT NUCLEUS, FLARE-UPS, AND PARTICLE EVAPORATION

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ABSTRACT

Analysis of four small-scale photographs of Comet West taken on 5–8 March 1976 offers evidence of five discrete bursts of dust from the comet's nucleus between 19 and 28 February, i.e., from six days before perihelion to three days after it. The images of the comet on the photographs were computer-enhanced to increase the contrast of the fine structure. The timing of two of the bursts suggests very strongly that they accompanied the two breakup events that gave birth to the companion nuclei D and B. The primary breakup, on 19 February, also coincides with a 2-magnitude surge in the comet's brightness. Some of the other dust bursts might be correlated with less conspicuous flare-ups observed in both the visual brightness and the thermal emission of the comet. A distinct intensity discontinuity makes up the trailing boundary of the main body of the dust tail. When the observed position of the discontinuity is corrected for an effect of particle-expulsion velocity, it is found to correspond to dust expelled from the comet exactly at perihelion. It is suggested that because of its timing, the intensity discontinuity could be a product of particle evaporation sharply peaked at perihelion.

I. THE STRUCTURE OF THE DUST TAIL OF COMET WEST

The richly developed dust tail of Comet West exhibited three kinds of noteworthy phenomena in early March 1976, during the two weeks following perihelion passage.

(1) A system of about two-dozen straight, narrow, nearly parallel striae dominating primarily the outer parts of the tail. These are sometimes referred to as the pseudosynchronic bands. When extended, they intersected the radius vector on the sunward side of the comet's nucleus.

(2) A definite intensity discontinuity along the trailing boundary of the main body of the tail, where the striae terminated on their sunward side.

(3) Several streamers of slight-to-moderate curvature pointing radially away from the nucleus. Some of these were superimposed on the striae and inclined to them at a distinct angle, others were located on the other side of the trailing boundary.

This paper presents a quantitative account and an interpretation of the features under (2) and (3).

II. PHOTOGRAPHIC OBSERVATIONS AND THE IMAGE-ENHANCEMENT PROCEDURE

Since the comet's dust tail extended over a large angular area, this study has been based on photographs taken with fast, small-scale cameras. Courtesy of Sky and Telescope, we acquired a number of photographic

observations of very good quality, made mostly by American amateur observers. Table I lists the four photographs on four consecutive nights that have been measured and analyzed in the present study.

The structures of interest in the dust tail are of low surface brightness and are superimposed on a variable background due to the intensity gradation in the tail, the low altitude of the comet during the exposure, and vignetting from the camera lens. Under the magnification of the measuring machine, the loss of contrast is so great that accurate measurements become difficult, if not impossible. Before measurement, the contrast of the structures was greatly increased with the use of digital image enhancement. This work was carried out by the Image Processing Group of Los Alamos Scientific Laboratory. Details of the procedure are given in Matuska *et al.* (1977, 1978). The images were digitized with a scanning aperture and sample interval of 50 μ . The first step was removal of the variable background by dividing each pixel by the corresponding pixel of a blurred image formed by the use of a Gaussian shaped, low-pass frequency filter. In the space domain, the width of the Gaussian was large compared to the widths of structures in the tail but small compared to the background variation. The contrast of the quotient image was increased by histogram equalization. Finally, a cosine rolloff, low-pass frequency filter was used to reduce the noise resulting from grain clumping in the photographic emulsion. The three adjustable parameters, the sample interval, Gaussian width, and cosine rolloff frequency, were determined empirically for a few test images and

TABLE I. Photographs of Comet West.

Date 1976 (UT)	Δ (AU)	r (AU)	Observer(s)	Camera	Emulsion	Exposure (min)	Observing location
5.49 March	0.838	0.385	D. Elmore, D. Woodman	50-mm $f/1.4$	IR ^a	10	Sacramento Mts., NM
6.51	0.852	0.413	D. R. Anderson	58-mm $f/1.8$	Tri-X	2	near Livingston, MT
7.54	0.866	0.441	M. R. O'Neal	55-mm $f/1.8$	103a-F	2½	Big Bear Obs., CA
8.49	0.879	0.467	D. K. and D. M. Speed	50-mm $f/2.0$	Tri-X	3	Portal, AZ

^aEktachrome with filter No. 15.

then applied to all subsequent images. Figure 1 shows the results obtained from the enhancement process.

