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21 — PHYSICAL PROCESSES IN COMET TAILS AND THEIR RELATION TO SOLAR ACTIVITY

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The investigations on cometary tails, about which I am going to give you an account, may be regarded as an application of plasma physics to an astronomical problem. The term « plasma » is used in this connection to indicate an ionized gas, in which the particles of opposite electric charge are distributed in space in such a way that, to a very high degree of approximation, no separation of opposite charges occurs *). Of course only structures consisting of CO^+, N_2^+ or other ions (CN^+ or C_2^+ would be invisible, as are also CO and N_2) can be looked upon from this point of view; but it is well known, that ionized gases are typical for a large class of tails (the others consisting chiefly of dust).

The first indication, that the plasma properties of the tail gas might be important, was furnished by the ray structure often observed; according to an investigation

*) more precicely : The electric space charges are assumed to be so small that all displacement currents and convective electric currents arising from mass motions as well as the mechanical forces resulting from the action of the electric fields on these space charges can be neglected.

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by Wurm a temperature of the order of 1°K would be just compatible with the observed properties of the rays, if only gravitation and the pressure of light act on the tail molecules.

The obvious suggestion, from the standpoint of plasma theory, is that there are magnetic fields connected with each single ray in such a way, that the diffusion of the cometary ions into the surrounding interplanetary gas is hindered. I considered this hypothesis in a paper read at the meeting of the « Astronomische Gesellschaft » of 1950. This investigation has not been published, since the results of my later work make necessary a rediscussion of this earlier one.

I now turn to the theory of the acceleration of the ionized matter in cometary tails. Accelerations of the order of 100 times solar gravity have often been observed; in some cases values $\gtrapprox 10^3$ have been found either directly from the motion of individual structures visible in the tail (as in Comet Halley on June 4 — 8, 1910 cf. Bobrovnikoff, Publ. Lick XVII, 1931, part 2) or from the form and the development of certain envelopes (Comet Morehouse, 1908 observations discussed by Eddington M. N. **70**, 442, 1910).

It seems quite impossible, to account for accelerations of this order of magnitude by the action of the pressure of solar light; the oscillator strength of the transitions in question would have to be of the order of 2 resp. $\gtrapprox 20$ for this, (Wurm, Hamb. Mitt. **8**, N° 51, 1943) whereas it is actually, according to all available evidence between 10^{-2} and 10^{-1}. Only the accelerations of the order of 1, usually observed in cometary structures consisting of

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non-ionized gases, are readily explained by the light pressure theory.

From geomagnetism much has been learned in recent years about the corpuscular radiation of the sun. It is known, that these streams (at least those producing geomagnetic effects) are ionized and travel with speeds of between some 100 and some 1 000 km/sec. Little was known until recently about the density of these streams. An estimate of Unsold and Chapman, based on spectrographic as well as on radio observations during storms was 10^5 ions/cm^3 for the density inside a stream producing a very strong magnetic storm.

I assume for the following discussion, that under normal, magnetically undisturbed conditions the particle density of solar corpuscular radiation is of the order of 10^3 particles/cm^3 in the vicinity of the earth, and that it goes up to 10^4 or 10^5 (cm^3) during magnetic storms. This estimate is based on the observation, that also on days magnetically quiet in middle latitudes almost always some magnetic activity is found in high latitudes, showing that corpuscular solar radiation is probably never absent. For the details of this estimate I may refer to my first paper (Z. Astrophysik **29**, 274, 1951).

It seems reasonable to regard the polarising part of the interplanetary matter found from observation of the zodiacal light as essentially consisting of this solar corpuscular radiation. Then Siedentopf's recent observations, leading to a value of $\approx 10^{2.8}$ cm^{-3}, appear to be in fair agreement with my estimate.

The electron temperature of the ionizing matter is assumed to be $\approx$ 10 000°.

I shall use the equations of plasma dynamics in a form

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proposed by A. Schlüter *). As far as physical consequences are concerned they are equivalent to those given for instance in the well known treatise of Chapman and Cowling. In astrophysical applications (in contrast to ionospheric ones) this formulation appears to have some advantages, but I do not propose to enter into a discussion of this problem, since it is of no particular interest in the present connection.

