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A VERY RAPID TURNING OF THE PLASMA-TAIL AXIS OF COMET BRADFIELD 1979l ON 1980 FEBRUARY 6

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ABSTRACT

Schmidt camera photographs of comet Bradfield 1979l obtained at the Joint Observatory for Cometary Research (JOCR) indicate that a rapid change took place in the comet's plasma tail on 1980 February 6. On that date, a sequence of photographs spanning 27.5 minutes shows a 10° shift occurring in the plasma-tail axis between the first and last exposures. The speed of this tail-turning event greatly exceeds that of any other known event and even exceeds turning rates for individual tail streamers. An interpretation based on the windsock theory of plasma tails is that the comet entered a region of rapidly changing solar-wind flow direction. While the search for an associated solar-wind event from near-Earth spacecraft observations is a future activity, the present analysis shows that a 50 km s^{-1} change in the polar component of the solar-wind velocity, from about 30 km s^{-1} northward to about 20 km s^{-1} southward, would have produced the 10° shift in the tail axis.

Subject headings: comets — Sun: solar wind

I. INTRODUCTION

The Joint Observatory for Cometary Research (JOCR) obtained several wide-angle (8° × 10°) plates of comet Bradfield 1979l with the 14″ f/2 Schmidt comet camera (see Brandt *et al.* 1975) in early February of 1980. Three photographs spanning 27.5 minutes on February 6 show a plasma tail at least 5° long, the inner part of which underwent a remarkable turning in position angle of ~10°. A description of this interesting event, and of its possible causes, is the subject of this *Letter.*

II. GEOMETRICAL CIRCUMSTANCES ON FEBRUARY 6

Figure 1 shows the orbital geometry of comet Bradfield during 1979 December–1980 February. The Sun-Earth line is fixed. The Earth-Sun-comet angles as plotted in the figures are the differences in heliographic longitude between the comet and the Earth, and the Sun-comet separations are true rather than projected distances. The heliographic latitude separations of the Earth and comet are given by the numbers above/below the dates along the comet's path. Positive values indicate that the comet was north of Earth, and vice versa for negative values. Finally, the small comet symbol shows the position of comet Bradfield on February 6.1 UT. The geometrical circumstances on that date are given in the figure.

III. THE JOCR OBSERVATIONS OF FEBRUARY 6

Figures 2*a*–2*c* (Plate L2) contain the three JOCR photographs of comet Bradfield taken on February 6. The times of mid-exposure were $2^h32^m.5$, $2^h48^m.0$, and $3^h00^m.0$ UT, and the exposures were 15, 12, and 10 minutes, respectively. To economize on space in the figure, only a portion of each original full field of view (8° × 10°) is shown. Angular and linear scales are provided, the latter on the assumption that separations along the plasma tail are segments of the prolonged radius vector.

The first photograph, Figure 2*a*, shows a gently curving plasma tail, the inner ~1.5×10^6 km of which is very linear and oriented in position angle P.A. = 72°.4. The outer segment of the tail labeled A-B has P.A. = 79°.5. The last exposure, Figure 2*c*, exhibits a radically different situation. The innermost 1.5×10^6 km of the plasma tail, instead of being straight as in Figure 2*a*, has a sharp bend (arrow) at ~6.2×10^5 km from the coma center. Inward of the bend, the tail is approximately linear in P.A. = 82°.4; thus the orientation of the very innermost tail, or *principal position angle*, has increased by 10° between Figures 2*a* and 2*c* (72°.4 vs. 82°.4). In contrast, the outer tail of Figure 2*c*, labeled A-B, lies in P.A. = 82°.4, which is only 2°.9 different from the corresponding measurement in Figure 2*a*. Thus all or most of the change in the

