PAPER 30

THE MAGNETIC FIELD IN THE CORONA

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ABSTRACT

The shapes of coronal features are discussed, on the basis that they are indicative of the configurations of the magnetic fields. Some considerations about the strength of the fields are advanced, and the forces that must be responsible for streamers and for the quiet corona are discussed. The magnetic fields would seem to dominate over all inertial hydrodynamic forces, leaving only such magnetic configurations as can be set up by variations of the gas pressure.

Several reasons can be given why the shapes of the corona can be taken to be indicative of a magnetic field. Indeed the coronal streamers and the polar plumes gave the first suggestion of the existence of the general magnetic field of the sun. These reasons can be classified as follows:

1. Many features look as if they trace out lines of force. What is meant by that, of course, is that they represent a pattern of lines that could be lines of force produced largely, though not entirely, by currents in the sun. They look like the external field of a magnet, distorted, but not beyond recognition (Plates I and II).

2. The shapes are of a sort that could not be expected from hydrodynamical motions on the rotating sun. There are no indications of eddies or of cyclons, but instead there are straight elongated features which one would not easily associate with pure hydrodynamic motions.

3. Coronal features appear to take part in the differential solar rotation of the surface underneath them. Petri has measured the rotation periods of photometrically recognizable coronal features and these measurements show the existence of approximately the correct differential rotation. Also the plumes and other features never show any loops which would result from the projected appearance of a spiral shape. Long-lived individual features must therefore be thought of as being in solid body rotation, and anchored in the photosphere below them.

4. There appear to exist substantial horizontal gradients of density and pressure (with the temperature positively correlated), and such differences

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would disappear quickly without a magnetic field. The observed velocities that are normally present are too low to lead to such pressure differences.

5. There exists a strong connexion between coronal shapes and the magnetic activity in the photosphere.

Even if one did not accept that the coronal lines are indicators of the magnetic field, one can still use them to indicate the absence of very different shapes of magnetic fields of significant strength. A particular type of field evidently not possessed by the sun should be mentioned here. A star condensing out of a large mass of magnetized gas would cause a curious deformation of the field: the star will no doubt rotate after contracting from the gas mass to which some lines of force remain connected. Such lines must, therefore, get twisted around one another in the vicinity of the poles before reaching out to the large gas masses in which they remain anchored. There is not the slightest tendency for such twisted knots in the corona (Fig. 1). It appears therefore that the fields of the rotating sun are not anchored in distant gas masses, but belong entirely to the sun.

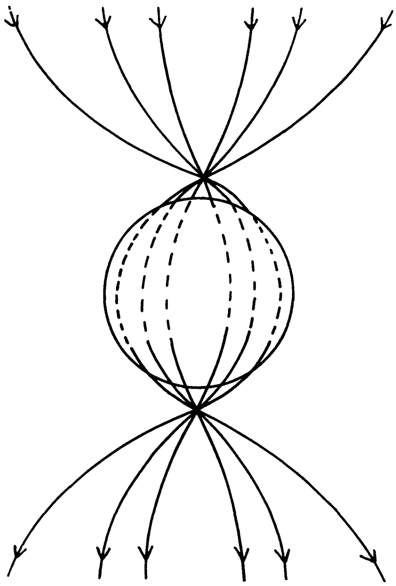

Fig. 1. Twisted knots.

Now let us deal with actual attempts to explain some of the features in magneto-hydrodynamical terms. For the large broad streamers there are two basic types of explanation possible. Either they really are streamers in which the outward flow of material is essential for maintaining the density distribution that is observed, or they may represent shapes which are in magneto-hydrostatic equilibrium and which, in the case of a perfect conductor, would require no flow at all. For the first explanation one has to meet van de Hulst's point that hydrodynamic continuity implies that a great acceleration of the material must occur as it rises from the solar surface.

