SOLAR-COMETARY RELATIONS AND THE EVENTS OF JUNE–AUGUST 1972

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Abstract. Evidence for correlations of brightness fluctuations of heads of comets with solar and solar-related phenomena is presented, and the examples of Comet Schwassmann-Wachmann (1) and Giacobini-Zinner in 1959 and 1972 are examined. Brightness behavior of comets and the general level of solar activity in the eleven-year cycle appear to be statistically related. At present the responses of individual comets to solar events are not sufficiently well calibrated to permit using them as reliable interplanetary probes.

> "Unlike the planets, the comets often traverse the entire solar system. They are, therefore, our only means of exploring the regions between the planetary orbits."
> Barnard (1899).

1. Introduction

The pre-space-age prediction quoted above was fulfilled some fifty years later by Biermann's inference, based upon anti-sunward accelerations in cometary Type I (plasma) tails, of continuous plasma ejection from the Sun (Biermann, 1951). Whatever conclusions may be drawn from efforts to correlate details of cometary and solar activity, the association postulated by Biermann is firmly established. Observed angles between the axes of Type I tails and the projections on the sky of the Sun-comet radius vectors (leading to 'aberration angles') have been used to study the velocity of the solar wind as a function of heliographic latitude, heliocentric distance, and phase in the sunspot cycle. A list of such investigations should include the work of Pflug (1966), Tarashchuk (1974a, b, c), and especially of Brandt and his collaborators. The latter series of papers includes painstaking assessment of the influence of assumptions and errors on determinations of the components of the solar wind velocity vector. As references it is sufficient to mention the extensive catalogue of comet tail orientations (Belton and Brandt, 1966), a paper by Brandt *et al.* (1972) which references earlier papers, and two subsequent contributions (Brandt *et al.*, 1973; 1975).

A reasonably complete bibliography of correlations of cometary events with solar and geophysical phenomena would run to several scores of entries; in his review of this topic, Richter (1963) lists a paper by Capocci (1827) which is the earliest read by this writer. This review must therefore be illustrative rather than exhaustive. The reader is also referred to a discussion by Dobrovol'skij (1966). The cometary data are for the most part of two varieties; fluctuations in the brightness of the head, and disturbances of the Type I tails. The solar-related phenomena range from the early use of sunspot numbers and geomagnetic indices to the great variety of solar and interplanetary data available in recent years. If comets could be observed frequently and at will, apparitions of earlier times might now be primarily of historical interest. Unfor-

Space Science Reviews **19** (1976) 739–759.

tunately, cometary observations accumulate slowly, and it is still profitable to utilize observations even of 19th century comets. As study of new observations of comets, the sun, and the interplanetary medium progresses, it may be useful to test conclusions against the recorded behavior of comets of earlier vintages.

2. Fluctuations in the Brightness of Comets

2.1. Brightness Data

Fluctuations in the brightness of the heads of comets, superposed on the expected variations due to changing geocentric and heliocentric distances, have provided the bulk of the material used in the study of solar-cometary relations. The amplitudes considered significant range from 20% to factors of 100 or more. In principle, such data can be obtained for any comet, whereas only for the relatively few displaying conspicuous Type I tails, can disruptions of these appendages be observed, and then only in a limited range of heliocentric distances. The cometary events associated with solar activity in the summer of 1972 consist only of brightness changes.

Measurements of the integrated brightness of the head on a consistent photometric system, and continued throughout a significant fraction of a comet's apparition, require special precautions, whether made visually (as for many comets, ancient and modern), photographically (relatively few), or photoelectrically (still fewer). The diffuse, centrally condensed comet image must be compared with a photometric scale represented by a set of point sources (stars) superposed on the sky, whose brightness depends upon twilight illumination and the phase of the moon. For visual observations, the aperture and magnification of the instrument have systematic effects. For discussions of the problems and pitfalls of comet photometry, the reader is referred to papers by Meisel (1970), Morris (1973), and Kresák (1974a).

For 45 comets from 1858 VI to 1937 V (names will generally be omitted in designating comets in this review) the primary source of data is the indispensable catalogue of Bobrovnikoff (1941, 1942) who collected from the literature 4447 observations, investigated instrumental corrections and stellar photometric systems, and finally reduced the data for each comet to a uniform scale. The most important single contributor to the study of comet brightness is Beyer, who, from 1921 to 1970, has made visual observations of 110 comet apparitions in a consistent manner. In numerous papers, magnitudes and other information on the heads and tails, and notes on the instrumentation are tabulated. An index paper (Beyer, 1969) lists for each comet the publication reference; a later paper (Beyer, 1972) is not included in the index. More recently members of the Comets Section of the Association of Lunar and Planetary Observers (ALPO) have made observations in a coordinated program which permits reduction of individual observations to a uniform system.

If one is forced to resort to the scattered observations reported in the IAU Circulars, Kometn. Tsirk, (Kiev), or Astr. Tsirk. (Kazan), a good deal of caution is required. Only since September 1970 has the distinction been systematically recorded between the total magnitude of the head (m_1) and the magnitude of the nuclear condensation (m_2). Undiscriminating use of raw published magnitudes measured by several observers with different classes of telescopes and by different methods may lead to meaningless light curves.

Photometric observations have been analyzed in a variety of ways. The most obvious is to construct a lightcurve which can be compared with the trend of solar or geophysical data. If the geocentric and heliocentric distances vary significantly in the period covered by the lightcurve, corrections for these variables must be made [Note 1]. Abrupt changes in brightness can be used as the primary cometary data without distance corrections. Less striking fluctuations can be characterized statistically by a parameter representing the departures of the observed magnitudes from a smooth lightcurve predicted as a function of geocentric and heliocentric distances. Beyer, in the series of publications mentioned above, frequently includes the differences between predicted and observed magnitudes.

2.2. Some analysis of cometary brightness fluctuations

From 1950, Beyer has included comments on solar activity and, when justified by the completeness of the data, comparisons of lightcurves of comets with daily sunspot numbers. In a summary covering 44 comets observed since 1932, Beyer (1956) concluded in part that "It has become clear that the short-period variations in the brightness of comets, which occupy a few days and are irregular, usually become more pronounced and intense at times of high solar activity than at times of sunspot minimum." In a recent letter to me, Beyer states that "... my opinion has not changed within the past two decades, apart from new knowledge (solar wind, etc.)."