III. THE STREAMERS AS INDICATORS OF DISCRETE BURSTS OF DUST MATERIAL

Five streamers can be clearly recognized on all four image-enhanced photographs listed in Table I. Three of the streamers, denoted I–III, are located east of the trailing boundary of the tail and are free of interference by the striated tail; however, their visibility is adversely affected by strong atmospheric extinction at very low altitudes. The remaining two streamers, IV and V, are projected on the main body of the dust tail and are by far the brightest of the five. We suspect one or two additional, less prominent streamers in the tail but have not

measured them as they are not easily distinguishable on all four dates.

Depending on the apparent length and definition of each streamer, three to five points, including the least and the most distant points visible, were measured. The apparent limits of the streamers depend strongly on the observing instrument, the exposure time, the emulsion used, the atmospheric conditions, etc., and also on the parameters employed in the image-enhancement routine and are therefore not indicative of their true lengths. Using the ambient star field as a reference grid, the rectangular coordinates of each measured point were converted by the method of dependences to give the angular separation from the comet's nucleus in right ascension and declination. In Fig. 2, the results of measurement and reduction for the five streamers are rep-

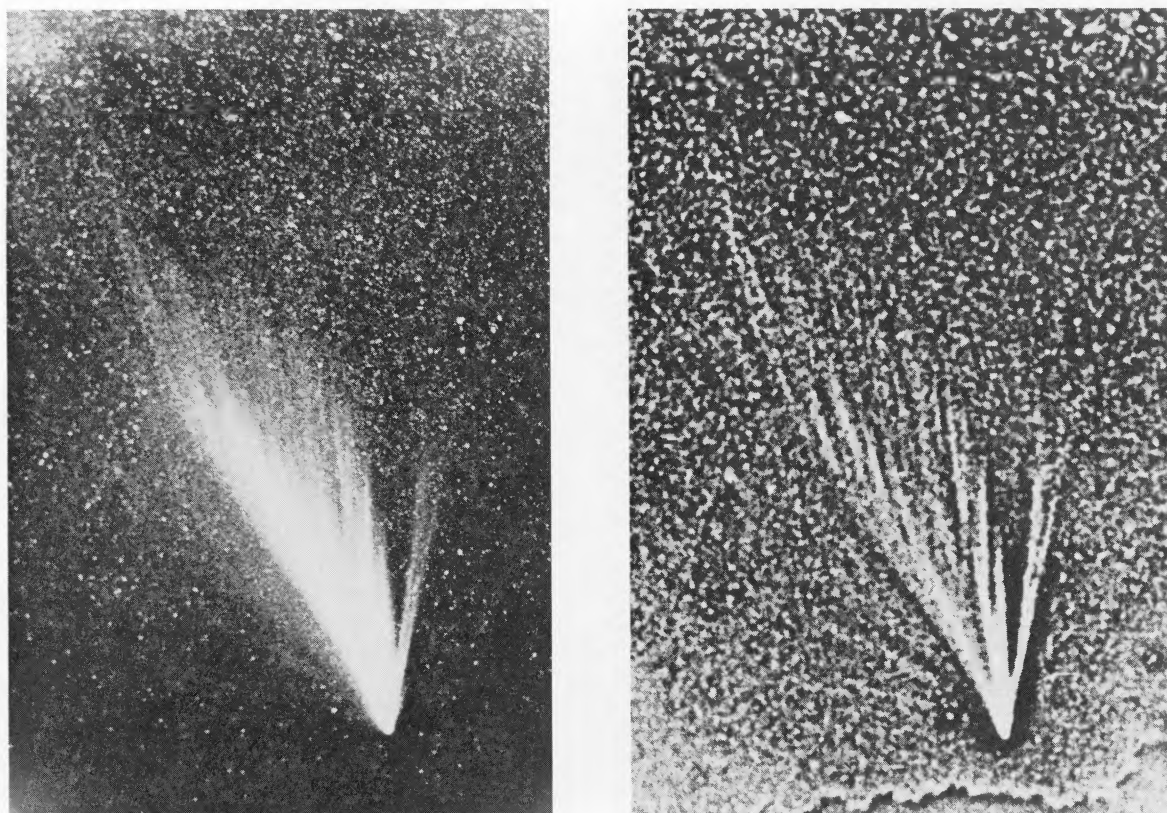
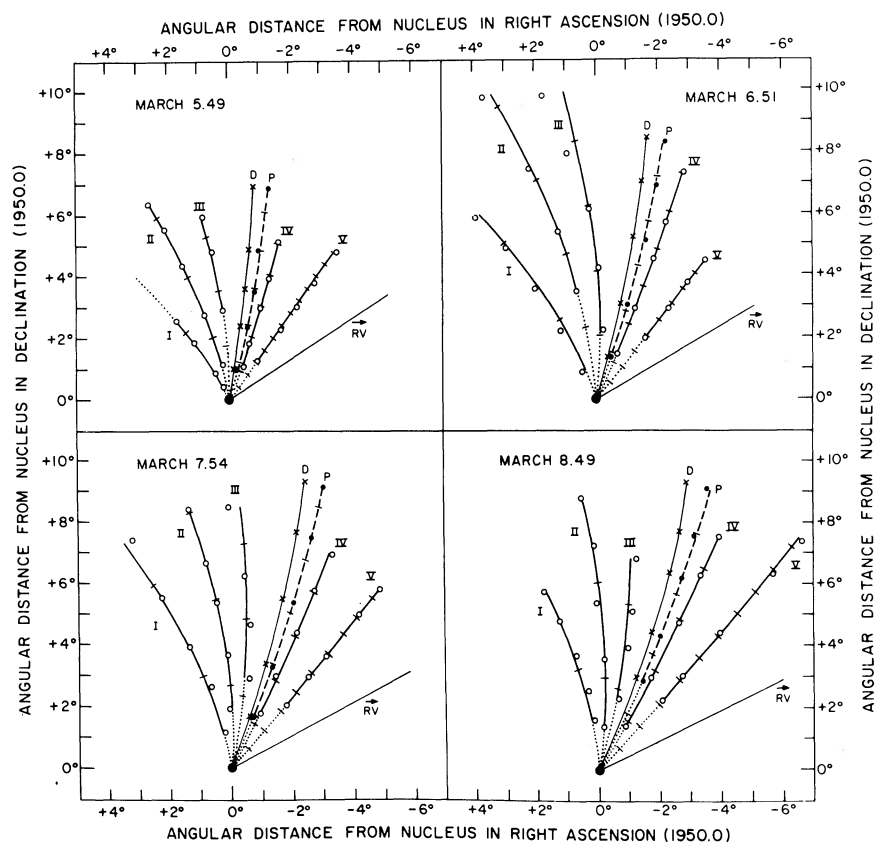


FIG. 1. The original (left) and the computer-enhanced image of Comet West on 7.54 March 1976 UT.

FIG. 2. The observed orientations of streamers I-V (open circles) and the intensity discontinuity D along the trailing boundary (crosses) in the dust tail of Comet West on 5-8 March 1976. The heavy solid curves are synchrones fitted through the streamers. The solid circles are the measured points on the discontinuity, corrected for the effect of particle-expulsion velocity; the heavy broken curve P fitted through them is the perihelion synchrone. The dotted sections of the synchrones could not be measured because of the background noise. The outward dotted section of the first synchrone on 5 March corresponds to the part of streamer I that ran into the horizon. The short marks on the synchrones give the magnitude β of radiation pressure in steps of 0.1 times the solar attraction measured from the split nucleus (large solid circle) outwards. $\vec{RV}$ indicates the orientation of the prolonged radius vector.



resented by open circles. Since the streamers are of perceptible and generally variable width, great care was exercised in measuring their apparent axes. The formal errors, typically less than 0.1° , represent fairly realistically the precision with which streamers IV and V are measured, but underestimate the actual uncertainty involved in the three much fainter streamers, especially III.

