On the Theory of Comet Tails

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Abstract

According to Biermann's theory the repulsive force in comet tails is due to a corpuscular radiation from the sun. It is shown that some of the difficulties of this theory can be overcome if the assumed radiation consists of beams with a frozen-in magnetic field of the same type as required in the electric field theory of magnetic storms and aurorae. The interaction between such a beam and the head of the comet produces an amplified magnetic field which determines the shape of the tail. The high accelerations, which have been observed in the tails may be due to electromagnetic forces.

§ 1

There are different types of comet tails. Some of them (type II and III) consist of dust and non-ionized gases. The motions in them show accelerations of the same order as the solar gravitational acceleration (0.56 cm sec^{-2} at a distance of one astronomical unit), or smaller. It seems possible to explain the motions as produced by the light pressure.

The main difficulty with the comet tails is associated with tails of type I. Such tails consist of ionized gases and exhibit usually a pattern of very narrow "streamers" and "envelopes". A representative pattern is shown in Fig. 1 (Fokker 1953). Accelerations of the order of several thousand times the solar gravitation are often observed. The attempts to understand the formation of tails of this type have usually followed the "fountain model" according to which matter is ejected from the head of the comet and moves under the influence of a repulsive force deriving from the sun.

The fountain model meets three difficulties.

1. The ejection velocity from the head must be assumed to be high, often 25—40 km/sec. which e.g. for the CO^+ ions observed in the tails would correspond to a temperature of the order of a million degrees (cf. for example Fokker 1953). It is difficult to understand how such high velocities could be produced in the head of the comet.

2. The repulsive force is up to thousand times the force which could result from the light pressure.

3. The fountain model should give a structure of "fountain" parabolas starting from the head. Instead the predominant shapes of the streamers are straight lines. The only parabola which is seen in Fig. 1 surrounds the head. In general, the luminous lines near the head are parabolas, but they surround the nucleus and do not start from it, as would have been most natural according to the fountain theory. It is important to note that according to Fokker there is a continuous transition between "envelopes" and "streamers".

§ 2. Biermann's theory

In order to avoid the second difficulty, Biermann (1953) has proposed that the repulsive force is due to the viscosity between

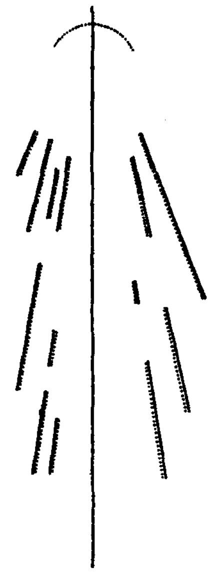

Fig. 1. Comet brooks 1911 nov. 13. Typical pattern ("envelope" and "streamers") in a comet tail according to FOKKER (1953).

gases ejected by the comet and an assumed corpuscular radiation emitted from the sun. The acceleration a, which he deduces, is numerically

$$a = 0.1\, n \text{ cm sec}^{-2}$$

where n is the density of the corpuscular radiation. Biermann assumes that the density is normally 10^2—10^3 cm^{-3} but that at intervals it may reach 10^5 cm^{-3}. The corpuscular radiation should be of the same type as assumed by Chapman and Ferraro in their theory of magnetic storms, and the assumed density are in agreement with this theory. Using these values Biermann finds accelerations of 10—100, and occasionally up to 10^4 cm sec^{-2}.

It seems difficult to accept the high densities of the corpuscular radiation, which Biermann's theory requires. The agreement with data derived from Chapman-Ferraro's theory is no real support because of the well-known difficulties of this theory. Further, a corpuscular radiation of this density cannot possibly pass the solar corona without being observed.

If a corpuscular radiation is ejected from the sun and moves out radially with a constant velocity, its density n is

$$n = \nu R^{-2} \tag{1}$$

where ν is a constant and R is the distance from the sun's centre, counted in solar radii. The maximum value which we could possibly attribute to ν is given by the minimum value nR^2 if for n we use the observational values of the density of the corona. Hence we obtain from van de Hulst's table (1953) of maximum corona.

R	1.1	2	3
n	$1.6 \cdot 10^8$	$2.8 \cdot 10^6$	$3.2 \cdot 10^5$
$\nu = n R_2$	$1.9 \cdot 10^8$	$1.1 \cdot 10^7$	$2.8 \cdot 10^6$

R	4	6
n	$8.9 \cdot 10^4$	$2.9 \cdot 10^4$
$\nu = n R^2$	$1.4 \cdot 10^6$	$1.0 \cdot 10^6$

The minimum corona gives somewhat lower values.

