On the Theory of Sunspots

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It seems not to be generally recognized that the magnetic energy of sunspots is so large that it is unlikely that it can be supplied by the non-uniform rotation of the sun.

The magnetic energy $W_S = \frac{H^2}{8\pi}\ \tau$ of a bipolar sunspot can be estimated in the following way. Let us put $H = 3{,}000$ gauss. Assuming that the magnetic field lines connect the two spots below the photosphere, we put the volume τ equal to

$$\tau = A_S \cdot d$$

where A_S is the area of a spot and d the distance between the spots. Let us put $d = 1.10^{10}$ cm.

The average area $A = \Sigma A_S$ covered by sunspots at a given moment is about $A = 3.10^{19}$ cm^2. Hence the energy stored in sunspot fields at a certain moment is

$$W = (3{,}000)^2 \cdot 10^{10} \cdot 3.10^{19}/8\pi = 10^{35} \text{ erg.}$$

The life-time of a sunspot is of the order 0.1 year. It is reasonable to assume that the energy W is dissipated in about this length of time. The power P which is consumed is

$$P = 10^{36} \text{ erg/year.}$$

According to some theories the sunspots are produced by the nonuniform rotation of the sun. This is unlikely because the kinetic energy of the differential rotation is only of the order 10^{39}—10^{40} erg. Hence, the energy of the differential rotation suffices only during 1,000—10,000 years, unless it is replenished in some way in such a short time, which seems rather unlikely.

This means that the nuclear energy released in the solar core is the most probable energy source of sunspots.

An important question is how this energy is converted into the magnetic energy of sunspots. The most reasonable assumption seems to be that the heat produced in the solar core is converted into mechanical and electromagnetic (magneto-hydrodynamic) energy in a convection region. This region could either be close to the surface or deeper down in the sun. A convection close to the surface should probably be independent of the latitude, and may be associated with the granulation, which is independent of the latitude. But it is unlikely that a phenomenon which is so strongly latitude-dependent as the solar activity takes its energy from a convection layer close to the surface.

On the other hand if the conversion takes place deep inside the sun, a latitude dependence is a natural result of the geometry of a general magnetic field which makes the solar matter anisotropic to magneto-hydrodynamic waves. Such waves may be generated at the convection (even if the details of this effect are not very well understood). For this interpretation speaks that although the sunspot phenomenon is highly irregular, the "sunspot progression curve" is very well reproduced from one cycle to another. This supports the view that this curve is given by the geometry of the sun's general magnetic field, as claimed by the magneto-hydrodynamic theory. A further confirmation of this is the recent result that the polar branch of the curve agrees very well with the prominence activity (ALFVÉN, 1956).

A decisive check of the hypothesis of a generation in the core is that sunspots in the northern hemisphere show a special type of correlation with spots on the southern hemisphere. This correlation has been confirmed empirically in three different ways (Galvenius and Wold, 1948; Whittle, 1954; Alfvén, 1953). It is very important that this correlation be checked in different ways by other authors.

In the chapter "Solar Electrodynamics" in Kuiper's "The Sun" Cowling (1953) has criticised the magneto-hydrodynamic theory of sunspots, which he finds "totally unacceptable". A general objection which Cowling makes is that "Alfvén exceeds the number of *ad hoc* assumptions which can reasonably be allowed to the author of a theory and that there are serious gaps and inconsistencies in his account".

To this should be remarked that in this field as in many other fields of astrophysics we are far from a definite formulation of a final theory. The investigations are obviously still in the stage where we must try different ways of approach even with the risk that a theory at present necessarily contains "serious gaps". It should be observed that Cowling, after having rejected *all* theories of the field, has no positive suggestion to make.

The number of *ad hoc* assumptions which a theory is considered to contain, depends essentially upon how the theory is presented and interpreted. The only real assumption of the magneto-hydrodynamic theory of sunspots is that sunspots—and perhaps other aspects of solar activity—draw their energy from nuclear energy which is released in the solar core, from which the energy is transmitted as magneto-hydrodynamic disturbances out to the surface. Most of what Cowling considers to be *ad hoc* assumptions can as well be regarded as consequences of the theory. For example, if our basic assumption is right the small latitude displacement of a spot shows that the whirl rings have a special orientation. All what we could do with this *consequence* of the basic assumption is to put it into connection with a reasonable convection mechanism producing the disturbances. It turns out that the mechanism is likely to favour the production of whirls of the required orientation. Even if perhaps Cowling does not accept this mechanism, it seems more adequate to list the question of the orientation as a point which requires further investigation than to imply that this still unsolved problem is an objection to the whole way of approach.

Further, according to the magneto-hydrodynamic theory of sunspots the convection in the solar core must be of a special type. In principle, this is not more of an *ad hoc* assumption than e.g. the inference that discontinuities exist in the earth's interior. If the solar activity, and especially the sunspots, are caused by magneto-hydrodynamic waves transmitted to the surface from the interior, we have a means of exploring the interior in the same way as we can explore the earth's interior through a study of seismic waves. Of course we are at present not so sure about the interpretation of the solar activity pattern as we are about the interpretation of a seismogram, but this does not affect the principle.

What has been stated should not conceal the fact that there are many unsolved problems in the theory of sunspots.

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