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MAGNETOHYDRODYNAMIC PHENOMENA IN COMETS AND THEIR CONNECTION WITH GEOACTIVE CURRENTS

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Introduction

INTRODUCTION

1. It has become quite clear in recent years that the interpretation of the large aggregate of effects in comets, due to solar corpuscular streams or to solar wind, encounter great obstacles. The fluxes must be exceedingly powerful to be able to explain with them many of the phenomena. Their density must be 2-3 orders of magnitude larger than the value obtained by direct measurements. The situation arises because the atmosphere of the comet and the corpuscular streams are exceedingly rarefied; the mean free path of the proton in the stream prior to collision with a molecule from the comet is 2-3 orders of magnitude higher than the linear transverse dimension of the head of a comet of average brightness.

In 1957, H. Alfven [1] pointed out the important role of the magnetic fields that are frozen in the streams (see Sec. 2). His paper [1] served as an impetus towards the development of the magnetohydrodynamic method in the physics of comets. S. B. Pikel'ner indicated[108] that in view of the smallness of the Larmor radius of interaction between the stream and the comet's atmosphere, the interaction is produced via the magnetic field. Interaction takes place also in the absence of collisions, that is, the stream density can be quite low.

Magnetohydrodynamics has reduced many of the difficulties, but even now many of the problems are far from quantitatively (and sometimes even qualitatively) explained.

The present review contains an attempt to detail the existing situation with an aim at attracting the physicist's attention to this group of astrophysical phenomena.

2. According to present notions, comets are ''small bodies'' of the solar system, with continuously renewed atmospheres [29]. The comet is divided into a nucleus, head, and tail. The nucleus of the comet is a solid body (or several bodies), the linear dimension of which apparently does not exceed 10 km [101,102]. The masses of the nuclei, obtained from independent estimates (celestial-mechanical estimates [29] and physical ones [126,127]), can differ greatly. For example, according to [126] the upper limit of the mass of the core of comet 1882I was approximately equal to 7.3×10^{22} g, whereas that of comet Neujmin I is $\sim 3.3 \times 10^{17}$ g.

The presently most prevalent physical model of the comet nucleus is proposed by F. Whipple [156,157], in which are synthesized the properties of the classical Laplace-Bessel model [4] and the later model of B. Yu. Levin [72,73] as supplemented by V. G. Riives [130] According to Whipple, the nucleus of the comet is a conglomerate of ices of different chemical compounds with stone-like particles embedded in them. The surface layer consists essentially of a high-melting-point component, through which the easy-melting component diffuses. There are also other models (see, for example [19,145,39,75,76]).

The nucleus is the source of the comet's atmosphere. On approaching the perihelion (the sun), it becomes more strongly heated, the evaporation increases, and the atmosphere of the comet grows. The head and the tail appear.

In most comets the linear dimension of the head ranges from several hundred thousand to several million kilometers. The visible outlines of the heads on the celestial sphere can vary greatly. According to S. V. Orlov [102], it is convenient to subdivide comet heads into three outline classes.

N-heads (N—nucleus), which include only a small region near the nucleus, and whose dimensions are tens of times smaller than the normal head observed apparently in comets whose nuclei are poor in absorbed gases.

In C-heads (C—coma) the nucleus is surrounded by a vaguely outlined nebula—the coma. In this case a characteristic onionlike structure is frequently observed, with a narrow tail emerging from the large diffuse coma. The tail is of the first type (a classification of tails will follow) and consists of individual jets and rays, which "collapse" in the course of time towards the symmetry axis of the tail (Fig. 1). The shape of the C-head can be interpreted in many cases with the aid of the isophots of the neutral gas which flows out uniformly in all directions from the nucleus.

E-heads (E—envelope) (Fig. 3) are surrounded by one or several envelopes.

It is also convenient to introduce a fourth type—M-head—which include comets such as Morehouse or Humason (Fig. 2) or Mrkos (Fig. 4). These are so to speak strongly outlined "headless" comets oblated on the sun's side, the outline of which is close to a parabola or a catenary.

According to the mechanical theory [32,101,109] the particles leaving the nucleus form a "fountain" (Fig. 5). The particle motion is due to solar gravitation (the gravitational field of the comet's nucleus is negligibly small) and light pressure. Calculation shows that the trajectory of each particle is a parabola and the envelope of these trajectories, in the case of isotropic escape of the matter, is a paraboloid of revolution. Therefore the outlines of the head should have parabolic contours. However, even Bond [14].and later N. F. Bobrovnikov [12] and S. V. Orlov [102] have found that the visible outline of the head on the celestial sphere is close to a catenary, something that is difficult to interpret within the framework of the mechanical theory. Some progress in this respect can be made by using electrodynamics (see Sec. 5).

The spectra of the comet heads consist of a continuous background in the central part and emission

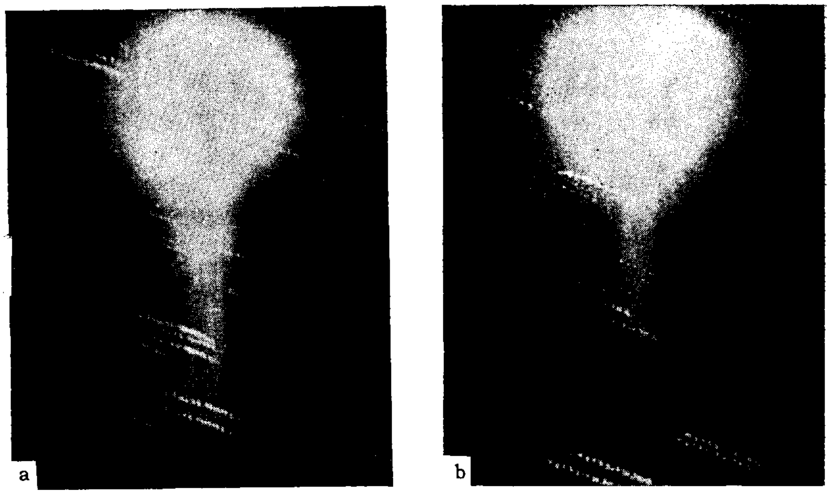

FIG. 1. Comet Burnham 1959k. a) and b) Successive photographs, which show quite clearly the "collapse" of the rays towards the axis of the tail during time (photograph from[168]).

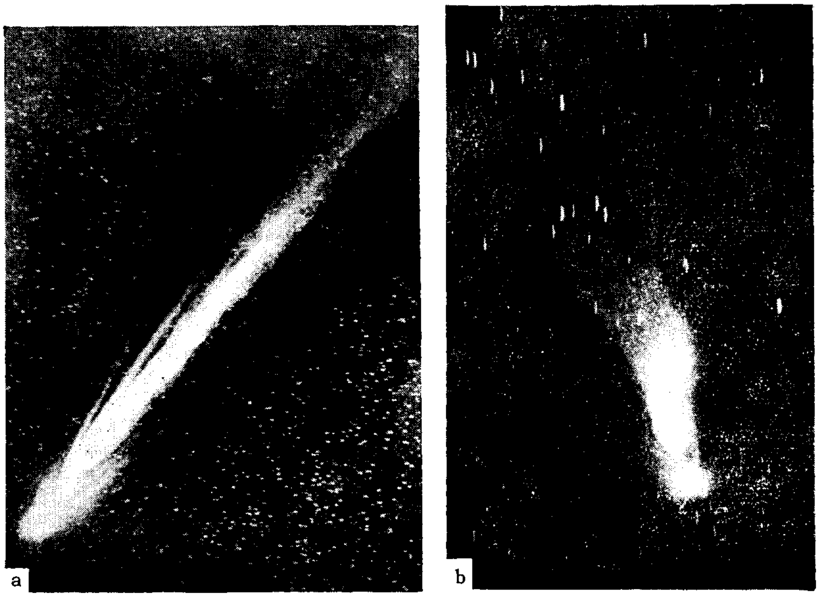

FIG. 2. Comet Morehouse photographed by E. Barnard on 15 September 1908. The waves are clearly seen. b) comet Humason 1961e. Photograph by Elizabeth Roemer[170] July 10, 1962. The shape of the comet changed greatly from night to night, and quite amazing shapes were observed. The comet together with the rays broke away. The new coma generated a new ray system.

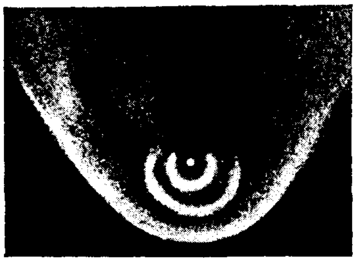

FIG. 3. Diagram of the halos and expanding dust envelopes in the head of comet Donati 1958 (from[102]).

FIG. 4. comet Mrkos 1957d. The picture shows a tail of type I with wavelike or spiral-like forms and a tail of type II (photograph from[82]).

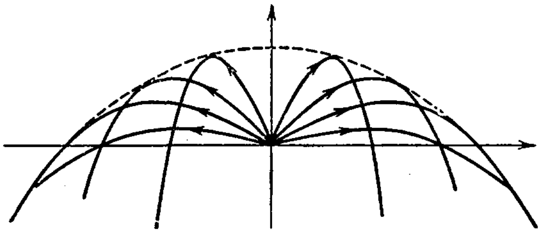

FIG. 5. Fountain gushing from a nucleus. The envelope of the jets and the jets themselves are parabolas.

molecular bands. As was shown by many workers [57,115,154], the continuous spectrum is due to scattering of the sun's light by dust particles with dimensions of the order of 0.1—0.7μ. The identification of the molecular bands shows that the comet heads contain the molecules C_2, CN, CH, OH, NH, NH_2, OH^+, and C_3. The comet molecules glow by fluorescence. As shown in [161,71,139,169,144,93,50] the comet gases reradiate the sun's light by resonance.

If the comet comes very close to the sun, atomic lines of Na, Mg(?), Fe, and Ni(?) are also observed. The most abundant in the head are C_2 and CN. Very frequently CO^+ and N_2^+ ions are spectrally observed in the immediate vicinity of the nucleus. Usually they do not extend beyond 500 km (from the center of the nucleus). A detailed review of the papers on comet spectroscopy prior to 1937 is contained in [13]. A modern review (list) of all the observed emissions and most photographs of the spectra are given in [146]. We see that a large number of comet molecules are free radicals. It is assumed that they are the results of dissociation and ionization of more stable parent molecules, which include CH_4, $NH_3(CN)_2$, H_2OH, and others [74,151].

From the apparent brilliance of the comet head, knowing its spectral composition, we can determine the number of glowing molecules and consequently estimate the lower limit of the comet mass. According to K. Wurm [161,167] the brilliance of the comet (or of the coma) in stellar magnitudes is

$$m = -2{,}5\,\mathrm{lg}\,\frac{10^{10}Ne^2}{2\varrho_c^2 c m_e M_c} I_\nu f_{ik}, \tag{1)*$$

where M_c is the mechanical equivalent of light, N the number of molecules in the electron ground state, I_ν the intensity of the solar radiation at frequency ν, and f_{ik} is the oscillator strength of the corresponding electronic transition.

For example, for the electronic transition $A^3\Pi_g \rightarrow X^3\Pi_u$ $\lambda 5550$ Å (Swann bands of C_2) assuming $f_{12} = 0.2$ and taking dilution into account, we obtain [161]

$$N \cong 1.74\cdot 10^{34-0.4m_{\rho_c}}, \tag{2}$$

where ρ_c—geocentric distance to the comet in astronomical units. If other molecules (in addition to C_2) are also taken into account, then according to[118] (2) must be increased by approximately one order of magnitude.