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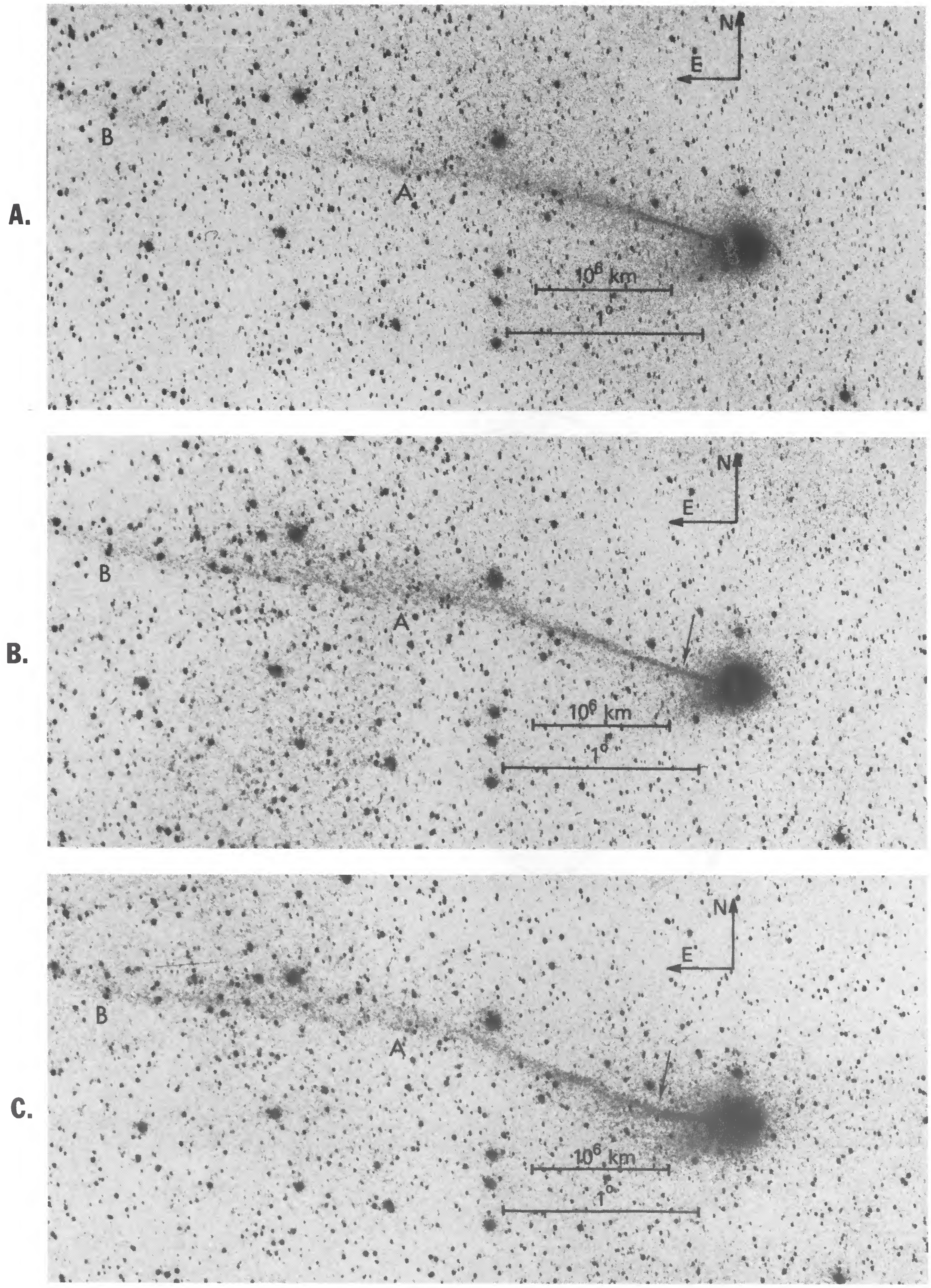

FIG. 2.—(*a*) Joint Observatory for Cometary Research (JOCR) plate S-1545 of comet Bradfield, taken 1980 February 6, $2^h32^m.5$ UT (mid-exposure). The large-scale plasma-tail structure has a slight curvature, but the inner tail is very linear. (*b*) JOCR plate S-1546, 1980 February 6, $2^h48^m.0$ UT (mid-exposure). The appearance of the tail structure is similar to that in Fig. 2*a*, except for a slight bend in the inner tail at $\sim 4.5 \times 10^5$ km from the head (*arrow*). (*c*) JOCR plate S-1547, 1980 February 6, $3^h00^m.0$ UT (mid-exposure). The slight bend of the inner tail in Fig. 2*b* has by now become a major discontinuity (*arrow*) in the orientation of the inner plasma tail. The change in principal position angle since the time of Fig. 2*a* is 10°.

