

# Tail Peculiarities in Comet Bennett Caused by Solar Wind Disturbances

K. Jockers and Rh. Lüst

Max-Planck-Institut für Physik und Astrophysik, München

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**Summary.** Peculiarities observed in the plasma tail of Comet Bennett between March 30 and April 7, 1970, were shown to be related to solar wind events. In particular two series of exposures taken from stations at different geographic longitudes are discussed which show the development of a secondary tail. One of these events is clearly connected with an interplanetary shock wave. We propose that the ions forming the secondary

tail originated in a region in front of the comet and were compressed during the shock event to a concentration dense enough to be observed. Further there seems to be a correlation between kinks in the tail axis and changes of the solar wind direction.

**Key words:** comet-solar wind interaction – plasma tails

## 1. Introduction

Comet Tago-Sato-Kosaka 1969 IX and Comet Bennett 1970 II were the first bright comets which appeared in the satellite era. In a previous study (Jockers *et al.*, 1972), a first attempt was made to correlate the kinematic behaviour of the plasma tail of Comet Tago-Sato-Kosaka with space probe observations. Burlaga *et al.* (1972) tried to establish correlations between tail events in Comet Bennett and solar wind data. From their negative results the authors doubt whether any correlation between cometary and solar wind events exists. In our opinion the failure of their attempt may be partly caused by the poor interplanetary data coverage and partly because perturbations influencing the comet did not reach the earth. Moreover, it should be kept in mind that, even though the comet could be observed well from the northern hemisphere and is one of the most photographed comets, a great number of photos are still unpublished. This makes investigations for which series of observations on special days are necessary very difficult. Also the present paper should be regarded in this light. Nevertheless we succeeded in establishing a correlation between an interplanetary shock wave and a comet tail event. Further some tail kinks could be related to changes in the solar wind direction.

## 2. The Interplanetary Plasma between March 30 and April 7, 1970

We have concentrated on this period, since it is the only one for which we have observational information about Comet Bennett complete enough to try some

correlations. The values of the solar wind velocity, density and direction, which we obtained from several sources, are given in Fig. 1. The OGO 5 and Vela 5 data are taken from the paper of Burlaga *et al.* (1972) with the particle density recalculated from the momentum flux data given there. The HEOS I data were kindly provided to us by Formisano, who sent us also the still preliminary angular measurements analyzed by Signorini. The ALSEP data are taken from Burlaga *et al.* (*l. c.*) and Neugebauer *et al.* (1972).

After a day of quiet solar wind, an SSC was registered on March 31 at 6<sup>h</sup> UT. The corresponding shock wave was observed by the ALSEP solar wind spectrometer, which has been set up by the Apollo-12 crew on the lunar surface. The registration curve showing the total current of the westward facing cup at the time around sunset at the Apollo landing site (April 1, 0<sup>h</sup> UT) shows a sudden rise on March 31 at 5.30 UT. From a comparison of the values of the current with the OGO 5 and HEOS I data it was possible to “calibrate” the ALSEP data and to determine the solar wind flux at the time of the passage of the shock wave. Interpreting the two first velocity values of the ALSEP spectrometer (given by Burlaga *et al.*) as the immediate pre- and postshock values we obtained the density data given in Fig. 1. The data allow a propagation speed of  $670 \text{ km s}^{-1}$  to be determined from mass conservation through the shock wave. The He-rich driving piston of compressed gas was observed by HEOS I from 15<sup>h</sup> to 20<sup>h</sup> UT (Cattaneo *et al.*, 1971). Shortly before the arrival of the driver gas a secondary maximum of the velocity was observed. The two velocity maxima, which are 7 hours