The mass of the dust component of the comet atmosphere can be estimated from formula (4) below.

The distribution of the density of the comet molecules as a function of the distance n(r) from the nucleus was frequently investigated photometrically [18,69,128–132].

Most astronomers believe that in many cases n has a quadratic variation

$$n = n_0\left(\frac{r_0}{r}\right)^2, \tag{3}$$

where n_0 is the density near the nucleus and r_0 is the radius of the nucleus.

However, more complicated distributions are also observed [29,79]. Usually $n_0 \cong 10^{10}$—10^{12} cm^{-3}, but in some cases it can reach 10^{14} cm^{-3} [118]. In peripheral parts of the head, at $r = \xi_0$(ξ_0—radius of the visible head) we have $n(\xi_0) \cong 10$—10^3 cm^{-3}.

It follows therefore that for a gas-kinetic effective cross section of the comet molecule $\sigma \cong 10^{-15}$ cm^2 the mean free path amounts to $l(\xi_0) = [n(\xi_0)\sigma]^{-1} \cong (10^2 \times 10^{-15}) \cong 10^{13}$ cm $\gg \xi_0 = 10^{10}$—10^{11} cm on the

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*lg = $\log_{10}$

periphery and $l(r_0) \cong (n_0\sigma)^{-1} \cong 10^{-12} \times 10^{15} \cong 10^3$ cm near the nucleus. Thus, there are no collisions between molecules in practically the entire volume of the head. They are significant, as can be readily shown, only in a small region next to the nucleus, with dimensions of the order $r_1 \cong 10^7-5 \times 10^8$ cm.

In the head of the comet one can observe halos which are uniformly expanding rings. The rate of expansion is ~0.1—0.01 km/sec, reaching sometimes several kilometers per second. If several halos are observed simultaneously, they form systems of concentric rings, the center of which very frequently (but not always) coincides with the nucleus of the comet (see Fig. 3). Sometimes envelopes (or a system of envelopes) are observed in the head; these constitute curves which are convex to the sun (see also Fig. 3). The expansion of the envelopes is much slower than the expansion of the halos. It is assumed that the halos and the envelopes are the result of a sudden ejection of matter from the nucleus. If, for example, we assume that only dust particles are ejected, then according to [158],

$$\lg M = \lg \delta h + 2 \lg \left(\frac{r_c \varrho_c \cdot 385 \cdot 10^5}{\sqrt{\Phi(\alpha)}}\right) - 0.40m + 2.10, \qquad (4)$$

where M—total mass of ejected matter, δ—density of dust particle, h—its linear dimension, r_c and ρ_c—the heliocentric and geocentric distances of the comet, respectively, expressed in astronomical units, $\Phi(\alpha)$ (phase function)—ratio of the brightness at a phase angle α to the brightness at opposition, and m—visible magnitude of the comet.

Using (4), Whitney [158] calculated the average value of M for several comets as a function of h, assuming $\delta = 1$. His results are listed in Table I. O. V. Dobrovol'skiĭ [29] made a similar calculation under the assumption that the halos are made of gas. He obtained $M \cong 2 \times 10^{10}$ g, which for $v_h \cong 1$ km/sec yields 10^{20} erg, a result which is close to the "dust" case with $h \cong 10^{-5}$ cm.

The sun's Planck radiation energy is generally speaking sufficient to produce the halo. However, the suddenness of the eruptions is not clear. Discrete-action mechanisms have therefore been proposed.

However, in none of the proposed mechanisms can the comet's nucleus absorb such an amount of energy during the time of its action. One could suggest, for example, that the eruptions are due to the disintegration of the nucleus surface by meteorites or by solar corpuscular streams. However, the first possibility is not realized [124,125,41,29] in view of the rareness of the encounters with meteorites. The action of the corpuscular streams can lead to cathode sputtering, which is insignificant [29], and also to the crumbling of the surface of the nucleus, to the appearance of microscopic cracks because of microscopic explosions produced by the protons of the streams [29]. It is doubtful, however, that such a mechanism would itself produce an eruption of a halo or an envelope, since there apparently is no energy balance here. Indeed, the total energy absorbed by the nucleus cannot exceed

$$Q \sim \frac{n_s m_H v_s^2}{2} s_0 t, \qquad (5)$$

where n_s and v_s are the density and velocity of the corpuscular stream, s_0 the area of the nucleus surface facing the stream, and t is the time of action of the corpuscles on the nucleus. Since the width of the stream is of the order of $L_s \cong 2 \times 10^{12}$ cm (see, for example,[40]) we obtain for $v_s \cong 10^8$ cm/sec, $n_s \cong 10$ cm^{-3}, and $s_0 = 10^{11}$ cm^2 a value $Q \sim 10^{16}$ erg ≪ E, where E is the energy necessary for the eruption in accordance with Table I.

Table I

h, cm	M, g	v_h=0.2 km/sec	v_h=0.8 km/sec	v_h=1,6 km/sec
		E, erg	E, erg	E, erg
10^{-3}	$5 \cdot 10^{12}$	$2 \cdot 10^{21}$	$3 \cdot 10^{22}$	10^{23}
10^{-4}	$5 \cdot 10^{11}$	$2 \cdot 10^{20}$	$3 \cdot 10^{21}$	10^{22}
10^{-5}	$5 \cdot 10^{10}$	$2 \cdot 10^{19}$	$3 \cdot 10^{20}$	10^{21}

Here h — dimension of dust particle, M — ejected mass, E — energy consumed in ejection of mass M at a halo expansion velocity v_h.

In addition to cathode sputtering and crumbling, Weigert [155] considered the heating of the surface of a nucleus by corpuscular streams. However, estimates show [155] that in order to eject a halo the comet should encounter at least once a year a flux of density $n_s \cong 10^5$ cm^{-3}, which is of little likelihood from the point of view of modern data on copuscular streams. Direct and indirect measurements show that n_s apparently does not exceed 20—30 cm^{-3} [22]. L. Boss [15] advanced the hypothesis that the surface of the nucleus might be disrupted by electrostatic forces; this theory was subsequently developed by N. Richter [124,125]. However, it was shown in [31] that such a possibility could be realized only in the presence of electrically charged corpuscular streams (not quasineutral ones), which is of little likelihood in light of presently available data on the streams.

Dohn and Urey [39] proposed that the halos can be due to explosions in the nucleus, resulting from several chemical reactions between the free radicals frozen it is, such as CH, OH, NH, and others. However, the radical concentration is low [147].

It is possible to approach the problem in a different way, by assuming the corpuscular streams and similar factors to be catalysts that increase the surface of the nucleus as a result of the destruction they produce, and consequently they increase the intensity of evaporation [38].

Thus, the question of the origin of the halos and the expanding shells remains open. The dynamics of these formations, if we disregard their causes and their physical nature (gas or dust?) can be described satisfactorily by the mechanical theory [101,4,43,100,32,33].

Sometimes, "collapsing" or contracting envelopes are produced in the comets. They appear on the edge facing the sun in that part of the head which moves rapidly towards the nucleus, and simultaneously "collapses" towards the straight line joinging the comet with the sun (a detailed description and analysis of these phenomena is given in Sec. 4). In this case, unlike the halos and the expanding envelopes, both the kinetics and the dynamics of these formations remain unclear to this day, since the mechanical theory is in principle powerless here [100,102,42,103,48,96,97]. Spectrally, the "collapsing" envolopes consist of CO^+ ions, so that these effects can be expected to have a plasma nature.

According to the mechanical theory, the particles which are released from the nucleus are deflected by the radiation pressure in a direction away from the sun and, owing to the conservation of momentum, they lag the sun as the comet moves along the orbit (Fig. 6), forming a tail directed away from the sun and bent in the direction of motion of the comet. The character of the tail (the curvature, the deviation from the radius vector, etc.) depends on the acceleration acquired by the particle under the influence of the repulsion forces, for example the radiation pressure.

Following a historical tradition, it is customary to express the accelerations in the tails by means of the dimensionless quantity

$$1+\mu=\frac{a}{g_\odot},$$

where a—repulsion acceleration and g.—solar gravitational acceleration at the given heliocentric distance. Most comets are investigated at $r \sim 1$ a.u., that is, in this case g. $\cong 0.6$ cm/sec^2.

Since the character of the tail is determined by the parameter $1 + \mu$, F. A. Bredikhin [10] (see also [43]) classified the tails in accordance with the value of $1 + \mu$, and this classification remains to this day.

In this classification, the tails of the comets are divided into three types:

Type I—straight and relatively narrow, close to the radius vector, in which large repulsive accelerations prevail, $1 + \mu > 20$. Accelerations on the order of $1 + \mu \sim 1000$ are quite frequently encountered.

Type II—broad, curving, and lagging the comet motion, with large deflections away from the radius vector. They correspond to $1 + \mu \sim 1$.

Type III—broad, short, weak, and highly curved away from the radius vector. They correspond to $1 + \mu \sim 0.1—0.3$.

The three types of tails are shown schematically in Fig. 6. Tails of type I are seen in Figs. 1, 2, and 4, those of type II are shown in Fig. 4. Tails of type II and III have a continuous spectrum, indicating that they are either dustlike or at least a mixture of dust and neutral gas.

The situation is worse with tails of type I. The mechanical theory is incapable of explaining, even in main outline, the manifold observed phenomena. Within the framework of the mechanical theory, it is impossible to explain, for example, such phenomena as the tremendous accelerations observed in tails of type I, the transverse motion of matter in the tail (perpendicular to the radius vector) observed in the form of converging "whiskers," ends of envelopes disappearing in the tail, wavelike motion in the tails, etc.

The key to the understanding of the entire set of these phenomena, which do not fit the classical theory, lies in the specific nature of type I tails. As shown by numerous spectral investigations [146], these tails consist essentially of ionized molecules (principally CO^+ and N_2^+), that is, they represent a plasma; this explains also the sharp difference between types II and III on the one hand and type I on the other.

However, the source of the ions in the comet are not clear, and none of the probable mechanisms can provide the observed degree of ionization (see Sec. 6).

A correlation was observed between the activity of the comets (accelerations in tails of type I, halos, flashes) and geomagnetic distrubances [6,81,54,34,126,127,56]. This points to the important role of solar corpuscular streams in the physics of comets. The interaction between the stream or the solar "wind" and the atmosphere of the comet can be regarded, as will be shown below, in terms of magnetohydrodynamics, which eliminates many of the mentioned (and unmentioned) difficulties which are unresolved within the framework of the mechanical theory.

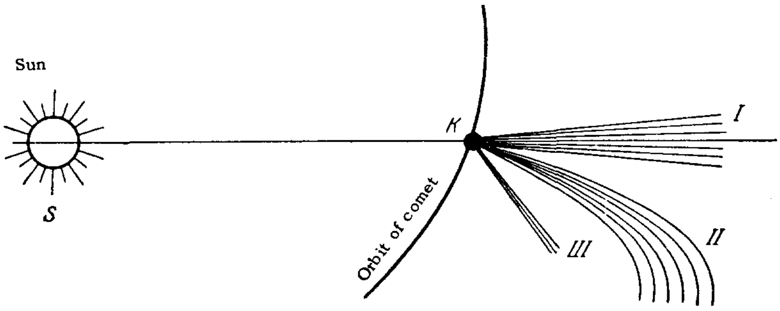

FIG. 6. Schematic diagram of three types of tails. SK – radius vector.

1. PLASMA NATURE OF THE COMET HEAD

As indicated in the introduction, the heads of most comets emit in the neutral-molecule bands, principally CN and C_2. CO^+, N_2^+ and other ions are observed in the small region of the nucleus and in type I tails. Therefore it has always been assumed that the coma is made up of neutral gas and contains no ions [101,102].

