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Photographic Observations of the Tail Activity of Comet Burnham 1960 II*

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The angle between the tail of Comet Burnham 1959*k* and the radius vector has been computed for 26 photographs. The angle varies with a periodicity of 3.9 days and an amplitude of 15°. The general structure of the tail also reflects the same periodicity. Correlation with solar activity is not apparent. The rotation of the nucleus, on the basis of a kinetic model only, does not seem to account for these observations, but it seems that the latter are closely related to the structure of the nucleus itself. Some spectral features show that the nucleus could also play a particular role in the ionization process.

The velocity of ions in the tail is 45±3 km/sec relative to the head at a distance of 6×10^5 km from the center of the head. The visible tail is probably composed of CH^+ ions.

OBSERVATIONS

During the passing of Comet Burnham 1959*k* near the earth in April–May 1960, several very good spectrograms were obtained at the "Observatoire de Haute Provence" in France with the coudé spectrograph of the 80-inch telescope (Dossin, Fehrenbach, Haser, and Swings 1961). At the same time a series of photographs was made with the small $f/2$ Schmidt camera, focal length 24 inches and covering a circular field 8° in diameter.

For each photograph, I computed the angle between the tail and the radius vector assuming that the tail lies in the orbital plane of the nucleus. The method of reduction is the same as that used by Osterbrock (1958). Since the tail is rather sharp and straight, I could measure the angles fairly accurately. In fact, several remeasurements made at intervals of 6 months are consistent within 1° for the best plates and 5° for the worst ones. The computations were carried out on a digital computer.

In the orbital plane (Fig. 1), CR is the radius vector from the sun, CT is the tangential vector opposite the orbital velocity, and CQ is any vector directed along the tail. I computed the angle ϵ between the radius vector and the tail, and the ratio $h=\mathrm{CR}/\mathrm{CT}$ of the projections of CQ along the radial and the tangential directions. In addition to these two parameters, Table I shows the universal time UT, the estimated error $\Delta\epsilon$ in ϵ, the orbital data $\beta=\tan\frac{1}{2}v$ (where v is the true anomaly), and the origin of the plates. The heliocentric distance varies from 0.89 to 1.04 a.u., the geocentric distance from 0.28 to 0.21 a.u.

In Fig. 2, the angle ϵ is plotted against time and displays a pseudo-periodicity of about 3.9 days with three full cycles and an amplitude of about 15°, the mean direction turning rather steeply toward the radial direction.

It must be noted that on the three plates of the night of April 30–May 1, the main tail lies 8° ahead of the radius vector. Figures 3(d), (e), show two of these photographs. The main tail (the longest segment) is well

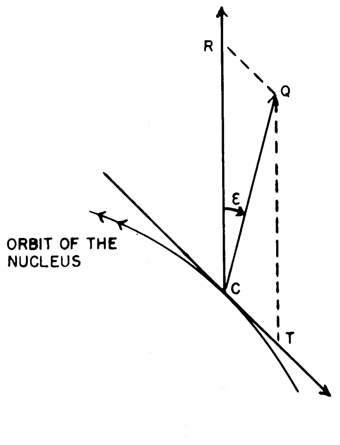

FIG. 1. The reference system adopted in this work and reproduced in Figs. 3, 4, and 5. CR is the radius vector from the sun, CT is the tangential vector opposite to the orbital velocity of the nucleus.

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* Formerly designated 1959*k*.