Observations do not really seem to allow one to exclude such accelerations, and Schlüter has given a mechanism which would provide it. If any gas were made available low down in the corona with the magnetization much less than that of its surroundings, it would act like a diamagnet and

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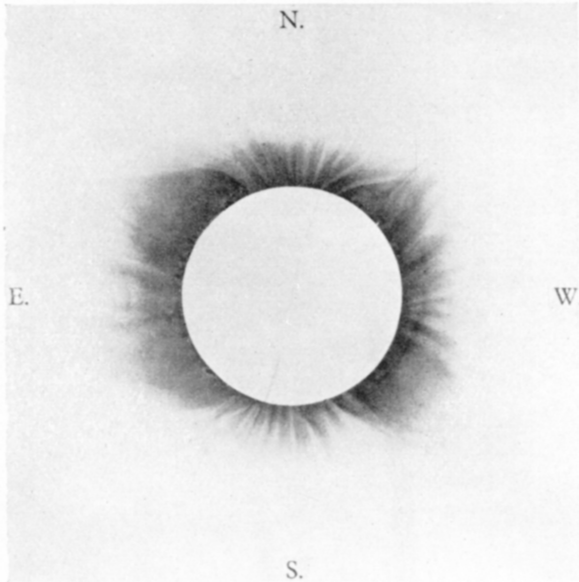
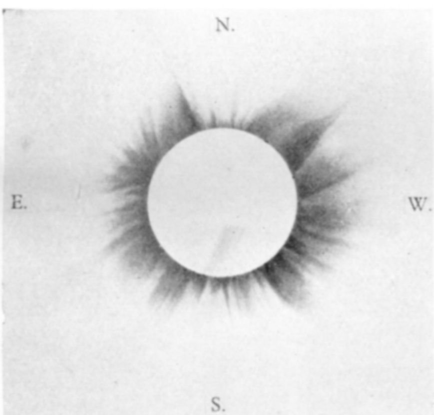
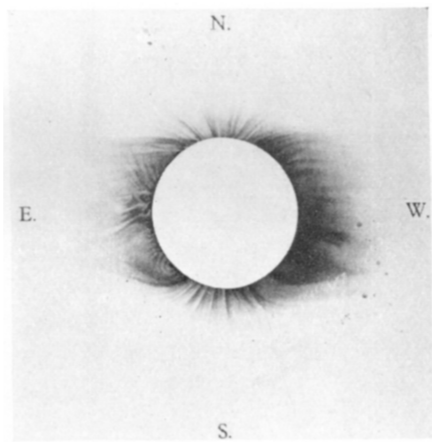


(a)



(b)



(c)

Plate I. Shapes of the corona. (*a*) 22 January 1898. (*b*) 3 January 1908. (*c*) 18 May 1901.

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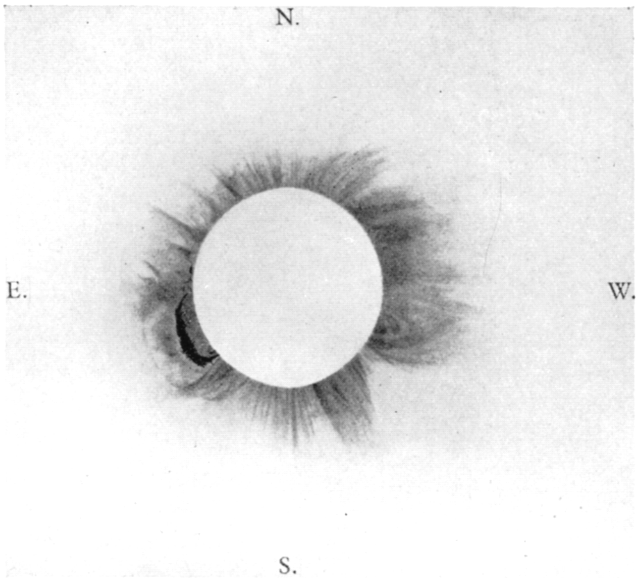
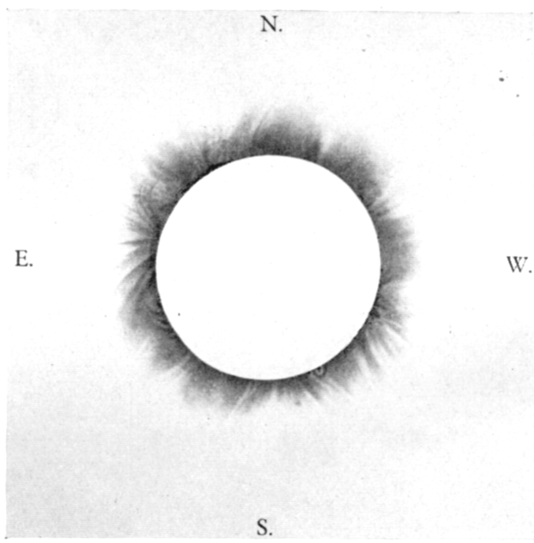


(*a*)



(*b*)

Plate II. Shapes of the corona. (*a*) 29 May 1919, (*b*) 30 August 1905.