It is shown in [87] that this is not the case and that the coma resembles a plasma. Favoring this statement are the following facts.

1. There can be many molecules and ions in the coma (other than C_2, CN, CO^+, N_2^+, etc.), but they cannot be detected by their spectra because of "cut-off" by the earth's atmosphere [121].

2. The observed CO^+ and N_2^+ ions can also extend over the entire coma (not only near the nucleus). If there are not enough of them, their bands will be masked by the intense C_2 and CN radiation [164,165].

3. There are known cases when the heads of the comets emit predominantly in the CO^+ bands. These include comet Morehouse 1908 III [164], and comet Humason 1961e [51] (Fig. 7). The CO^+ bands began to predominate in the spectra of the heads of comet Brooks 1911V [146] and Comets 1893 IV [164] and 1939 III [146] as they approached the sun.

In the opinion of K. Wurm [164], for example, the head of comet Morehouse 1908 III has emitted in the CO^+ bands because this comet is very poor in cyan (CN), which is plentiful in other comets. This also is evidence in favor of item 2 above.

4. The presence of "collapsing" envelopes (see Sec. 4).

The degree of ionization of the coma fluctuates between one and several dozen per cent [87]. Its plasma nature explains many of the observed effects.

2. FUNDAMENTAL POSSIBILITY OF MAGNETOHYDRODYNAMIC DESCRIPTION OF PHENOMENA IN COMETS

Most electrodynamic effects in comets result from the interaction between the atmosphere of the comet and the solar corpuscular streams or the "solar wind" (we shall henceforth speak only of the streams, but it must be borne in mind that unless otherwise stipulated everything stated above applies equally well to "solar wind").

However, the stream and the coma are so rarefied, that the proton mean free path prior to the collision with the comet molecule exceeds the dimensions of the head of practically any comet (see below). Therefore, as already indicated in the introduction, the direct interaction between the stream plasma and the comet's atmosphere is exceedingly small: in order to explain the observed effects the streams must have the unrealistically high density $n_s \cong 10^3 - 10^4 \text{ cm}^{-3}$ (Secs. 6 and 7). The interpretation of many comet phenomena thus contradicts the data on the interplanetary medium and the corpuscular streams. It has become clear that the decisive role in the described interaction is played by the magnetic field.

The influence of the interplanetary field on the accelerations in type I tails was considered in [110]. The *turning point, however, was apparently the paper by* Alfven [1], which served as a basis for a new theory—the magnetohydrodynamics of comets. According to Alfven's hypothesis, the shock wave produced upon encounter with the solar corpuscular stream causes thermal ionization of the comet gas, which in turn causes the "freezing in" of the force lines inside the gas of the comet. As the latter continues to move the force lines are crowded out by the head of the comet and become straight rays which fan out away from

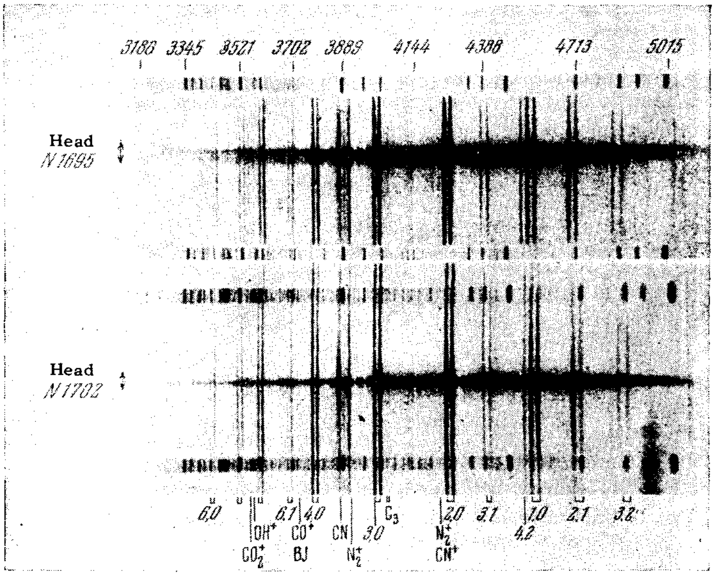

FIG. 7. Spectrum of comet Humason 1961e, obtained by Greenstein. As in comet Morehouse, ions are abundantly represented in the head (photograph from [51]).

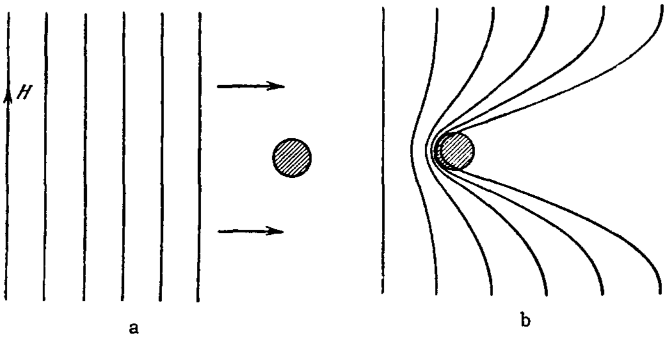

FIG. 8. Collision between corpuscular stream and the comet, after Alfven[1]. a) Situation prior to the collision; b) deformation of the force lines of the magnetic field under the pressure of the comet.

the sun, and along which the magnetohydrodynamic waves can move. The resultant picture is shown in Fig. 8.

As shown in [87], the picture actually produced is somewhat different, for example there is no thermal ionization, but an important factor in Alfven's scheme is that the ions are produced in the magnetic field of the stream, resulting in a "freezing in" of the field H in the comet gas. This raises the question of the applicability of magnetohydrodynamics in this case.

If the collision with the stream can be described hydrodynamically, then it is natural to expect the occurrence of shock waves. It is known that hydrodynamics is applicable at least if the following inequality is satisfied

$$\frac{l}{L} \ll 1, \tag{2.1}$$

where l—mean free path, L—characteristic dimension in the problem under consideration. In the present case it is natural to choose for L the quantity ξ_0 —the radius of the head of a comet of average brightness. In the theory of shock waves (2.1) it is replaced by the analogous relation

$$\frac{\Delta x}{L} \ll 1, \tag{2.2}$$

where Δx is the width of the shock wave front. As is well known, $\Delta x \gtrsim l$. Thus, (2.1) and (2.2) are not satisfied and hydrodynamics in pure form is not applicable here. The situation changes, however, if the head of the comet is made up of plasma (see Sec. 1). Then the collision with the corpuscular stream can be regarded as an interpenetration of two clouds of rarefied quasineutral plasma.

Much attention has been paid recently to collisionless shock waves (that is, shock waves in a plasma where the Coulomb collisions are infrequent or nonexistent). That is of importance for the physics of hot plasma [49] et al, (controlled thermonuclear fusion) and for astrophysics (theory of sudden start of a magnetic storm [28] or of a comet, etc.). The width of the front of a collisionless shock wave propagating transversely to the magnetic field is found to be a quantity of the order of

$$\Delta x \sim \sqrt{r_H^i r_H^e} \tag{2.3}$$

or [136,66,47,106,137,107,11]

$$\Delta x \sim r_H^i, \tag{2.4}$$

where r_H^i and r_H^e are the average Larmor radii of the ion and electron.

Powerful corpuscular streams from chromospheric flares, which propagate with a velocity $v_s \cong 10^8$ cm/sec, contain magnetic fields $H \gtrsim 10^{-4}$ Oe. The velocity of the solar "wind" is about $v_s \cong 3 \times 10^7$ cm/sec, and the magnetic fields frozen in it are of the order of $H \gtrsim 10^{-5}$ Oe[108,153,22]. Consequently the Larmor radius of the proton is $r_H^i \cong 2 \times 10^8$ cm $\ll \xi_0$, that is, condition (2.2) is satisfied in this case. A shock wave is formed and travels towards the sun in the plasma of the stream. Since the comets are continuously exposed to the solar wind near the perihelion (≅ 1–2 a.u.) and frequently enter into the corpuscular stream, a magnetic field from the penetrating magnetized solar plasma "gets stuck" in the coma. This is caused by the ionization produced when the stream passes through the head of the comet and the magnetic field "frozen in" the coma (Sec. 6). The field can be dissipated primarily by Joule losses, but these are not large enough to destroy the field during the time of encounter with two successive streams or large-scale inhomogeneities of the "wind."

The lifetime of the field in the head can be roughly estimated from the formula[27]

$$t_H \cong \frac{4\pi\lambda\xi_0^2}{c^2}, \tag{2.5}$$

where λ is the conductivity. For about 1% ionization (see Sec. 1), λ can be obtained from the dependence [140,108]

$$\lambda = \frac{0.58 \cdot 4 \cdot (2kT)^{3/2}}{\pi^{3/2} m_e^{1/2} e^2 \ln \Lambda}. \tag{2.6}$$

Assuming $T \cong 10^4$ °K and a Coulomb logarithm $\ln \Lambda = 44$, we obtain $\lambda \cong 7 \times 10^{12}$ sec^{-1}. Consequently $t_H \cong 10^{12}$ sec, whereas the time between entry of the comet in two succeeding streams apparently does not exceed one week. We note also that $t_H \gg t_c$, where t_c is the characteristic time of the physical processes in the head of the comet. Usually

$$t_c \sim \frac{\xi_0}{V_t} \sim 10^5 \text{ sec}$$

where V_t is the average thermal velocity.

In some papers it is postulated that the coma contains a magnetic field of unknown origin with a source in the nucleus [16,134], the field decreasing from the nucleus towards the periphery of the head. Such a distribution of H can actually be established in light of Alfven's ideas[1]: during the incidence of the stream on the coma, the force lines become more concentrated near the nucleus (see Fig. 8), and a sort of magnetic "cushion" is produced. However, the source of the field, as can be seen, has no bearing whatever on the nucleus: the field of the stream "freezes in" and remains in the coma.

If there is relative motion of the ionized and neutral components the dissipation of H increases strongly because of the losses to collisions with the neutral particles [108] (see Sec. 7). Such a situation takes place when a corpuscular stream "holes through" a weakly ionized coma. In this case, however, the field is continuously supplied to the coma by the stream itself, and the dissipation stops once the stream departs. The coma should apparently contain a magnetic field with an intensity of the order of that observed in the streams. Collision therefore produces in the comet, as in the stream, a shock wave which travels along the plasma in the head and further into the type I tail.

Physically this is connected with the fact that the protons of the stream transfer their momentum to the comet ions via the magnetic field, even if there are no collisions. We note that the hydrodynamic analysis of the collisionless plasma is valid only if the motion is perpendicular to the magnetic field [23]; only in this case is the system of equations for the moments of the distribution function of the ions closed without additional assumptions. The field configuration in the stream is unknown. However, the distribution of H can hardly be regarded as sufficiently ordered. A shock wave is therefore apparently produced, although naturally nothing can be said about the structure of its front or some of the fine details.

We note incidentally that under favorable conditions the shock waves can be produced by collision between the stream and the comet even in the absence of an initial magnetic field. According to [95] a certain instability arises in such a situation, and the magnetic field of the resultant perturbation keeps the transition region from spreading out. The width of the front is described by the formula [95]

$$\Delta x \sim \frac{m_i}{m_e}\frac{c}{\omega_{0i}}\left(\frac{T_{\parallel}}{\Delta T}\right)^{\frac{1}{2}}\left(\frac{T_{\parallel}}{T_e}\right)^{\frac{1}{2}}\left(\frac{T_{\perp}}{T_e}\right)^{\frac{1}{2}}, \tag{2.7}$$

where

$$\Delta T = T_{\perp} - T_{\parallel} > 0, \qquad T_{\perp} = \frac{m_i}{2}\overline{(v_{\perp} - \bar{v}_{\perp})^2},$$

$$T_{\parallel} = \frac{m_i}{2}\overline{(v_{\parallel} - \bar{v}_{\parallel})^2},$$

$\omega_{0i} = \sqrt{4\pi e^2 n_i/m_i}$ is the ion plasma frequency and T_e is the electron temperature. The ion distribution function can be arbitrary and anisotropic, while the electrons are assumed to have an isotropic distribution because of their short relaxation time.

