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ON THE MECHANISM OF SOLAR OUTBURSTS

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Today it is taken for granted that the solar outbursts are produced by plasma oscillations of coronal matter, excited by a corpuscular radiation originating in the inner corona (Pawsey and Smerd, 1953) [1]. A certain component of this corpuscular radiation is obviously identical with that generating geomagnetic storms.

In favour of such a hypothesis is the fact that the order of magnitude of the velocity of the exciting corpuscles (500 to 1500 km./sec. for type II bursts) is the same as that deduced for geomagnetic storms. Also plasma oscillations are observed in the laboratory when corpuscles are shot through a gas. Adopting this hypothesis we may derive some interesting conclusions on the mechanism of outbursts and also on the properties of the corpuscular radiation. The physical interpretation of the outbursts, which belong to the most direct manifestations of solar activity, in some respects even more directly than chromospheric flares (Davies, 1955) [2], is of great importance to the solar physicist as well as to the radio astronomer.

First, we mention a few conclusions that may be drawn from the observed band-width, variation of frequency and region of frequency emitted by bursts.

Band width. It is of the order of 10 Mc./s., which is only one-tenth of the total region of frequency covered. The extent of the exciting corpuscular radiation in the direction of its motion therefore can be only a small fraction of the radial extension of the corona, probably less than 10^{10} cm. It would be better to speak about a corpuscular cloud than about a corpuscular stream.

Range of frequency. Co-ordinating the observed frequencies with the corresponding electronic coronal densities, it follows that the exciting corpuscles already reach their final velocity in the very inner corona. The process of acceleration therefore occurs along a very short distance of the order of 20,000 to 50,000 km.

Variation of frequency. Assuming a constant velocity of the exciting corpuscles, the observed variation of frequency with time corresponds to an undisturbed decrease of the density of coronal electrons. This result is reasonable if one concludes that the normal distribution of electronic density in the corona is not disturbed appreciably by the corpuscular radiation penetrating the corona.

Next, we mention a few more quantitative data about this type of solar corpuscles as they can be estimated from the analysis of geomagnetic storms (Kiepenheuer, 1953) [3]. In the vicinity of the earth the corpuscular cloud should have the form of a gaseous shell, the thickness of which ($\sim 10^{11}$ cm.) is small compared with its lateral extension ($\sim 10^{13}$ cm.). The total mass of this gaseous skin should be of the order of 10^{12} gm. (10^{-20} of the solar mass). Assuming that this mass is taken from the inner corona and originally filled the volume of a sphere of 50,000 km. diameter (= extension of a mean spot group), an initial density of 10^7 to 10^8 protons/cm.^{3} is needed. This is a density similar to that of the corona. The mass is of the order of an average prominence.

The kinetic energy of the corpuscular cloud is estimated as 10^{28} to 10^{29} ergs. The total radio emission of an outburst generally does not exceed 10^{22} ergs. It follows that only a very small part of the kinetic energy is used for the generation of electro-magnetic radiation.

I. ORIGIN OF THE CORPUSCULAR CLOUD

What mechanism can accelerate a corpuscular cloud of the described properties in the very inner corona? There is very little doubt that the kinetic energy of the cloud comes from the field energy of a local magnetic perturbation. All other stocks of energy are quite inadequate. Only by the intervention of a magnetic field can it happen that the energy of a great collection of particles is transferred to a small number of particles with a reasonable efficiency, thus giving them very high kinetic energies.

Outbursts as well as geomagnetic storms suggest that the corpuscular cloud is always produced in the very vicinity of a spot-group within the inner corona and that it reaches its final velocity—a multiple of the velocity of sound—along the short distance of 20,000 to 50,000 km. For this reason we had better speak of a coronal explosion, in which the conversion of magnetic field energy into kinetic energy is occurring very rapidly. The following proposed model of this explosion is in a certain sense the reverse of a process, which, according to the theory of Chapman and Ferraro (1931, 1932, 1933) [4], happens when the same cloud of corpuscles enters the outer parts of the magnetic field of the earth.