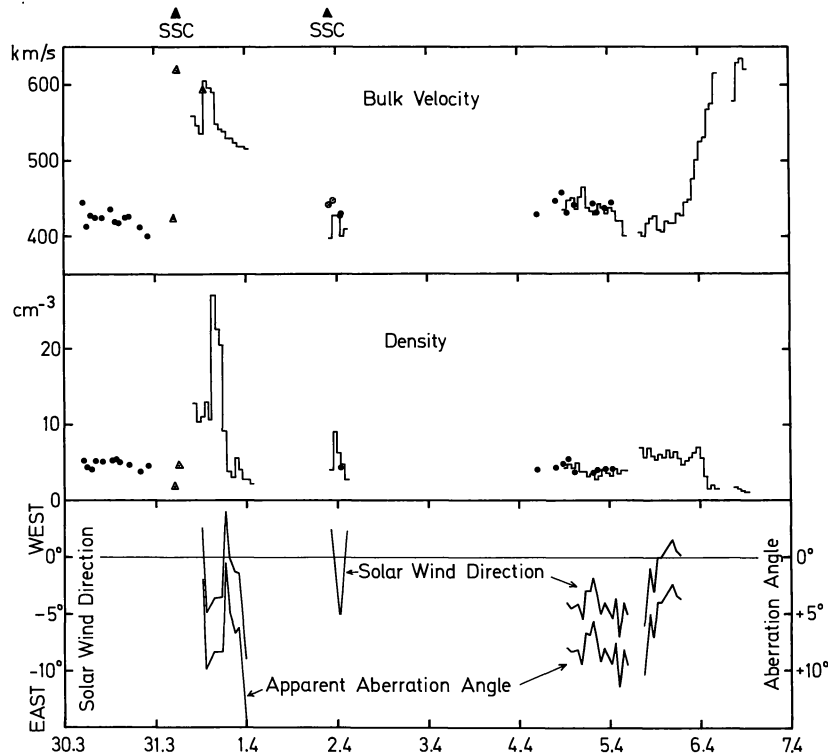


Fig. 1. Solar wind data from March 30 to April 7, 1970. Full circles = OGO 5. Open circles = Vela 5. Triangles = ALSEP. Steps = HEOS 1. Solar wind direction from HEOS 1. Lowest curve: Calculated instantaneous apparent aberration angle, i.e. angle projected on the sky between solar wind and solar direction, as seen from the comet. Positive when solar wind comes from preceding side of comet. Under stationary conditions this angle coincides with angle between radius vector and tail, projected on sky

apart, both correspond to material coming from the western side of the sun. This correspondence of high velocity streams with a tendency to antirotation holds quite generally, as has been shown by Coon (1968) and later by Siscoe *et al.* (1969).

There is a data gap on April 1 and after some data around April 2.0 again between April 2 and 3. For the latter days Burlaga *et al.* give some reasons to suggest that the solar wind was undisturbed. On April 1, however, there might have been another solar wind event. Burlaga *et al.* mention an SSC on 21.53 UT, April 1, which, however, is not included in the Goettingen list of  $K_p$  indices. On April 5 and 6, a steady rise of the solar wind speed occurred, which was followed by a decreasing density. According to the criteria given by Hundhausen (1972) this behaviour points more to a corotating high speed stream than to a flare induced event. From the  $K_p$  data we see, however, that there is no series of recurrent events to which this stream might be attributed. Again the solar wind turned to a more western direction.

According to Hundhausen (1972) there is a good correlation between combined type II/IV radio events and flare induced shock waves. While several such events occurred on March 25 and 26, one of which may be connected with an interplanetary shock wave of March 27, only two events of type II or type IV are

reported in the ESSA Solar Geophysical data in the time interval from March 27 to April 7: the combined type II/IV events on March 29, 0<sup>h</sup>40, at a solar position of N 14 W 36 and on March 31, 18<sup>h</sup>06, at S 12 E 45. The first one is evidently the source of the interplanetary shock wave of March 31. From the time difference we get an average propagation speed of  $780 \text{ km s}^{-1}$ , which corresponds well with the  $670 \text{ km s}^{-1}$  given above, if one takes into account small deceleration as is normally observed (Taylor *et al.*, 1969). A solar wind response to the event of March 31 should be expected on April 2 or 3 where we have no interplanetary data. This influence, however, cannot have been very spectacular since the  $K_p$  index during these days was less than 4.

### 3. Definitions and Equations for the Interpretation of Comet Tail Observations

In order to correlate comet tail and solar wind observations it is necessary to compare changes of the tail angle in the plane of the sky with directions which refer to the heliocentric heliographic polar coordinate system. Therefore it is necessary to transform the components of the relevant vectors into a coordinate system given by the tangential plane centred at the comet and the direction of the line of sight. Thus we

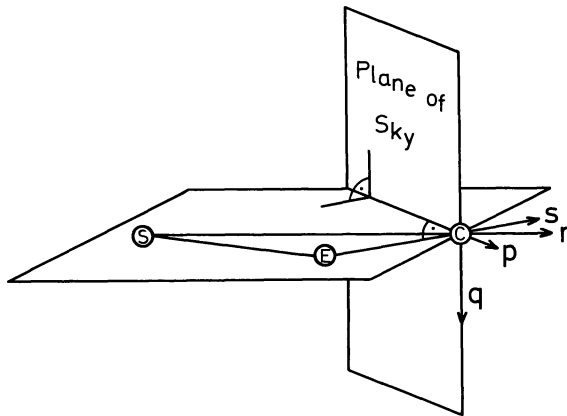


Fig. 2. Observational coordinate system consisting of the unit vectors  $p$  (projection of the radius vector  $r$  on the plane of the sky),  $q = s \times p$  and  $s$  (line of sight)

define a new system by the three unit vectors  $p$  (the projection of the radius vector sun-comet on the sky),  $q = s \times p$  (in the tangential plane perpendicular to  $p$ ) and  $s$  (in the line of sight). Note that, while the vectors  $p$  and  $q$  define the plane of the sky, the vectors  $p$  and  $s$  define the common plane of earth, sun, and comet (Fig. 2).