As follows from (2.7), the width of the wave front in a corpuscular stream which has no magnetic field is of the order of

$$\Delta x_s \sim 3\cdot 10^{10}\frac{1}{\sqrt{n_s}}\frac{T_{\parallel}}{T_e}\sqrt{\frac{T_{\perp}}{\Delta T}}, \tag{2.8}$$

and in a comet

$$\Delta x_c \sim 5\cdot 10^{12}\frac{1}{\sqrt{n_c^i}}\frac{T_{\parallel}}{T_e}\sqrt{\frac{T_{\perp}}{\Delta T}}, \tag{2.9}$$

where n_s is the stream density and n_c^i the ion density in the comet. It is easy to see that at sufficiently large (but feasible) n_s, n_c, ΔT, and T_e it is possible to obtain Δx_s and $\Delta x_c \ll \xi_0$, that is, a shock wave.

3. SHOCK WAVES IN COMETS

Shock waves are thus produced when a comet enters into a corpuscular stream. One wave propagates in the stream plasma towards the sun, and the second travels along the coma to the nucleus and further to the tail. Behind the wave front traveling in the coma there is a separation boundary (between the flux and the comet) which serves as a unique magnetic "piston" which sweeps out the ionized gas from the head and from the tail. The neutral molecules pass through the "piston" into the stream without opposition, become ionized (see Sec. 6), and are then also dragged by the magnetic field. Since the mean free path of a neutral particle is $l \gg \xi_0$, the shock wave in the coma travels only over the ions. The density of the plasma in the head decreases from the center towards the periphery (see the introduction), and the wave front and the separation boundary therefore become deformed. The deceleration of the front will be a maximal along the shock axis, and minimal on the edges of the head. The front and the separation boundary begin to "collapse" towards the symmetry axis (Fig. 9). The magnetic field will be focused towards the center of the head.

The initial parameters of the shock waves (that is, the jumps in the velocity, pressure, etc. at the instant of collision) were calculated in [86,88], where initially plane and perpendicular waves were assumed. As is well known, the action of oblique waves at angles of encounter up to 45° differs little from that of perpendicular waves [53], so that such an assumption is justified in a first semi-qualitative calculation [86,88].

The interaction between the atmosphere of the comet and the solar corpuscular stream produced by a chromospheric flare was considered in [88]. Such streams contain cosmic rays causing the pressure p_s inside the stream to be of the order of the kinetic

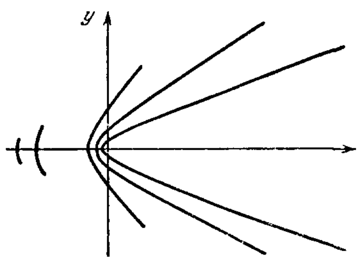

FIG. 9. Schematic representation of the occurrence and motion of "collapsing" envelopes. On approaching the nucleus, the visible lengths of the arcs of the shells increase, and the ends draw closer towards the continuation of the radius vector.

energy of relative motion of the stream and the comet

$$p_s \approx \frac{\varrho_s v^2}{2},$$

where $\rho_s = m_H n_s$ is the mass density of the stream and $v \approx v_s \approx 10^8$ cm/sec (the relative velocity is $v \approx v_s$, since the orbital velocity of the comet is $v_c \approx 30-40$ km/sec $\ll v_s$). Therefore the shock wave in the stream will be weak. The shock wave in the coma will be strong since

$$p_c \ll \frac{\varrho_c^i v^2}{2}$$

The compression of the gas in such a wave is

$$\alpha_c \approx \frac{\gamma+1}{\gamma-1} = 6,$$

where

$$\gamma = \frac{c_p}{c_V} = \frac{7}{5}$$

for a diatomic comet gas.

The compression in the stream is obtained from gasdynamic conservation laws [88]:

$$\left.\begin{aligned} \varrho_1 v_1 &= \varrho_2 v_2, \\ p_1^* + \varrho_1 v_1^2 &= \varrho_2 v_2^2 + p_2^*, \\ \varepsilon_2^* - \varepsilon_1^* &= \frac{1}{2}(p_2^* + p_1^*)(\varrho_1^{-1} - \varrho_2^{-2}), \end{aligned}\right\} \tag{3.1}$$

where the subscript 1 refers to the unperturbed plasma of the stream and 2 refers to the state behind the wave front; $p^* = p + p_{cr}$ is the total pressure (gas plus cosmic-ray pressure); $\varepsilon^* = \varepsilon^+\varepsilon_{cr}$ is the total internal energy. Inasmuch as

$$\frac{H^2}{8\pi} \ll p_{cr},$$

the magnetic pressure is not taken into account. The cosmic-ray gas is assumed to be polytropic with $\gamma_{cr} = 1/3$, while for the gas in the stream $\gamma_s = 5/3$. The compression in the stream is found to be $\alpha_s = 2.53$.

At the instant of collision, the situation illustrated in Fig. 10 is produced. The velocities of the separation boundary and of the shock waves and the pressure discontinuity are determined by the formulas [141, 88]

$$\frac{u_{imp}}{v_s} = \frac{\left\{\frac{\varrho_c(1-\alpha_s^{-1})}{\varrho_s(1-\alpha_c^{-1})} + \frac{p_s^* - p_c}{\varrho_c v_s^2}\left[\frac{\varrho_c(1-\alpha_s^{-1})}{\varrho_s(1-\alpha_c^{-1})} - 1\right]\right\}^{\frac{1}{2}} - 1}{\frac{\varrho_c(1-\alpha_s^{-1})}{\varrho_s(1-\alpha_c^{-1})} - 1}, \tag{3.2}$$

$$D_{2c} = \frac{u_{imp}}{1-\alpha_c^{-1}}, \tag{3.3}$$

$$D_{2s} \cong v_s - \frac{v_s - u_{imp}}{1-\alpha_s^{-1}}, \tag{3.4}$$

$$p_{imp} = p_c + \frac{\varrho_c u_{imp}^2}{1-\alpha_c^{-1}} = p_s^* + \frac{\varrho_s(u_{imp} - v_s)^2}{1-\alpha_s^{-1}}, \tag{3.5}$$

where u_{imp}—velocity of the separation boundary, $\rho_c = 28\, m_H n_c^i$—mass density of the ionized component of the coma, D_{2c} and D_{2s}—velocity of the front of the shock wave in the comet and in the stream, respectively, and p_{imp}—pressure on the boundary between the two media at the instant of impact. The results are summarized in Table II.

Owing to the drop in the density from the center of the comet head towards the edges, the shock wave front and the separation boundary are decelerated as they travel through the coma. The separation boundary will stop where $p_{imp} \approx p_c(z_1)$. From this we can find that z_1 is of the order of 100—5000 km, that is, it corresponds to a region near the nucleus, filled with ions and of unknown origin. The sphere centered about the nucleus, with radius $z_1 = r_1$, can be called the effective nucleus [88]. The separation boundary—the magnetic "piston"—"gets stuck" in the effective nucleus, but the shock wave, which attenuates to a sound wave, passes through this nucleus. Since the density again decreases when $z > 0$ (see Fig. 10), the sound wave is accelerated and again turns into a shock wave (Secs. 7—8). The gas conductivity in the effective nucleus is low, so that the trapped magnetic field of the stream will diffuse through the stream and go over into the tail (the diffusion velocity is estimated in Sec. 7).

In [86] there is considered the interaction between a comet or a "wind" or corpuscular stream of kind II (from a solar facula). In such streams there are no cosmic rays and they are less intense ($v_s \cong 3 \times 10^7$ cm/sec, $H \sim 10^{-5}$ Oe, $n_s \sim 1-10$ cm^{-3}, $p_s \cong H_s^2/8\pi \ll \rho v^2/2$). The quantities u_{imp}, D_{2c}, D_{2s}, p_{imp}, etc., can be calculated from formulas (3.1)—(3.5) by successive approximations [86]. For the same values of n_c/n_s, the values of u_{imp}, D_{2c}, p_{imp}, etc., turn out to be smaller than in the case of a "flare." For example, for $n_c/n_s \cong 3.3 \times 10$ we have $u_{imp} \cong 6.3 \times 10^5$ cm/sec, $T_{2c}/T_{1c} \cong 4.75$, and $p_{imp}/p_c \cong 13.4$ (see fourth line of Table II).

The motion of the separation boundary and of the

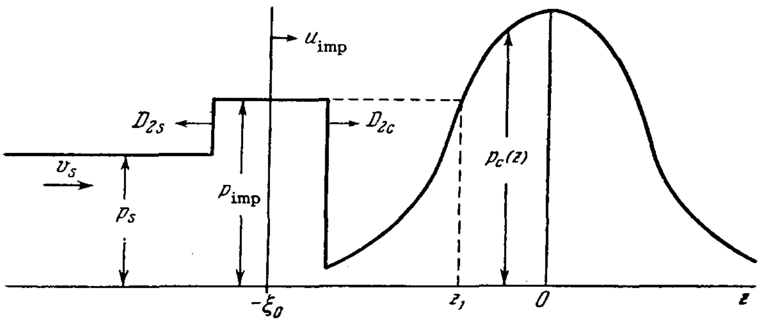

FIG. 10. Illustrating the collision of a comet with a stream. ρ_{imp} – pressure produced on the boundary between the stream and the comet upon impact; u_{imp} – velocity of the boundary; D_{2s}, D_{2c} – velocities of the shock waves produced upon collision and propagating in the stream and in the coma, respectively. The coordinate system is centered in the comet.

Table II

$\frac{n_c^i}{n_s}$	$\frac{u_{\text{imp}}}{v_s}$	n_c^i cm^{-3} for $n_s=10\,\text{cm}^{-3}$	u_{imp} cm/sec for $v_s=10^8$cm/sec	$\frac{p_{\text{imp}}}{p_c}$	$\frac{T_{2c}}{T_{1c}} \approx \frac{p_{\text{imp}}}{p_c}\frac{\gamma-1}{\gamma+1}$	T_{2c} (eV) for $T_{1c}=10^4$ °K
$3.3\cdot10^{-2}$	0.78	$3.3\cdot10^{-1}$	$7.8\cdot10^7$	$2.4\cdot10^5$	$4\cdot10^4$	$3.45\cdot10^4$
$3.3\cdot10^{-1}$	0.45	3.3	$4.5\cdot10^7$	$7.8\cdot10^4$	$1.3\cdot10^4$	$1.12\cdot10^4$
3.3	0.12	$3.3\cdot10$	$1.2\cdot10^7$	$5.6\cdot10^3$	$9.3\cdot10^2$	$8\cdot10^2$
$3.3\cdot10$	0.038	$3.3\cdot10^2$	$3.8\cdot10^6$	$5.9\cdot10^2$	98	84.5
$3.3\cdot10^2$	0.013	$3.3\cdot10^3$	$1.3\cdot10^6$	67	11.2	9.7

Here T_{2c}/T_{1c} – ion-temperature jump behind the front of the wave propagating towards the coma.

shock wave causes the appearance of the "collapsing" envelopes in the head of the comet, described in the introduction (see Sec. 4).

