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ENERGY TRANSPORT IN A SUNSPOT

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IT WAS suggested by BIERMANN⁽¹⁾ that sunspots owe their darkness to the inhibition of the convective energy transport which is due to the magnetic braking of the upward convective motions. In this paper the process of the inhibition is discussed in some detail.

In a vertical magnetic field upward motions along the lines of force are not inhibited but the associated random smaller scale turbulence which leads to dissipation of the convective energy flow by viscosity cannot take place. It is by this mechanism that the convective energy *transport* is inhibited.

We assume the magnetic field of the sunspots to be homogeneous, perpendicular to the solar surface, constant with depth and extending infinitely deep into the solar body. In the deep parts of a spot, where the kinetic energy of the convective motions exceeds the magnetic energy of the spot, convection can unimpededly take place. We call h_c the depth of the level where the kinetic energy of convection is equal to the magnetic energy of the field. The value of h_c ranges from some hundreds of kilometers below the top of the convection zone (for a field $B \approx 200$ G) to 10,000 km for a field of 3000 G. In the region below h_c the field of convective motions is transformed into a field of hydromagnetic waves. Approximately one third of these waves has the character of (longitudinal) pressure waves. They propagate upward, but the greater part of them is reflected because of the smaller scale height in the upper, near photospheric layers: the transmitted part of the motion spectrum is the fraction, of which $\omega > \omega_0$, where ω_0 is the resonance frequency $= c_s/2H$. Here c_s is the local velocity of sound and H is the scale height. Assuming that the velocity spectrum near h_c has the shape given by MOFFATT⁽²⁾, one finds that only $\frac{1}{10}$ of the pressure wave spectrum escapes to the photosphere. These waves manifest themselves in the photospheric part of the spot as an anisotropic field of "turbulence". A vertical velocity amplitude of 0·8 km/sec is expected; the horizontal component is much smaller. This value agrees with Elste's upper limit, communicated at this Colloquium. Should we have assumed a Kolmogoroff spectrum near h_c, then the predicted vertical velocity amplitude of the pressure waves would have been about 2·5 km/sec. So, accurate measurements of the "turbulent" velocities in sunspots should give information on the velocity spectrum near h_c.

About $\frac{2}{3}$ of the energy of the magnetohydrodynamical motion field in the region below h_c has the character of Alfvén waves. These propagate outward, but do not come far, since they are reflected because of the decreasing density. So, the energy of the Alfvén waves is brought back below h_c where the motion field changes into one of hydrodynamical turbulence. There the energy of these waves is dissipated by viscosity. It can be shown that other mechanisms for the absorption of the Alfvén wave energy (drag against neutral particles, ohmic losses and viscosity effects on the Alfvén waves) do not play a part in the regions considered.

So, ultimately, the process of the inhibition of convection in a sunspot has the result that the convective energy flux, which would normally reach the photosphere when there would be no magnetic field, is reflected in the regions around h_c and dissipated into heat below that level. Thus the convective energy flux (which is in the deep parts of the convection zone of the same order as the solar constant) is transformed into heat in the region below h_c; hence, an extra source of energy appears near the h_c level. Our model of a spot thus becomes the one given in Fig. 1. The heat from this source is emitted into all directions and transmitted radiatively (convective transport being inhibited).