Table 1 contains the components of the heliographic polar coordinate unit vectors  $r$  (radial direction),  $\phi$  (azimuthal direction) and  $\theta$  (polar direction) expressed in the coordinate system defined above for the period of interest. These values can be calculated from the relative positions of sun, earth and comet, as e.g. given in cartesian heliographic coordinates of the comet and the earth. The table contains further the components  $v_p$ ,  $v_q$ ,  $v_s$  of the comet's heliocentric velocity. The

components of the solar wind velocity  $w$  follow from its heliographic polar coordinates by the equations:

$$\begin{aligned} w_p &= w_r \cdot r \cdot p + w_\phi \cdot \phi \cdot p + w_\theta \cdot \theta \cdot p \\ w_q &= w_\phi \cdot \phi \cdot q + w_\theta \cdot \theta \cdot q \quad (q \cdot r = 0) \\ w_s &= w_r \cdot r \cdot s + w_\phi \cdot \phi \cdot s + w_\theta \cdot \theta \cdot s. \end{aligned} \quad (1)$$

The apparent aberration angle, i.e. the angle between  $p$  and the observed tail axis on the sky, follows easily from the components  $T_p$  and  $T_q$  of the tail vector  $T = w - v$ :

$$\tan \psi = \frac{T_q}{T_p} = \frac{w_q - v_q}{w_p - v_p}. \quad (2)$$

#### 4. Position of Comet and Earth Relative to the Sun and Solar Wind Delay Times

Comet Bennett had a parabolic orbit almost exactly perpendicular to the plane of the ecliptic. Therefore, after having passed the direction of the ecliptic south pole in mid-February, the comet had a nearly constant ecliptic longitude of about  $224^\circ$ , the ascending node of its orbit. It reached its perihelion on March 20.05 at a solar distance of 0.54 a.u. about  $6^\circ$  below the ecliptic plane. On that day the ecliptic longitude of the earth was  $179^\circ$ . The situation on April 4 is shown in Fig. 3. The phase angle sun-comet-earth went through  $90^\circ$  on that day. This is reflected in Table 1 by the fact that  $r$  has nearly the components  $\{1, 0, 0\}$ , i.e.  $p$  coincides with the radius vector  $r$ . Therefore  $w_r = w_p$ . If we assume that the polar component  $w_\theta$  of the solar wind is zero,

Table 1. Comet ephemeris data

| Date                                                                           | March 30.634     | April 2.113 | April 4.103 | April 6.111 |
|--------------------------------------------------------------------------------|------------------|-------------|-------------|-------------|
| Geocentric distance of comet (a.u.)                                            | .7071            | .7334       | .7614       | .7949       |
| Heliocentric distance of comet (a.u.)                                          | .5912            | .6167       | .6399       | .6651       |
| Heliographic longitude of comet                                                | 145.7253°        | 144.7390°   | 143.9070°   | 143.0196°   |
| Heliographic latitude of comet                                                 | 25.3006°         | 32.1962°    | 37.3030°    | 42.0743°    |
| Heliographic longitude of earth                                                | 114.3314°        | 116.7904°   | 118.7612°   | 120.7465°   |
| Heliographic latitude of earth                                                 | — 6.6120°        | — 6.4788°   | — 6.3634°   | — 6.2396°   |
| In the observer's coordinate system $p, q, s$ :                                |                  |             |             |             |
| Components of the unit radius vector $r$                                       | $r \cdot p$      | .984        | .996        | 1.000       |
|                                                                                | $r \cdot s$      | — .177      | — .089      | — .011      |
|                                                                                | $\phi \cdot p$   | .132        | .057        | .006        |
|                                                                                | $\phi \cdot q$   | .670        | .771        | .832        |
| Components of the unit azimuthal vector $\phi$                                 | $\phi \cdot s$   | .731        | .635        | .555        |
|                                                                                | $\theta \cdot p$ | .119        | .069        | .010        |
|                                                                                | $\theta \cdot q$ | — .743      | — .637      | — .555      |
|                                                                                | $\theta \cdot s$ | .659        | .767        | .832        |
| Components of the unit polar vector $\theta$                                   | $v \cdot p$      | 21.5        | 22.1        | 21.4        |
|                                                                                | $v \cdot q$      | — 42.7      | — 36.6      | — 32.0      |
|                                                                                | $v \cdot s$      | 26.6        | 32.3        | 35.8        |
| Components of the heliocentric velocity of the comet $v$ (km s <sup>-1</sup> ) |                  |             |             |             |
|                                                                                |                  |             |             |             |
|                                                                                |                  |             |             |             |

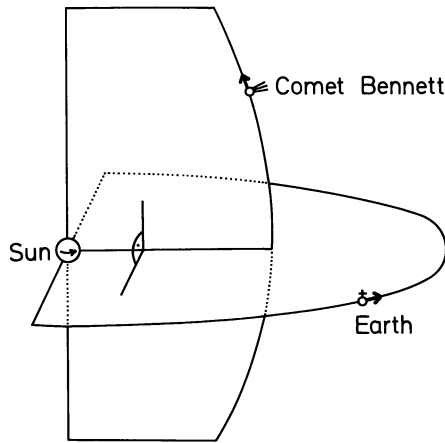


Fig. 3. Relative position of Comet Bennett, sun and earth around April 4, 1970

we obtain for the apparent tail aberration angle in our special case ( $r = p$ ):