The most comprehensive program of correlating comet brightness behavior with solar and geomagnetic phenomena has been carried on by Andrienko and his co-workers. Three of these papers are discussed below, and a fourth (Andrienko and Demenko, 1969) may be cited without further comment as an example of a one-to-one association of surges in brightness of a single comet with sharp increases in solar flare area.

Brobrovnikoff's catalogue provided the data for Andrienko *et al.* (1972) to carry out straightforward analyses of the correlation between the magnitude of a comet and geomagnetic index (the latter for dates corrected for the differences in heliocentric longitudes of the comet and the Earth). Twenty-nine comets were selected, and if the range in heliocentric ecliptic latitude [Note 2] was sufficiently large, the material was subdivided into two or three latitude intervals. Thus 57 correlation analyses were performed. The resulting correlation coefficients (excluding six negative values) range from 0.04 to 0.93, with 90% confidence intervals of the order of ± 0.04 to ± 0.3. The results are summarized in three interesting graphs, depicting the dependence of the correlation coefficients upon, respectively, ecliptic latitude, heliocentric distance, and phase of the sunspot cycle. These show convincing systematic variations of the coefficients, which decrease with increasing latitude and distance. The relation between coefficient and solar cycle phase exhibits a distinct maximum of the coefficient between phases 0.5 and 0.8. This, the authors comment, is consistent with the hypothesis that solar corpuscular streams are most stable when solar activity is waning, and that outbursts in cometary brightness appear to be closely connected with solar corpuscular radiation. Eleven of the comets were observed between phases 0.5 and 0.8, and for these I have examined the table of geomagnetic index C9. Only in one case (Comet 1900 II) was there no evidence for 27-day recurrence of geomagnetic activity. An examination of the records shows that Comet 1921 II, under observation from April to June 1921, was a special case. An unusually large (1000 millionths of the disc) complex spot at latitude $+0\overset{\circ}{.}5$ persisted for several rotations. Its influence on C9 is apparent for three rotations, and four SCs were recorded (Spencer Jones, 1955). In this instance the correlation (coefficient = 0.66) when the comet was between latitudes $+14°$ and $+36°$ was apparently not induced by an M-region.

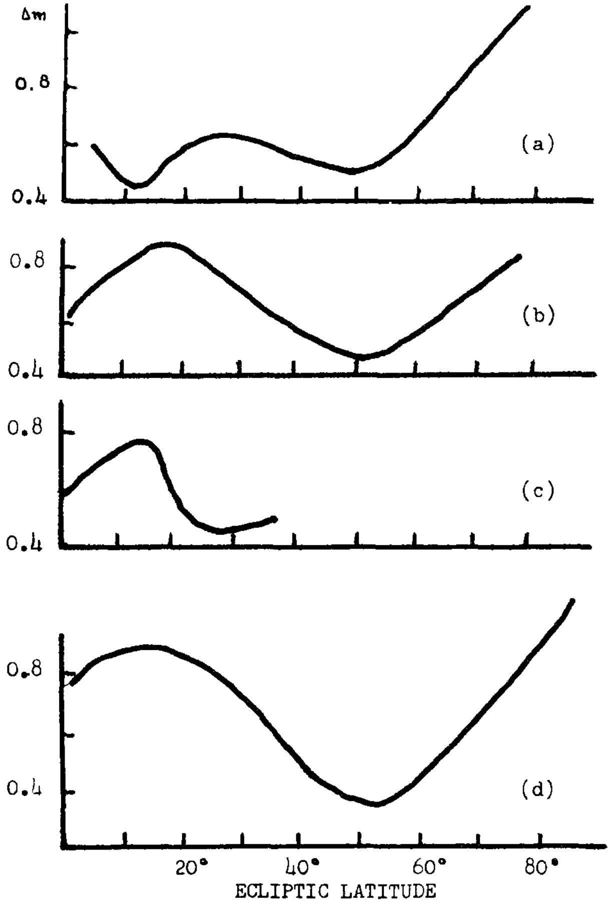

Fig. 1. Amplitude of comet brightness fluctuations (Δm) as function of ecliptic latitude. Andrienko (1974). (a) minimum phase of solar activity cycle; (b) increasing phase; (c) maximum phase; (d) decreasing phase.

In two papers (Andrienko and Ghezloun, 1973; Andrienko, 1974) the differences Δm between observed magnitudes and those predicted from the changes in geocentric and heliocentric distances are studied. Thirty-six comets observed by Beyer are discussed in the first paper, and 33 from Bobrovnikoff's catalogue in the second. For each group of comets $|\Delta m|$ is plotted as a function of ecliptic latitude, the data being divided into four groups by phase in the sunspot cycle. The resulting curves in the two papers are similar; Figure 1 is adapted from Figure 2 of the second paper, omitting individual points. One notes the low-latitude maximum, and (except at maximum phase for which no data were available) the rise at high latitudes. At minimum phase, and in the case of Beyer's observations, at minimum and descending phases, the low-latitude maximum is double. The principal low-latitude peak displaces toward lower latitudes as the solar cycle progresses. The authors interpret the curves as reflecting cometary response to corpuscular streams originating in the solar activity zones, and to increased intensity of corpuscular radiation escaping from high-latitude regions of open magnetic configuration. In a further analysis of Beyer's data, the positive and negative values of Δm are treated separately. In both cases there is a maximum of $|\Delta m|$ at low latitudes and an increase toward high latitudes. This is considered by the authors to mean that an immediate brightening in response to encounter with a corpuscular stream will be followed by a period of abnormally low luminosity, due to temporary depletion of luminous material in the cometary atmosphere.

Statistical investigations such as those summarized above draw on a storehouse of data accumulated over many decades. If we wish to confine ourselves to observations made at a particular point in time, statistical methods will not serve. For example, during the events of June and August 1972, although eight comets were under observation, adequate lightcurves are available only for two. It is of some interest to inquire how much significance can be attached to the behavior of a single comet that, through accidents of apparent brightness, accessibility in the sky, and good weather, has been favored by observers.

The list of 29 comets analyzed by Andrienko *et al.* (1972) includes eighteen for which the observations were subdivided into two or three latitude groups for correlation with geomagnetic indices. In twelve instances, I judged that the range in latitude was sufficient that a decrease of correlation coefficient with increasing latitude might reasonably be expected. In eight of these cases, plots of correlation coefficient against latitude are consistent with the anticipated behavior. In two other cases, heliocentric distance increased as latitude decreased, and the competing influences cannot be disentangled. For the two remaining comets, one or both of the correlation coefficients for two latitude groups were negative, but a trend toward positive correlation with decreasing latitude appears.