We denote mass velocities by **v** and indicate the constituent, to which it refers, by the index m (ionized cometary molecule), p (proton, as main constituent of the solar ionized matter), or e (electron). Similarly by m_m, m_p, m_e the masses resp. of a molecule, a proton or an electron, by γ_{mp} sec^{-1} the probability, that a particular molecule suffers a collision with a proton; hence γ_{mp} and γ_{pm} are proportional to the volume densities n_p, n_m. The condition of quasineutrality is expressed by $n_p + n_m = n_e$. Finally **E**, **H**, e and c have there usual meaning.

The equations expressing the balance of momentum for each of the three constituents are now :

$$m_m \frac{d\mathbf{v}_m}{dt} + \frac{m_m m_p}{m_m + m_p} \gamma_{mp}(\mathbf{v}_m - \mathbf{v}_p) + \frac{m_m m_e}{m_m + m_e} \gamma_{me}(\mathbf{v}_m - \mathbf{v}_e) = $$

$$= e\mathbf{E} + \frac{e}{c}[\mathbf{v}_m \mathbf{H}]$$

$$m_p \frac{d\mathbf{v}_p}{dt} + \frac{m_p m_m}{m_m + m_p} \gamma_{pm}(\mathbf{v}_p - \mathbf{v}_m) + \frac{m_p m_e}{m_p + m_e} \gamma_{pe}(\mathbf{v}_p - \mathbf{v}_e) = $$

$$= e\mathbf{E} + \frac{e}{c}[\mathbf{v}_p \mathbf{H}]$$

*) Z. Naturforschung 5a, 72, 1950.

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$$m_e \frac{dv_e}{dt} + \frac{m_m m_e}{m_m + m_e} \gamma_{em}(\mathbf{v}_e - \mathbf{v}_m) + \frac{m_p\, m_e}{m_p + m_e} \gamma_{ep}(\mathbf{v}_e - \mathbf{v}_p) =$$

$$= - e\mathbf{E} - \frac{e}{c}[\mathbf{v}_e \mathbf{H})]$$

These equations may easily be brought into a form expressing Ohm's law; by this the connection between the γ's and the ordinary electric conductivity σ [e.s.u.] is found to be :

$$\gamma_{em} + \gamma_{ep} = \frac{e^2 n_e}{\sigma m_e} = 10^{-4.3}\, n_e \quad (T_e = 10^4)$$

The resulting value of the γ's corresponds to an effective collision cross section higher by some powers of 10 than the ordinary cross section of nonionized molecules.

We shall now consider the special case $n_p \gg n_m$ and $v_m \ll v_p$ at the time $t = 0$; the ionized molecules are supposed to be produced by one of the mechanisms to be discussed later, their non-ionized parents exerting practically no influence on the plasma on account of their comparatively small collision cross section. Then $\mathbf{v}_m$ and $\mathbf{v}_e$ will be practically parallel to $\mathbf{v}_p$. Furthermore we neglect for this treatment variations of n_m or n_p in space; this means, that we exclude from our discussion phenomena such as the ray structures. Our present purpose is only to get an insight into the mechanism by which the acceleration is produced.

Finally, we work now with the assumption $\mathbf{H} = 0$, but we shall return to this point later.

Numerically we assume $n_p \approx 10^3$ (eventually 10^4 or 10^5) (cm^{-3}), $v_p = 10^8$ cm/sec and $n_m \approx 10^1$.

The discussion in my paper referred to already shows

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that the following picture is probably a fair approximation to reality. Momentum is gained by the ionized molecules by their collisions with the electrons, which move practically with the same velocity as do the protons; the collisions of solar protons with cometary ions, may be neglected to a first approximation. Thus it may be said, that there is much friction between the solar protons and the electrons and between the latter and the cometary ions, but little friction between solar and cometary ions. The electrons transfer momentum between the ions of the two kinds. :

The acceleration of the cometary ions (CO^+, N_2^+) is now seen to be :

$$\frac{dv_m}{dt} \approx \gamma_{me} \frac{m_e}{m_m} v_e =$$

$$= \frac{e^2}{\sigma m_m} n_e v_e \approx 10^2 \frac{\text{cm}}{\text{sec}^2}$$

with $n_e = 10^3$; in magnetic storms values up to 10^4 cm/sec² appear possible. A very small electric field — of order 10^{-16} e.s.u. — turns out to be sufficient to keep this state stationary, by giving the electrons the necessary deceleration.

It is thus found, that the accelerations of the CO^+ and N_2^+ formations observed in the tails are easily explained in terms of the friction between the solar and the cometary ions.