On approaching the earth the corpuscular cloud is exposed to an increasing magnetic field. This induces a system of currents along the surface of the cloud facing the earth, which screens the rear parts of the cloud completely against the earth's field. The thickness of this current system is of the order of $\sqrt{\tau/\sigma}$, where σ is the electric conductivity of the cloud's material and τ the time taken by the field to increase sensibly. The thickness of the current system can also be regarded as the penetration depth of an electro-magnetic wave of the period τ into a conductor of the conductivity σ. It is extraordinarily small compared with the dimensions of the cloud. The formation of the current system and the deformation of the earth's field resulting from it is made at the expense of the kinetic energy of the cloud. The braking force of the induced current system per unit area is $H^2/2\pi$ and affects only the thin current-bearing layer, forming a strong compression along the top front of the cloud. The deformation of the earth's field resulting from this current system is, according to Chapman and Ferraro, recorded on the earth's surface and is supposed to represent the initial phase of a geomagnetic storm.

So much for Chapman and Ferraro's model of a geomagnetic storm. Let us now try to picture the reverse of this process in the solar atmosphere, where, on the contrary, a solar magnetic storm should set in motion a swarm of corpuscles. H. D. and H. W. Babcock (1955) [5] have shown that such storms occur in the solar photosphere. They observed field changes of several gauss in a few minutes within regions of more than 10,000 km. Much stronger changes of field are to be expected in the centres of activity, i.e. in the vicinity of spot-groups. Unfortunately no reliable measurements of these rapid field changes are available up to now. There can be little doubt, however, that the main cause of the group of phenomena occurring in a solar centre of activity is of magnetic nature. Especially chromospheric flares and the violent surge activity sometimes coinciding with a flare should be caused by a local magnetic perturbation rising from greater depth. It is known that the photospheric granulation behaves rather normally in these centres of activity. For this reason, it seems clear that the disturbing field is transported into the photosphere by the regular convection observed in the form of granulation. This is also to be expected because in this region the mean kinetic energy (>100 ergs/cm.^{3}) probably exceeds the magnetic field energy (about 5 ergs/cm.^{3} for 10 gauss). Observational results are not yet quite conclusive, but outside the penumbra of spots in general no fields greater than 10 gauss are observed. All solar magnetic fields as observed by the Zeeman-effect are located in a photospheric layer which is even greater in depth than the layers seen in a spectrohelioscope.

Almost nothing is known about how these observed photospheric field variations are transferred into the chromosphere or to the corona. The region between the depth of line formation and the height where chromospheric structures penetrate into the inner corona or where variable magnetic fields could be injected into the corona is *terra incognita*, a region where probably strong sound-, shock- and hydrodynamic-waves occur. There is no doubt that the observed surge activity, represented by chromospheric matter injected into the corona with velocities up to 700 km./sec., is one of the consequences of such deeper-seated magnetic field variations and that this injected matter carries with it magnetic fields of the order of 1 gauss or more. For this reason we have to expect rather rapid field changes in these parts of the inner corona. The existence of such field changes can be inferred with certainty from the observed rapid motions and changes of form of the so-called active filaments in the vicinity of sunspots. Without going into details, we may represent such a field change by a perturbation of the dimension $2a_0$ with a 'magnetization' H_0, which emerges into the corona within the time τ.

The arrival of this perturbation produces in the adjacent coronal matter a system of induction currents, the depth of which is again of the order $\sqrt{\tau/\sigma}$. Putting $\tau = 200$ sec., and $\sigma = 2.10^{-5}$ e.m.u., a depth of the current system of only 3000 cm. results. This means only that the thickness of the current-bearing layer is very small compared with the dimension of the disturbance. The actual layer will have at least the thickness of several free-paths.

This current-bearing skin is set in motion by the magnetic pressure $H^2/2\pi$, that is, by the repulsing force between the inducing and the induced current system. The moving layer pushes the coronal matter above it. The detachment of the induced current system from the primary perturbation in its first stage is difficult to understand. It might occur easily, however, when the density of the perturbation (chromosphere) is much greater than that of the initial current-bearing layer (corona). In other words, it will start preferably in regions with a steep density gradient. After a small detachment is accomplished, the separation will grow rapidly.

The magnetic disturbance, therefore, repels the adjacent coronal matter in such a way that an almost empty bubble is formed, the inner surface of which becomes the bearer of the induced current system. By this system the region outside this bubble is screened completely against the primary disturbance. If the disturbance has a dipole character, then the pressure on the unit area will decrease as H^2 or as $(a_0/a)^6$, where a is the radius of the bubble, a_0 that of the perturbation. The acceleration, therefore, has to be accomplished along a distance of the order of $a_0/2$. The amount of mass collected by the current-bearing layer along this distance per unit area will be of the order of

$$m \approx \tfrac{1}{2} a_0 \rho_0,$$

where ρ is the mean density of the inner corona. The acquired final velocity $\dot{r}_\infty$ can be estimated from an approximated energy balance

$$\frac{m}{2}\dot{r}_\infty^2 \approx \frac{a_v}{4}\rho_0 \dot{r}_\infty^2 \approx \frac{1}{2\pi}\int_{a_0}^{\infty} H^2 dr,$$

and thus is

$$\dot{r}_\infty^2 \approx \frac{H_0^2 a_0}{2\pi m} \approx \frac{H_0^2}{\pi \rho_0}.$$