Having established the orientation of the streamers relative to the comet's nucleus in the equatorial system of coordinates, the observed motions of the streamers from day to day can now be compared with theoretical trajectories of dust particles. We find that each streamer can be satisfactorily described by the motions of particles expelled from the comet simultaneously and subjected to a wide range of radiation-pressure accelerations. The curves describing such particle trajectories are commonly known as synchrones, and their presence in a dust tail is unquestionable evidence of discrete bursts of dust from the comet. The times of the bursts, derived by establishing the best possible match between the synchrones and the observed axes of the five streamers, are presented in Table II. Also listed are the peak values of the radiation pressure β (in units of solar attraction) to which particles were subjected on the observed sections of the synchrones. The particles in streamers I-IV could be either dielectric or absorbing as the observed $\beta < 0.6$.

Streamer V definitively contains some contribution from absorbing particles as $\beta_{\text{peak}} \gtrsim 1$.

There is a suggestion of a periodicity in the burst sequence. The times spanning bursts I and II, III and IV, and IV and V average about 2.5 days; the time between bursts II and III is 1.3 day, or just one-half the other. Since there already existed two nuclei during the whole span of the time between bursts I and V, and since there is no way of knowing which of the bursts II-V are related to nucleus A and which to D, we will not speculate on the rotation of the comet as a possible source of the periodicity and will regard the latter as coincidental.

The widths of the streamers have not been measured systematically, partly because their edges are poorly defined and partly because the interpretation of the observed widths is ambiguous, due to combined contributions from the distribution of particle-expulsion velocities and the durations of the bursts. While theoretical synchrones refer strictly to particles released at rest with respect to the nucleus, particles expelled simultaneously and more or less isotropically with a finite velocity will, on their way through the tail, occupy a conical volume of space whose axis is identical with the synchrone and whose vertex angle depends on the expulsion velocity. When the burst has a finite duration, a streamer can be envisaged as a composite of a large number of such conelike volumes slightly displaced with respect to each

TABLE II. Discrete bursts of dust from Comet West.

Streamer (burst)	Date 1976 (UT)	Time of burst from perihelion (days)	Distance from sun at burst (AU)	5 March	6 March	β_{peak}	7 March	8 March
I	19.4 ± 0.4 Feb.	-5.8	0.29	0.12	0.23		0.25	0.17
II	22.0 ± 0.1	-3.2	0.23	0.32	0.42		0.31	0.29
III	23.3 ± 0.3	-1.9	0.21	0.34	0.47		0.35	0.25
IV	25.8 ± 0.1	+0.6	0.20	0.51	0.60		0.49	0.46
V	28.1 ± 0.1	+2.9	0.23	1.22	0.89		0.94	1.04

other. The edges of the streamer are then defined, respectively, by the trailing side of the initial cone and by the leading side of the terminal cone. In this scenario, the axis of the streamer is the synchrone of the middle of the burst.

In order to gain insight into the problem of burst duration, a few random measures of the widths of some of the streamers were made. When interpreted as due to a particle-velocity distribution alone, they suggest velocities consistent with or slightly lower than those determined from the position of the intensity discontinuity along the trailing boundary of the tail. (See Sec. V.) It therefore appears that the duration of the bursts was indeed insignificant, almost certainly shorter than 0.1 day.

IV. CORRELATION OF THE BURSTS OF DUST WITH THE COMET'S BREAKUP AND WITH FLARE-UPS IN THE VISUAL AND INFRARED BRIGHTNESS

One of the most intriguing problems not yet satisfactorily understood is the splitting of a cometary nucleus: its cause and nature, the energetics associated with it, and, last but not least, its manifestation in the observable characteristics of comets. The reasons for our ignorance are basically twofold. (1) Separate images of the fragments cannot be sighted until long after separation, about a week in the most favorable cases, but often months or even years. (2) Until very recently, we have had no model that adequately explains the observed motions of the fragments of the split comets, resulting in unacceptably large uncertainties in the estimated separation times.