There remain six comets for which the latitude range of the groups is small; one would expect that the correlation coefficients calculated for nearly coincident latitudes would agree. The coefficients derived for these pairs (in one case a triple) of groups are: 0.35, 0.35; 0.44, 0.44; 0.69, 0.61, 0.65; 0.93, 0.55; 0.35, 0.04; 0.38, −0.78. The internal agreement is as good as one might hope for the first four comets, the fifth yields low correlation for both groups, and only for the last comet is there a significant discordance. Although not conclusive, the evidence from these 18 comets is that their behavior was, on the whole, consistent.

The great majority of papers on this subject emphasize positive conclusions; presumably some investigators have not reported studies leading to inconclusive results. Grudzińska (1962a, b) examined the brightness fluctuations of Comets 1957 III and V. For the former, no correlation was found with sunspot numbers, radio observations at several frequencies from 200 to 3000 MHz, with geomagnetic indices, or with solar flares or filaments. For Comet 1957 V, no correlation appeared with solar phenomena or geomagnetic activity. Meisel (1970) has made a careful reduction of visual observations by members of ALPO, of Comets 1967 VII and X, eliminating instrumental, atmospheric and moonlight effects. He finds no relation between the brightness fluctuations and the geomagnetic index K_p, 10-cm solar flux, the intensity of λ5303 coronal line about the comet's heliocentric subpoint, density and strength of chromospheric eruptions near the subpoint, occurrence of the strongest flares visible from the comet, or terrestrial auroral activity.

3. Disturbances in Type I Tails

Identification of a distortion of the normally almost rectilinear Type I (plasma) tail does not depend, as does recognition of a change in brightness of the head, upon elimination of instrumental and other systematic effects. Accordingly, an observation of such an event has a high degree of credibility. Unfortunately, the tail of Comet Giacobini-Zinner is too short and faint to bear witness to solar and interplanetary events, and a discussion of the interesting problems of this kind of cometary response is not relevant to the principal topic of this review.

To the writer's knowledge, no systematic study has been made of concurrent brightness fluctuations and plasma tail disturbances. As an illustration the behavior of Comet 1970 II will be examined briefly. In March-April 1970 the Type I tail underwent a series of disruptions, which have been studied for correlation with solar activity by Burlaga *et al.* (1973) and by Jockers and Lüst (1973). Dramatic disturbances were seen on 30 March and 4 April (see Figures 5 and 6 of the paper by Jockers and Lüst), and minor distortions occurred on 2 and 6 April. Were these events accompanied by brightness variations? No published series of magnitude measurements are known to me, but D. Milon and C. S. Morris have graciously provided a compilation of determinations by members of ALPO, which yields independent lightcurves by four observers. These are presented in Figure 2. Since it is my opinion that fluctuations in brightness are most firmly established by the homogeneous data of a single observer, the lightcurves are displaced vertically, so that the significance of each can be judged easily. The occurrences of the tail events are marked above the lightcurves, and below them is Marsden's curve (IAU Circular 2219, 2226) calculated for brightness varying

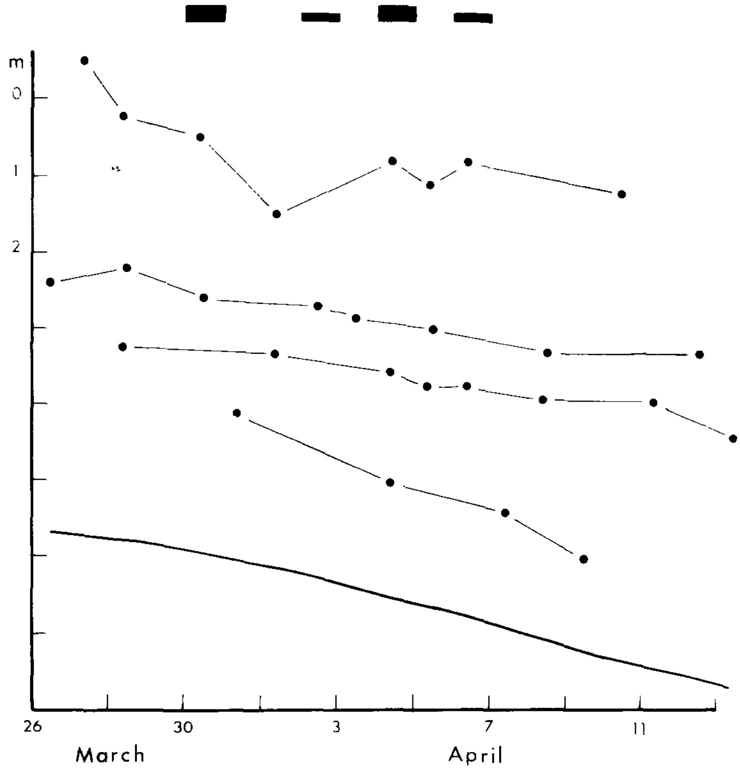

Fig. 2. Lightcurves of Comet Bennett 1970 II. Unpublished observations by Comets Section of ALPO. From top: W. S. Houston, H. G. Solberg, J. E. Bortle, K. Simmons. Bottom curve is magnitude predicted by Marsden (IAU Circular 2219, 2226) with Holetschek formula, $n=4$. Magnitude scale is for upper lightcurve, each successive curve is displaced downward one magnitude. Wide horizontal bars mark days of major disruptions of Type I tail, narrow bars mark days of minor disturbances.

as the inverse fourth power of distance from the sun. Apart from the subnormal brightness recorded by Houston on 1 April, the individual lightcurves certainly do not suggest any significant departures from a smooth variation.

Failure of the brightness to fluctuate in synchronism with the disturbances of the tail is not disconcerting; the brightness is a measure of the activity of neutral molecules and dust in the head, and different mechanisms may be responsible for head and tail responses to solar and interplanetary activity.