The total mass being accelerated to this velocity is of the order of

$$M \approx 2\pi \left(\frac{a_0}{2}\right) m \approx \frac{\pi}{2}\rho_0 a_0^3,$$

and the total kinetic energy gained becomes

$$E_{\text{kin.}} \approx a_0^3 \rho_0 \frac{\dot{r}_\infty^2}{2}.$$

As can easily be verified, the kinetic energy gained by this process equals the total magnetic energy of the perturbation.

This high efficiency is not real, however, because two effects may, under certain circumstances, reduce it drastically. First of all, the reaction of the induced on the inducing current system has been neglected in our simplified model. This reaction, however, cannot seriously alter the magnitude of the resulting acceleration. The second objection concerns the nature of the primary field perturbation. If this perturbation is represented by a rigid body carrying a magnetic field with it, then the building up of its external field will be a very slow process. Because of the 'skin effect' only the currents in the very outer parts of this magnetized body will contribute. This skin effect, however, can be annulled almost entirely by internal turbulence, which brings in succession the internal fields to the surface, as long as the field is small enough not to prevent the turbulent motion.

The acceleration was estimated on the assumption that the emerging time τ of the disturbance is smaller than the time of acceleration t, which is

$$t \approx \frac{a_0 \sqrt{\rho_0}}{H}.$$

Taking plausible values for a_0, ρ_0 and H an acceleration time of the order of a few seconds seems quite possible. The question is, whether appreciable field changes are to be expected in this short interval of time. The emerging time of a magnetic disturbance transported into the inner corona by a chromospheric surge will be of the order of a_0/v, where a_0 is the diameter and v the velocity of the surge. For a velocity of the surge of 100 km./sec. and a diameter of 1000 km. an emerging time of about 10 sec. results. Assuming that the field increases linearly in this time, a field change of

$$\frac{dH}{dt} \approx \frac{v}{a_0} H_0$$

will be produced, which can amount easily to 5 gauss/sec. in the vicinity of active spot-groups.

As the observations of Wild, Roberts and Murray (1954) [6] have shown, type II bursts ($\sim$500 to 1500 km./sec.) are often preceded by type III bursts ($>$10,000 km./sec.) of short duration. One is tempted to believe that the fast corpuscles exciting the type III bursts originate in the same coronal explosion as depicted above. But why, then, is not the entire spectrum of velocities between 500 and 50,000 km./sec. observed? To answer this question would require a deep look into the mechanism of the explosion. But even without going into too much detail, it can be shown that there must be at least two groups of velocities.

Let us assume for a moment that the magnetic perturbation leaking into the inner corona is surrounded by a vacuum and that there is no other field than that of the perturbation. Then the lines of force of the developing field move outward with a velocity which satisfies the condition

$$\left(\frac{\partial H}{\partial t}\right)_r + \dot{r}\,\frac{\partial H}{\partial r} = 0, \quad \text{so} \quad \dot{r} = \frac{\partial H}{\partial t}\Big/\frac{\partial H}{\partial r}.$$

Assuming a dipole field, we find

$$\dot{r} = \frac{a_0}{3}\frac{\dot{H}_0}{H_0}.$$

This means that in the very first moment, when the field breaks through into the corona and H_0 is still very small, the lines of force will fly into space with a very high velocity. But how can this field develop in the corona with its high electric conductivity? It is known that the material is bound to the lines of force. The initial rapid outward motion of the lines of force must be accompanied therefore by a mass motion. This will be true only as long as the magnetic drag force exceeds the forces of inertia acting on accelerated material. That is, as long as $H^2/2\pi \gg m\ddot{r}$ (m = the total mass per cm.^{2}, set into motion by the field). This condition is best fulfilled for the type II bursts, which require an acceleration of about 2×10^6 cm./sec.^{2} For the type III bursts, however, accelerations up to about 10^9 cm./sec.^{2} are needed.

