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HIGH ALTITUDE OBSERVATORY

Solar Research Memorandum No. 29

From: Walter Orr Roberts

Subject: Visit of A. Schlüter.

Schlüter visited the High Altitude Observatory from 18 October 1954 through 14 November 1954. From 25 October through 17 November he held a visiting appointment at the HAO, working half of this period on problems of coronal motions with sponsorship of ONR Contract 393(04) with the HAO, and working the other half with the sponsorship of Contract CST 3048 between the HAO and the Central Radio Propagation Laboratory of the National Bureau of Standards, on the closely related question of the relation of the corona to the corpuscular emission of the sun.

This work culminated in the following first draft of a scientific paper, reproduced here in a solar research memorandum for informal discussion by the Solar Associates, but still subject to correction and modification by the author before publication.

A Theory of Solar Corpuscular Emission

by A. Schlüter

I. Empirical Effect.

The existence of corpuscular emission from the sun was first deduced from observations of disturbances of the earth's magnetic field. The occurrence of such disturbances simultaneously or almost simultaneously over the whole earth over day and night time, their concentration towards the auroral zone of the earth and their relations to solar phenomena like sunspots, flares, and so on, suggested that they must be caused by corpuscular emission from the sun. Biermann has shown that the deflections observed in the tails of comets can be understood only if one assumes the existence of corpuscular emission, as indicated by geomagnetic observations, since radiation pressure alone is not sufficient. Radio observations of the sun also imply the existence of such corpuscular emission. Particularly the shift to lower emission frequencies which is a most general feature of the so-called radio "outbursts", is most easily explained if one assumes that the observed radiation originates in a knot of matter which is emitted from the sun and expands during its travel through the solar corona, and that due to this expansion the plasma frequency decreases with time, which produces the observed frequency shift.

Even apart from these indirect proofs, the structure of the solar corona suggests by itself the existence of corpuscular emission. Or even more, it suggests that the full solar corona is being expelled from the sun. This is particularly apparent for the plumes observed near the poles of the sun, and for the broad "fans" which are particularly spectacular at the minimum phase of solar activity.

II. Conditions for a Theory of Corpuscular Emission.

One essential fact which has to be taken account of in any theory of corpuscular emission is the existence of magnetic fields on the sun. Direct observations of magnetic fields on the surface of the sun, particularly by H. W. Babcock, have shown that magnetic fields are always present. We can make distinctions between three magnetic regions on the sun. The two polar caps of the sun at latitudes higher than approximately 50° show a persistent magnitization, opposite on each hemisphere. In the circumequatorial belt, between these polar caps, only local magnetic fields of varying strength and varying location have been observed. The magnetic lines of force originating in both polar caps have to be closed, and the only simple way to do it is let the magnetic lines of force originating in one polar cap pass through the solar corona and enter the solar surface again at the other polar cap. Thus we postulate a magnetic field in the solar corona which probably resembles to some extent the field of a magnetic dipole.

In addition to the local perturbations due to field patches and sunspots, such a magnetic field must have a great influence on the dynamical state of the solar corona since the solar corona is a very good conductor. As is well known, the conductivity of ionized gas is, to a good approximation, independent of the density of the gas and is a function of temperature only, increasing with high temperature. It has been shown by the present author that the so-called "reduction of conductivity" of the ionized gas in the presence of a magnetic field is spurious. The full value of conductivity is effective, and this is not much lower than the conductivity of a metallic conductor. Due to the fact that the dimensions involved are very large, this means that the relative motion of matter and magnetic lines of force must be extremely small, or as one usually says, the magnetic fields must effectively be "frozen" into the conducting material. So, if we assume that the magnetic field in the corona penetrates the coronal material and if we then try to eject this material from the solar corona, we are forced to conclude that the coronal gas would drag the magnetic lines of force along with its motion. Thereby the magnetic lines of force would become longer and longer, and we would convert kinetic energy into magnetic field energy.

As soon as the kinetic energy would be used up, the magnetic lines of force would pull the material back towards the sun. The magnetic field would thus represent a resistant force in the solar atmosphere.

Since solar corpuscles seem to have velocities of more than 500km/s in the neighborhood of the earth, as deduced from the time-lag between the arrival near the earth and events on the solar surface which are obviously correlated with the emission, and since at the same time no velocities this great are observed in the solar corona near the solar surface, we have to assume that the acceleration takes place in the corona itself, if it takes place near the sun at all. So we need an accelerating force in the solar corona rather than the decelerating force of the magnetic field on magnetized matter.