The second problem is now essentially settled. A multiparameter model of split comets (Sekanina 1978), based on a premise that the fragments separate at a rate that depends primarily on repulsive forces from outgassing (Sekanina 1977) and also allowing for a possible effect from the momentum transfer at breakup, represents very satisfactorily the motions of fragments of all well-observed split comets, including Comet West.

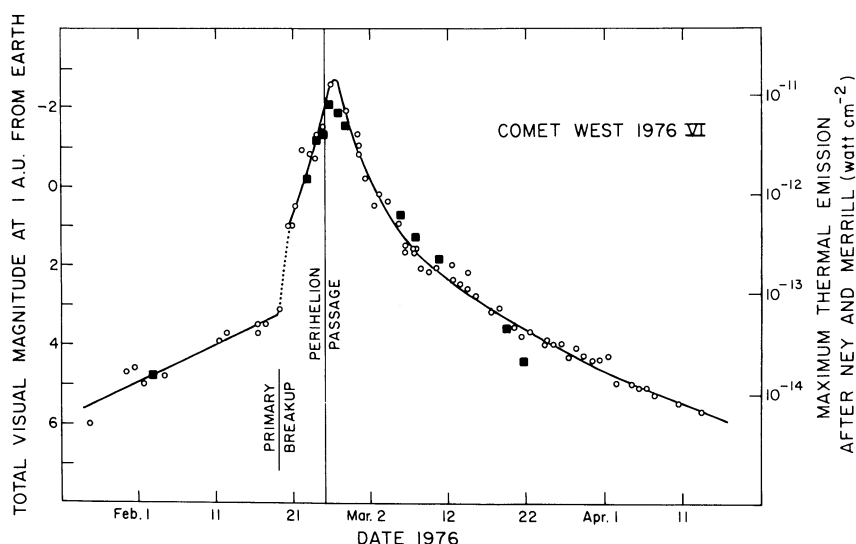
The most significant result of the present study is strong evidence of a correlation of burst I, on 19.4 ± 0.4 February UT, with the primary breakup of the nucleus into parts A and D, on 19.1 ± 0.2 February. Similarly, burst V on 28.1 ± 0.1 February, compares very favorably with the separation of nucleus B, whether from A on 27.7

± 0.2 February or from D on 27.6 ± 0.8 February. No secondary nuclei are known to be correlated with the other three bursts, whereas nucleus C, a short-lived fragment, separated from A on 6 March and no prominent streamer could develop until a few days later, when the dust tail had faded appreciably.

Figure 3 presents the light curve of the comet between late January and mid-April 1976, derived from total-brightness estimates made with naked eye or binoculars and published by the Central Bureau for Astronomical Telegrams (Marsden 1976). The sample is augmented by a few preperihelion observations reported by Bennett (1976). It is well known that visual brightness estimates are very susceptible to the observing conditions and that any conclusions drawn from them must be considered with great caution. Yet, the light curve of Comet West exhibits such a strong asymmetry with respect to perihelion that there can be no doubt that the comet was intrinsically much brighter after perihelion. Most important, the major contribution to the asymmetry comes from a 2-magnitude flare-up between 19.4 and 20.4 February UT, which coincides with burst I and the primary breakup.

Also plotted in Fig. 3 are Ney and Merrill's (1976) measures of the comet's thermal emission, scaled from their Fig. 2. Ney and Merrill have claimed that the times of two sudden surges observed by them in both the scattered sunlight and the thermal emission, one between 22.8 and 23.8 February and the other between 24.8 and 25.8 February, are in fair agreement with the times of splitting. Unfortunately, the results based on the improved model of split comets, not available at the time Ney and Merrill's paper was completed, have revised the times of separation, which now offer no correlation with the Ney-Merrill data. However, the two events classified as surges by Ney and Merrill are likely to be associated with some of the dust bursts. Since their diaphragm, centered on the nuclear region, was 20×20 arcsec, they could only detect an increased emission associated with a burst within ~ 0.3 day of its outset (in order to get the optically and thermally important particles with expulsion velocities $\gtrsim 0.3$ km/s in the beam). Their 22.8 February measure apparently came too late to detect any remaining traces of burst II. This burst, however, might have shown up in the reported visual magnitudes. On 22.05 February, at just about the time of burst II, R. Keen and G. Emerson found the comet to be about 2