Assuming fields of the order of a few gauss it can be seen easily from the above conditions that magnetic pressure and inertia become equal for an accelerated mass of 10^{-10} gm./cm.^{2}, that is, for a coronal column of about 10 km. length.

The conclusion may be drawn that the swarms of fast corpuscles producing the type III bursts originate in those low layers of the corona which are hit first by the emerging magnetic perturbation. As shown elsewhere (Kiepenheuer, to be published) [7], it also seems reasonable to explain the acceleration of cosmic-ray particles on the sun in terms of such a mechanism. The radio observation of solar corpuscles up to velocities of 0·2 the velocity of light favours strongly such an hypothesis.

2. DETACHMENT OF THE CORPUSCULAR CLOUD AND ITS MOTION THROUGH THE CORONA

When the accelerating force of the magnetic disturbance has ceased because of the increasing distance of the induced current system, the protons and electrons are exposed only to gravitation and friction. Gravitation can be ignored for velocities exceeding the velocity of escape, which is about 600 km./sec. on the sun's surface. The friction is represented by the interaction of protons and protons, the collisional cross-section being

$$q \approx 8\pi \frac{c^4}{m_p^2 v^4} \log\left(\frac{1}{\theta_{\min}}\right),$$

where m_p is the protons mass, v the relative velocity of the colliding protons and $\theta_{\min}$ is the smallest angle of deviation, which still means a collision. It turns out, that protons with $v \gtrsim 4 \cdot 10^7$ cm./sec. are capable of escaping from the inner corona without collision. For this reason the fast protons, responsible for type III bursts, after being blown into the corona during the initial phase of the explosion, will detach themselves and penetrate the corona unimpeded while the main explosion is going on.

The bulk of exploding material will continue to heap up and to compress coronal matter, as long as its velocity relative to the surrounding corona is sensibly less than 400 km./sec. and as long as the magnetic pressure lasts. When the critical velocity and distance from the primary disturbance is reached, the shell of collected coronal material flies freely through the corona, steadily increasing its dimensions but without disturbing the shape of the corona.

It remains to discover whether the corpuscular cloud flying through the corona almost without friction can transfer enough energy to the corona to excite plasma oscillations of the required intensity. For a corpuscular velocity of 1000 km./sec. the cross-section per proton amounts to 5×10^{-21} cm.^{2}, the cross-section of the total corona to about 5×10^{-3} cm.^{2}/cm.^{2}. Therefore about five per mille of the kinetic energy of the cloud, that is 5×10^{25} to 5×10^{26} ergs, are transferred to the corona. This is about 10^4 times the radio energy transmitted by an outburst. The required efficiency of the mechanism of excitation of plasma oscillations, therefore, turns out to be of the order of 10^{-4}.

H. D. and H. W. Babcock have also proposed a model for the acceleration of solar corpuscles [5]. They believe that by the occasional encounters of photospheric turbulent bodies magnetic fields and matter can be squeezed into a tube-like volume. The compressed matter can then escape only along the lines of force parallel to this tube. According to the steep gradient of density in the solar atmosphere the velocity of expansion would become very high in the upper parts of this tube. The material thus accelerated is identified by the authors with the solar corpuscular radiation. This simple mechanism, which transfers the kinetic energy of large photospheric masses to the ejection of a few particles by the intervention of a magnetic field, is tempting but is subject to serious objections. In particular, it is difficult to imagine what forces are able to maintain the form of the postulated tube formed by the lines of force. This tube has to survive a drop of density of the order $1:10^5$ to permit the desired mechanism of acceleration to work. We think that the field fluctuations produced by photospheric or chromospheric turbulence manifest themselves in the explosional process described in this paper.

In order to come to a quantitative estimate of the accelerating force in a coronal explosion, the mechanism proposed by us has been very much simplified and idealized. Certain details which might be of great importance in a thorough treatment of the process have been ignored completely, such as shock-waves and hydromagnetic-waves. Also very important observational details have been omitted in order to get a clear picture of the explosion as such. It is my hope that the wrong as well as the right parts of my mechanism might be a stimulus to the experts in this complicated field.

It is evident that a very close co-operation between solar physicists (especially those who can measuer weak magnetic fields on the sun) and radio astronomers can contribute greatly to a better understanding of this type of coronal phenomena.

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Discussion

Ellison: We have as yet no optical evidence for the expulsion of particles from the flare regions at speeds of 60,000 km./sec., but there is considerable evidence for the emission of hydrogen atoms at speeds of the order of 500 km./sec. [1, 2].

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