4. The Comets of July–August 1972

Despite present uncertainty concerning the mechanisms which may govern the responses of comets to solar and interplanetary phenomena, one can be certain that the sensitivity of a comet to solar-related events will depend upon its physical characteristics. At one extreme are asteroid-like objects which some would identify as 'worn-out' short-period comets; such objects would be inert, and useless as space probes. On the other hand, a comet which is 'new' in the sense that the term was introduced by Oort [Note 3] might be expected to respond in a variety of ways to solar and interplanetary influences. For example, the 'new' Comet 1960 II, in the space of 24 days exhibited a 'wagging' of its Type I tail (Malaise, 1963); fluctuations in total magnitude (Barber, 1960; Sekanina, 1968); decrease in diameter of the C_2 coma from 5!6 to 2!3 within 49 min (Liller, private communication); fading and recovery of the Type I tail in two days (Malaise, 1963); and remarkable increases in the brightness of C_2 and dust in the head (O'Dell, 1961). Perhaps the description of an ideal comet for exploration of interplanetary space would require a compromise between the richer array of responses that a 'new' comet might provide, and the opportunity of evaluating the behavior of a less active periodic comet through study of its performance at more than one perihelion passage.

At least one observation is recorded for each of eight comets in July-August 1972. In mid-August they were distributed in heliocentric distance from 1.0 to 5.6 AU, from heliographic longitude E90° to W92° with respect to the Earth, in heliographic latitude from $-1°$ to $+38°$, and in apparent magnitude from 9^m to 20^m. Donn (IAU Circular 2386) called attention to the value of observations of Comet 1972 II for correlation with satellite data, and Dryer (IAU Circular 2432) initiated a last-minute appeal for observations of Comet Schwassman-Wachmann (1), anticipating a possible response to an 2 August solar flare, but these messages stimulated limited interest. It should be said, however, that by mid-August the first object had faded to 20^m, and the second is normally about 18^m.

Only for Comets Giacobini-Zinner, Schwassman-Wachmann (1), and Sandage 1972 IX are the observations sufficiently numerous to be of interest.

Comet Giacobini-Zinner, discovered in 1900 (period 6.5 years) has been observed at nine perihelion passages, of which only that of 1959 provides a useful comparison with the 1972 apparition. A variety of evidence from direct photography, broad-band photoelectric photometry and spectroscopy of Comet Giacobini-Zinner supports statements by Swings (1963, 1965) that reflected sunlight is extremely strong in its spectrum, and that it is probably a 'new' comet. It may be inferred that, if not 'new', it is 'young'. Marsden (1967) finds its orbit to have been little changed from 1725 to the present. Roemer (1960) reproduced photographs taken in blue and yellow light in 1959, which show a Type I tail 0°5 long, and several comments (e.g., Sykes, 1972) describe a broad, diffuse tail, presumably Type II (dust). This comet is celebrated for its associated Draconid meteor shower. The meteroroids are evidently very fragile and of low density, characteristic of a 'new' comet (Jacchia, 1963; Whipple, 1963).

Comet Schwassmann-Wachmann (1) has long been of particular interest; it is unique for its nearly circular orbit (perihelion distance 5.4 AU) and for its surges in brightness amounting to as much as nine magnitudes – a factor of 4000 in brightness! This behavior has incited an extensive literature, from which one item is relevant to the present review. Vsekhsvyatskij (1966) found that outbursts tend to recur at intervals of 25–27 and 50–60 days, and inferred that they are responses to co-rotating solar streams. This implies that solar flares are not the dominant agent in the production of the brightness surges. Miller (1973) point out that the statistics may be biased by the influence of moonlight on the observations; the recorded brightenings occur predominantly near new phase. The third comet, Sandage 1972 IX was 'new' with the unusually large perihelion distance for an observable comet of 4.3 AU. The first two comets in 1959, as in 1972, were under observation simultaneously.

5. Comets Giacobini-Zinner and Schwassmann-Wachmann (1) in 1959

5.1. Comet Giacobini-Zinner

Four homogeneous series of magnitude measurements are available, which are plotted in Figure 3, displaced vertically to facilitate examination of each. The visual observations made after the first week of October scatter more about a smooth curve than those of earlier dates, perhaps due to moonlight and other unfavorable conditions. Two of the three later observations that Beyer noted as uncertain are accompanied by

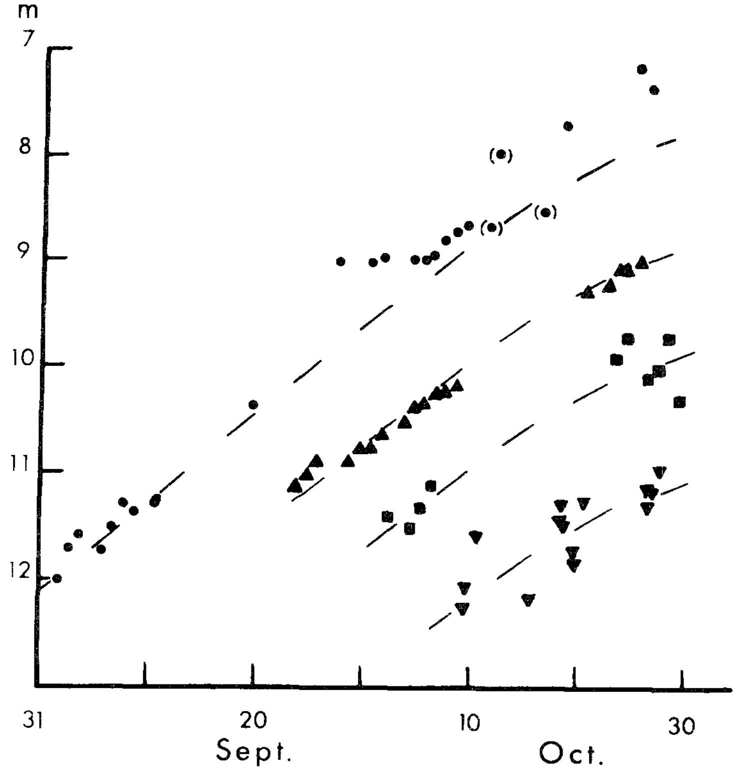

Fig. 3. Lightcurves of Comet Giacobini-Zinner in 1959. From top: Beyer (1962), with observations designated uncertain in parentheses; Baldet and Bertaud (1962); Bakharev, see Baldet and Bertaud (1962); Vsekhsvyatskij (1959). Dashed curves – see text. Magnitude scale is for upper lightcurve, each successive curve is displaced downward one magnitude.

references to the moon, and both Vsekhsvyatskij and Bakharev in Astr. Tsirk. 207 mentioned the low altitude of the comet, bright sky, and mist or dust. The photometric parameters m_0 and n have been evaluated by Beyer (1962) as 10.2, 9.4; by Baldet and Bertaud (1962) as 10.7, 5.4 for 23 September to 8 October, and 10.8, 11.2 thereafter; and by Vsekhsvyatskij (1963) as 10.3, 4.0. The latter assumed $n = 4.0$ in the absence of data adequate for independent determination. I have computed the shape of the lightcurve, arbitrarily adopting $n = 8.2$, and adjusting m_0 to fit each of the four series of observations in Figure 3. Except for Vsekhsvyatskij's work, the dates of each series fall into an early and a late group, and the zero-point adjustment was made on the earlier set. With two exceptions, the development of the lightcurves is represented tolerably well by the form of the calculated curve. Beyer's magnitudes after 27 September are brighter than predicted, and from 27 September to 6 October, the brightness is constant. Neither phenomenon appears in the other lightcurves.