In order to estimate the deceleration due to the increase in density, it is necessary to know the dependence of the force of the wave on n. On the basis of the data of [99], the following dependence was derived in [91]:

$$\frac{\Delta p}{p} \cong \frac{\text{const}}{n_c^{0.43}}, \qquad (3.6)$$

where $\Delta p/p$ (force of the wave) is the ratio of the pressure jump on the front to the pressure in the unperturbed plasma. From this we can obtain the degree of deformation of the front. At each instant of time its outlines are described by the equation

$$t=\text{const}=\int_{-\xi_0}^{z}\frac{dz}{D_{2c}}, \qquad (3.7)$$

with

$$D_{2c}^2=v_T^2\left(1+\frac{\gamma+1}{2\gamma}\frac{\Delta p}{p}\right), \qquad (3.8)$$

where v_T is the velocity of sound.

In calculating (3.7) account must be taken of (3.6) and of formula (3) from the introduction. It is clear that the front "collapses" towards the Oz axis in the xy plane because of the presence of a density gradient (see Fig. 9).

So long as the wave is strong ($\Delta p/p \gg 1$), the separation boundary duplicates exactly the form of the front of the shock wave preceding it. In this case the compression ceases to depend on $\Delta p/p$ and assumes a value $\alpha_c = 6$. It then follows from (3.3) that

$$D_{2c}=1.2u_{\text{imp}}. \qquad (3.9)$$

Thus, the magnetic "piston" which follows the front of the wave becomes focused towards the center, so that noticeable cumulative effects can be expected. By sweeping the ions of the comet, such a focusing "piston" concentrates them in a small region in the center. Since the "piston" stops at a distance $z_1 = r_1 \approx 100$-5000 km from the center (see above), the dimension of the region in which the ions enter will apparently also be close to r_1. This explains why the ions are observed near the nucleus.

Can a shock wave produce an explosion in the nucleus and an eruption of a halo? This thought was first advanced by the author [84] and analyzed in greater detail in [86,91]. It was later discussed in [134].

Without account of cumulation (in so far as we know, at the present time there are no gasdynamic solutions of the problem of a shock wave converging towards the center in a medium with variable density), the energy given up by the wave to a solid core is of the order of $Q' \cong 10^{12}$ erg [91], that is, considerably lower than necessary for the formation of a halo (see Table I).

In order to take account of the cumulative effect in first approximation, we multiply Q' by a factor S/S_0, where S is the area of the surface of the comet head and S_0 is the area of the surface of the nucleus.

It is easy to see that an energy

$$Q \sim Q'\frac{S}{S_0}$$

is sufficient for halo production with some margin.

4. "COLLAPSING" ENVELOPES

In the head of comet Morehouse 1908 III there were observed envelopes which moved towards the nucleus and simultaneously "collapsed" in the direction towards the radius vector, gradually going over into the tail. According to Eddington's observations [42], the visible arcs lengths of these envelopes increased continuously during the motion, so that when the central part reached the nucleus the ends turned out to be already far in the tail, forming the well-known "whisker" rays which move towards the continuation of the radius vector. The velocities of the envelopes observed in comet Morehouse ranged from 1–2 to 14–15 km/sec.

The outlines of the envelopes became sharper as they approached the center of the head, and disappeared near the nucleus. Such envelopes were observed in distinct form (directly) only in comet Morehouse 1908 III, the head of which contained according to spectroscopic data, principally CO^+ gas [146,164]. However, "collapsing" envelopes are apparently characteristic not only of comet Morehouse but also of all comets with developed type I tails [29]. The numerous "whisker" rays (ends of the envelopes) are seen, for example, in comets Brooks 1893 IV, Daniel 1907 IV, Finsler 1937 V, and many others. As noted correctly by K. Wurm [164], the difference between the envelopes in comet Morehouse and the envelopes in the other comets (the former were observed, as already indicated, directly in the second only from the motion of the rays in the tail) is apparently due to the difference in the chemical composition: the heads glow essentially in the neutral lines C_2, CN, C_3, etc., whereas in the head of Morehouse comet the glow is produced essentially by the CO^+ ions. In any case, this is one of the main reasons.

It was impossible to compare the appearance of the envelopes with the solar data, for even the Bartels geomagnetic indices are given every four hours, whereas the envelopes were generated sufficiently frequently one after the other, with intervals ranging from 20 minutes to two hours [42].

However, as noted by Eddington [42] and later by O. V. Dobrovol'skiĭ [29], during the observations of 2 October 1908, the altitudes at which the envelopes of comet Morehouse appeared were considerably larger than in other days, and a flare of solar activity occurred during the same night (allowing for reduction of the data to the comet): the Bartels index was twice the average of the remaining days [29]. It can thus be thought that a connection exists between the occurrence of the envelopes and the solar corpuscular streams. The first to point to such a possibility was Eddington [42], who proposed that this phenomenon is due to the entry of the comet into the stream of charged particles that move from the sun and exert an appreciable influence on the nucleus of the comet.

Later on S. V. Orlov [101,102] noted still another interesting fact, namely that the "collapsing" envelopes in comet Morehouse were generated at approximately the same altitude where the multilayer expanding dust envelopes are observed. For example, in the case of comet Morehouse the envelopes appear at an altitude of approximately one million kilometers [102].

The known parameters characterizing the envelopes include their velocities and the ratios of the sections of the visible arcs [42]. Nothing definite can be said concerning the change in velocity on approaching the nucleus, since there are only a few measurements and these are furthermore qualitatively different: for example on 27 October 1908 the envelope velocities clearly decreased, while on 30 October they were practically constant. This is particularly seen on the plots presented in [29,35].

The utter inconsistency of the mechanical theory when it comes to the "collapsing" envelopes was first pointed out by Eddington [42]. This was subsequently confirmed in [101-103,48,96,97].

The fact that the envelopes consist of ionized gas points to the important role of electrodynamics in this phenomenon. The first and apparently unsuccessful attempt to present an electrodynamic explanation of the "collapsing" envelopes are contained in [35,29]. According to [35] the envelope velocity is $v \cong 2 \times 10^4 t^2$ cm/sec, where t is the time of interaction between the head of the comet and the stream. For $t \sim L_S/v_S \sim 10^{12}/10^8 \sim 10^4$ sec (L_S is the "thickness" of the stream) we arrive at an absurdly large envelope velocity. The hypothesis of [35] also encounters many other difficulties.

A more probable scheme is proposed in [90]. The "collapsing" envelope is produced upon encounter with a corpuscular stream (or "wind" inhomogeneity), and constitutes the magnetic "piston" described in Sec. 3. The "collapse" is a consequence of the presence of a density gradient (see Sec. 3); so long as the wave is strong, the form of the envelope is determined by (3.7). The envelopes are observed because of the compression of the plasma in the shock wave which travels in front of the "piston." Since they have been photographed in integral light, it is clear that the compression of the ions in the shock wave by a factor of 6 will be more noticeable provided the gas of the coma is practically completely ionized as is the case, for example, in the Morehouse comet. In comets with a coma of low ionization the envelopes can hardly be observed at all, because of the insignificant increase in the glow of the ions, the number of which is small (numerical estimates are found in [90]). In this case, however, the envelopes still exist, although they are unobservable. This agrees with the opinion of K. Wurm [164].

The calculated envelope velocities, as can be seen from Table II and the data of Sec. 3, agree with the observations, and this agreement is better for the weaker streams—faculas and solar "wind."

The frequent appearance of envelopes is apparently connected with the structure of the stream. This idea belongs to O. V. Dobrovol'skiĭ and was confirmed by him by observations of the streams [35].

The existence of envelopes (even when they cannot be seen in the head but are detected by the motion of rays in a type I tail) once more offers evidence of the plasma nature of the coma: the envelope can be produced and move only when the protons of the stream transfer momentum to the gas of the comet via a magnetic field, which is possible if the coma is a plasma (Sec. 1). This "collapse" mechanism acts also in tails of type I (see Sec. 8); it explains in natural manner, as will be shown later, the dynamics of the ray systems. A detailed analysis of the phenomenon is contained in [90].

It is appropriate to note here the following. When comet Arend-Roland 1956h passed through perihelion in 1957, radio signals were received from it at frequencies 27.7, 600, and 1420 Mc. The 600 Mc signals were received in an 8° region centered about the nucleus. They were identified with monochromatic emission from the CH molecules, due to the transition between the sublevels of the Λ-doubling of the $J'' = 15$ level of the $^2\Pi_{3/2}$ state [26,148]. The radiation at 27.6 Mc (intensity $I = 5 \times 10^{-22}$ W/m^2 cps) was observed approximately 7000 miles from the nucleus in the tail, and the source moved away along the continuation of the radius vector [68,94]. However, this emission could not be observed in Cambridge [78]. Attempts were made also to observe radio emission from comet Burnham 1959k [25], comet Wilson [45], and comet Seki-Lines 1961c [135]. The results are contradictory: the effect was observed in [135] but not in [25,45]. In spite of the resultant doubts, it is appropriate to discuss briefly the probable mechanisms of radio emission from comets.

The equilibrium mechanisms analyzed in [120,150] are too weak. Nonequilibrium mechanisms are considered in [36], where it is shown that the radio emission due to the interaction between protons of the corpuscular stream with the dust component [44] and to synchrotron and Cerenkov radiation of electrons in a magnetic field, or the radio emission from atomic hydrogen in the comet atmosphere are all of low efficiency.

The hypothesis was advanced in [36] that the radio emission observed at 27.6 Mc is due to plasma oscillations. Favoring such a hypothesis are the singularities of the effect: decrease in intensity with the increasing frequency, continuous fluctuations in the intensity, and motion of the source. The 27 Mc frequency corresponds to an electron density $n_e \cong 3 \times 10^8$ cm^{-3}; it is therefore proposed in [36] that the tail ($n^e_{\text{tail}} \cong 10$—$10^3$ cm^{-3}) has inhomogeneities of the same density. The latter is doubtful [90], but the main idea advanced in [36] concerning the plasma oscillations is apparently correct.

A different scheme was proposed in [90]: the "collapsing" envelope described above sweeps the ionized component of the coma towards the center, and in some cases the density in the effective nucleus is, $n_e \cong 10^8$ cm^{-3}. A sausage-type instability in the front of the shock wave may cause plasma oscillations. The source moves along the tail because the plasma is swept by the magnetic field of the stream.

The transformation of plasma waves into radio emission having an intensity close to that from comets can be due to the scattering of these waves by fluctuations of the dielectric constant, and also in regions where geometrical optics are violated in the presence of large density gradients [21,85].

It is shown in [85,36] that radio emission from the comets cannot be reflected radio emission from the sun, as suggested in [159].

5. OUTLINES OF COMET HEADS

The shapes of the N, E, and C heads are due to understandable causes (see the introduction). The situation is worse with the M head, the outlines of which is close to a catenary [102,14,12] whereas mechanical theory leads to a parabola [102,101]. The round diffuse C head approaching the sun frequently decreases in size, becomes sharper, and goes over into an M head, and at the same time the type I tail increases.

If the densities of the ions and the neutrals are approximately equal in the peripheral parts of the coma, the outline of the head on the celestial sphere is determined by the configuration of the magnetic field which produces the ionized component. It is shown in [83,87] that in this case the outline of the head is actually described by the equation of the catenary

$$z = a \cosh \frac{y}{a}. \tag{5.1}$$

Of course, if the ionization is low, no ions can be seen in the spectrum and the field cannot determine the shape of the head [87].