The high conductivity of coronal material has also another effect. Suppose we take some matter out of the solar photosphere or chromosphere and put it into the solar corona. Due to the fact that the density in the corona is much less, this material has to expand. And even if it carried some closed lines of force with it from the photosphere or chromosphere, this magnetic field will be greatly diminished in the course of the expansion. Since the original field in the photosphere or chromosphere and the magnetic fields in the corona must be of the same order of magnitude, material brought into the corona from the photosphere can be regarded as essentially unmagnetized. The coronal field has then to adjust itself in such a way that its magnetic lines of force do not penetrate into this knot of material brought into the corona. A deformation of the magnetic field results, causing forces on the knot of matter, and the theory which we propose considers these forces as the ones responsible for the acceleration of the matter.

III. The Diamagnetic Approximation.

In electromagnetic theory, a material which has the property to deflect the lines of force of a given field in such a way that the flux through it is diminished is called diamagnetic. Therefore we call our knots of material, which deflect the lines of force completely so that no flux enters into them, completely diamagnetic. Electromagnetic theory, (see, for instance, Stratton) allows us to compute very easily the forces on such a completely diamagnetic body.

Consider the following situation. We have somewhere a system of electric currents which generate magnetic field. Somewhere in this magnetic field, but outside the region where the currents flow, we put a completely diamagnetic body and keep constant the current which produced the original field. Then the total electromagnetic energy is simply the integral,

$$\int_V H^2/8\pi \; dv \tag{1}$$

This integration has to be carried out over the volume of the completely diamagnetic body. H is the magnetic field as it would be in the absence of the body, in the volume occupied by the body. If the diamagnetic body consists of a gas, as it does in our case, then the condition for equilibrium is that for a small virtual change of the volume, the change of the magnetic energy just equals the work done against the gas pressure. So, in equilibrium, the gas pressure inside the body has to be equal to $H^2/8\pi$. This pressure compensates the magnetic forces at the surface of the diamagnetic gas while in the interior of it no magnetic forces are acting. To get the equation of motion we take the usual hydrodynamic equation expressed in non-magnetic terms, namely:

$$\frac{d\vec{V}}{dt} = -\frac{1}{\rho} \text{ grad } p - \text{grad } \phi \tag{2}$$

The magnetic field enters only as an auxiliary condition:

$$p = H^2/8\pi \tag{3}$$

In this equation $\frac{d}{dt}$ denotes the substantial derivative, $\vec{V}$ the velocity vector, ρ the density, and ϕ the gravitational potential. Equation (3) has to be fulfilled at the interface between the conducting gas and the magnetized vacuum. To make the system of equations complete, the relation between the mass density ρ and the gas pressure p has to be given.

IV. A Simple Model.

To arrive at a first simple model we introduce a set of simplifying assumptions.

A. Temperature.

To fix the relation between the pressure and the density along the trajectory of the ejected material we have to make an assumption about the temperature. By necessity this assumption will be largely arbitrary since the heating mechanism for the corona is not yet fully understood. We can, however, consider two limiting cases between which the real case presumably will lie. The first case would be where the gas starts at a certain temperature and while it is moving into a region of lesser magnetic field strength, that is to say while its gas pressure diminishes, it cooled adiabatically. The second possibility would be to assume that the loss of internal energy of the gas, during its expansion and its motion, is compensated by the unknown heating mechanism in the corona, so as to make its temperature essentially constant.

In both cases the final kinetic and potential energy of the ejected matter is supplied by the heating mechanism of the corona. The heating mechanism first supplies the internal energy of the gas, and this internal energy then does work during the knot's passage through regions of lesser and lesser pressure. The gas thereby is accelerated. The difference between the two cases is that in the adiabatic case, the heating mechanism is assumed to occur at once, before the acceleration starts, while in the isothermal case, energy is constantly fed into the beam during the whole acceleration process. The later assumption seems to be the more reasonable one particularly for the part of the acceleration which takes place within a few solar radii of the solar surface. It is clear that the isothermal case also gives considerably higher final velocities for a given gas temperature than the adiabatic case, where obviously the final velocity can hardly exceed the thermal velocity of the initial temperature. In the isothermal case the equation of motion (2) takes then the following form:

$$\frac{d\vec{V}}{dt} = - \text{grad} \left[\frac{RT}{\mu} \ln p + \phi\right] \qquad (4)$$

where T is the constant temperature, R the gas constant and μ the molecular weight.

B. Dipole Field.

We assume the general magnetic field of the sun in the solar corona to be exactly a dipole field. That is to say, we neglect deviations from a dipole field due to the fact that the phosospheric magnetic field of the sun does not correspond to a dipole field. We also neglect the possible reaction of the acceleration mechanism on the magnetic field.