FIG. 3. The light curve of Comet West between late January and mid-April 1976. Total magnitudes, estimated with binoculars or the naked eye, are plotted as open circles. The squares are Ney and Merrill's (1976) scaled measures of the maximum thermal emission. Note the 2-magnitude flare-up on 19/20 February and the good match between the visual and infrared data.



magnitudes brighter than estimated by another three observers 17–39 h earlier, but they failed to record any further brightness increase 24 h later. Ney and Merrill's next observation was made just 0.5 day following burst III, and given the uncertainty of that event, they could have detected a part of it. The following sharp increase on Ney and Merrill's thermal-flux curve coincides with burst IV and here the correlation is very suggestive. It is corroborated by the visual estimates secured by J. E. Bortle, a very experienced observer, who reported the comet ~ 0.1 day after burst IV to be more than 1 magnitude brighter than 1 day earlier, although he noticed a brightness increase of only 0.3 magnitude during the immediately preceding 24-h period. As for burst V, it must have been narrowly missed by Ney and Merrill on 27.9 February, while their next observation, one week later, came of course much too late.

V. THE TRAILING BOUNDARY OF THE TAIL

The same technique of measurement applied to the axes of streamers was also used to determine the position of the intensity discontinuity along the trailing boundary of the tail. On the computer-enhanced photographs, the discontinuity is remarkably sharp, so its measures in Fig. 2 are better than those of any streamer.

Following the consideration on the width of a streamer, the sharp trailing boundary of the tail should obviously be identified not with the synchronic itself, but with the trailing side of the corresponding cone. A comparison of the measured points on the trailing boundary of the tail with a set of synchrones indeed confirms that the boundary is not a synchronic formation, and that the measured points leave *systematic* residuals equivalent to a range of expulsion times from up to 1 day before perihelion at distances $\sim 1^\circ$ from the nucleus down to 0.3 day before perihelion at $\sim 10^\circ$.

Because of the very good definition of the trailing boundary, we have attempted to determine the instant of the sudden increase of dust production, using an approach that also provides data on the particle-expulsion velocities. For a plausible solution, the variations in the expulsion velocity with the radiation-pressure parameter β as derived from the four dates should be reasonably consistent with each other and the expulsion velocities should not exceed the anticipated terminal expansion velocity of the parent molecules (Probstein 1968; Delsemme and Miller 1971), estimated at ~ 1 km/s. The solution that most closely satisfies these conditions suggests that the sudden increase in the production of dust occurred exactly at perihelion with an estimated uncertainty of less than ± 0.1 day.

The plot of the expulsion velocity versus β in Fig. 4 suggests an essentially linear dependence between $\beta = 0.1$ and 0.6, with the velocities varying from 0.4 to 1.3 km/s. This empirical dependence of the expulsion velocity on radiation pressure differs somewhat from the model based on Probstein's (1968) theory of momentum transfer between cometary gas and dust, which predicts a law $\sim \beta^s$, where $s \leq 1/2$.

In the light of the fact that sudden bursts of dust are distributed over a span of more than one week around perihelion, the perfect coincidence in timing between the brightness discontinuity along the trailing boundary and the perihelion passage suggests that a process other than a sudden increase in the level of the continuous dust production might have taken place here. As we have pointed out earlier from a visual inspection of a number of photographs of this comet (Sekanina 1976), particle evaporation could be such a process. From considerations similar to those we used for Comet 1973 XII (Sekanina 1974), we can infer, for example, that of all 40- μ -sized and smaller particles expelled before perihelion those made of substances with a heat of vaporization less than about 40 kcal/mol (at a black-body approximation)