$$\tan \psi = \frac{w_{\phi} \phi \cdot q - v_q}{w_r - v_p} \quad (3)$$

Knowing the solar wind behaviour and the relative position of earth and comet in the heliographic system we can now calculate theoretical arrival times of solar wind perturbations at the comet. We begin with the flare induced events. Since the comet was at 0.6 a.u. heliocentric distance, the shock wave which originated at the sun on March 29.03 and reached the earth on March 31.25 hit the comet on March 30.36, if we assume a constant propagation speed. Taking into account the deceleration of the wave and the fact that the angular distance between flare and comet was much less than between flare and earth, we expect the shock wave at the comet somewhat earlier. If we assume a similar propagation speed for the event of March 31.75, it should have influenced the comet around April 2.0. As was mentioned earlier, the solar wind event of April 6 was probably corotating. Assuming a propagation speed of  $625 \text{ km s}^{-1}$ , which is the maximum value observed, the disturbance needed 1.11 d to propagate from 0.6 to 1 a.u. The time necessary to corotate the stream  $22^\circ$  westward (from the earth's to the comet's longitude) is 1.55 d. Hence the high speed stream reached the comet about 0.44 d, i.e. about 10 hours later than the earth.

## 5. The Cometary Observations

### a) An Event Corresponding to the April 5 Solar Wind High Speed Stream

What kind of reaction on a high speed solar wind stream is to be expected at the comet? If the density decreases with increasing velocity (see Fig. 1), the change

in the solar wind momentum flux is not large. Therefore, having in mind the wind bag model of a cometary plasma tail, we expect to see only a change in the aberration angle. After the transition region from the quiet solar wind to the high speed stream has passed the cometary head, we expect three tail regions: Far out there should be tail material which has not yet noticed that the high speed stream is approaching; in this region the tail aberration angle should correspond to the direction of the quiet wind. In the transition region, the tail is expected not to be in equilibrium with the ambient wind. The third region close to the head should show an aberration angle corresponding to the high speed stream.

According to this theoretical picture we calculated for the April 5 event "instantaneous" apparent aberration angles from the solar wind data using Eq. (3) and the value of  $\phi \cdot q = 0.88$  for April 6.111 (Table 1). Taking into account the different heliographic latitudes  $b$  and solar distances  $r$  of the comet and the earth, we scaled the azimuthal solar wind values by  $\cos b/r$  (see Brandt *et al.*, 1972). From the result shown in Fig. 1 we see that the change in solar wind direction, which occurred between 9<sup>h</sup> and 14<sup>h</sup> on April 5 effects the aberration angle much more than the later rise in solar wind speed. Therefore we expected the influence on the comet to begin about April 6.0. On a photograph taken April 6.111 (Fig. 4) we notice indeed traces of a kink at about  $2 \cdot 10^6 \text{ km}$  from the head; it shows qualitatively the discussed behaviour. Unfortunately the exposure has poor guiding. The kink is visible also on another exposure, taken 15 min later, which was correctly guided. Unfortunately this later exposure contains a defect in the emulsion very near to the kink, therefore we reproduced the first one. In addition a well developed ray system is visible on the later picture at the preceding side of the comet tail, which was lost in Fig. 4 because of the uneven guiding. Even though the observation of a tail kink at the predicted time is striking, we are aware that this coincidence should not be regarded as a proof. However, if there is a physical connection between the kink and the near earth solar wind events, this would mean that the source of the high velocity stream was quite extended in heliographic latitude, because as opposed to blast waves the high speed stream cannot influence heliographic latitudes different from that of the source region.

### b) An Event Corresponding to the March 31.75 Solar Radio Burst

From the estimate above, this disturbance should have arrived at the comet on April 2.0. On an exposure of April 2.113 we see a picture similar to that of April 6.111 (Fig. 4) discussed before. The main tail, which is more distinct on this photo, is bended in the same way,