BRANDT, HAWLEY, AND NIEDNER (*see* page L51)

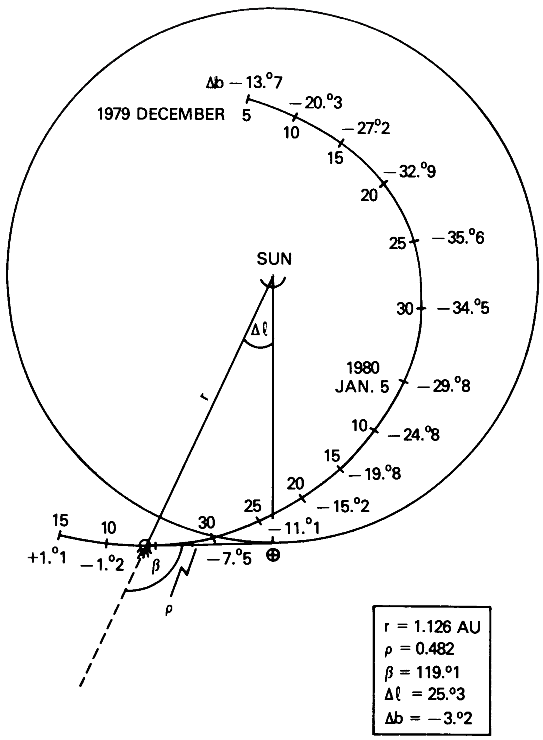

FIG. 1.—Earth-Sun-comet geometrical circumstances for comet Bradfield 1979l during 1979 December–1980 February. The boxed quantities refer to conditions on 1980 February 6.1 UT.

plasma tail between the first and third photographs took place in the inner tail regions.

The beginning of the turning of the inner plasma tail can be seen in the middle photograph, Figure 2*b*. Examination of the photograph shows the inner tail to have a slight bend, in the sense that the innermost section lies in slightly greater position angle. This is the direction of turning of the tail between Figures 2*a* and 2*c* (i.e., toward greater position angles). The tail out to $\sim 4.5 \times 10^5$ km from the coma center (arrow) is linear and has (principal) P.A. = 77°.4. The orientation of the outer tail segment A-B in Figure 2*b* is P.A. = 80°.7, which is little different from those of Figures 2*a* and 2*c*.

The changes which occurred in the inner tail during the JOCR sequence were remarkably rapid, in at least two respects. First, the angular turning rate of the principal tail axis, $\dot{\Theta} = 10°/0.46 \text{ hr} = 21°.8 \text{ hr}^{-1}$, is very large in comparison with, say, the turning rates associated with the "wagging tail" of comet Burnham 1959k. Malaise (1963) measured position angles of the tail of this comet and projected them onto the comet's orbit plane. The angle ϵ between the tail and the prolonged radius vector underwent several 15° amplitude cycles within a period of ~ 3.9 days. The average turning rate was thus $\dot{\epsilon} \approx 15°/1.85 \text{ days} = 0°.34 \text{ hr}^{-1}$. In addition, the tailward turning of tail ray pairs, which is very apparent from exposures taken a short time apart (see the sequence of comet 1975h in Fig. 2 of Niedner and Brandt 1979, for example), is usually much slower than the $21°.8 \text{ hr}^{-1}$ value measured here for the *entire tail* of comet Bradfield. This is apparent from an examination of the tail-ray data presented by Wurm and Mammano (1972) in their Figure 3.