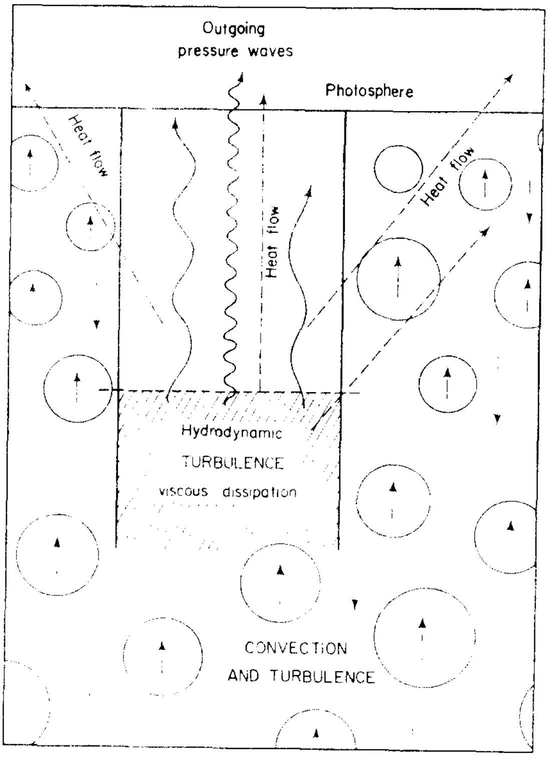

Fig. 1

The intensity to be observed in the umbral centres can be computed on the basis of the above hypothesis, making use of the well known statistical relations between the field strength and the spot diameters. In the table below we give the ratio i_0 of the umbral intensity to that of the adjacent non-magnetic photosphere:

B	260	550	1000	1700	3000	gauss
i_0	0·150	0·065	0·055	0·115	0·195	

For fields slightly smaller than 260 G the umbral intensity will increase rapidly, almost discontinuously, with decreasing fieldstrength, and will be virtually equal to the normal photospheric value for fields smaller than about 200 G: for such weak fields inhibition of convection cannot take place, since then the convective kinetic energy in the whole convection zone is larger than the magnetic energy. On the contrary, we may expect, for these smaller fields, a slight *increase* of the photospheric brightness. It was shown by Kulsrud that the generation of acoustic noise in the convection zone reaches a maximum value for magnetic fields between 50 and 100 G: this leads to a greater heating of the upper photospheric and chromospheric layers, which manifests itself in the photospheric and chromospheric faculae around a sunspot.

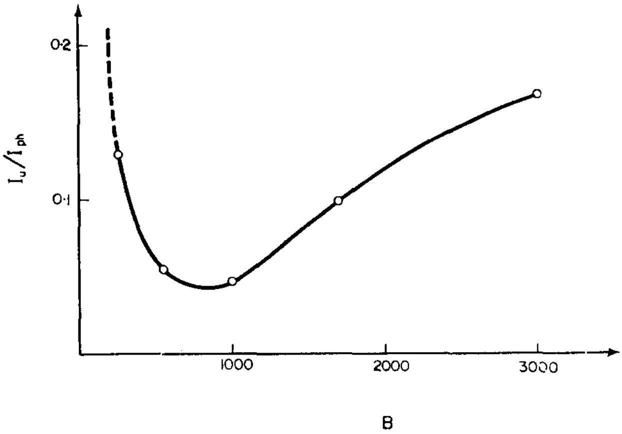

FIG. 2

Apart from that, the extra energy from the source below h_c will lead to an additional energy flux in the region just around the sunspots, presumably causing a phenomenon that might be interpreted as the well known bright ring.

The above considerations will shortly be published in more detail in the *Bulletin of the Astronomical Institutes of the Netherlands.*

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DISCUSSION

R. N. THOMAS: What is the difference in appearance between the granulation in spots and that outside?

J. C. PECKER: According to Rösch, sunspot granulation is similar in size to photospheric granulation but granules there have a much longer life-time, so far as I remember. Nothing, I think, can be said on the intensity contrast.

C. DE JAGER: The life-time of spot-granules is of the order of 40 min. This is fairly well equal to the reciprocal of the computed wavenumber of the waves at a depth of around 10,000 km, and this is another argument for the theory exposed here.

G. ELSTE: Where is the work on the life-time of granulation in sunspots published?

J. C. PECKER: I can refer Dr. Elste to: C. MACRIS, *Ann. Astrophys.* **16** (1953); especially p. 35 *et seq.*

R. N. Thomas: Then if you would interpret this granulation in spots as a field of acoustic waves, why not do the same with the granulation outside spots, as Schatzmann and I independently suggested some years ago?