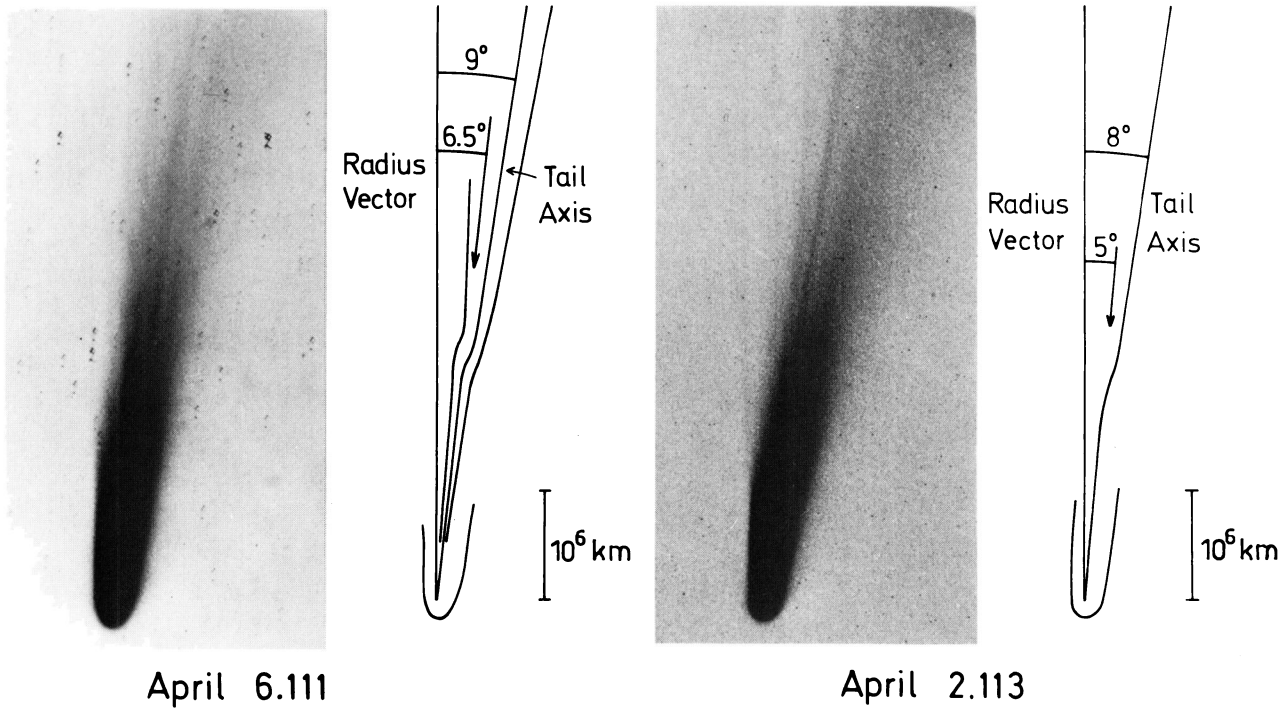


Fig. 4. The two kink events. (Observational parameters of the pictures reproduced in Figs. 4–6, see Table 2)

Table 2. List of exposures of the comet (Fig. 4–6)

| Date         | Emulsion    | Instrument            |                | Location               | Observer           | Remarks                                                                                                   |
|--------------|-------------|-----------------------|----------------|------------------------|--------------------|-----------------------------------------------------------------------------------------------------------|
|              |             | focal<br>length<br>mm | focal<br>ratio |                        |                    |                                                                                                           |
| March 30.117 | 103 a–O     | 1800                  | 3              | Budapest               | L. Balazs          | Series of 3 plates No. 3448–3451<br>published in <sup>a)</sup> p. 186<br>published in <sup>b)</sup> p. 42 |
| 30.501       | Royal X–Pan | 600                   | 6              | Tucson, Arizona        | R. B. Minton       |                                                                                                           |
| 30.811       | Tri–X       | 135                   | 3.5            | Tsuyama                | Akihiko Tago       |                                                                                                           |
| 31.107       | 103 a–O     | 1800                  | 3              | Budapest               | L. Balázs          | Series of 5 plates No. 3452–3456                                                                          |
| April 2.113  | 103 a–O     | 1800                  | 3              | Budapest               | L. Balázs          | Series of 6 plates No. 3457–3462                                                                          |
| 3.766        | Tri–X       | 200                   | 4              | Kitami                 | Giichi Yatame      | published in <sup>b)</sup> p. 45                                                                          |
| 4.041        | A–600       | 625                   | 1.4            | Abastumani             | I. R. Beytrishvili | Series of 6 films No. 16279–16284                                                                         |
| 4.124        | 103 a–O     | 2400                  | 3              | Hamburg–Bergedorf      | K. Lübeck          | Series of 2 plates No. 4520/4521                                                                          |
| 4.479        | 103 a–O     | 135                   | 3.5            | Woodland Hills, Calif. | R. G. Coutchie     | published in <sup>c)</sup> p. 352                                                                         |
| 6.111        | 103 a–O     | 1800                  | 3              | Budapest               | M. Lovas           | Series of 2 plates No. 3480/3481                                                                          |

<sup>a)</sup> Comets, Scientific Data and Missions, Proc. Tucson Comet Conference, Ed. G. P. Kuiper and E. Roemer, Tucson, Arizona 1. July 1972.  
<sup>b)</sup> The Guide (a journal of the Japanese amateur astronomer, in Japanese) 7, 1970.  
<sup>c)</sup> Sky and Telescope 39, 1970.

though less pronounced. However, the correlation between the two events must be considered as uncertain since we have so little information about the solar wind behaviour.

c) The Event Corresponding to the March 31 Interplanetary Shock Wave

Figure 5 shows a series of photographs taken during March 30. These photos reveal conspicuous tail motions which, according to our calculations, must without

doubt be attributed to the influence of the shock wave. At first sight the situation looks quite similar to those discussed before: we see a kink propagating outward. Therefore we again calculated instantaneous aberration angles from the solar wind data. Even though the instantaneous aberration angle varied rapidly during the time of the shock event, it was always positive, i.e. as seen from the comet, the solar wind always came from the preceding direction. From this information we can draw two conclusions.