The second aspect of rapid change concerns the speed with which the reorientation of the tail propagated down the tail. Specifically, the quantity of interest here is the rate of lengthening of the *innermost straight tail section* during the turning of the tail. For example, between Figures 2*b* and 2*c*, the bend in the tail advanced from 4.5×10^5 to 6.2×10^5 km from the coma center in 12 minutes. The resulting propagation speed is $V \approx 235 \text{ km s}^{-1}$. Because the plasma tail cannot be followed inside of $\sim 1.2 \times 10^5$ km from the coma center in Figure 2*a*, the lower limit to the mean recession speed between Figures 2*a* and 2*c* is $V \geq 300 \text{ km s}^{-1}$. Considering the difficulty encountered in accurately locating the bend in Figure 2*b*, this somewhat higher velocity (vs. 235 km s^{-1}) does not necessarily indicate a deceleration of the propagation speed down the tail, however.

The most important point to be made about the measured recession speed is that plasma-tail features almost never travel at such large velocities. For example, the speeds measured by Jockers and Lüst (1972) of features in the plasma tail of comet Tago-Sato-Kosaka 1969g were regularly in the $50\text{–}100 \text{ km s}^{-1}$ range. However, the only other *tail-turning event* of which we are aware occurred in comet Kohoutek 1973f on 1974 January 20 (Niedner, Rothe, and Brandt 1978), and the tail reorientation speed *was high:* $V \approx 350 \text{ km s}^{-1}$. The interpretation of this large value was that a change in the solar-wind flow direction reoriented the tail, and that it produced a *pattern* in the tail moving at the solar-wind bulk speed. In the absence of in situ solar-wind data, we will preliminarily adopt such an interpretation here for comet Bradfield, and in the next section discuss the likely characteristics of the solar wind which turned the tail axis.

IV. DISCUSSION

The basis for the following discussion is the windsock model of cometary plasma tails (Brandt and Rothe 1976). The model predicts that the spatial orientation of the tail $\boldsymbol{t}$ is given by the vector equation

$$\boldsymbol{t} = \boldsymbol{w} - \boldsymbol{V}, \qquad (1)$$

where $\boldsymbol{w}$ and $\boldsymbol{V}$ are, respectively, the solar-wind velocity and the orbital velocity of the comet. In principle, specification of $\boldsymbol{w}$ and $\boldsymbol{V}$ in equation (1) yields a unique $\boldsymbol{t}$, which can then be projected onto the plane of the sky to yield a unique predicted principal position angle, Θ. Uniqueness does not operate in the other direction. Namely, an *observed* Θ gives rise only to an infinite family of solutions of $\boldsymbol{w}$ which are consistent with that Θ (the components of $\boldsymbol{V}$ are known from the comet's orbit).

In order to determine the change in $\boldsymbol{w}$ which *most likely* produced the tail turning, it is necessary to examine the sensitivity of Θ to the individual components of $\boldsymbol{w}$. Using equation (1) and the computational procedures developed in earlier papers (e.g., Brandt, Roosen, and Harrington 1972), we computed predicted position angles for various sets of $w_{r,\theta,\phi}$, where the velocity components are referred to a Sun-centered spherical coordinate system. For $w_r = 350\ \mathrm{km\ s^{-1}}$ and $w_\theta = w_\phi = 0$, the results are that

$$\frac{\partial w_r}{\partial \Theta} = 83.3\ \mathrm{km\ s^{-1}\ deg^{-1}}\,, \tag{2a}$$

$$\frac{\partial w_\theta}{\partial \Theta} = 5.2\ \mathrm{km\ s^{-1}\ deg^{-1}}\,, \tag{2b}$$

$$\frac{\partial w_\phi}{\partial \Theta} = 45.5\ \mathrm{km\ s^{-1}\ deg^{-1}}\,. \tag{2c}$$

What these relationships say is that, for typical conditions in the solar wind, the position angle Θ of the tail of comet Bradfield on 1980 February 6.1 was very sensitive to the polar component w_θ, and extremely *insensitive* to w_r and w_ϕ. The relative insensitivity to w_r is intuitively obvious. The small response of Θ to dw_ϕ results from the low latitude of the comet, $b_c = -9\overset{\circ}{.}6$, combined with the rather shallow inclination of the orbit plane to the plane of the ecliptic ($i = 148\overset{\circ}{.}6$). Equations (2a) and (2c) strongly suggest that the 10° turning of the tail of comet Bradfield was *not* produced primarily by changes in w_r and w_ϕ. The required gradients are simply too large to be reasonable. A sudden change in the polar component of magnitude $|dw_\theta| = 50\ \mathrm{km\ s^{-1}}$ not only seems physically plausible, however, but it also is sufficient to turn the tail by the observed 10°.