C. de Jager: Granulation is a complex of phenomena and it is certainly incorrect to say that granulation is merely "a field of acoustic waves" or that it is merely "a field of upward moving gas bubbles". My idea about the photospheric granulation is that the observed *brightness* fluctuations are mainly due to the up- and downward (convective) motion of large-scale masses of gas (motions mainly deeper than $\tau \approx 1$). However the motions observed from widening of spectral lines, mainly at $\tau \approx 0{\cdot}3$, are presumably due to pressure waves originating in the convection region and moving upward with increasing velocity amplitude.

K. Hunger: How can a regular shaped magnetic field as observed in a sunspot, remain stable over a period of say a month if the field lines below the critical depth h_c should move chaotically, and how could the spot field originate under this condition?

May I draw your attention to a (not yet published) paper by Deinzer (Max Planck Inst. F. Astrophysik, Munchen) on the same subject. Deinzer is able to derive the statistical relation between intensity of the field and dimension of the spot on the basis of magnetic hydrodynamics and radiative transfer under the assumption that approximately half of the energy flux is blocked by the magnetic field.

J. C. Pecker: What are the consequences of your theory as far as the heating of the chromosphere above the sunspot is concerned especially when one asks how different it is from what happens above faculae, or above normal photosphere?

C. de Jager: Let us consider three cases: (a) the normal photosphere (magnetic field B is zero); (b) the faculae ($B \approx 100$ G) and the spot ($B \approx 3000$ G).

(a) We know that the *quiet parts* of the chromosphere and the corona are heated by a flux of shock waves, which originate as pressure waves in the upper part of the solar convection region. Computations show that one may expect a coronal temperature of 7×10^5 °K (De Jager and Kuperus, *Bull. Ast. Inst. Netherlands* **16**, 71, 1962).

(b) In the *faculae* the magnetic fields are not yet large enough to inhibit the convective motions; these can take place and are not the least inhibited. Moreover, according to calculations by Kulsrud, the generation of pressure waves is increased for magnetic fields of the order 50–100 G; a tenfold increase is even possible under favourable conditions. Kuperus (*Bull. Astr. Inst. Netherlands*, in press) was able to show that this enhanced flux of pressure waves leads to a corona with a 50 per cent higher temperature than the quiet corona, and a density about 4 times that of the quiet one. These values agree nicely with those observed for the so-called coronal activity regions.

(c) In a spot, with $B \approx 3000$ G the situation is again different, as explained in the present paper. Convection is wholly inhibited, and so is the generation of a pressure wave flux in the near sub-photospheric layers. As shown in the paper, only a small flux of pressure waves, originating in the deep layers, escapes and should give rise to a much reduced corona, just above the spot.

We should like to draw attention to the interesting transition region around $B = 150$–200 G. For slightly smaller fields photospheric faculae originate (some 1 per cent brighter than the surrounding photosphere), and for slightly greater fields the photosphere is fairly dark. Also this is in agreement with the observations; never have sunspots been observed with $B < 200$ G. It would be extremely interesting to watch the development of an originating spot, when the magnetic field changes from—say—100 to 300 G.

R. N. Thomas: Can you elaborate on the difference in behaviour to be expected between normal, plage and sunspot regions vis a vis the mechanical energy produced?

C. de Jager: The answer has been formulated in the reply to Pecker.

K. Hunger: The bright ring around a sunspot should be explained by a sunspot theory too.

C. de Jager: This is indeed easy to do with the present theory. From the energy between h_c radiation will be emitted into all directions. The greatest excess of surface brightness will occur in the spot umbrae, causing there an umbrae intensity of around 10 per cent of the undisturbed photosphere. A smaller part will arrive in the regions around the spot, causing a local increase of the radiation flux; I estimate the brightness of the ring, in my theory, at about 5 per cent just outside the penumbra. The brightness will rapidly decrease further outward.