For example, it is proposed in [134] that the compression of the coma on approaching the perihelion is caused by the magnetic and kinetic pressures of the solar "wind." Corroborating calculations are presented for the Encke's comet in which, according to the spectra, the coma is purely neutral. It is thus clear that the calculations of [134] are incorrect.

6. MOLECULE IONIZATION IN COMETS

As indicated, the CO^+, N_2^+, and CO_2^+ ions which are observed in the comets form type I tails. The ions are observed spectrally in the head only in a small region near a solid nucleus, the dimensions of which do not exceed 5000 km [165], whereas the diameter of the head of a comet of average brightness is on the order of $(2$—$5) \times 10^5$ km. The lifetimes of the parent molecules prior to the production of the ions of the kinds indicated can be obtained from different considerations, and amount approximately to $\tau_{p(CO^+)}$ $10^{3.5}$ sec [165]. Indeed, the temperature of the neutral gas ranges apparently from $T \cong 200°$K (temperature of the nucleus) to $T \cong 10^4$ °K (acquired by the "fragments" of the parent molecules during the dissociation [151]). Therefore a molecule moving with thermal velocity ($v_{T=104°K} = 2 \times 10^5$ cm/sec, $v_{T=200°K} = 2.83 \times 10^4$ cm/sec) will cover a path of 5000 km (the path prior to ionization) in a time $\tau = 2.5 \times 10^3$—1.77×10^4 sec.

Approximately the same value of $\tau_{p(CO^+)}$ is obtained from the oscillations in the emission of CO^+ [163]. The interval between the appearances of the "collapsing" envelopes such as of the comet Morehouse are also of the order of 1—2 hours; the ionization disturbed by the passing envelope, the magnetic field of which sweeps the ions from the head in a type I tail, should be restored within this time.

The causes of the molecule ionization in the comets are still not clear, since all the mechanisms considered are too weak to provide the observed degree of ionization. This was emphasized in the literature many times [165-167].

Indeed, in the field of solar photospheric radiation, $\tau_{p(CO^+)} \cong 10^{8.5}$ sec [29,165], which is five orders of magnitude larger than the observed value. In the field of the hard radiation from the chromosphere and the corona, $\tau_{p(N_2^+)} \cong 10^6$ sec [29,119]. Thus, the photoionization is apparently insignificant. Ionization by electron impact when the comet enters the solar corpusular stream is negligibly small [87]. Ion production by charge exchange [7,21] in accordance with the scheme $H^+ + M \rightarrow M^+ + H$, where M is the comet molecule, also leads to an exceedingly large time $\tau \cong 3 \times 10^6$ sec at a stream density $n_s \cong 10$ cm^{-3}. The need for such a large proton concentration in the stream, 2–3 orders of magnitude larger than the real value, is the main shortcoming of L. Biermann's theory [7].

Thermal ionization in a shock wave (according to Alfven's idea) is also insignificant, owing to low densities of the stream and of the coma [87].

It was proposed in [59] that the ionization of the comet molecules is due to the same factors as in the experiment of U. Fahleson [46]. Partially ionized gas (H_2, N_2) was placed between two coaxial cylinders A_1 and A_2 situated in a magnetic field, as shown in Fig. 11a. Following a discharge, the ionized component started to rotate, so that the situation analogous to that in a comet was created—a magnetized plasma "holing through" a neutral gas.

With increasing voltage, the speed of rotation increased, until some critical value was reached, after which the degree of ionization increased and the velocity remained constant at $v = v_{cr} =$ const. When the ionization approached 100%, the speed again began to increase (Fig. 11b). It is clear that if $v < v_{cr}$ the energy fed to the plasma goes into increase of the speed of rotation; at $v = v_{cr}$ saturation sets in and the energy goes into ionization. An extremely interesting fact is that v_{cr} satisfies the relation

$$\frac{Mv_{cr}^2}{2} = \chi_i, \qquad (6.1)$$

where M is the mass of the atom (molecule) of the gas under consideration and χ_i its ionization potential.

If the causes of this effect exist also in comets, then the ionization problem can be regarded as solved, since the energy of the corpuscular-stream protons satisfies Eq. (6.1) with some margin.

It is known that Eq. (6.1) can be satisfied for electrons by stretching the point somewhat ($M \rightarrow m_e$). For impact ionization the ion kinetic energy should be on the order of $\sim M\chi_i/m_e$. In this connection, Alfven [2] propose that in this case energy is being pumped over from the ions to the electrons. According to Alfven the colliding atoms knock out the ions from regions having excess electrons. The resultant potential difference accelerates the electrons to an energy on the order of χ_i. However, the Alfven mechanism is apparently not enough, since the distance over which the stratification of the charges occurs is on the order of the Debye distance. The potential difference resulting from this is $\ll \chi_i$ (S. B. Pikel'ner).

The theory of the Fahleson effect is given in [77]. In final analysis, the relaxation of the energy (of the electrons and ions) is the result of collisions, and does not take place in the "comet" case, when the relaxation time is exceedingly large [87] owing to the low stream density. Thus, the results of [46] can apparently not be extrapolated to include comets.

A qualitative solution of the ionization problem was proposed in [92], but quantitative calculations are necessary for final conclusions. The idea of [92] consists in the following. With progressing compression of the envelope, as described in Secs. 3-4, the magnetic field focuses the protons of the stream ("wind") towards the center of the head (see Fig. 9), and their density increases. The growth of the proton concentration in the stream increases the intensity of their charge exchange with the comet molecules. The decrease in the translational velocity of the magnetic "wall" and of the frozen-in protons, which results from the deceleration described in Secs. 3-4, does not affect the charge-exchange efficiency, in view of the conservation of the adiabatic invariant. Since the law governing the increase in the density of the ionizing protons should be close to the law governing the distribution of the density of the comet gas that decelerates the magnetic wall, we can apparently assume, in first approximation,

$$n_s = n_s^0 \left(\frac{\xi_0}{r}\right)^2, \qquad (6.2)$$

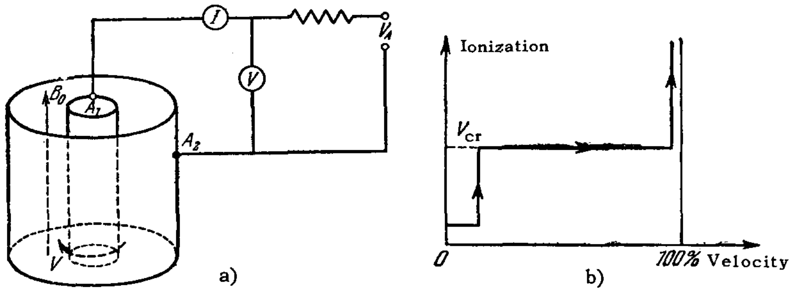

FIG. 11. Diagram for Fahleson's experiment[2, 46].

where ξ_0 is the radius of the comet head, r is the distance to the nucleus, and n_s^0 is the unperturbed density of the protons of the stream.

It is seen from (6.2) that prior to collision with the comet the stream can be quite rarefied. For example, for $\xi_0 \cong 10^{10}$ cm, $r_1 = 5 \times 10^8$ cm (region in which the ions are observed), and $n_s^0 \cong 10$ cm [3] we get $n_s(r_1) \cong 4 \times 10^3$ cm^{-3}. This ensures for the parent molecules a lifetime prior to ionization on the order of $\tau_{p(CO^+)} \cong 1.3 \times 10^4$ sec at $v_s \cong 3 \times 10^7$ cm/sec and $\tau_{p(CO^+)} \cong 4 \times 10^3$ sec at $v_s \cong 10^8$ cm/sec. Thus, in order to explain the observed ionization where is no need to use exceedingly dense corpuscular streams as was done by L. Biermann[7], for the focusing of the protons by the magnetic field explains both the observed lifetimes of the molecules in the comets prior to ionization and the nature of the small region near the nucleus where the ions are observed.

7. ACCELERATIONS IN IONIZED TAILS

As mentioned in the introduction, accelerations in type II and III comet tails are well explained by the radiation pressure of the sunlight ($1 + \mu \lesssim 1$). In type I tails, the accelerations are detected by the motion of the clouds (we do not know how these arise). Here $1 + \mu > 20$, and frequently $1 + \mu \sim 100$–1000 [133]. Once it became clear that these tails are gaseous, attempts were made to explain such high accelerations with the aid of the Pauli theory of radiation pressure in gases. Its first application to comets was presented by Wurm [162]. The acceleration of the comet molecules by radiation pressure was calculated by S. M. Poloskov [116,117].

The induced emission under the conditions prevailing in comets is practically nil. The recoil momenta in spontaneous re-emission are arbitrarily oriented and on the average the recoil is equal to zero. The acceleration is therefore determined by the momentum acquired by the molecule per unit time during the absorption of the quanta $\hbar\nu$. The upper limit of $1 + \mu$ is, in accordance with [116,117,162, 29],

$$1+\mu = \frac{2\pi e^2 h\nu^3 f_{12}}{m_e c^4 m_c (e^{h\nu/kT} - 1)} \frac{r_\odot^2}{a_\odot r_c^2}, \qquad (7.1)$$

where f_{12} is the corresponding oscillator strength, $r_\odot$ the radius of the sun, r_c the heliocentric distance of the comet, $a_\odot$ the acceleration of the force of gravity on the sun, and m_c the mass of the molecule.

The characteristic wavelengths were determined for the main components (CO^+, N_2^+). The CO^+ emissions—the so-called comet-tail bands—are due to the electron transitions $X\Sigma \to A^2\Pi$ with principal emissions at λ 4401–4023 Å. The N_2^+ emission is the first negative system $X^2\Sigma \to B^2\Sigma$ with principal emission at λ 3914 Å. This has made it possible to calculate the upper limit of the accelerations (f_{12} = 1) due to the radiation pressure, using formula (7.1). It was found to be large, $1 + \mu \cong 56$ [116,117], but insufficient to account for such high accelerations as $1 + \mu \cong 100$–1000. However, the gas in type I tails is a (CO^+, N_2^+) plasma, and the activity of such tails in different comets correlates well with the geomagnetic disturbances [6,81,54,34]. One can thus expect large $1 + \mu$ to be due to the interaction of plasma tails with corpuscular streams.

The first calculations of this kind were made by L. Biermann [5-9]. According to Biermann, the comet ions acquire momentum from the stream protons via dynamic friction with the electrons. The acceleration of a comet ion receiving momentum from a solar proton via friction with electrons is then given by [114]

$$\frac{dv_c}{dt} \approx \gamma_{ce} \frac{m_e}{m_c} v_e \approx \frac{e^2 n_e}{\lambda m_c} v_e, \qquad (7.2)$$

where λ is the conductivity.

At $T = 10^4$ °K we have $v_e = 10^8$ cm/sec, $n_e = 10^3$ cm^{-3}, and $dv_c/dt \approx 100$ cm/sec^2. However, as already mentioned, in streams and in the "wind" we have $n_e \ll 1000$ cm^{-3}, and the accelerations are $\gg 100$ cm/sec^2. Thus, dynamic friction seemingly does not explain the large values of $1 + \mu$. We note that exact allowance for the dynamic friction yields for the rate of energy transfer from the protons to the stream electrons [114]

$$\left(\frac{dw}{dt}\right)_{ei} = -\frac{4\pi}{\sqrt{2}} \ln \Lambda \frac{n_e e^4 m_p^{1/2}}{m_e w^{1/2}}. \qquad (7.3)$$

It is easy to verify that the energy transfer time will be less than the time necessary for the stream to pass through the head only when $n_e = n_s \approx 10^3$–10^4 cm^{-3}. In other words, the protons of the stream cannot transfer momentum to the comet ions via dynamic friction, owing to the large rarefaction of the plasmas in the stream and in the tail.