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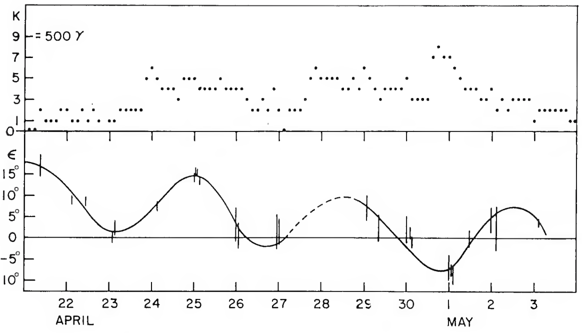

FIG. 2. The angle ϵ between the radius vector and the tail is plotted against time starting on 21 April 1960. This angle has positive values when the tail lies "behind" the radius vector. A tentative curve has been drawn to fit the observations and displays a pseudo-periodicity of four days. In the upper part of the figure the geomagnetic activity is plotted for the same interval of time in a scale where the ordinate $9=500\gamma$.

defined and was measured with great accuracy on the original plates. A shorter tail, 15° ahead of the radius vector, can also be seen.

STRUCTURE OF THE TAIL

The tail shows two different patterns. In Fig. 3, a dissymmetrical pattern of several secondary tails on both sides of the main tail is seen. This pattern is repeated on the plates taken on April 22 (this photograph is not shown in Fig. 3), 23, 26, 30, and May 1, and always appears when the angle ϵ is near its minimum value, as illustrated in Fig. 2. In Fig. 4, which reproduces the plates taken on April 25, 29, and May 3, the tail is single, very sharp close to the head, and progressively spreads out to the end. Figure 4(a), (b), shows a slight curvature near the head. This second pattern appears when the angle ϵ passes through its maximum value. The alternation of these two configurations suggests a periodicity of 4 days.

TABLE I.

	UT	β	h	ϵ	$\Delta\epsilon$	Origin of Plates[a]
April	21.4309	0.85774	3.13	17°.0	3°	ER
	22.1368	0.87146	5.49	8°.9	1°	OHP
	22.4643	0.87778	5.51	8°.8	1°	AMC
	23.0833	0.88957	255	0°.2	1°	OHP
	23.1066	0.89002	18.1	2°.45	2°	OHP
	24.1250	0.90914	6.36	7°.4	1°	OHP
	25.0215	0.92568	3.55	14°.3	1°	OHP
	25.0503	0.92621	3.32	15°.5	1°	OHP
	25.0803	0.92676	3.36	15°.3	1°	OHP
	25.1269	0.92761	3.77	13°.35	1°	OHP
	25.9841	0.94290	13.6	3°.2	4°	OHP
	26.0444	0.94422	75.6	0°.6	3°	OHP
	26.9601	0.96054	27.8	1°.5	4°	OHP
	27.0031	0.96130	36.0	1°.2	3°	OHP
	29.0576	0.99693	6.66	6°.8	3°	OHP
	29.3444	1.00181	16.3	2°.6	3°	ER
	30.0028	1.01291	20.2	2°.1	3°	OHP
	30.0868	1.01432	15.2	1°.2	1°	OHP
	30.1187	1.01485	−30.5	−1°.3	1°	OHP
	30.9834	1.02932	−4.9	−7°	3°	OHP
May	1.0514	1.03034	−4.4	−7°.7	2°	OHP
	1.0805	1.03082	−3.6	−9°.7	2°	OHP
	1.4680	1.03720	−97.0	−0°.4	2°	AMC
	1.9980	1.04582	10.9	3°.9	3°	OHP
	2.1187	1.04778	17.9	2°.3	5°	OHP
	3.1156	1.06380	12.3	3°.4	1°	OHP

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CORRELATION WITH SOLAR ACTIVITY

The position of Burnham 1959*k* was exceptionally favorable for establishing a correlation with solar activity; its ecliptical coordinates did not differ very much from those of the earth, so that any solar event influencing the earth's atmosphere would have influenced the comet at approximately the same instant. I plotted in the upper part of Fig. 2 the index of geomagnetic activity *K* measured in a scale where the ordinate 9 corresponds to 500γ; there is no clear

