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THE MAGNETIC FIELDS OF SUNSPOTS AND THE EVERSHED EFFECT

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ABSTRACT

The observational data on the magnetic fields and the physical parameters in sunspots indicate in a qualitative way how the magnetic lines of force run relative to the isobaric surfaces. If matter is confined to move only along the lines of force it is shown that for sufficient tilt between these lines and the isobars, matter will be accelerated outward along the lines of force. The flow corresponding to this forced convection works as a cooling cap for the core of the spot. It is indicated how a stationary state may be reached with the outward velocity adapted to the temperature difference between the spot and the photosphere.

It is the purpose of this note to suggest a self-maintaining mechanism, which at the same time provides the driving force of the Evershed-motion and maintains the low temperature in the upper layers of the spots. We shall deal mainly with the outer layers of a fully developed stationary sunspot, leaving questions as to the formation and development of the spots open.

As is generally accepted, the electrical conductivity, even in the relatively cool spot region, is sufficiently high for matter to be effectively 'glued' to the magnetic lines of force (for example [1]). With magnetic fields of the order observed in sunspots this has the consequence that in a stationary spot the motion takes place along the magnetic lines of force, as suggested by Hoyle [2]. We shall make this assumption in the following. It should be remarked, however, that this assumption does not fit the observations very well. According to Kinman [3] no vertical component of the Evershed-motion is observed at the boundary between the umbra and the penumbra. In one of the spots observed by him the mean error is given as 0·26 km/sec. and the measured horizontal velocity component at this point is 1 km/sec. Since no vertical velocity was observed we may conclude that the magnetic lines of force are here inclined at least 75° to the vertical. On the other hand, according to the Mount Wilson observations [4] this angle is only about 40°, if a linear penumbra-umbra ratio of 2·3 is assumed. This discrepancy may perhaps be explained as a level effect. Considering this possibility and the many sources of error involved both in the measurement of velocities and magnetic fields we shall stick to our assumption that the motion follows the magnetic lines of force.

In Michard's empirical model of a large sunspot[5], not only is the temperature of the spot found to be lower than in the surroundings, the density is also less at the same level. Both effects contribute towards a smaller gas pressure in the spot region. As has been emphasized by Sweet[6], this model shows departures from hydrostatic equilibrium. The gas pressure at a given level turns out to be too small to support the weight of the matter above. Near the centre of the spot the electromagnetic force has, however, no vertical component. Thus the discrepancy cannot be explained by taking this force into account. Further observational data are required to decide whether this effect is real.

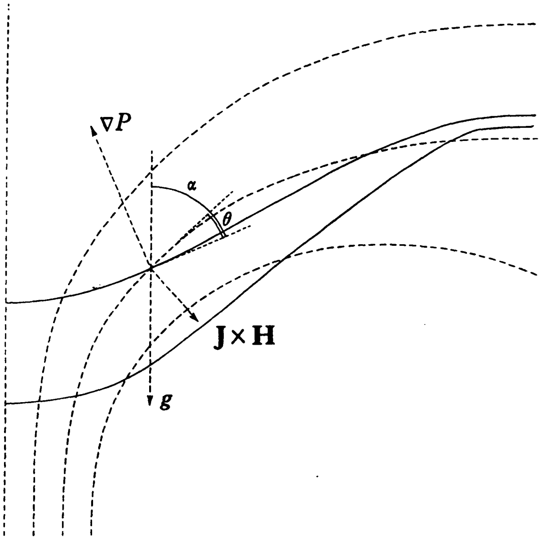

Fig. 1. Schematic drawing of the magnetic lines of force (dotted curves) and the isobars (solid curves) of a sunspot.

Even if the physical conditions in sunspots are not known with great accuracy, we may consider sunspots as low-pressure regions. For such a region to be in equilibrium with a magnetic field, certain conditions concerning the orientation of the isobaric surfaces relative to the magnetic lines of force must be fulfilled. The situation is somewhat similar to that shown in Fig. 1, where the magnetic field is supposed to be axially symmetrical and with the axis vertical. In the central region the isobaric surfaces are perpendicular to the magnetic field and gravity. Here the electromagnetic force on matter is probably quite small and has no vertical component. Further out this force is larger, and here the isobaric surfaces are also tilted relative to the direction of gravity.