K. O. Kiepenheuer [67] proposed to take account of dynamic friction by making the substitution $m_e \to m_p$ in the formula for the force acting on the comet ion, so that $1 + \mu$ is increased, naturally by three orders of magnitude. However, such an assumption is utterly unjustified from physical considerations.

The acceleration of the comet ion in the plasma stream due to Coulomb and collective interactions is described by the well-known formula [24,140,108]

$$\frac{dv_c}{dt} = \frac{4\pi n e^4 \ln \Lambda}{m_c m_e c_e^2} G\left(\frac{v_c}{c_e}\right), \qquad (7.4)$$

where $c_e = \sqrt{2kT/m_e}$; the form of the function G is given in [108]. It is easy to verify that (7.4) yields dv_c/dt which is 3-4 orders of magnitude smaller than observed.

On the basis of the theory developed in [17,63,64,65, 104,105], the authors of [30,60] considered the deceleration of a comet plasma cloud in a corpuscular stream as a result of instability excitation. However, the heating of the electrons was not taken into account. As shown by R. Z. Sagdeev (see [108], Chap. 5, Sec. 15), this leads to incorrect results.

The question of the deceleration of a cloud by a comet plasma in a corpuscular stream by excitation of sausage instability is considered in greatest detail and from all aspects by Hoyle and Harwit [58]. It is assumed that there is no magnetic field or else that the magnetic field is parallel to the direction of relative motion of the stream and the cloud. In the latter case, as is well known, it exerts practically no influence on the character of the resultant instability. A four-component plasma is considered (comet and solar electrons, protons, and comet ions) in which the particles of species j has a distribution function

$$f_j(\mathbf{r}, \mathbf{v}, t) = n_j f_{0j}(\mathbf{v}) + f_{1j}(\mathbf{r}, \mathbf{v}, t), \tag{7.5}$$

where $n_j f_{0j}$ pertains to the equilibrium state. The function f_j satisfies the Boltzmann equation with a zero collision integral

$$\frac{\partial f_j}{\partial t} + \mathbf{v}\frac{\partial f_j}{\partial \mathbf{r}} + \frac{e_j}{m_j}\mathbf{E}\frac{\partial f_j}{\partial \mathbf{v}} = 0, \tag{7.6}$$

where

$$\mathbf{E} = \sum_j \int \frac{\mathbf{r}-\mathbf{r}_j}{|\mathbf{r}-\mathbf{r}'_j|^3} \int e_j f_{1j}(\mathbf{r}'_j, \mathbf{v}', t)\, d\mathbf{v}'\, d\mathbf{r}'_j.$$

The first approximation of f_j, as usual, satisfies the equation

$$\frac{\partial f_{1j}}{\partial t} + \mathbf{v}\frac{\partial f_{1j}}{\partial \mathbf{r}} + \frac{e_j}{m_j}\mathbf{E}\frac{\partial f_{0j}}{\partial \mathbf{v}} = 0. \tag{7.7}$$

If we introduce the notation

$$F_1 = \sum_j e_j f_{1j}, \qquad F_2 = \sum_j \omega_{0j}^2 f_{0j} = \sum_j \frac{4\pi n_j e_j^2}{m_j} f_{0j},$$

then, multiplying (7.7) by e_j and summing over j, we get

$$\frac{\partial F_1}{\partial t} + \mathbf{v}\frac{\partial F_1}{\partial \mathbf{r}} + \frac{\mathbf{E}}{4\pi}\frac{\partial F_2}{\partial \mathbf{v}} = 0. \tag{7.8}$$

It is easy to see that (7.8) coincides, apart from a constant, with the equation for the first approximation of f_1 to the distribution function of a one-component plasma.

The problem reduces therefore to the application of the known stability criteria of a one-component plasma to the function F.

The correction F_1 is given in the form

$$F_1(\mathbf{r}, \mathbf{v}, t) = g(\mathbf{v})\, e^{i(\mathbf{kr}-\omega t)},$$

where ω and k are constants. Choosing the coordinate system such that the relative motion is on the Oz direction, they introduce the quantities

$$F_0(v) = \int\!\!\int_{-\infty}^{+\infty} F_2(\mathbf{v})\, dv_x\, dv_y, \tag{7.9}$$

$$u = \frac{\omega}{k}, \tag{7.10}$$

where $v = v_z$ and $|\mathbf{k}| = k_z$.

Then, using the Nordlinger criterion [98], the authors obtain a stability condition in the form

$$U(u) \equiv \mathcal{P}\int_{-\infty}^{+\infty} \frac{F'_0(v)\, dv}{v-u} > 0, \tag{7.11}$$

where $\mathcal{P}$ denotes that the integral is taken in the sense of the principal value; u is a real quantity satisfying the condition

$$F_0(u) = \min. \tag{7.12}$$

If all the unperturbed distribution functions f_{0j} are Maxwellian, then the final general expression for F_0 is

$$\begin{aligned} F_0(v) = \int_{-\infty}^{+\infty} \Big\{ & \omega_{se}^2 \left(\frac{2\pi kT_{se}}{m_e}\right)^{-\frac{3}{2}} \exp\left[-\frac{m_e(\mathbf{v}-\mathbf{v}_s)^2}{2kT_{se}}\right] \\ & + \omega_{ce}^2 \left(\frac{2\pi kT_{ce}}{m_e}\right)^{-\frac{3}{2}} \exp\left(-\frac{m_e\mathbf{v}^2}{2kT_{ce}}\right) \\ & + \omega_{sp}^2 \left(\frac{2\pi kT_{sp}}{m_p}\right)^{-\frac{3}{2}} \exp\left[-\frac{m_p(\mathbf{v}-\mathbf{v}_s)^2}{2kT_{sp}}\right] \\ & + \omega_{ci}^2 \left(\frac{2\pi kT_{ci}}{m_i}\right)^{-\frac{3}{2}} \exp\left[-\frac{m_i\mathbf{v}^2}{2kT_{ci}}\right]\Big\}\, dv_x\, dv_y, \end{aligned} \tag{7.13}$$

where the subscripts se and sp stand for the solar electrons and protons, ce and ci for the comet electrons and protons, and ω_{se}, ω_{sp}, ω_{ce}, and ω_{ci} are the corresponding plasma-oscillation frequencies.

Having (7.13) and (7.11), we can investigate cases in which the interaction between the stream and the plasma of the tail gives rise to an instability.

It is suggested in [58] that the main mechanism for the production of comet ions is the already-described charge exchange

$$\mathrm{H}^+ + \mathrm{M} \rightarrow \mathrm{M}^+ + \mathrm{H}.$$

This leaves in (7.13) the solar electrons and the comet ions, and after making the change of variables

$$\xi = \frac{v}{v_s}, \quad \alpha_1 = \left(\frac{kT_{se}}{m_e}\right)^{\frac{1}{2}} v_s^{-1}, \quad \alpha_2 = \left(\frac{kT_{ci}}{m_c}\right)^{\frac{1}{2}} v_s^{-1} \tag{7.14}$$

the stability criterion (7.11) takes on the form

$$U(\xi) = -\left[\frac{\omega_1^2}{\alpha_1^2}\frac{h(\xi-1)}{\alpha_1} + \frac{\omega_2^2}{\alpha_2^2} h\left(\frac{\xi}{\alpha_2}\right)\right] v_s^{-1} > 0, \tag{7.15}$$

where

$$h(y) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} \frac{x}{x-y}\, e^{-\frac{x^2}{2}}\, dx$$

is a function tabulated by Unsold [149].

The authors of [58] assumed a stream electron temperature $T_{se} \sim 2 \times 10^6$ °K, that is, a temperature equal to the electron temperature of the solar corona. In this case the interpenetrating plasmas of the stream and the comet are stable. If we choose T_{se} considerably lower (for example, $T_{se} \approx 10^4$ °K, which is closer to the truth), then instability sets in. However, owing to the heating of the electrons, the instability rapidly terminates and the total momentum transferred by the stream to the cloud is exceedingly small [58]. Thus, the results of [58] confirm the conclusions of R. Z. Sagdeev (see [108], Chap. 5, Sec. 15). Summarizing we can state that the loss of relative-motion energy to the excitation of the instability is too small to explain the observed accelerations.

Taking into account Alfven's ideas [1] on the importance of the magnetic fields "frozen in" the streams, the author has advanced in [84,87,90,91] the hypothesis that the proton momentum is transferred from the stream to the comet ions via a transverse magnetic field (see Sec. 2). The stream can penetrate into the magnetic field, which is localized in the cloud, a distance on the order of $\Delta x \approx \sqrt{r_H^i r_H^e}$ [52]. For $v_s \approx 10^8$ cm/sec and $H = 10^{-4}$—10^{-5} Oe we get $\Delta x \approx 2 \times 10^7$—$2 \times 10^6$ cm, whereas the linear dimensions of the clouds are of the order of $l_0 \approx 10^9$ cm, so that the stream practically does not penetrate into the cloud. We can thus assume in first approximation that the stream flows around the cloud as if the latter were some "solid" body (the arguments can be modified by assuming that the magnetic field is present only in the stream). Therefore the acceleration acquired by the cloud can be estimated qualitatively by using the formula for the pressure on a streamlined body [70] (a similar method was first used by L. I. Dorman [40]). The acceleration of the cloud is expressed by the formula [91]

$$\frac{dv}{dt} \approx \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}} \gamma^{-\frac{1}{\gamma-1}} \frac{PM^2}{n_c m_c l}, \qquad (7.16)$$

where P is the pressure in the stream, M is the mach number, and $\gamma = c_p/c_V$.

If, for example, the cloud is exposed to a solar "wind" ($v_s \sim 3 \times 10^7$ cm/sec, $n_s \approx 1$ cm^{-3}; $n_c \approx 10^2$ cm^{-3} is the ion density in the cloud), then $dv/dt \approx 300$ cm/sec^2.

An idea which is similar in general outline, namely the transfer of momentum via a magnetic field, was independently advanced in [52].

This question was considered quantitatively in [86,91]. The shock wave passing through the effective nucleus (see Sec. 3) is accelerated by the decrease in the plasma density along the tail axis (Oz). The density fluctuations can "compress" the front of the wave, owing to an instability of the Rayleigh-Taylor type. The apparent results are cloud formations with localized magnetic fields. Clouds together with the remaining plasma are accelerated behind the acceleration front. The gas behind the front (and the clouds) are set in motion by a magnetic field which "seeps in" together with the front through the effective nucleus; this is the "piston," dragged by the stream, which transfers the momentum to the plasma behind the front.

Indeed, as indicated in Sec. 3, the stream is stopped by the effective nucleus; the shock wave attenuates to a sound wave and passes through the nucleus. At $T = 10^4$ °K, the front velocity is $D_{2c} \approx v_T \approx 3 \times 10^5$ cm/sec. Owing to the low degree of ionization, the magnetic field diffuses through the effective nucleus with velocity [108]

$$v_D \approx \frac{c^2}{4\pi\lambda_3 r_1}, \qquad (7.17)$$

where r_1 is the radius of the effective nucleus and λ_3 is the effective conductivity, which is much lower than λ because of the losses to collisions with the neutral molecules.