Thus we find that even if the total light of the corona at 4—6 solar radii should derive from corpuscular radiation, the value of ν could not surpass 10^6. However, there are good reasons to suppose that the corona is essentially an atmosphere in thermal equilibrium (see van de Hulst). This means that a corpuscular radiation passing through the atmosphere must have a density which is considerably lower, and $\nu = 10^5$ would be a more reasonable upper limit.

With $\nu = 10^5$ the density at one astronomical unit is

$$n = 2.2 \text{ cm}^{-3} \tag{2}$$

Even the maximum value $\nu = 10^6$ does not bring us up to more than

$$n = 22 \text{ cm}^{-3} \tag{3}$$

With Biermann's formula this gives accelerations of only 0.22 or 2.2 cm sec^{-2} which is even less than the light pressure may give.

Higher densities can be obtained if the corpuscular radiation does not move radially but is focussed in some way. Certainly the intensity of the corpuscular radiation varies and is larger in some directions, as indicated by the occurrence of magnetic storms at the earth and associated increases in comet activity. But tail accelerations far above 0.25 or 2.5 cm sec^{-2} are observed during months and occur with the comet at different heliographic latitudes. This puts a rather tight limit to the degree of focussing we should assume. In fact a density of $n = 10^5$, as required by Biermann's theory means a concentration by focussing by a factor of about 10^4. This implies that a beam which passes the corona under a solid angle of say $100° \times 100°$ should be concentrated to 1 square degree. It is difficult to invent a mechanism for this. Still more important is that a focussing implies that the chance that a comet at a random position is hit by a beam is only of the order 10^{-4}.

Finally it should be observed that Biermann's theory does not give any satisfactory solution to the first and third difficulty of the fountain theory.

§ 3. Magneto-hydrodynamic mechanism

As Biermann's basic idea that the repulsion is due to corpuscular radiation from the sun seems to be sound, we shall try to modify this theory by substituting Chapman-Ferraro's corpuscular radiation by the type of radiation which is required by the electric field theory of magnetic storms and aurorae (ALFVÉN 1955). This radiation is supposed to be emitted from the sun in form of beams in certain directions. The motion is essentially radial so that when the sun rotates the beam gets the form as shown in Fig. 4 similar to the beam of Chapman and Ferraro. The velocity is of the order 10^8 cm sec^{-1}. Contrary to Chapman-Ferraro's beam the density satisfies the condition (2). In fact, a density of $n = 10^{-1}$ or 10^{-2} is acceptable in the theory of magnetic storms and aurora. The beam carries a magnetic field of the order of 10^{-5} gauss which is frozen in. In the central parts of the beam the direction of the magnetic field is preferentially perpendicular to the sun's equatorial plane. There may be turbulence in the beam, but this vill be neglected here. At the borders of the beam the field may be essentially radial, but even this is not important in this connection. It should be observed that a beam of this type is compatible with cosmic ray data and is used in the theory of cosmic ray storm effects. In fact the value of the magnetic field derives essentially from cosmic ray data.

Suppose that a beam of this type hits the head of a comet, which consists of dust and of gas which is not ionized or only partially ionized. (The comet may also have a type II or III tail of neutral gas and dust, expelled by light pressure.) At the collision a shock wave is produced and an intense heating of the gas in the head occurs so that the degree of ionization increases. As the ionization, at least in part, takes place in the magnetic field of the beam, the lines of force are "frozen in" in the gas of the comet head. As the beam continues outwards from the sun the lines of force are dragged out.

Figs 2 and 3 show what is likely to happen when the beam moves outwards. After some time the lines of force are "hanged up" on the comet head and ending in the beam which now may be far out. On these lines magneto-hydrodynamic waves may travel, possibly giving rise to the wavy patterns which are sometimes observed. In absence of such waves the lines of force are *straight* lines except very close to the head, where they are curved because they take up the shock wave from the gases ejected from the head. It is natural to assume that ionized gas ejected from the comet forms "streamers" along the magnetic field lines. This gives us a pattern which shows a striking resemblance to the observed tail structure with its "streamers" and "envelopes". It is important to note that theories employing light pressure or viscous forces predict an essentially parabolic structure of the tails, whereas very often a rectilinear fan-like structure is observed (compare Fig. 1) which according to the present theory should be given by the magnetic field lines. These effects could of course also be described as produced by the electric field $E = v \times H$ associated with the beam. This field produces a current in the gas of the comet, and the magnetic field around the comet is produced by this current and the primary magnetic field of the beam. Hence the basic phenomenon is the same as in the electric field theory of magnetic storms and aurora. The difference between the phenomena around the earth and around the head of a comet are essentially due to the terrestrial magnetic field.