From 28 August to 5 September, when the comet was 1.25 AU from the Sun, a volley of major flares erupted, as summarized in Table 1, of which two were beyond the west limb as viewed from the comet. Responding, presumably, to this activity, an SC was recorded on 3 September (Lincoln, 1960a) but, judging from Beyer's observations, the comet was unimpressed. For his nine magnitudes of 1 to 10 September the average deviation from the predicted curve of Figure 3 is only $\pm 0\overset{m}{.}11$.

Several excuses for the failure of the comet to respond to the 28 August–5 September flares can be advanced:

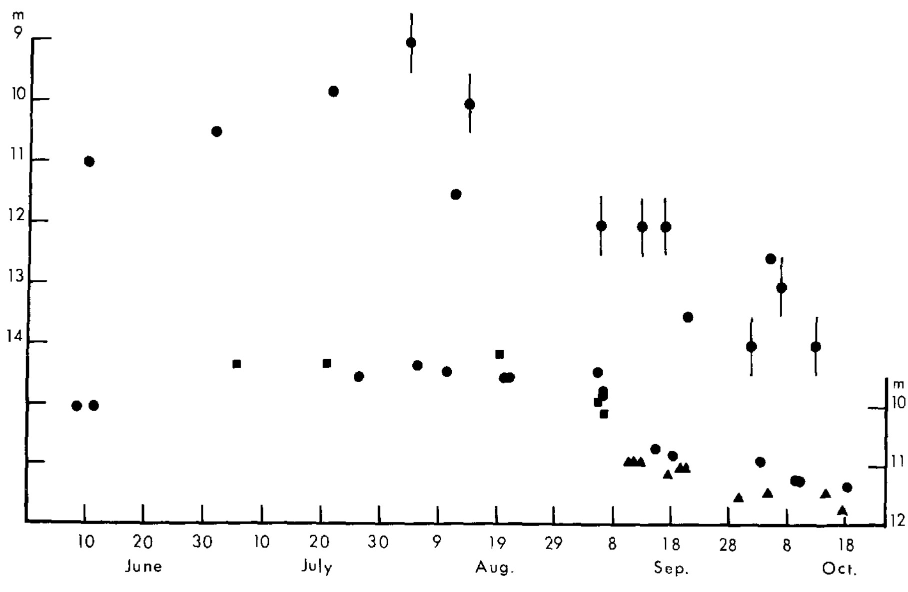

Fig. 4. Lightcurves of Comet Giacobini-Zinner in 1972. Upper curve, observations by Seki, from IAU Circular 2423, 2429, 2433, 2437, 2458; vertical bars mark observations given only to nearest magnitude. Lower curve, observations by ALPO observers (Morris, 1973); circles, Bortle, triangles, Jones; squares, Seslar and Kleine.

TABLE I

Major flares, 28 August–5 September 1959

Date	Start	Position[a]	Hα Imp.	McMath Plage	CFI[b]
28 Aug.	*0027*	N11 E37	1	5344	11
31 Aug.	*1850*	N10 W24	1+	5344	10
1 Sep.	*1923*	N12 E26	2+	5354	8
2 Sep.	*0720*	N10 W44	2+	5344	⩾8
2 Sep.	*1602*	N25 W111	2	5339	10
3 Sep.	*0421*	N25 W120	1	5339	11
5 Sep.	*1556*	N13 W86	1	5344	8

[a] The longitude is referred to the central meridian viewed from Comet Giacobini-Zinner.
[b] Dodson and Hedeman, 1971.

(1) The flares were unfavorably located in heliographic longitude. This is not very plausible; the first four flares listed in Table I were in full view from the comet, and within 45° of the central meridian. Dodson and Hedeman (1972) have shown that flares associated with the most severe geomagnetic storms cluster toward the central part of the disc, and a preponderance of storm-associated flares group in the western half of the disc, with maximum frequency in longitudes W50° to W59°. Perhaps it would be well not to overemphasize the geomagnetic storm-producing characteristics of flares – properties responsible for the storms may not be the most important for interaction between a flare and a comet. However, the correlations obtained by Andrienko *et al.* (1972) hint at a common agent influencing both cometary brightness and geomagnetic index.

(2) The comet was too far from the plane of the solar equator. During the period in question the comet's latitude was N35°, and the first four flares in Table II were between N10° and N12°. If this explains the passivity of the comet, it does not bode well for comets as out-of-the-equator probes! The analyses of Andrienko and Ghez-

TABLE II

Observations of comet Giacobini-Zinner – August 1972

Date	Observer	Magnitude
6.8 Aug.	Urata	Invisible with 20-cm refractor
7.1 Aug.	Guthier	$9^{m}.3$
11.8 Aug.	Seki	$11^{m}.5$
12.0 Aug.	Waterfield	$11^{m}.0$
12.0 Aug.	Guthier	Invisible with 15-cm reflector
13.8 Aug.	Seki	10^{m}
20.1 Aug.	Guthier	11^{m} or fainter

loun (1973) and Andrienko (1974) indicate that near time of sunspot maximum, fluctuations of cometary brightness are weak at latitudes as high as 35°, but this is a statistical conclusion, and does not predict the response to a single major flare.

(3) The mechanism by which the comet responds to a solar stimulus may, like those proposed by Donn and Urey (1956) and Shul'man (1972, 1974), be such that the comet requires a period of recuperation before it becomes sensitive to another solar event. Dodson and Hedeman (1971) list four flares with Comprehensive Flare Index (CFI) $\geqslant 7$ for 17–18 August. That starting 18 August at 1014 UT had Hα Importance 3 and CFI 13. An SC was recorded on 20 August (Lincoln, 1960a). At this time the comet was 1.37 AU from the Sun at heliographic latitude N35°, and saw the flare at heliographic longitude W64°. The shock should have reached the comet on 20 or 21 August when no magnitude observations are available. This explanation for the inactivity of the comet beginning 1 September can therefore not be verified.