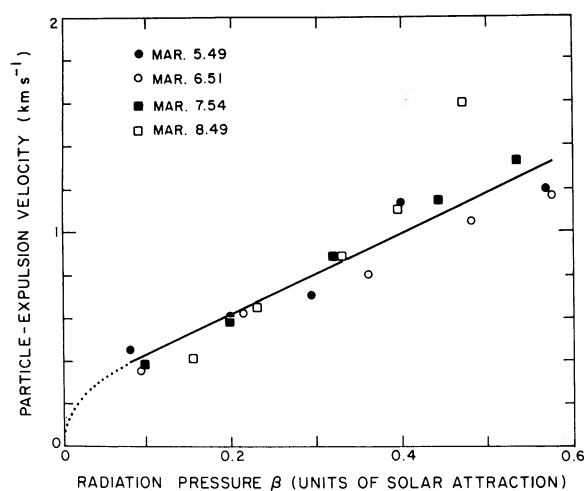


FIG. 4. The particle-expulsion velocity versus the radiation pressure as derived empirically from the position of the intensity discontinuity along the trailing boundary of the tail.

should not survive perihelion passage. The timing and sharpness of the boundary discontinuity in the tail can be explained qualitatively by the fact that the evaporation rate of dust particles is a very steep function of the temperature and therefore sharply peaked at perihelion. Effects of particle evaporation of course imply that the three preperihelion streamers (Table II) consisted of particles of a high latent heat of vaporization, such as various metals.

VI. CONCLUSIONS

(1) Five discrete bursts of dust particles from Comet West have been detected from the presence of distinct streamers in the comet's dust tail. The streamers fit synchroes, loci of particles expelled from the comet simultaneously. The derived times of the bursts range from about 6 days before perihelion to 3 days after it. One or two more bursts are suspected.

(2) Several random measures of the widths of the streamers suggest that the durations of the bursts were less than 0.1 day. The extent of the streamers into the tail implies that the particles were subjected to radiation-pressure accelerations up to at least $\sim 25\%$ the solar attraction for burst I, and up to at least $\sim 50\%$ for bursts II–IV. The radiation pressure exceeded the solar attraction for some particles in burst V, which is indicative

of the presence of absorbing particles.

(3) Burst I is clearly correlated with the breakup of the parent nucleus of the comet into components A and D, and also with a flare-up of ~ 2 magnitudes in the comet's total brightness. Burst V is very probably correlated with the secondary breakup that gave birth to fragment B. Burst IV is likely to be the cause of a surge in the comet's scattered light and thermal emission as measured by Ney and Merrill, and is probably also responsible for a 1-magnitude increase in the total visual brightness reported by Bortle. Possible flare-ups associated with bursts II and III are also suggested.

(4) There is some evidence of a periodicity of 2.5 days in the occurrence of the bursts, with half of the period between two particular bursts. It is believed that this apparent periodicity is coincidental.

(5) Unlike the streamers, a distinct intensity discontinuity along the trailing boundary of the main body of the dust tail fails to fit a synchro unless its position is corrected for the effect of particle-expulsion velocity. After correction, the intensity discontinuity becomes identical with the perihelion synchro. The expulsion velocity is found to increase linearly with the radiation-pressure acceleration on the particles, from 0.4 km/s at 10% the solar attraction to 1.3 km/s near a 60% mark. This increase is steeper than predicted by Probstein's theory.

(6) It is proposed that the timing of the intensity discontinuity along the trailing boundary might not be due to a coincidental stepwise increase in the level of the continuous dust production at perihelion. Rather, it might signal particle evaporation steeply increasing with decreasing heliocentric distance, in which case a substantial fraction of particles expelled before perihelion should not survive perihelion passage.

We thank the editors of *Sky and Telescope* for offering us the opportunity to inspect a rich collection of photographic material on Comet West and to copy those photographs that we found useful for prospective tail studies. We are grateful to D. H. Janney and R. O'Connor of the Los Alamos Image Processing Group for the digital image enhancement of the photographs. The first author acknowledges support from the Planetary Atmospheres program of the National Aeronautics and Space Administration under grant NGR 09-015-159. This work was supported in part by the Department of Energy, contract No. 7405-ENG-36.

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