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would be expelled by pushing the existing field apart and finding its way out in between. In fact one can give a general reason why Schlüter's process should be expected on the surfaces of stars. A chaotic magnetic field would possess an average strength varying with the two-thirds power of the density in the case of expansion or contraction of the gas. If a star forming from tenuous interstellar gas possessed the appropriate field strength at each level, then the Schlüter instability on the surface would be avoided. Material brought from one level to another would bring with it the correct amount of magnetic field for the new surroundings. But over long periods of time ohmic dissipation of the fields must be considered. In places where the gradient of the density is high ohmic dissipation will in general mean that in the higher density region the fields will be weakened and in the adjoining lower density regions they will be strengthened, as compared with those appropriate to the density. The surface of the photosphere is a region where this effect would be most pronounced and where any material would become unstable against expulsion as soon as its field strength has been diminished by a certain margin as a result of ohmic decay. It is interesting to think that there is a mechanism here for the continuous emission of matter from stars.

The alternative possibility is to regard the coronal streamers as approximations to magneto-hydrostatically stable equilibrium shapes. Using the approximation of infinite conductivity and the usual notation, the equation

$$-\operatorname{grad} p + \rho \mathbf{g} + \frac{1}{4\pi} \operatorname{curl} \mathbf{H} \times \mathbf{H} = 0$$

would have to be satisfied. What configurations can satisfy this equation for the boundary conditions that the lines of force are anchored on the surface does not yet seem to have received any consideration. It is likely that stable shapes of overlying arches exist, and a stability condition will have to be satisfied according to which the field strength in the center has to diminish sufficiently rapidly with height (Fig. 2). It would be extremely valuable if such configurations with the appropriate boundary condition on the surface could be calculated by electronic computing machines, if only to see whether the observed shapes are at all of the right kind. In particular one would like to know whether as narrow a structure of arches can be expected as occurs commonly in coronal streamers. If such magneto-hydrostatic stable shapes exist, then they would really be expected to occur in the corona, provided the magnetic field is strong enough. This explanation would then take precedence over any other requiring similarly strong fields.

In the 1954 eclipse the field was sufficiently regular to make it worth while to discuss the departures it possessed from a dipole field. Fig. 3 demonstrates the type of departure and it will be seen that the angle of the lines at the photosphere, as well as their position far out in equatorial regions, corresponds simply to that deformation of a dipole field where the

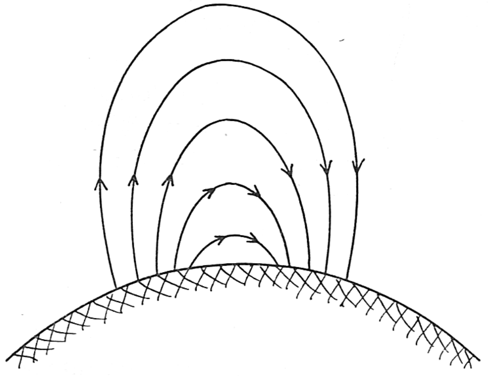

Fig. 2. A magneto-hydrostatic configuration anchored on the solar surface.

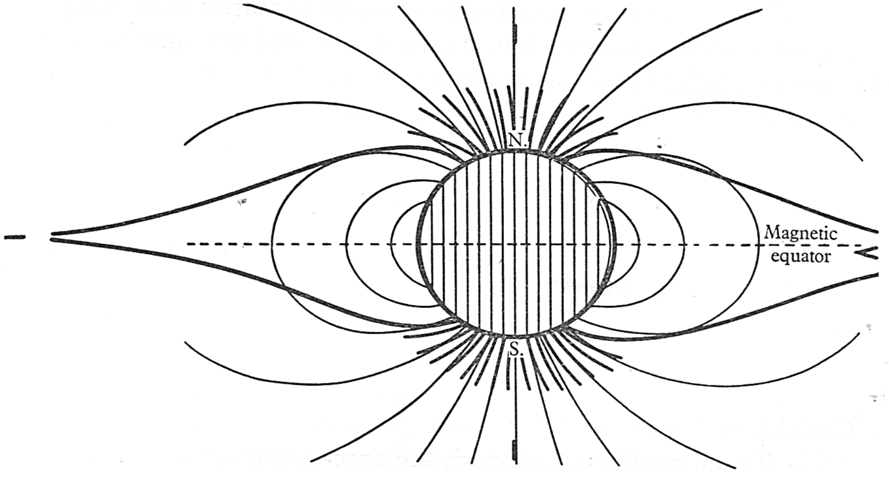

Fig. 3. Magnetic field in the corona during the 1954 eclipse (thick lines). The dipole field component is indicated for comparison (thin lines).