If the magnetic field of the beam is strictly homogeneous, the tail should be plane, so that when seen parallel to the field of the beam it should look like Fig. 3. Gas ejected from the head may be caught by the field lines and form a "condensation" which moves out close to the tail. If looked upon as in Fig. 2 the

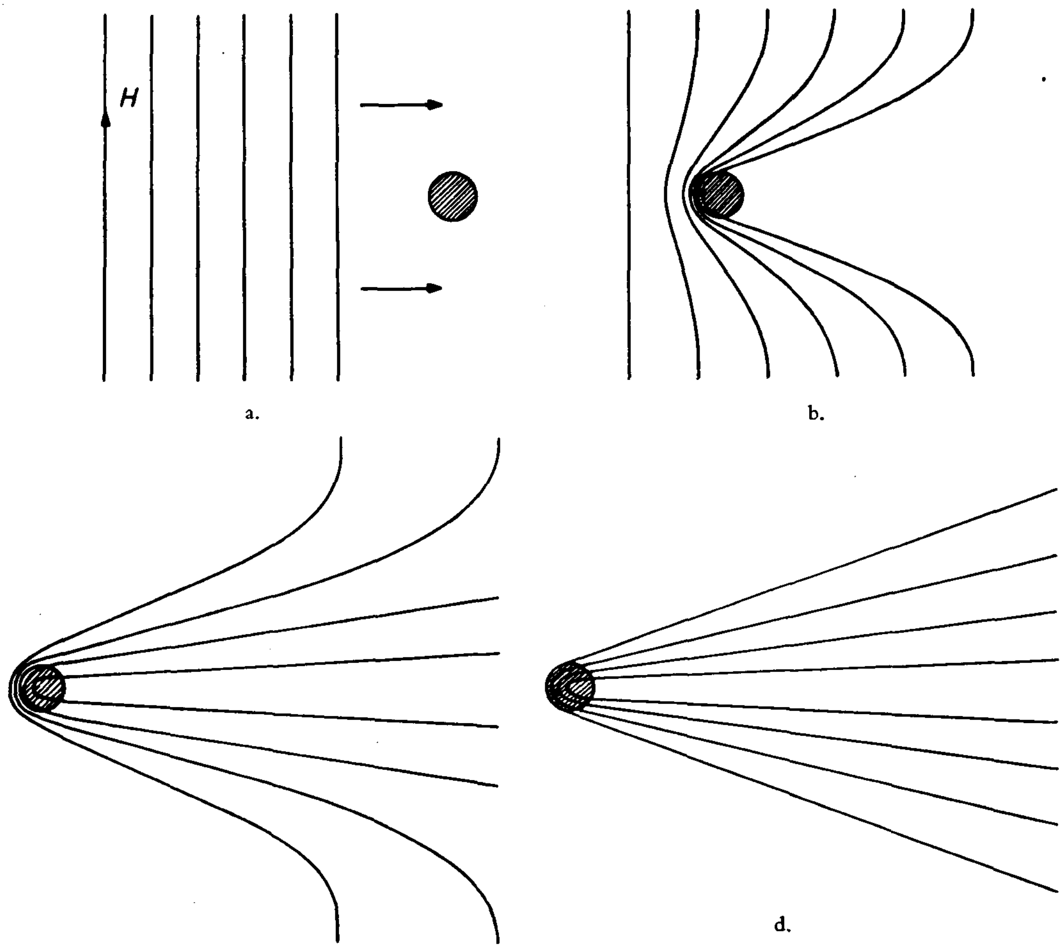

Fig. 2. A beam with a frozen-in magnetic field *H* approaches the head of a comet (2 a). The field is deformed (2 b and 2 c). Final state when the beam has passed (2 d). Viewed perpendicular to the field of the beam.

"condensation" would be identified as a part of the tail.

The possibility that comet tails are "flat" is interesting and may be checked observationally. Some comets with very thin tails may be comets of ordinary type looked upon parallel to the magnetic field. However, if there is a considerable turbulence in the beam, the conclusion may not be valid.