1. The tail feature in the preceding part of the comet cannot be in pressure equilibrium with its surroundings.

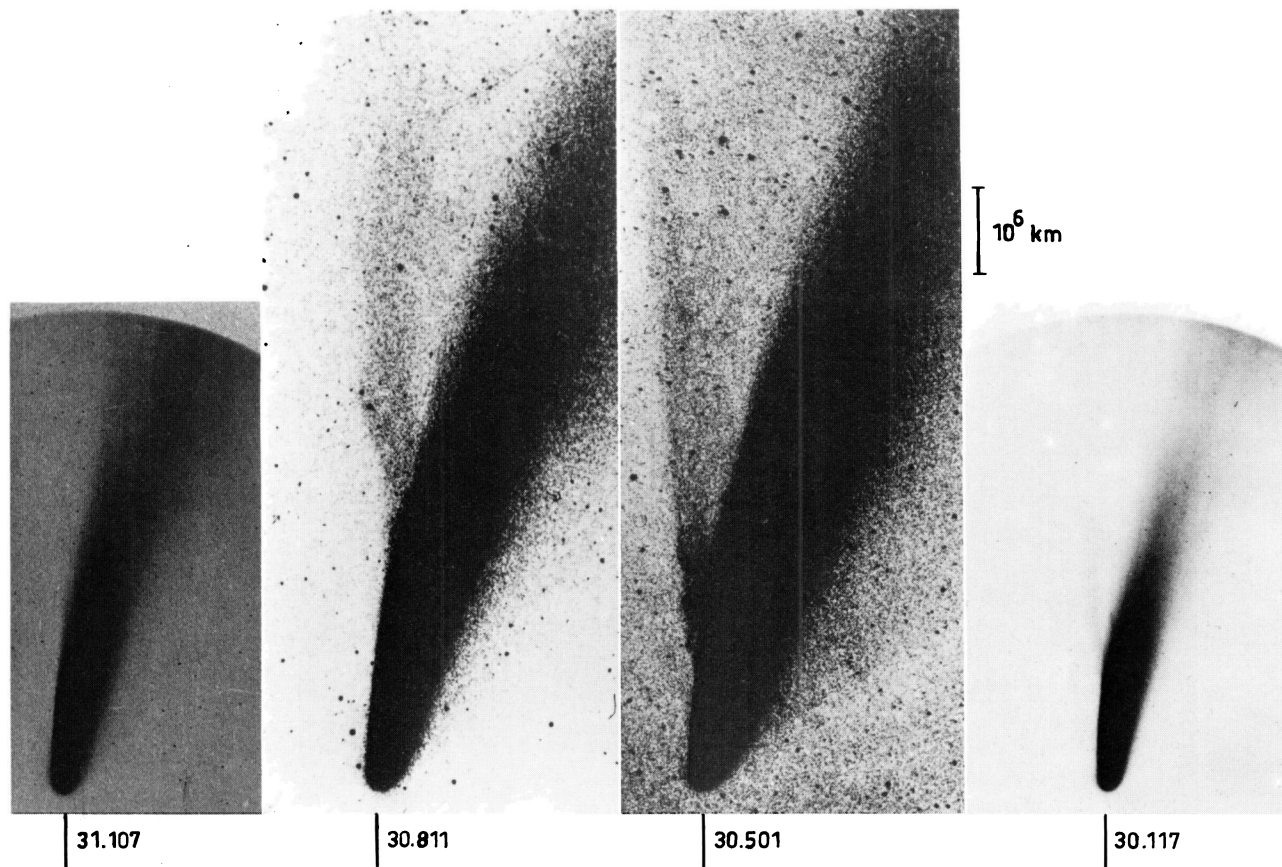


Fig. 5. The secondary tail event corresponding to the interplanetary shock wave of March 31. The pictures are arranged in such a way that the linear distances between the cometary heads of subsequent photographs are proportional to the time difference between the exposures. The projection of the radius vector sun-comet on the sky, which roughly coincides with the radius vector itself, is vertical. The time is progressing in the same direction as the comet. The numbers denote the time of observation

In fact we notice that the outer part of the tail feature flaps towards the axis as it is usually observed with tail rays. Since on the picture of March 30.117 there seem to be traces of a plasma tail with an aberration angle close to normal values, we shall refer in the following to the tail feature preceding the comet as a secondary tail.

2. It was not possible to transport the material forming the secondary tail from the main tail or even from the coma to the region where it is observed.

From the observations of March 30.501 and 30.811 a velocity of the kink of about  $60 \text{ km s}^{-1}$  can be derived. With such a velocity the kink should just be visible on the picture of March 31.107, and this seems indeed to be the case. But if this velocity was approximately constant in the course of the event, the secondary tail of the last three pictures cannot correspond to the large secondary tail of March 30.117, but only to the faint ray visible near the coma. The difference in distance between this faint ray and the larger secondary tail on the same exposure is about  $10^6 \text{ km}$ . With the velocity of  $60 \text{ km s}^{-1}$  this leads to a time difference of about 5 hours which compares

interestingly well with the 7 hours between the two velocity maxima of the shock wave.

From these facts it seems plausible to interpret the secondary tails as cometary plasma, swept up from regions ahead of the comet and compressed by the shock event so that it became dense enough to be recorded on the photographs. The comparatively small angles between the secondary tails and the radius vector are caused by the bending of the shock front due to the retardation by the comet's plasma and magnetic field.