C. Equilibrium.

We assume that the magnetic forces on the surface of the gas cloud and the internal gas pressure are in exact equilibrium. This probably is not quite true since the gas presumably has a tendency to spread out along the magnetic lines of force. But since the diamagnetic forces depend only on the volume and the original magnetic field, and not on the form of the diamagnetic body, one would assume this to be a good approximation.

D. Homogeneity.

We consider either an isolated knot of matter or a continuous beam of matter. In the first case we neglect the velocity corresponding to the expansion of the knot compared to its velocity due to its motion. In the second case we neglect the variation of the velocity over a cross-section of the beam. Then we can describe the motion of the center of the knot by a time-dependent velocity given by equation (4), and the same equation will also describe the motion of matter along the axis of a beam and thereby give its form.

Using all our assumptions we can write the equation of motion in the form of the equation of motion of a single particle accelerated by a conservative force, the potential of which is Ψ,

$$\frac{d^2\vec{r}}{dt^2} = - \text{grad}\, \Psi$$

$$\Psi = \frac{RT}{\mu} \ln H^2 + \phi \qquad (5)$$

$$= -\frac{RT}{\mu} \left[6 \ln r - \ln (1 + 3 \sin^2 \Theta) \right] + \frac{\phi_o}{r}$$

Here r represents a coordinate of the center of a knot $\frac{d\vec{r}}{dt}$ the velocity. ϕ_o is the gravitational potential of the sun near the solar surface and is a negative quantity, while r is measured in units of the solar radius. Since this fictitious force-field is conservative, the equivalent to the energy conservation law holds and can be expressed in the form,

$$\frac{d}{dt} \left(\frac{v^2}{2} + \Psi \right) = 0 \qquad (6)$$

V. Consequences of the model.

The quasi-potential Ψ posseses a maximum with respect to its dependence on r at a certain critical value of r, which we call r_m, which does not depend on the heliocentric latitude Θ:

$$r_m = -\phi_o \mu / G\,RT \tag{7}$$

This critical radius is larger the smaller the temperature. For a temperature of about 2,000,000° A it coincides with the solar radius. For this case, figure 1 shows the equi-potential lines of Ψ. The difference between two successive equi-potential lines shown in this figure corresponds to a difference in energy equal to a tenth of the energy of escape from the solar surface. For smaller values of the temperature the maximum of Ψ lies outside the solar surface and diamagnetic matter starting with zero velocity from the surface of the sun could not reach infinity. So the temperature for which $\gamma m = 1$ represents a critical minimum temperature.

To obtain the final velocity of the corpuscular emission we have to make an assumption about the magnetic field near the earth. It is probable that the magnetic field which would result if we extrapolated the solar dipole to the distance of the earth gives a considerable underestimate of the magnetic field strength. Since, however, the final velocity depends only on the logarithm of the magnetic field strength this lack of knowledge is not too serious. Assuming the temperature to be just the critical temperature of about 2,000,000° we arrive at a final kinetic energy which is a few times the energy of escape from the solar surface. This value is somewhat too large and this might easily be due to the fact that a large part of the acceleration takes place, according to figure 1, at distances from the sun which are so great that our isothermal approximation is probably no longer adequate.

The equi-potential lines of the quasi-potential Ψ show a characteristic deviation from spherical shape, in such a way that particles are accelerated towards the solar equator. Numerical integrations of trajectories according to equation (5) by Miss Marian Wood of CRPL have shown that this force is so great that particles which start with zero velocity at low latitudes cross the equator. Deflection of corpuscular beams towards but not across the equator is indicated by eclipse observation. It also seems, from the results of B. Bell, that such particles do not cross the solar equator. But this particular feature of our theory depends very critically on the correctness of our assumption of a dipole field and should not be given too great weight.

VI. Synthesis of the Corona

In the preceding paragraphs we have considered the motion of isolated knots of matter or of isolated beams of matter in a given magnetic field. To get a more realistic description of the whole corona we have the possibility of two extreme positions. We can either say that the bulk of the coronal matter is magnetized, so that the magnetic lines of force of the corona penetrate most of the matter, and we are considering relatively small portions of the solar ejecta which are diamagnetic and accelerated by the present mechanism. For this we would have to take into account, in the equations of motion, also the gas pressure of the magnetized matter. Or, alternatively, we can say that the whole corona consists principally of diamagnetic material, which is being accelerated. In this case the total accelerating force on all coronal material together is quite appreciable and has to be compensated by stresses in the magnetic field. This implies that the magnetic field would be considerably deformed by this acceleration mechanism. The deformation would be in such a sense that the drop of the magnetic field with its distance from the sun would become steeper. This would have two consequences: first, the acceleration would take place nearer to the sun and the ciritical temperature would be diminished. The effect of this reaction remains to be more closely investigated, but it seems probable that the empirical density distributions through the solar corona and the empirically observed temperatures of about 1,000,000° are in accordance with the theory with such modifications.