(4) Finally, the comet may be insensitive to solar events such as those of 28 August to 5 September, either because of the characteristics of the comet or those of the flares. This is an escape-hatch but an unsatisfactory one for obvious reasons.

After 5 September no flare with CFI exceeding 7 appeared on the visible hemisphere until November. Neither a great flare nor an SC can be associated with the still-stand on Beyer's lightcurve between 27 September and 6 October. At that time a sector of 29° in solar longitude was at the eastern limit of the disc as seen from the comet, but invisible from the Earth. None of the McMath plage regions which transited this sector between 25 September and 6 October is listed by Dodson *et al.* (1974) as 'most flare-rich', nor in any case is the preceding or following return of a region so listed. Furthermore, a flare within 30° of the east limb is (if the analogy with geomagnetic phenomena holds good) unfavorably placed to influence a comet. The still-stand in Beyer's lightcurve is therefore unexplained.

It may be thought that undue emphasis has been placed here upon the interpretation of a single series of observations (those of Beyer) but the writer believes that if observations of cometary brightness are to be utilized as indicators of solar-related events, a closely-spaced series by a single observer is the best data to use.

5.2. Comet Schwassmann-Wachmann (1) in 1959

The observations are scattered in time; the following summary depends upon Roemer (1960), Jeffers and Gibson (1960), Van Biesbroeck (1961) and Beyer (1962). On 1 September an outburst was well developed, and another was in progress on 1 October, when Beyer recorded the magnitude as $11^{m}.5$. It is difficult to unravel the sequence of events, since some observations are visual and others photographic, but all are consistent with irregular fluctuations and a gradual decline in brightness continuing through December, when Beyer found the comet still slightly brighter than $13^{m}.0$. An examination of his lightcurve is recommended.

The geomagnetic indices for this period do not indicate the presence of marked recurrent solar streams. If the surges in brightness about 1 September and 1 October when the comet was 5.9 AU from the Sun were induced by inteplanetary shock waves, the latter might have reached 1 AU some 10 to 20 days earlier. Since the comet was at heliographic latitude $+14°$ and the longitude differed from the Earth's by no more than 45°, the same shocks might have been recorded at the Earth. SCs were observed on 16 and 20 August, 3, 19 and 20 September (Lincoln, 1960a). The solar flares listed in Table I could not, of course, be responsible for the comet outburst observed on 1 September, but may have contributed to the enhanced brightness recorded on 1 October. Additional SCs took place in October and November (Lincoln, 1960b), when the heliographic longitudes of Earth and comet did not differ by more than 40° and it is tempting to suggest that the delay in return to normal brightness was a response to this supplementary stimulation. But such a proposal stands on very weak statistical grounds. One difficulty in relating cometary to solar-related events is the opportunity for purely accidental coincidences. Miller (1969) found that the probability was 0.16 that a disturbance in the tail of Comet 1957 III could be associated by chance with a moderate increase in the geomagnetic index C9. Kresák (1974b) has also commented on this problem.

5.3. Summary of the 1959 events

In August and September Comet Giacobini-Zinner was exposed to a series of energetic solar flares and an interplanetary shock (inferred from an SC). If reliance is to be placed upon response of a comet at intermediate heliographic latitude to solar activity, a reaction would be anticipated in this instance, but none is seen. The failure is disappointing, but, if rightly interpreted, may contain a lesson in solar-cometary relations. Comet Schwassmann-Wachmann (1) on the other hand, appears to have responded to interplanetary shocks in a satisfactory manner, but this agreeable result can properly be viewed only as one more statistic in the complex history of this object.

6. Cometary Activity, July-September 1972

6.1. Comet giacobini-zinner

As Comet 1972 VI, this received more attention from observers than any other comet visible at the time of the August 1972 solar events. The IAU Circulars contain 38 measurements or estimates of the total magnitude (m_1) between 8 June and 12 October. Of these, fourteen were by Seki (Figure 4); the remainder were contributed by several observers in insufficient numbers to form individual lightcurves. An important series of observations was made by five members of ALPO, and reduced to a uniform system by Morris (1973), it appears in Figure 4. Gaps near full moon on 24 August and 23 September will be noticed in both lightcurves.

Evidence for an interesting episode is assembled from IAU. Circulars 2437 and 2451 in Table II. Four observers attest to a rapid decline in brightness of about 2 magnitudes, which appears to have been in progress on 6 August.

Turning to the ALPO observations, Bortle (IAU Circular 2445) reported that the fading was not nearly as striking in his visual observations, and one sees that the ALPO observers recorded no abnormally faint magnitudes through 21 August. At first sight the ALPO lightcurve is inconsistent with the behavior implied by the data of Table II, but placing confidence in the work of experienced observers, one may suppose that the comet underwent a series of rapid fluctuations in brightness. This is suggested by Guthier's observation of 7.1 August ($9^{m}.3$) less than half a day after Urata failed to see the comet on 6.8 August. An equally rapid recovery is required by Guthier's observation on 20.1 August and an ALPO magnitude of $9^{m}.5$ on 20.35 August. These pairs of observations impose time limits of 6 to 8 h for substantial brightness changes. But having in mind such an event as the decrease in diameter of the coma of Comet 1960 II by 59% in less than an hour (Section 4), a time scale of hours in the present case should not be ruled out.

A second less erratic decline in brightness appears in the ALPO lightcurve beginning about 6 September and levelling off by 10 September, a period when Seki published only one observation, and that only to the nearest full magnitude.

Finally it must be conceded that it is impossible to reconcile Seki's observations with those of Bortle and Jones from 29 September to 18 October. There is a systematic difference of roughly 2 magnitudes; this might be explained by a difference in observational techniques, but the writer has been unable to learn the method used by Seki.

In the subsequent comparison of cometary and solar activities, attention will be centered upon what is interpreted here as a period of marked brightness fluctuations from 6 to 20 August, followed by a rapid decline of about 1.5 magnitudes between 5 and 10 September.

6.2. Comet Schwassmann-Wachmann (1)

The following description is drawn from IAU Circulars 2424, 2439, 2440, and 2464 and Roemer (1972). Pereyra found the comet at its normal photographic magnitude ($17^{m}.5$ to $18^{m}.0$) on 16, 17 and 19 June, as did Dryer *et al.* (1975) on 6.0 July. On 8 July, Pereyra determined the photographic magnitude as 13.5 to $14^{m}.0$, and on the following day a little brighter, declining by 10 August to 15.0 to $15^{m}.5$. According to Roemer and others it was static on 14 to 17 August, its appearance typical of that several weeks after a major outburst. On a number of nights during the September dark-of-the-moon (new moon 7 September) they observed only low level activity, consistent with the late phases of the July outburst. On 9 October a photograph by Swings and Dossin provided evidence that there had recently been another outburst.