lines of force in the equatorial plane are stretched outwards. An extra source of heat or any other outward force in equatorial regions acting on the coronal gas would produce this type of deformation.

Now it is worth while noting the orders of magnitude of the quantities concerned. Although the magnetic and hydrodynamical forces would depend in detail upon the configurations and the flow, the comparison of the gas pressure variations, the stagnation pressure appropriate to the velocities that are reported (Waldmeier), and the magnetic pressure, may be of interest. The variations of the gas pressure at the same level appear to be of the same order as the gas pressure. At a distance of 1/10 radius above the photosphere one has the gas pressure $p \approx 2 \times 10^{-2}$ dynes/cm^2, the stagnation pressure $\frac{1}{2}\rho v^2$ (at 10 km/sec) $\approx 10^{-4}$ dynes/cm^2 and for $H = 1$ oersted $H^2/8\pi = 4 \times 10^{-2}$ dynes/cm^2. Such values would allow of the magneto-hydrostatic interpretation. The velocities of flow would only introduce insignificant variations of pressure, while the magnetic field could exercise a decisive influence. If stable configurations exist then one must expect any variation in the heat supply to set them up. But with fields much weaker than 1 oersted one could not expect the large density variations at the same level.

Recent radio observations by Conway in Cambridge appear to place an upper limit on the mean field strength over a hemisphere of about 2 or 3 oersted. This conclusion depends upon the absence of circular polarization. If these considerations turn out to be correct, it will thus be possible to bracket the strength of the coronal field very closely, and to compare it with values inferred from other types of observation. At present photospheric fields are inferred by Babcock from his magnetograph tracings.

Discussion

Righini: I want to point out that we have observational evidence that the poles of the sun, as indicated by the polar plumes of the corona, are not antipodal but there is a difference of a few degrees.

Schatzman: I would like to mention that Trellis at the Pic du Midi had made an extensive study on the coronal streamers. He has studied the motions of the coronal streamers in longitude and latitude and found observations of the coronal lines, the distribution of density and temperature inside the coronal streamers.

Alfvén: I would like to ask Dr Gold about the argument for putting a maximum value of two gauss in the corona. Was that in the inner corona?

Gold: The field of one or two gauss is estimated as the limiting value of the surface field, assuming it to tail off into the corona more or less like a dipole field. A stronger field in the corona of opposite sense in the two hemispheres would have produced a measurable amount of the two senses of circular polarization.

Alfvén: Polarizarization of radio waves?

Gold: Yes.

Alfvén: I see, but does that take account of the fine structure of the corona?

Gold: No, that is on the basis of a distributed field.

Alfvén: I am rather surprised that it is possible to accept such a limit if you are not very sure about the fine structure of the corona.

Gold: It is quite true that the surface flux could be compressed into narrow bundles and then guided through the coronal material, leaving most of it unmagnetized. Then the flux could be anything you like.

Alfvén: Oh, yes.

Schlüter: I completely agree with Dr Gold as to the importance of getting as many solutions of the magneto-hydrodynamic and magneto-hydrostatic equations as possible. In most actual cases the problem is essentially three-dimensional and even a numerical solution on the largest electronic computers is very difficult. Finding a solution, however, is only part of the problem—one has also always to establish the stability behaviour of it. Obviously, this is even more difficult.

van de Hulst: I think what Dr Gold said in the beginning of his paper somewhat defeats the argument at the end. He said it seemed as if most of the currents would be in the sun. If that is true, of course, the magnetic pressure vanishes outside. I see nothing wrong with your picture excluding all magneto-hydrostatic data.

Gold: But I do. The shapes which are commonly seen in the corona just cannot be made with currents entirely in the sun. It is not a curl-free field.

Cowling: The shape of the polar plumes of the corona appears to suggest that the magnetic field near the equator is small, since the plumes bend over towards the equator more than the lines of force of a dipole.