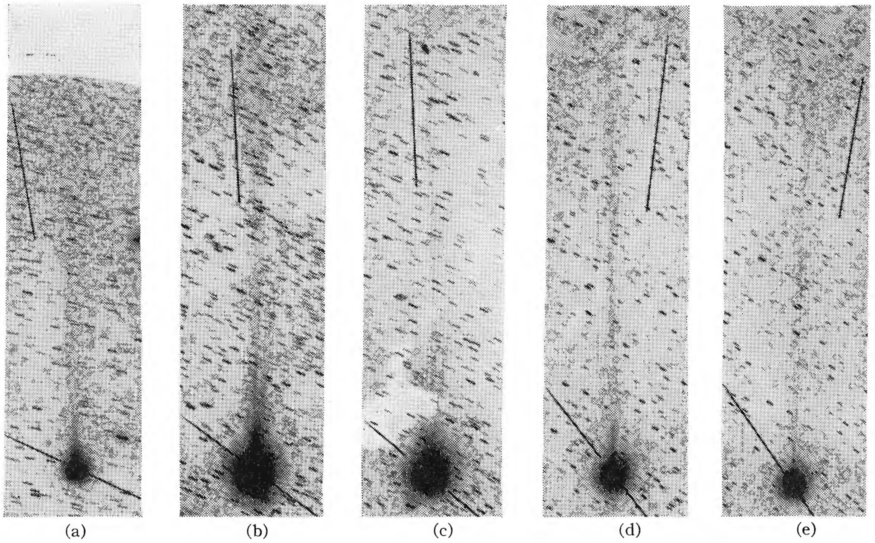
(a) (b) (c) (d) (e)

FIG. 3. Photographed on (a) April 23.0833; (b) April 26.0444; (c) April 30.0868; (d) May 1.0514; (e) May 1.0805. The directions of the radius vector and of the tangent to the orbit have been drawn in accordance with Fig. 1. The angle between the tangential vector and the trails of the stars is due to the orbital movement of the earth. Note in (b) how the end of the tail spreads out in the "forward" direction.

evidence of correlation. Another observation is at variance with an eventual correlation: Figure 5 reproduces two photographs taken on May 2 within an interval of three hours. By comparing the faintest stars visible on these photographs it appears that the weakening of the tail as shown in Fig. 5(b) is real. [The plates were not taken for photometric purposes. Although they were exposed and processed under exactly the same conditions, the sky background differs in density on the two plates. A very careful examination of the original plates, however, shows that the fading of the tail did actually occur since it is not possible to find a star on the plate of Fig. 5(a) which does not show clearly on the plate of Fig. 5(b).] By comparing the latter with the photograph taken on May 3 [Fig. 4(c)], we must conclude that the tail faded swiftly between May 2 and May 3 and regained its brightness on May 3. No solar event can be correlated with this extinction, and it seems probable that this observation and more generally the changes in tail activity can be attributed to perturbations in the release mechanism of ions from the nucleus. It is also noteworthy that the direction of the tail does not change, but the luminosity of the head is weaker in Fig. 5(b) than in Fig. 5(a).

VELOCITY OF PARTICLES IN THE TAIL

It has been possible to follow a knot on a series of four plates taken within an interval of three hours on April 25 [see Fig. 4(a)]. The mean velocity of the knot reduced to the orbital plane is 45±3 km/sec with respect to the head and at a distance of 6×10^5 km from the center of the head. The time interval is too short to permit the measurement of acceleration.

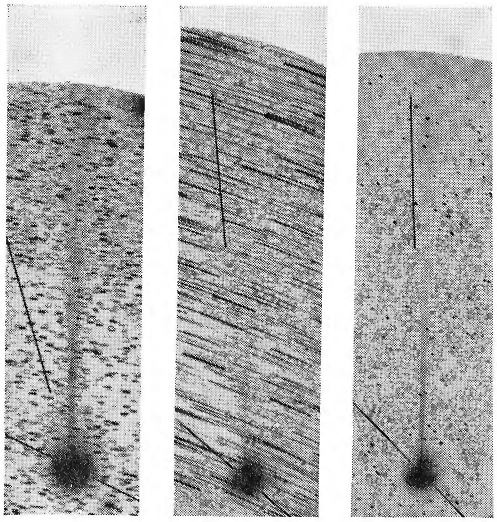
(a) (b) (c)

FIG. 4. Photographed on (a) April 25.0503; (b) April 29.0576; (c) May 3.1156. (a) One of the photographs which were used to measure the velocity of a knot in the tail. (b) This plate has been taken with a yellow filter on a 103aF red-sensitive plate with an exposure time of 1 h. It is not very good for comparison, but it is the only plate available for this date.