#### d) The Comet Tail Event of April 4

We include this event (Fig. 6) because of its striking similarity with that of March 30 discussed before. As was stated by Burlaga *et al.*, no corresponding solar wind event was observed. Nevertheless, from the similarity of the two events it seems very probable that also this one was caused by an interplanetary shock wave, which, however, was not registered by solar or solar wind observations. As before we see a secondary tail developing from a ray system and later on flapping

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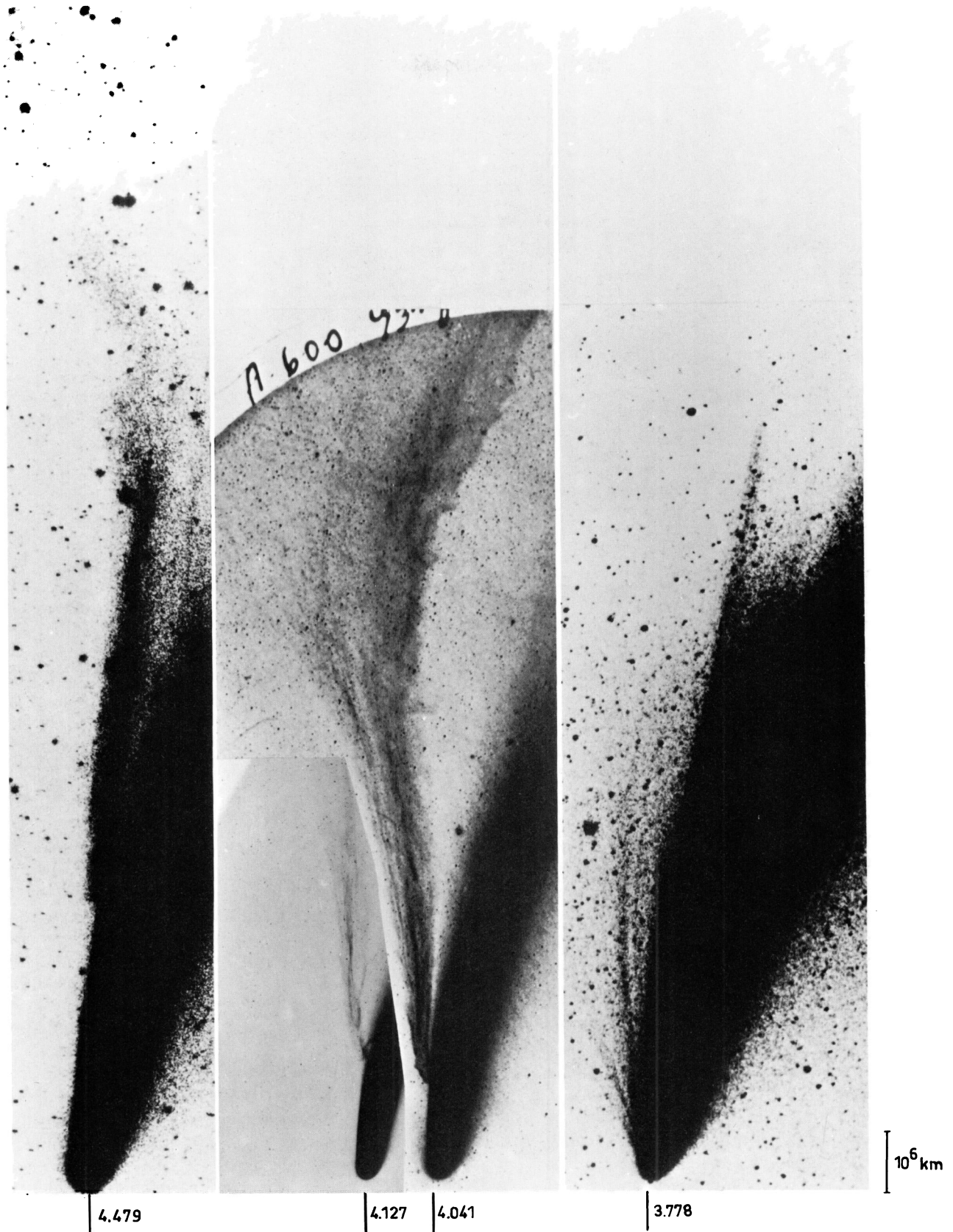


Fig. 6. The event of April 4, arranged as in Fig. 5

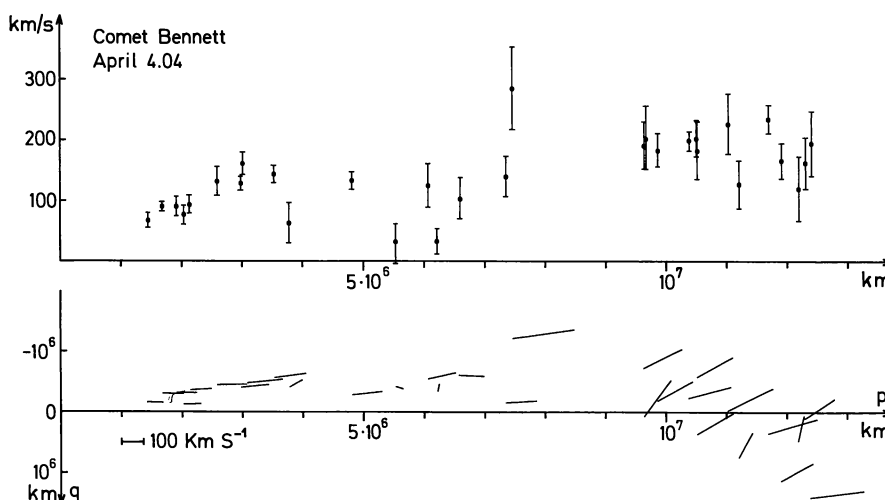


Fig. 7. Velocities of tail structures in the secondary tail of comet Bennett on April 4.04. Upper diagram: absolute values of the velocities versus distance from the cometary head in  $p$  direction. Lower diagram: velocity vectors in the  $p, q$  plane (plane of sky)