The three forces which determine the equilibrium are: the gradient of the gas pressure, the electromagnetic force, $\mathbf{J} \times \mathbf{H}$ (where $\mathbf{H}$ denotes the magnetic field strength, and $\mathbf{J} = (1/4\pi)$ curl $\mathbf{H}$ the current density) and gravity. Since matter may move freely only along the magnetic lines of force, the important quantity is the resulting force-component along the direction of the magnetic field.

Let α denote the angle between the magnetic lines of force and the vertical at a given point, and $\pi/2 - \Theta$ the angle between the gas-pressure gradient ∇P and the field vector $\mathbf{H}$. Then the force component F directed outward in the direction of the lines of force, is

$$F = |\nabla P| \sin \Theta - \rho \, |g| \cos \alpha. \qquad (1)$$

In the direction perpendicular to the magnetic lines of force of a fully developed spot we assume the forces to be in equilibrium, thus,

$$|\nabla P| \cos \Theta - \rho \, |g| \sin \alpha - JH = 0, \qquad (2)$$

where $\mathbf{J}$ is assumed to be at right angles to $\mathbf{H}$. When $\rho\,|g|$ is eliminated between the Eqs. (1) and (2) the following expression for F is obtained,

$$F = \frac{|\nabla P|}{\sin \alpha} \{\beta \cos \alpha - \cos (\alpha + \Theta)\}, \qquad (3)$$

where we have introduced the parameter $\beta = JH/\nabla\,|P|$, the ratio between the magnetic force on matter perpendicular to the lines of force and the absolute value of the gas-pressure gradient. This parameter, β, will attain its maximum value somewhere outside the spot centre, probably near the border between the umbra and the penumbra, and approach zero in the outer region of the penumbra.

The condition for equilibrium is that F is everywhere equal to zero. If F is positive, we get an outward directed acceleration, if it is negative, matter will fall into the low-pressure region.

When motions are taking place, other additional forces will act on the moving material, and somewhat disturb this simple picture. First of all inertial effects will come into play. These will be most important where the curvature of the lines of force is largest. The dissipative effects of viscosity must also be considered.

Any specification of the quantitative dependence of β on α must necessarily be only rough guesswork. The most probable value of the limiting angle Θ_1 making F vanish, seems to be of the order of 15–30° in the penumbra region of the spots.

A static equilibrium with the tilt everywhere attaining the value Θ_1 is clearly not a stable one. As shown by Walén [7] at least the upper layers of the cool core of the spot when exposed to the radiation from the hotter surroundings, would be heated to photospheric temperature in a time very much shorter than the lifetime of a spot. Thus some effective cooling mechanism must be operating.

From the previous considerations, we may see what will happen to a spot with Θ equal to Θ_1 when its temperature is increased. First of all the gas pressure will increase in the spot region, thus the isobaric surfaces are partly levelled out, making the low-pressure region less marked. Provided the magnetic field is not altered significantly, this means that the angle Θ is increased above the equilibrium value, thus making F positive. This force will set the matter moving outwards and upwards, sucking material along the magnetic lines of force from the deeper layers. This forced convection will, since the upper layers of a spot are in stable radiative equilibrium, lead to a cooling of the moving matter relative to the surroundings. Another effect may be of importance here, that is the cooling which results when conductive matter is forced through a strongly divergent magnetic field. The material which is set into motion will thus act as a cooling cap for the umbra regions of the spot. After the motion has started protecting the spot from the incoming radiation, the temperature in the spot will decrease, leading to a corresponding decrease in the tilt. In a stable spot where conditions to a good approximation are stationary, we can imagine that the tilt (and thus the force F) is adjusted to the dissipative forces. The stationary velocity of the Evershed-motion will depend upon the temperature difference to be maintained.

The largest spots are also the coolest (cf. [5], and the Evershed-velocity is found to increase with spot size (cf. [8] and [9])). This would seem to confirm our hypothesis. However, the efficiency of the cooling depends upon many parameters besides the velocity. The thickness of the moving layer, the temperature gradient within this layer and the topography of the magnetic field all enter.

In the discussion above we have tacitly assumed that some mechanism is at work in deeper layers which cuts down the energy flux in the spot region. Inhibition of convection by the magnetic field, according to Biermann's idea [10] would seem the most plausible.

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