When the corpuscular solar radiation carries with it magnetic fields, even stronger forces might act on the cometary ions, as suggested to me by Dr A. Schlüter. But so far — owing to the difficulty of making detailed assumptions on the fields in question — no quantitative estimate

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(beyond one showing just the possibility of this mechanism) has become possible.

If the considerations presented so far correspond to reality, one should expect a correlation between solar corpuscular activity, as shown e.g. by geomagnetic data, on one hand, and the accelerations in the comets on the other hand. The difficulty to establish such a correlation is, of course, that the active regions on the sun not only radiate into certain solid angles, the direction of which changes with the rotation of the sun, but vary also considerably with time. A close correlation therefore will be expected only, if the angle comet-sun-earth is not too large. Another difficulty is, that only for few comets the accelerations in the tail have been observed sufficiently.

So far only three comets have been studied from this point of view. The work on comet Whipple-Fedtke (1942g) and that on comet Halley (1910) has been published [1]), while that on comet Morehouse (1908) has not yet been finished. But the results obtained so far for this latter comet seem to confirm, in a general way, those found for the two comets first named.

The comet 1942g was observed extensively on the Sonneberg observatory by Hoffmeister and his colleagues in the first months of 1943. By far the highest accelerations (up to $10^{2.8}$ ⊙, ⊙ denoting solar gravity) were observed in the night 29./30. III., when the angle comet-sun-earth was rather small, (compared with the probable width of the emitting cone on the sun). On this date there was a magnetic storm (of intensity 7 in the scale of 9).

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[1]) *Z. Astrophysik l. c. a.*; *Z. Naturforschung* 7a, 127, 1952.

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The second highest accelerations (and other unusual features similar to such observed on March 29/30, exclusively) were observed on March 3; the synodic rotation period of the sun, as viewed from the comet, was 26.5 days at that time. There was no particular geomagnetic activity on this date, but 27 days later, when the comet was no longer observable at Sonneberg, there was again a small magnetic storm. Hence it appears reasonable to attribute all these phenomena to the action of the same active region on the sun.

The observations of the 1910 apparition of Halley's comet have been discussed very fully by Bobrovnikoff (l.c.a.). From his study it appears that accelerations higher than 100 ⊙, were observed on April 21.7 when it was 238 ⊙ and in the period June 5-9; in the latter period values up to 2300 were observed.

The motion of Comet Halley is retrograde; the angle between its orbit and the plane of the ecliptic is 18°, and the solar distance at perihelion (April 20) is 0.59 a.u. From these data it is found, that on April 22 and on June 6 the comet was (when the change in heliographic latitude is neglected) above the same region on the sun, the mean synodic rotation period of the sun (as viewed from the comet) being only 22 days. On the intermediate date (May 14) the comet was approaching an inferior conjunction with the sun, which took place on May 18. No accelerations were observed during the period May 13-23.

The dates (of cometary phenomena) April 22 and June 6 correspond, when referred to the earth, to the 18th day of rotation 1058 and 1060 of the sun, in the system of Chapman and Bartels (Geomagnetism). It corresponds to a fairly long lived active region on the sun, which is

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easily recognized in the table of the character figures of geomagnetic activity *) and is, on the average, probably the most active one during the 13 rotation periods 1053-1065.

1053	N15	-52	2.6	44.	..2	5.3	765	23.	3--	-.-
1054	D12	.56	454	433	543	-.2	2.2	.43	..3	32.
1055	J 8	-4.	-44	3--	623	.35	466	642	.--	.55
1056	F 4	42-	--3	22.	.54	365	.66	435	644	444
1057	M 3	355	55.	332	-55	455	325	54.	---	686
1058	M30	676	635	22-	-.-	-52	.-2	464	.-3	543
1059	A26	376	553	443	223	-32	2.5	443	455	3.2
1060	M23	356	534	334	2.-	.-2	.55	442	3--	-.-
1061	J19	276	543	442	.4-	--3	465	534	42-	--2
1062	J16	.22	32.	344	32-	.53	255	454	---	274
1063	A12	.35	3.2	565	675	52.	266	544	3..	254
1064	S 8	2.4	4.4	525	2.-	555	457	555	754	667
1065	O 5	474	423	467	42-	--7	664	556	676	442
Number of										
$C_g \geq 5$		187	532	223	332	355	2910	643	332	353
$C_g \geq 4$		399	856	765	453	455	5911	11107	544	586

Daily geomagnetic character figures of the rotations 1053 tot 1065 (beg. Nov. 15, 1909).