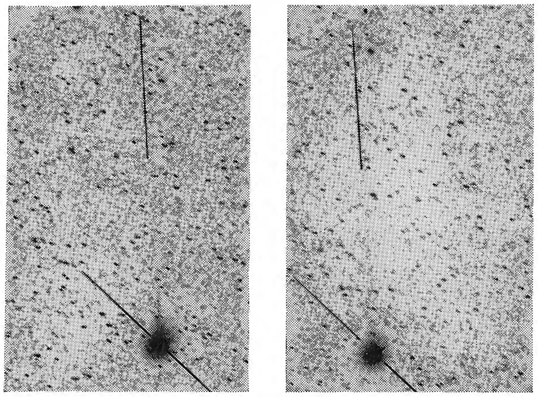
(a) (b)

FIG. 5. Photographed on (a) May 1.9980; (b) May 2.1187. Compare the faintest stars which appear on (a) and (b). These were taken 3 h apart. Then compare with Fig. 4(c) which was taken the following night.

Assuming a constant acceleration and zero initial velocity, we see that a particle takes 12 h to travel 3×10^6 km along the tail. This is, of course, a very rough estimate, but it gives us some kind of time scale for the changes in the tail structure. In fact, a thorough description of the evolution of tail structures would require observations at hourly intervals.

COMPOSITION OF THE TAIL

We have no spectrum of the tail, but it is quite easy to distinguish ion tails from dust tails. Indeed, 1959*k* displays all the features and activities common to ion tails and the spectra of the head show a very faint continuum. The identification of the tail ions, though somewhat more difficult, is nevertheless still possible because ionization takes place in the head (Wurm 1962) and tail ions are detectable in the spectrum of the head. The spectrograms of 1959*k* show a few emissions of CH^+ (Dossin *et al.* 1961); the lines of CO^+ are scarcely detectable and those of N_2^+ do not appear at all. This is contrary to the usual case, where the CO^+ and N_2^+ emissions largely dominate those of CH^+. Hence, Burnham's tail could be a CH^+ tail; this would also account for the anomalous weakness of the tail due to the deficiency of the main constituents of bright active tails.

CONCLUSION

It is scarcely questionable that the repulsive force acting on ions is of electrodynamical origin.

According to Biermann's basic mechanism (1951, 1952, 1953) and its successive developments by several authors (Alfvèn 1957; Hoyle and Harwit 1962), the acceleration of the ions is proportional to their relative velocity in the solar wind. Considering a tail 2×10^6 km long (this is a typical length for the tail appearing on my photographs of comet Burnham. The scale of the reproduction is 1°.5 per inch) and an acceleration which fits the observational data, we find that ions leaving the close neighborhood of the nucleus with a negligible initial velocity will form a straight tail lying in the orbital plane of the nucleus. The angle between the tail and the radius vector is given by

$$\epsilon = \arctan[v_1/(V-v_2)],$$

where V is the radial expansion velocity of the solar wind, v_1 is the orbital velocity component normal to the radius vector, and v_2 is the orbital velocity component parallel to the radius vector.

Under these conditions, a short-period variation of ϵ is possible only if V varies in direction or absolute value or both.

In order to explain the streamers appearing in active tails and their connection with parabolic envelopes in the heads, Wurm (1953, 1961, 1962) has successfully introduced the concept of initial velocity variable with time. He could thus explain not only the simultaneous presence of several streamers, but also the shrinking of the envelopes correlated to the motion of the streamers toward the tail axis.