These observations fit the pattern of representative outbursts as described by Roemer (1958), the return to the normal state requiring about a month, or prolonged by further activity for several months, as was the case in 1959.

6.3. Comet Sandage 1972 IX

Observations reported on several IAU Circulars covering the period from discovery on 9 June through 11 October, place the magnitude between $13^{m}.0$ and $13^{m}.5$ except on 13 July when Kojima (IAU Circular 2428) gives $12^{m}.5$. A fairly steady brightness remaining within half a magnitude of $13^{m}.0$ summarizes the observations.

7. Cometary Responses to Solar Activity in July and August 1972

It is unnecessary to review here the solar activity of the summer of 1972. The purpose of this section is to describe and speculate upon cometary events (and non-events) at or about those dates when responses to the solar activity might be expected. Attention will be focused upon the flares discussed by Dryer *et al.* (1975) henceforth referred to as 'D–W', and I have adopted their model of the associations of particular flares with SCs and events observed at spacecraft and Jupiter.

7.1. The flares of 15 June, 1972

Associations of these two major flares (both of Comprehensive Flare Index 8) with events at the Earth, Pioneer 10, Jupiter, and Comet Schwassmann-Wachmann (1) are summarized by D–W in their Table 1, in which the flares are designated IA and IIA. The comet was then at heliographic latitude S1° and within 3° of the heliographic longitude of the Earth. Its outburst which began between 6 and 8 July is considered by D–W to be a probable reaction to the first flare; the second flare, which began 3.5 h later, is a less likely candidate for progenitor of the cometary outburst. In the D–W model, a non-Io-related Jovian radio event ascribed to Flare IIA took place on 8 July, and the shock wave would have encountered the comet after the probable time of beginning of the outburst. The association of Flare IA and the cometary outburst (which requires a considerable decrease of the shock velocity in the 0.4 AU between Jupiter and the comet) is entirely reasonable. Association of the outburst with Flare IIA would be equally plausible in the absence of radio evidence from Jupiter.

If the comet responded also to Flare IIA, the event was not detected. The trajectory of the shock wave (D–W, Figure 2) places it at the comet on 9 or 10 July, for which no observations are available. However, the comet was described as increasing in brightness from 8 to 9 July, and it would be difficult to distinguish between an initial response to Flare IA, and an augmentation of the outburst by IIA.

Comet Sandage was at this time 4.4 AU from the Sun at heliographic latitude N32°, and in heliographic longitude about 50° east of the Earth. According to the trajectories of D–W it would have experienced the shocks generated by the two flares about 28 June and 4 July respectively. Magnitude observations have been published for 23 June, 30 June (two observers), 4, 6 and 7 July, all placing the brightness at 13^{m}. There is no suggestion of a perturbation of the stable brightness of this comet in response to the flares.

For Comet Giacobini-Zinner, observations are too few in number to permit any judgment about a possible response to either flare.

7.2. The August Flares

We are interested here in possible responses to the four great flares of 2, 4 and 7 August for which the Comprehensive Flare Indices were in chronological order 12, 13, 16 and 15. These were designated as Flares IB to IVB by D–W, who summarized the progress of the associated shock waves across the solar system in their Table 2 and Figures 8–12.

At this time Comet Schwassmann-Wachmann (1) was 5.6 AU from the Sun, near heliographic latitude S1°, and in longitudes E32° and E46° with respect to the Earth on 15 and 30 August respectively. Although the magnitude data summarized in Section 6.2 are few and scattered, those of 14–17 August and the moon-free period of early September are consistent with a typical brightness decline after the July outburst, and D–W infer with good reason that there was no cometary response to the August flares.

Comet Sandage during this period was insufficiently observed to contribute to the present discussion.

Turning now to Comet Giacobini-Zinner, one faces the problem of interpreting a series of magnitude observations made by several observers. The supposed behavior of the comet in August and September is a matter of personal judgment, as can be seen by comparing the lightcurve of D–W Figure 6 with Section 6.1 above. D–W did not make use of the ALPO data, and lacking published information on the instrumentation, plotted uncorrected magnitudes from the IAU Circulars to form their lightcurve. Excluding the two nuclear magnitudes (m_2) by Roemer, the data were contributed by 10 observers, six of whom are represented by only one or two points apiece.

The discussion by D–W of the response of comet to the flares of 2, 4 and 7 August centers on their conclusion that there was a precipitous decline in brightness *circa* 9 August, whereas, to this writer, the ensemble of available observations suggests a period of brightness instability setting in as early as 6 August, and continuing for at least two weeks. These two descriptions of the activity of the comet are entirely consistent; the sharp drop in brightness pinpointed by D–W falls within the period of instability indicated by the data of Table II. However, the downward swing on 9 August cannot be unambiguously attributed to Flare IVB (7 August) as proposed by D–W. Assignment of the onset of brightness instability to a reaction to Flare IIIB (4 August) would agree better with the trajectories.

The brightness decline on 6 September will now be considered on the assumption that it was an independent cometary event. On that date the comet was 1.1 AU from the Sun, at heliographic latitude S10°, longitude W56° with respect to the Earth. No flares with Comprehensive Flare Indices $\geqslant 5$ were observed in September until the 6th, when two with Indices 8 and 7 were seen, and no SCs are recorded in *Solar-Geophysical Data* from 28 August to 12 September. In the sector of the Sun visible at the comet but beyond the west limb as seen from Earth, there were no McMath Plage regions with a history of great flare activity. The maximum Regional Flare Index (*Solar-*

Geophysical Data) of any of these regions was 35.06, compared to 344.79 for Plage 11976, the site of the great August flares. There is, in other words, no evident solar event which can be assigned as the agent of the 6 September decrease in brightness of the comet. Accordingly, the writer would be inclined to extend the period of brightness instability which commenced about 6 August to include the fading seen by ALPO observers on or about 6 September. The date of the onset of instability is close to that of perihelion passage on 5 August, but it seems unwarranted to attribute the instability to that event *per se*. Perihelion distance was 1.0 AU, and the comet was within 1.1 AU of the Sun for a total period of two months. The association by D–W of cometary activity with the August flares is a reasonable working hypothesis.