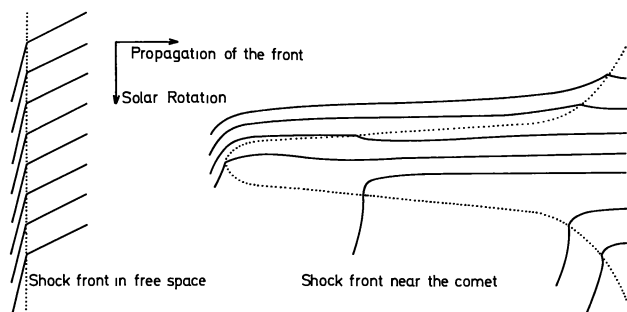


Fig. 8. Topology of the magnetic field to be expected when the shock wave passed Comet Bennett, as projected on the plane of the sky. Note that the comet is north of the earth. Hence the solar rotation is directed clockwise

towards the main tail, which again is partly obscured by dust. Subsequently the secondary tail is transported downstream by the ordinary flow field around the comet. From a series of exposures, made in Abastumani, it was possible to determine the flow field by the method given by Jockers *et al.* (1972). The results (Fig. 7) show velocities which are higher by a factor of two than the average values found in Comet Tago-Sato-Kosaka. In about 6 hours, which is the time difference between the two first exposures in Fig. 6, a plasma condensation (in the secondary tail) with a velocity of  $200 \text{ km s}^{-1}$  moves  $4.4 \cdot 10^6 \text{ km}$ , while the shock front in the solar wind far from the comet propagates more than  $10^7 \text{ km}$ . The growth of the secondary tail in the time between April 3.788 and April 4.041 seems to correspond more to the latter value, which would again support the theory of a sweeping up mechanism.

On the exposure of April 4.041 the secondary tail shows a filamentary structure parallel to itself. It is quite plausible that these structures are field aligned,

which means that the magnetic field is parallel to the secondary tail. If we assume a magnetic field topology of the flare induced shock wave in accordance with present understanding (e.g. Hundhausen, 1972, p. 169) we expect – because of the retardation of the shock front near the comet – a magnetic field topology as shown in Fig. 8. From this sketch the maximum compression must indeed be expected just where we see the secondary tail. If the picture is true, the shock front itself would be just at the downstream border of the secondary tail. The arc which is visible near the cometary head would indicate the location where the shock front crosses the main tail. However, in order to confirm this interpretation it would be necessary to study more cometary events of this type.

## 6. Conclusions

In establishing correlations between solar wind and cometary events, we discussed two types of tail behaviour, namely kinks in an otherwise undisturbed cometary plasma tail which were attributed to comparatively weak solar wind events and the formation of secondary tails.

The kinks were interpreted as being caused primarily by a change in the solar wind direction, the tail regions at the two sides of the kink having aberration angles corresponding to the old and new solar wind direction, respectively. In this model, the kink itself consists of material which altered its motion under the influence of the change in solar wind direction. We studied two such events, the correlation of which with the solar wind seems probable, but could not be proved because of the poor solar wind and cometary data coverage.

One of the two secondary tail evolutions belongs without doubt to an interplanetary shock wave observed as a type II/IV burst on the sun and with space probes near the earth. The other event could not be correlated to any solar, solar wind or geomagnetic peculiarity, but from its striking similarity with the first one we concluded that it was caused by an interplanetary shock wave too. In both cases the secondary tail developed in a few hours in the region preceding the comet.

In case of the event which is covered by solar wind data it could be demonstrated that the solar wind pressure could not have transported the material of the secondary tail from the coma to the region where it was observed. Therefore we concluded that the material of the secondary tail was swept up by the shock wave from the source region of cometary ions, which may extend about  $10^6$  km ahead of the comet in the solar direction. In the second case we had evidence from the filamentary structure of the cometary ions that the magnetic field was parallel to the secondary tail. This seems to be in accordance with the expected global magnetic field configuration.

For obvious reasons the theoretical interpretation of the events studied in this paper must still be very sketchy. To reach final conclusions about the nature of the forms of type I tails, it is necessary to study more of these kink and secondary tail events. Once the correlation with solar wind events has been established, such a study could also be done with exposures of comets, for which we have no solar wind data. However, the most valuable information could be obtained from the continuous recording of a bright comet observed from different geographic longitudes.

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K. Jockers  
 Rhea Lüst  
 Max-Planck-Institut  
 für Physik und Astrophysik  
 D-8000 München 40  
 Föhringer Ring 6  
 Federal Republic of Germany