In fact, we are confronted with two alternatives, briefly outlined as follows:

(1) The initial velocity of the ions plays no significant role in the future development of the streamers, except that it accounts for their diffusion; the streamers are formed by ions flowing into magnetic tubes bent in front of the head by the pressure resulting from the charge exchange process. The direction of the streamers is directly governed by the external environment of the head. The ions are focused by the magnetic field. Unfortunately, the appearance of perfectly straight and well-defined streamers of length 10^6 km on both sides of the tail axis would require an unperturbed tangential magnetic field highly constant over distances of the order of 2×10^6 km. The space probes equipped with magnetometers have shown that the interplanetary magnetic field is highly disturbed (Sonett, Judge, Sims, and Kelso 1960) and can hardly account for the steady observed features of the streamers.

(2) The initial velocity of ions is entirely responsible for the future development of the streamers. The ions should be ejected sunward in a few focused beams, and the velocity component normal to the radius vector should decrease with increasing time; the ions should be highly monoenergetic. The release mechanism for the ions is not understood, but this theory has the striking advantage that no observational fact contradicts it.

Now, if the sweeping movement of what does appear to be the tail axis of Burnham is real, neither of the above two alternatives seems to account for this observation.

It is difficult to imagine why the solar wind velocity would sweep back and forth with a periodicity of four days which cannot be correlated with anything in the solar system. On the other hand, Wurm's concept accounts for symmetric streamers converging toward the tail axis from both sides, but not for a sweeping movement of the whole pattern of tails.

The rotation of an icy-conglomerate or "Whipple" nucleus (1950, 1951, 1961) would give an initial velocity varying periodically with time; but this requires the direction of ejection of ions to be directly correlated to the mechanical structure of the nucleus. The ionization would occur at the surface of the nucleus. The "time constant" of the tail being small compared with the presumed period of rotation (4 days), the tail would remain more or less straight.

A quantitative description of what would happen in the case of a jet of ions rotating with the nucleus is difficult, because the resulting shape of the tail depends strongly upon the velocity of the expanding plasma and upon the "viscosity" between the plasma and the ions. Furthermore, we have the choice of six parameters to describe the velocity of ejection. But qualitatively, a pure kinematic description based on jets of ions ejected in a few directions, rotating with the nucleus and drawn back by an acceleration proportional to the velocity relative to the solar wind, does not seem to account for the shape and motion of the tail.

The suggestion by Brandt (1962) that a magnetic field could be embedded in a Whipple nucleus promises to be very constructive. Many features in the tail seem to be closely related to the nucleus rather than to depend directly on the solar wind, which of course provides the energy and the dominant force acting on the ions. With a magnetic field embedded in the nucleus, fairly strong local electric fields could build up in the close neighborhood of the nucleus on a scale of a few kilometers. Wurm's (1962) detailed discussion of the ionization process in comets shows some evidence that the ionization takes place in the close vicinity of the nucleus; I have suggested that the ionization could occur on the surface of the nucleus. This is supported by the fact that some spectra of Comet Burnham 1959*k* (Dossin *et al.* 1961) show emissions due to both $CH^+(^1\Pi-^1\Sigma)$ near 4200 Å and to $CH(A^2\Delta-x^2\Pi)$ near 4300 Å. While the strong emissions due to CH extend on both sides of the nucleus, the very weak emissions due to CH^+ are visible only on the side of the nucleus opposite to the sun (the nucleus is marked on the spectrum by a very thin continuum the width of which corresponds to 500 km). It is of course impossible to decide whether the emission originates at the nucleus, but it is quite evident that the ionization did not take place evenly in the CH head. Hence, it seems that the surface condition and mechanical structure of the nucleus will play a decisive role in explaining the detailed structure of the tails, and since the nucleus is very hard to observe from the earth, the launching of a bypassing probe to an active comet would be a decisive step towards increasing our knowledge of the physics of comets.

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