It remains to consider briefly why Comet Giacobini-Zinner seems to have responded so vigorously to the August 1972 flares, but was not visibly influenced by the flares of

TABLE III

Comet Giacobini-Zinner and major solar flares, 1959 and 1972

Year	r (AU)	Comprehensive Flare indices	Comet lat.	Flare latitudes	Flare Longitudes as seen from comet
1959	1.3	11, 10, 8, ≥8, 8[a]	N35	N10 to N13	E37, W24, E26, W44, W86
1972	1.0	12, 13, 16, 15	N10	N13 to N15	E90, E82, E63, E19

[a] Excluding two flares with CFI 10 and 11, 21° and 30° beyond west limb as seen from comet.

August and September 1959. In Table III are assembled some comparative data for the two epochs. As measured by the Comprehensive Flare Index, the 1972 flares were conspicuously more vigorous in emission of electromagnetic radiation. Only one of the 1959 flares has CFI exceeding 10, whereas the Indices of the four 1972 flares are 12 or greater. In their preliminary investigation of the significance of the CFI, Dodson and Hedeman (1971) found that only flares of Index exceeding 10 were statistically associated with geomagnetic disturbances. It should be repeated that the characteristics of a flare responsible for geomagnetic events, as evidence by SCs and enhanced values of K_p may not be the most relevant to cometary brightness fluctuations. The study by Dodson and Hedeman also suggested that only under unusual circumstances is an energetic particle event associated with a flare with a small CFI – for PCA flares, 70% of the Indices exceeded 10. Of the 1959 flares in Tables II and III, only that of 18 August had a certain association with a particle event, and that of 1 September a probable association (Švestka and Simon, 1974), but the intense particle activity associated with the August 1972 flares was a striking feature of those events.

Two other variables which may influence the response of a comet to solar flares were different in 1959 and 1972. The comet was at higher heliographic latitude in

1959, and three of the 1959 flares were seen by the comet in the western solar hemisphere, whereas in 1972 the flares were to the east, and, except for one case, well to the east of the central meridian.

8. Concluding Comments

The examples presented above of comparisons of cometary brightness fluctuations with solar and solar-related phenomena lead the writer to agree with Pflug (1966) that, in the present state of our understanding, 'Kometen keinsfalls ideale Raumsonde sind.'. Statistical studies such as those of Andrienko and his co-workers encourage belief in mechanisms connecting cometary with solar activity, but the testimony of individual comets is unclear.

As the variety, sophistication, and volume of solar and interplanetary data increase, parallel improvements in cometary programs are needed. A major and obvious requirement is for more nearly continuous photometric observations. These should include photoelectric measurements (but not to displace the work of visual observers) with broad-band filters to distinguish between molecular emissions and reflected sunlight. The observations by O'Dell (1961) of Comet 1960 II demonstrated that both sources of radiation were involved in the activity of that object. Recent photoelectric observations by Isserstedt and Schlosser (1975) of Comet 1973 XII, which revealed brightness oscillations with a quasi-period of the order of 5 minutes, should be singled out as a significant advance in comet photometry.

Observations of comets such as Giacobini-Zinner and Schwassmann-Wachmann (1) should be programmed to avoid bias in favor of reporting only on period of unusual activity. The writer is attempting to compare solar-related activity in periods when Comet Schwassmann-Wachmann (1) was quiescent or active. It is extraordinarily difficult to establish the dates of extended quiet periods, whereas information on outbursts is comparatively abundant. An impartial selection of observing dates according to a predetermined schedule would not preclude more closely space observations if criteria such as the *Forecast of Solar Activity* issued by World Data Center A, Colorado, or interplanetary scintillation observations, as proposed by Dryer (Cronyn and Shawhan, 1975), predict possible cometary activity.

This review has focused upon brightness fluctuations as a commonly observed type of cometary activity, since only data of this sort is available for June–August 1972. Plasma tail disturbances; possible contributions to the study of solar-cometary relations by spacecraft such as the proposed mission to the 'old' Comet Encke (Mumma, 1975); and the stimulating influence of hypotheses designed to account for cometary responses to solar activity, all lie beyond the scope of this article.

Appendix (Notes)

1. The absolute magnitude of a comet (m_0) is defined as the magnitude that would be observed if the comet were displaced to a distance of 1 AU from the Sun, and the

observer were then 1 AU from the comet. The conventional relation is the Holetschek formula:

$$m = m_0 + 5 \log \Delta + 2.5\, n \log r$$

in which Δ and r are the actual geocentric and heliocentric distances respectively. This assumes that the brightness varies inversely as the square of the distance from the observer, and inversely as the nth power of the heliocentric distance. The photometric index n is often taken to be 4 in the absence of concrete information, but values obtained by fitting the Holetschek formula to observations differ considerably from one comet to another. The index may even be different for the same comet at different periods of a single apparition. The correct form for a physically significant relation is subject to debate; a comprehensive discussion will be found in a paper by Meisel (1970). For brightness measurements of the kind discussed throughout this review, the problem is complicated by the fact that the observed radiation is, in general, partly sunlight scattered from solid grains and partly emission bands of molecules. These two components cannot be expected to vary with the same value of the index n.

2. In studies of solar-cometary relations, the heliocentric position of the comet is sometimes stated in the system having the ecliptic as the fundamental plane. Since the planes of the ecliptic and the solar equator are inclined 7° to one another, two members of the solar system at the same ecliptic latitude but different longitudes, may differ in heliographic latitude by as much as 14°. Heliographic coordinates are used in this review unless a quoted author adopted the ecliptic system.

3. The concept of a 'new' comet in the Oort sense is now some 25 years old. A discussion will be found in Oort (1963). Briefly, a 'new' comet is defined by Oort as one which has arrived for the first time in the inner region of the solar system. Prior to this it is presumed to have orbited at tens of thousands of astronomical units from the Sun, suffering no depletion of its volatile constituents. The alteration in its orbit which brought it into the immediate neighbourhood of the Sun was accomplished by stellar and perhaps planetary perturbations.

Acknowledgements

The author is most grateful to Dr H. W. Dodson and to E. R. Hedeman for instructive discussions on solar and solar-terrestrial topics, and for providing Comprehensive Flare Indices for 1972 in advance of publication. The heliocentric distances and heliographic coordinates cited so frequently depend on published orbital calculations by Drs. B. G. Marsden, P. Herget and N. A. Belyaev. This work was supported in part by a grant from the National Science Foundation.

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