It is known [108,62] that

$$\frac{\lambda}{\lambda_3} \approx 1 + \frac{\varphi^2}{kk_e + kk_i + k_e k_i},$$

where $\varphi = n_n/n$—fraction of the neutral molecules, $k = (\omega_e \tau)^{-1}$, $k_e = (\omega_e \tau_e)^{-1}$, $k_i = (\omega_i \tau_i)^{-1}$, ω_e and ω_i—electron and ion gyrofrequencies, $\tau_e \approx (n_e \overline{v}_e \sigma_{en})^{-1}$, $\tau_i \approx (n_i \overline{v}_i \sigma_{in})^{-1}$,

$$\tau \approx \frac{(kT)^2}{n_e e^4 \overline{v}_e \ln \Lambda}$$

is the lifetime prior to the collision between the electron and the ion with the neutral molecule or the electron with the ion, respectively, and σ_{en} and σ_i are the corresponding effective cross sections.

Since $kk_i \gg kk_e \gg k_e k_i$, we have $\lambda/\lambda_3 \approx \varphi^2/kk_i$. If the charge density in the effective nucleus is $\overline{n}_i \approx \overline{n}_e \approx 10^6$ cm^{-3} [86,164], the field $H \approx 10^{-5}$ Oe, $T = 10^4$ °K, and $\lambda_3 \approx 2 \times 10^{-6} \lambda$. For $\lambda \approx 7 \times 10^{12}$ sec^{-1} (see Sec. 2) this yields $v_D \approx 10^5$—10^6 cm/sec, *that is, a quantity on the order of* v_T.

The cloud acceleration due to the decrease in the density along the tail axis is described by the approximate formula [91]

$$\frac{dv}{dt} \approx -540 v_T^2 n^{-1.43} \frac{dn}{dz} \ \frac{\text{cm}}{\text{sec}^2}. \qquad (7.19)$$

It is curious that (7.19) leads to still another effect, which has long been known to observers [29,55], namely the decrease in the acceleration along the tail with increasing distance from the nucleus. It is easy to see that it is a consequence of the type of density distribution n(z), and always takes place when $n \approx n_0 (z_0/z)^2$.

8. STRUCTURAL FEATURES OF IONIZED TAILS

Unlike dust and gas-dust tails of types II and III, type I tails have a rich and highly varied structure (see Fig. 2) and abound with fine details. This is connected with their plasma nature, since the structure is determined by the electrodynamics.

The most substantial current work on the statistical laws that are inherent in tails of type I is that of C. Hoffmeister [54], in which 202 pictures of 13 comets are investigated.

The main laws are as follows [54] (cited in [29]):

1. The so-called primary ray (primäre Schweifstrahle) is deflected, as a rule, back from the continuation of the radius vector, that is, in the direction from which the comet moves; the deflection angles β are most frequently smaller than 5° but reach 15—20° in exceptional cases. Forward deflections from the continuation of the radius vector are rare and small. Rapid changes in the direction of the primary ray are observed for several hours and occur in such a way that the ray breaks away and a new ray with

different direction appears in the internal part of the coma.

2. The more active the comet, the larger the backward deflection of the primary ray and reaches a maximum at the time of the richest development of the structure of the coma and the tail, frequently in connection with the increasing brightness.

3. There is a statistical connection between β and r_c; the backward deflections decrease with increasing r_c; the few examples of forward deflections are observed predominantly at large r_c.

4. The degree of activity of different comets is quite different. Some respond very rapidly and even at large r_c disclose lively activity and a rich structure (1908 III), while others have low activity (1894 II).

All this needs to be explained. We note that in the opinion of Biermann [7]

$$\tan\beta = \frac{v_t}{v_s},$$

where v_t is the transverse component of the orbital velocity of the comet, and v_s is the velocity of the corpuscular stream. An analogous formula was written down by Alfven [1].

In addition to the general laws written above, which pertain to tails as a whole, there are many effects which can likewise not be explained by the mechanical theory. These include, for example, wave motion in tails, helical motion, the appearance of individual jets and streams which form in their aggregate the ray system, the "collapse" of the rays (jets) towards the axis of the tail, and many others.

Of all the mentioned and unmentioned effects, the literature deals principally with the "collapse" of the rays and the wave motion. For example, as noted by Wurm [166], the origin of the jets and streams in the tails is not clear in principle. Their length is of the order of [47] $l \approx 10^{11}-10^{13}$ cm and the diameter is $d \approx 2000$ km. It can be assumed that they are the results of a flute-type instability (S. B. Pikel'ner): the magnetic "piston" breaks up and the plasma flows off in the "flutes." In order to confine the plasma in such a ray, it is necessary to have a field on the order of $H \cong 6 \times 10^{-6}$ Oe [82] ($d \cong r_H^i$ at the thermal velocity of the comet ion).

The "collapse" of the rays towards the tail axis, which is reminiscent, in accordance with the picturesque expression of O. V. Dobrovol'skiĭ [29] of "the motion of the ribs of a closing umbrella" (see Fig. 1), was considered by many authors.

The ray system in the tail of the comet Morehouse 1908 III was considered in [143]. According to [143] the "collapse" is a kinematic effect; the head of the comet screens the tail against the corpuscular stream. The screening is stronger near the nucleus, where the density is larger and where there are more collisions, and is smaller near the edges of the head. Consequently an acceleration gradient along the Oy axis exists in the tail (Fig. 12) and this visually leads to a "collapse": the points farther away from the symmetry axis move more rapidly than those close to the axis.

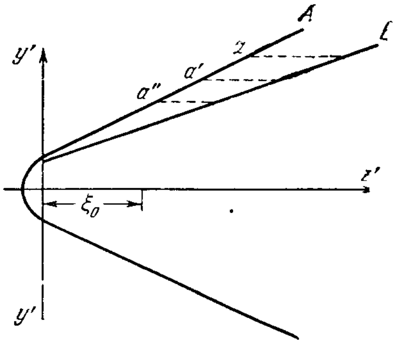

FIG. 12. "Collapse" of rays – ends of envelopes – to the end of the tail, a kinematic effect. The density gradient along the Oy axis produces an acceleration gradient in the same direction, so that $v_a > v_{a'} > v_{a''}$ (see also[166]).

It is shown in [166] and [37] that the screening described above does not take place. The cause is still the same: in order to screen the tail effectively it is necessary to have many collisions, whereas the stream and the coma are rarefied. In order to reconcile theory with observations it is necessary to increase the density of the coma by 2–3 orders of magnitude [37] over the really possible values. However, Wurm [166] still assumes that the "collapse" is a kinematic effect, although the origin of the acceleration gradient along the Oy axis remains unclear (the screening is refuted, as in [37]). It is probable that the "collapse" of the rays towards the tail axis is caused by the same factors as the contraction of the envelopes [86,90] (all the more since the rays are ends of envelopes). Owing to the presence of a density gradient along the Oy axis, the parts of the shock wave front and of the magnetic "piston" closer to the tail axis move more slowly and the farther parts move more rapidly. An acceleration gradient is produced in the Oy direction, along with a kinematic "collapse" (see Fig. 12). In this case there is no need for high densities, since the momentum is transferred via the magnetic field even in the absence of collisions.

Quantitative calculations of such a model were made in [122]. The geometry of the front (ray) is described by (3.7); the distribution of the plasma density in the tail was chosen in the form

$$n \cong n_0 \left(\frac{z_0}{z}\right)^{1/2} \left(\frac{y_0}{y}\right)^2 .$$

The calculated velocities and accelerations of the "collapse" agree with the observations. The theoretically calculated outlines of the rays are also close to those observed.

A hypothesis has been advanced (B. Yu. Levin) that an important role may be played in the motion of the ray towards the tail axis by the reflection of the plasma from the magnetic field localized in the ray. The form of the ray was calculated in [61] using an "elastic" model analogous to that of [83].

Wave motion is usually observed in well developed type I tails. They are clearly seen on Figs. 3 and 4. The parameters of the waves were measured only for comet Morehouse 1908 III by Wolf [160]. According to Wolf, the amplitude A and the wavelength Λ increase with increasing distance from the nucleus in the tail. The measurement results are given in [169]. An attempt is made in [89] to analyze the phenomenon theoretically.

In accordance with [1], it is assumed that the waves propagating along the rays are Alfven waves. It is shown that the increase of A and of Λ with increasing distance from the nucleus is due to the increase in the local Alfven velocity $V = H/\sqrt{4\pi\rho}$.

The increase in V(z) denotes that the field H in the tail decreases with increasing z more slowly than the density ρ. The distribution of the field in the tail of comet Morehouse 1908 III was found theoretically within the framework of these assumptions.

We note that when the tail enters the corpuscular stream, the instability condition with respect to excitation of Alfven waves is satisfied with a large margin; this condition is of the form [3]

$$v_s^2 > V^2 + V_s^2,$$

where V_S and V are the Alfven velocities of the plasmas in the stream and in the comet.

Thus, the appearance of Alfven waves in type I tails is quite probable.

The helical motions of some details in tails of type I were observed in [82,160]. The question of the origin of this effect remains presently open, although some possibilities are discussed in [89]. It has been shown that the helical is not the result of the motion of electric space charge in the magnetic field of the tail, since its magnitude (in order to reconcile it with the experimental data) should be five orders larger than the permissible values [109].

Interaction between the corpuscular stream and the plasma tail stops the electrons rapidly and causes the protons to move farther. The resultant current in the magnetic field is acted upon by an Ampere force j × **H** normal to the velocity, which can therefore result in helical motion. The motion of the nodes in solar prominences was interpreted in this manner in [112,113].

According to calculation [89], this effect is small in comets, owing to the large self-inductance (the electrons are rapidly attracted to the protons). To ensure accelerations on the order of $\sim 10^3$ cm/sec^2 it is necessary to have an unrealistically large field $H \cong 1-10$ Oe. However, sausage instability arises in the case described, as already mentioned. This leads to an effective decrease in the conductivity and self inductance [111], and this may greatly reduce the estimates of [89].

A helix can occur also for another reason, the presence of force-free fields. For example, for stationary flow of solar "wind" around the tail, the equations of magnetohydrodynamics take the form*

$$[\mathbf{v}\,\mathrm{rot}\,\mathbf{v}] + \frac{1}{4\pi\varrho}[\mathbf{H}\,\mathrm{rot}\,\mathbf{H}] = -\frac{1}{\varrho}\nabla\left(p + \frac{\varrho v^2}{2}\right), \quad (8.1)$$

$$\mathrm{rot}\,[\mathbf{v}\mathbf{H}] = 0, \quad (8.2)$$

$$\mathrm{div}\,\mathbf{H} = \mathrm{div}\,\mathbf{v} = 0. \quad (8.3)$$

In first approximation the plasma is assumed to be incompressible, non-viscous, non-heat-conducting, and with infinite electric conductivity. Since the field H in the tail is approximately parallel to the axis of the tail Oz, and the "wind" is also radial, we can put v ∥ H. Then for

$$p + \frac{\varrho v^2}{2} = \mathrm{const}$$

H satisfies the equation [89]

$$\mathrm{rot}\,\mathbf{H} = \frac{\mathrm{const}}{1-A^2}\mathbf{H} = \beta\mathbf{H}, \quad (8.4)$$

where A = v/V, to which the system (8.1)—(8.3) reduces.

The solution of (8.4) yields the known force-free helix [80]

$$H_z = cJ_0(\beta r), \qquad H_\varphi = cJ_1(\beta r), \quad (8.5)$$

where J_0 and J_1 are Bessel functions of zeroth and first orders, while r, φ, and z are the polar coordinates.

If a force-free magnetic field therefore exists in the tail, then, by virtue of the "freezing-in" principle, the clouds of the comet plasma will move along **H** in a helix. However, all these qualitative considerations call for a quantitative verification. It is also very important to consider the influence of the electric fields on the processes in the comets.

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*rot = curl, [vH] = v × H.

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