The author wishes to express his sincere thanks to the Director of the High Altitude Observatory, and to the Central Radio Propagation Laboratory of the National Bureau of Standards for their hospitality during the period of time in which the present work was performed.

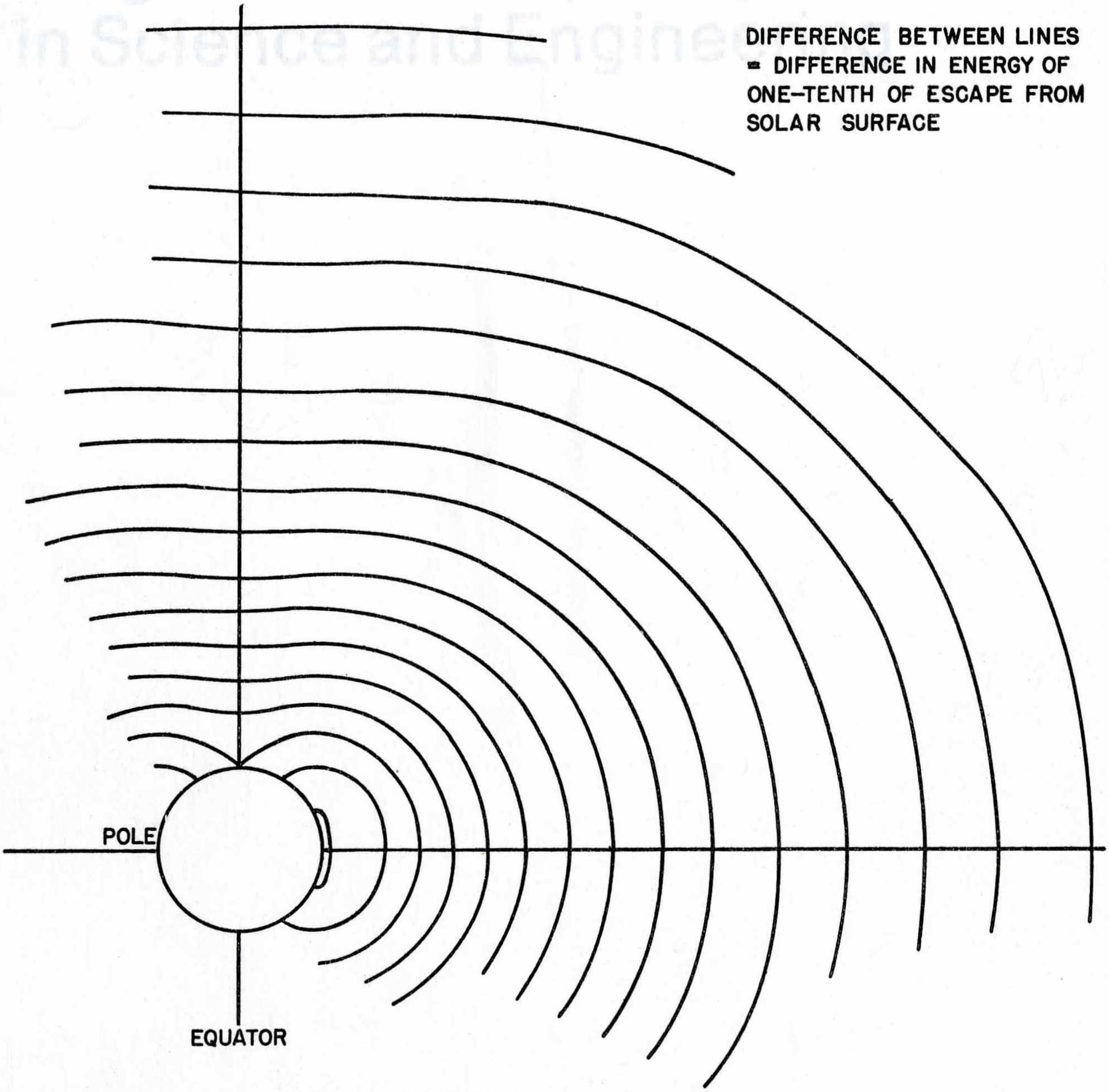

FIG. I EQUIPOTENTIAL LINES OF ψ