TABLE 1

POSITION-ANGLE MEASUREMENTS OF THE PLASMA TAIL ON FEBRUARY 6

Plate	Mid-Exposure	Principal P.A.	P.A. of Tail Segment A-B
S-1545.....	$2^h32^m30^s$	$72\overset{\circ}{.}4$	$79\overset{\circ}{.}5$
S-1546.....	$2^h48^m00^s$	$77\overset{\circ}{.}4$	$80\overset{\circ}{.}7$
S-1547.....	$3^h00^m00^s$	$82\overset{\circ}{.}4$	$82\overset{\circ}{.}4$

Figure 3 contains, for the three principal position angles in Table 1, families of $\boldsymbol{w}$ consistent with those P.A.'s within the framework of the windsock theory. The sign conventions are as follows: Positive w_θ indicates flow from the north (to the south), and positive w_ϕ denotes flow in the direction of solar rotation (east to west). The first photograph in the JOCR sequence ($\Theta = 72\overset{\circ}{.}4$) suggests the presence of strong northward flows ($w_\theta < 0$), regardless of the choices of w_r and w_ϕ. In contrast, the last observation ($\Theta = 82\overset{\circ}{.}4$) seems to require strong southward flows ($w_\theta > 0$) to produce the observed position angle, and this too is highly independent of the assumed w_r and w_ϕ. The middle observation ($\Theta = 77\overset{\circ}{.}4$) is simply the transition case, in which w_θ may be either positive or negative. The most important observation to make about the diagram is that, over the large ranges considered for w_r (300–700 km s^{-1}) and w_ϕ (-60 to $+60$ km s^{-1}), the *minimum* separation in w_θ between the $\Theta = 72\overset{\circ}{.}4$ and $\Theta = 82\overset{\circ}{.}4$ solutions is 35.4 km s^{-1}. For the perhaps most reasonable case of w_r = const. = 350, w_ϕ = const. =

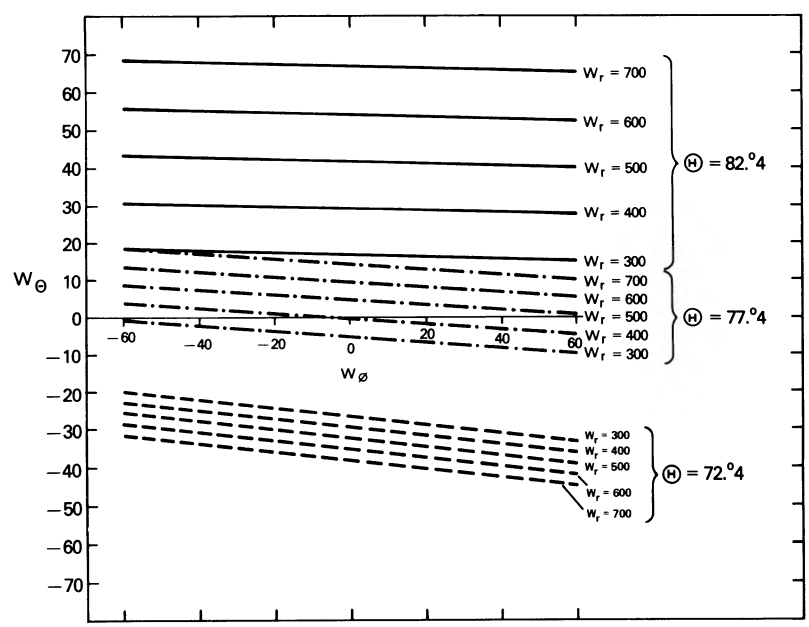

FIG. 3.—Windsock theory solutions of the solar-wind velocity vector $w_{r,\theta,\phi}$ for plates S-1545 ($\Theta = 72\overset{\circ}{.}4$, Fig. 2*a*), S-1546 ($\Theta = 77\overset{\circ}{.}4$, Fig. 2*b*), and S-1547 ($\Theta = 82\overset{\circ}{.}4$, Fig. 2*c*). The families of curves indicate that a major change in the polar component, w_θ, was required to rotate the tail from $\Theta = 72\overset{\circ}{.}4$ to $\Theta = 82\overset{\circ}{.}4$.