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*) Chapman, S. and J. Bartels, *Geomagnetism*, Oxford Univ. Press., 1940.

J. Bartels, *Tägliche erdmagnetische Charakterzahlen* 1884-1950, Göttingen Vandenhoeck ù. Ruprecht 1951.

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As far as these facts are concerned, the theoretical expectations may probably be said to be substantiated by the observations. It has not been found possible, to account similarly for the minor variations of cometary activity (as shown by observations of the tails); it seems reasonable to assume, that for these the correlation is rather completely blurred by the variation with time of the solar activity.

Another observational fact, which may be related to the theoretical picture presented here, is this. Hoffmeister found, from the discussion of a large number of comets, that there is generally an angle between what he calls the primary tail and the radius vector sun-comet, in such a sense, that the tail appears to lag behind in the plane of the comet's orbit by an angle of a few degrees.

Since the comet is moving across the plasma in interplanetary space with a velocity of the order of 40 km /sec, the acceleration should not be exactly in the direction away from the sun, but inclined to it by an angle given by the proportion of this transverse component of its velocity to the velocity of the solar matter (of order 1 000 km /sec). Hence generally speaking theory and observation seem to be in accord. When looking into details, it is found, however, that there are certainly other still agents (magnetic fields ?) influencing the direction of the tails. Certain occurrences (e. g. in the history of comet Morehouse 1908) give rather definite indications for this.

According to our picture the comet's tails may now be regarded as test objects for the corpuscular activity of the sun. In contrast to the earth comets may reach any heliographic latitude. In particular no gross decrease

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towards high latitudes of the intensity of the solar corpuscular radiation would be expected, but, of course, this point has to be investigated more closely.

All that has been said so far, may be found in greater detail in my two papers mentioned already. Now I wish to enter into the discussion of another subject, that is the mechanism, by which the ionization of two cometary molecules takes place.

The ionization potential of CO and N_2 is resp. 14 and 16 eV, hence only solar radiation in the Lyman range is effective. Wurm has shown, that the rapid variation with time of the CO^+ density observed sometimes in cometary tails would set a lower limit to the intensity of this radiation; he found, that an excess of about 10^8 over black body radiation would be necessary in order to explain changes taking place in about one hour or less.

At the time of Wurm's investigation the possibility of a very large excess over black body radiation in the Lyman region of the sun's spectrum was under discussion. In the last years, however, it was realized, that an excess of more than one or two powers of 10 in this spectral region is most unlikely. Hence the question arises, to which mechanism the molecule ions are due.

I now propose to show, that the process called « Umladung » in German (that is the exchange of an electron between a solar proton and a cometary molecule) is, under the conditions in question, likely to ionize molecules rather effectively.

The experimental cross sections for this process for molecules like those of air or similar gases hit by protons of a velocity of the order of 1 000 km/sec are of the order of 10^{-15} cm². The lifetime of such a molecule in a stream of 10^{11} solar proton/cm²/sec is, therefore, only of the

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order of a few hours. Hence it seems to be quite easy to understand the observations of comet Morehouse on these lines. The cross sections for the computing process of dissociation by collision are probably of the order of 10^{-16} cm² or smaller.

It will be asked (remark by Dr. Wurm) why only CO^+ and N_2^+ appear in substantial quantities in the comets tails. The answer suggests itself, that the cross sections for this process may be quite different for different molecules of about the same ionization potential; this is so since we have here an exchange process (Dr. B. Rosen). Under these circumstances one would expect, beside CO^+ and N_2^+, CN^+ and C_2^+ in abundance, but these are spectroscopically invisible, since their ultimate lines are in the spectral region below 3 000 A (Dr. P. Swings).

I hope to deal with the details of the ionization mechanism (including the possible role of radiation processes) in a future communication.

This finishes the account I had intended to present to you. But I may be allowed, perhaps to add a suggestion, which is meant as a discussion remark relating to the preceding papers and the consequent discussion. It is this : the comet's nucleus including the regions immediatly surrounding it should perhaps be regarded as a source of a stream of ionized matter, which leaves it with a velocity of, say 10 km/sec and interacts with the stream of solar matter. In this picture the phenomena of the changing envelopes (comet Morehouse 1908) should be regarded as belonging to plasma dynamics rather then to ordinary dynamics. The physics of this scheme, which is so far only phenomenological, remains of course to be worked out.