An important feature of the present theory is that a continuous tail activity need not necessarily mean that the sun continuously emits corpuscular radiation in all directions. If a beam has passed a comet, the lines of force are dragged out so that during some time the comet is "hanged up" on lines of force which are fastened in a part of the beam which may be very far out (see Fig. 4). As the beam elements move out radially, the magnetic drag acts essentially along the vector radius from the sun. In the moment when the beam passes the comet, the tail activity should increase, as it does according to Biermann, and thereafter the activity should in general decrease until a new beam hits it. In absence of beams during a sufficiently long time the comet should loose its type I tail.

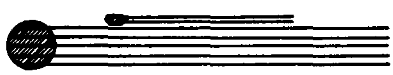

Fig. 3. The same as Fig. 2 but viewed parallel to the field of the beam.

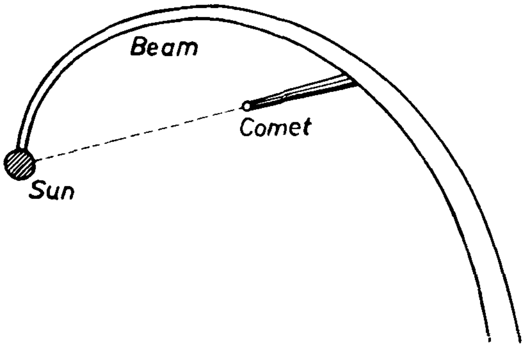

Fig. 4. Beam emitted from the sun, and comet.

§ 4. Properties of the tail

According to the present theory the problem which we should solve in order to understand the formation of comet tails is how a ball of gas and dust reacts when it is hit by a magnetized beam of rarified gas. We do not need to postulate any complicated mechanism ejecting gas in the head of the comet, a problem which leads to absurd assumption in the fountain model. In fact, the directions of the tail is given by the magnetic field, the direction of which is determined by the relative motion of the beam and the comet. The tail should no more be considered as gas moving freely in space. Instead the tail is a real part of the comet, fastened to the head by magnetic field lines.

Seen from the coordinate system of the comet the tail should point in the direction in which the matter of the beam moves. Hence if the velocity of the comet has a radial component v_r and a tangential component v_t and the beam moves out radially with the velocity v_b, the tail of the comet will make an angle α with the vector radius from the sun. The angle is given by

$$\operatorname{tg} \alpha = \frac{v_t}{v_b - v_r}$$

If for example $v_t = 3.10^6$ cm sec^{-1}, $v_r = 0$, and $v_b = 10^8$ cm sec^{-1}, we obtain $\alpha = 0.03 = 2°$. Larger angles are obtained if v_b is smaller. The value $v_b = 10^8$ cm sec^{-1} is derived from the delay of magnetic storms after a solar event and corresponds to a time of passage from the sun to the earth of $1.5 \cdot 10^5$ seconds.

As the direction and the structure of the tail is not immediately connected with the ejection of gas from the head of the comet, the ejection velocity may be quite small.

The structure of the "envelopes" and "streamers" is given by the magnetic field and the matter forming them need not necessarily move with a large velocity in relation to the comet. The high velocities which in some cases have been actually observed, may be due to magneto-hydrodynamic waves, travelling along the tail. In a beam with the density $\varrho = 10^{-25}$ g cm^{-3} corresponding to $n = 0.1$ cm^{-3}, and a magnetic field of 10^{-5} gauss the magneto-hydrodynamic velocity is $V = (4\pi\varrho)^{-1/2} = 10^7$ cm sec^{-1}. In a tail the field has been amplified considerably, so much higher velocities are possible. On the other hand the density is also larger. Wave velocities of 10^7 or 10^8 cm sec^{-1} seem reasonable. Another possibility is that the observed motion of "condensations" in the tail is due to small gas clouds torn away from the head as indicated in Fig. 3. The electromagnetic forces tend to make such a cloud move with the beam, and as the magnetic field may be amplified up to 0.01 gauss or more near the head, it is easily seen that they are strong enough to produce very large accelerations.

REFERENCES

Fokker, A. D., 1953: Notes on the fountain model of cometary envelopes and streamers. *La Physique des Comètes*, Louvain.

Biermann, L., 1953: Physical processes in comet tails and their relation to solar activity. *La Physique des Comètes*, Louvain.

van de Hulst, H. C., 1953: The chromosphere and the solar corona, p. 262, *Kuiper's "The Sun"*, Chicago.

Alfvén, H., 1955: On the electric field theory of magnetic storms and aurora, *Tellus*, **7**, p. 50. Compare also: Alfvén, H., 1954. On the Origin of Cosmic radiation, *Tellus*, **6**, p. 232, and Alfvén, H., 1955: On the sun's general magnetic field, *Tellus*, **8**, p. 1.