0, we have $|dw_\theta| = 51.2$ km s^{-1}. Barring extreme changes in w_r and w_ϕ, the possible existence of which we acknowledge but regard as unlikely, Figure 3 suggests strongly that it was a change in the polar component of $dw_\theta \approx 50$ km s^{-1} from northward to southward flow which had the dominant effect.

Having identified a possible solar-wind cause of the observed tail-turning in comet Bradfield (strictly from the comet's position angles), we searched some published satellite data to check the plausibility and existence of sudden ($\Delta t \leq 1$ hr) 50 km s^{-1} changes in the polar component of the solar-wind speed. Our source was *Solar Wind Data from the MIT Plasma Experiments on Pioneer 6 and Pioneer 7* (Lazarus *et al.* 1973). The first 1,045 hourly averages contain four cases in which the hour-to-next hour variation in V_n, the velocity component normal to the ecliptic ($\sim w_\theta$), exceeded 50 km s^{-1}. Twenty cases were observed in which $|dV_n| > 40$ km s^{-1}. Thus, while such discontinuities in V_n (or w_θ) are probably rare, they do exist. The likely location of these sharp gradients in flow are the leading edges of high-speed streams (compression regions) and interplanetary shock fronts caused by solar flares. One or the other of these features was probably responsible for the comet Bradfield activity under discussion. If the solar wind in question also intercepted the Earth, the approximate arrival time would have been February 5.7 for a flare ($w = 500$ km s^{-1} assumed) and February 7.2 for a corotating stream leading edge ($w = 350$ km s^{-1}). When in situ data become available in the near future, it should be possible to make a more definitive statement.

Comparisons of the comet Bradfield tail-turning with that of comet Kohoutek 1973f on 1974 January 20 (Niedner, Rothe, and Brandt 1978) are interesting. The similarities are that both tail reorientations propagated down the tail at speeds typical of solar-wind bulk velocities, and that it was the polar component of the solar-wind speed, w_θ, which was considered the most probable cause. In the comet Kohoutek study, an associated $dw_\theta \approx 30$ km s^{-1} was actually observed in the near-Earth data of *IMP 8*. The differences between the two events are perhaps more interesting. First, the tail of comet Bradfield turned through a substantially greater angle (10° vs. 3°.4), and second, the required $dw_\theta \geq 50$ km s^{-1} took place in *less than 0.5 hr*. In contrast, examination of Figures 10–12 of Niedner, Rothe, and Brandt (1978) shows that the solar-wind flow change associated with the comet Kohoutek observations was much more gradual ($\Delta t \approx 6$ hr). The tail of comet Bradfield was probably responding to a much more discontinuous solar wind, and "velocity shear" is perhaps the best term to describe the proposed solar-wind variations.

V. CONCLUSION

JOCR photographs of comet Bradfield 1979l were analyzed to establish possible causes of a rapid 10° shift in the inner tail axis which occurred in less than 30 minutes on 1980 February 6. The turning of the tail propagated at a speed typical of solar-wind bulk velocties, which established that the present event was probably physically similar to a turning event observed earlier in comet Kohoutek (Niedner, Rothe, and Brandt 1978).

The proposed most probable solar-wind cause of the comet Bradfield tail activity was that the comet encountered a velocity shear in the solar wind, across which the polar component changed by $\sim$50 km s^{-1}. The shear could have occurred either on the leading edge of a high-speed stream, or near the shock front of a solar flare–generated interplanetary disturbance. This hypothesis will be examined in the light of satellite solar-wind data when they become available.

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