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## HOW COULD A ROTATING BODY SUCH AS THE SUN BECOME A MAGNET?

[From *Report of the British Association*, Bournemouth, 1919.]

The problem.

THE obvious solution by convection of an electric charge, or of electric polarization, is excluded; because electric fields in and near the body would be involved, which would be too enormous. Direct magnetization is also ruled out by the high temperature, notwithstanding the high density. But several feasible possibilities seem to be open.

Field possibly self-exciting like a dynamo.

Characteristics of sunspot field.

(1) In the case of the Sun, surface phenomena point to the existence of a residual internal circulation mainly in meridian planes. Such internal motion induces an electric field acting on the moving matter: and if any conducting path around the Solar axis happens to be open, an electric current will flow round it, which may in turn increase the inducing magnetic field. In this way it is possible for the internal cyclic motion to act after the manner of the cycle of a self-exciting dynamo, and maintain a permanent magnetic field from insignificant beginnings, at the expense of some of the energy of the internal circulation. Again, if a sunspot is regarded as a superficial source or sink of radial flow of strongly ionized material, with the familiar vortical features, its strong magnetic field would, on these lines, be a natural accompaniment: and if it were an inflow at one level compensated by outflow at another level, the flatness and radial restriction of its magnetic field would be intelligible. [Cf. Appendix VI.]

Polarization by gravitation, or rotation,

not excluded, for it can be compensated electrically, by a free charge,

(2) Theories have been advanced which depend on a hypothesis that the force of gravitation, or centrifugal force, can excite electric polarization, which, by its rotation, produces a magnetic field. But, in order to obtain sensible magnetic effect, there would be a very intense internal electric field such as no kind of matter could sustain. That, however, is actually got rid of by a masking distribution of electric charge, which would accumulate on the surface, and in part in the interior where the polarization is not uniform. The circumstance that the two compensating fields are each enormous is not an objection; for it is recognized, and is illustrated by radioactive phenomena, that molecular electric fields are, in fact, enormous. But though the electric masking would be complete, the two distributions would not compensate each other as regards the magnetic effects of rotational

while a magnetic effect remains over.

convection: and there would be an outstanding magnetic field comparable with that of either distribution taken separately. Only rotation would count in this way; as the effect of the actual translation, along with the solar system, is masked by relativity.

Natural electric polarization in a crystal must be intense, though masked by surface charge; could produce a magnetic field by rotation, but not by convection.

(3) A crystal possesses permanent intrinsic electric polarization, because its polar molecules are orientated: and if this natural orientation is pronounced, the polarization must be nearly complete, so that if the crystal were of the size of the Earth it would produce an enormous electric field. But, great or small, this field will become annulled by masking electric charge as above. The explanation of pyro-electric phenomena by Lord Kelvin was that change of temperature alters the polarization, while the masking charge has not had opportunity to adapt itself: and piezo-electric phenomena might have been anticipated on the same lines. Thus, as there is not complete compensation magnetically, an electrically neutralized crystalline body moving with high speed of rotation through the aether would be expected to produce a magnetic field: and a planet whose materials have crystallized out in some rough relation to the direction of gravity, or of its rotation, would possess a magnetic field. But relativity forbids that a crystalline body translated without rotation, even at astronomical speeds, should exhibit any magnetic field relative to the moving system. [Cf. p. 620.]

The great terrestrial magnetic changes negligible astronomically: a criterion thus afforded, restricting to one cause, of permanent nature.

The very extraordinary feature of the Earth's magnetic field is its great and rapid changes, comparable with its whole amount. Yet the almost absolute fixity of length of the astronomical day shows extreme stability of the Earth as regards its structure [cf. p. 335]. This consideration would seem to exclude entirely theories of terrestrial magnetism of the type of (2) and (3). But the type (1), which appears to be reasonable for the case of the Sun, would account for magnetic change, sudden or gradual, on the Earth merely by change of internal conducting channels: though, on the other hand, it would require fluidity and residual circulation in deep-seated regions. In any case, in a celestial body residual circulation would be extremely permanent, as the large size would make effects of ordinary viscosity nearly negligible.

## (1927) Appendix.—*On the Solar Magnetic Fields.*

The discovery and exploration, by G. E. Hale and his associates, of the intense magnetic fields of sunspots, and of the smaller general field of the Sun, must be significant for general electrical theory: for the Sun is a simple gaseous mass, in contrast with the molecular complexity of solid magnets, and the problem thus restricted should be amenable to molecular theory.

Problem of Sun's magnetic field:

The image that first naturally presents itself is a vortex of whirling electrons or ions: but their numerical density would have to be enormous: and indeed there would have to be as many positive as negative ions in the whirl to avoid impossible electric fields, and then there could be no magnetism.

A modification however invites serious consideration. The countervailing positive ions are massive atomic nuclei, as compared with the electrons: in an electric field the two would be urged different ways, yet both producing current the same way, but the electrons would percolate readily through the more sluggish atomic ions: thus the electric current produced by the field would be mainly one of negative electrons, after the manner of an ordinary current in a metallic conductor. The problem would be solved if we can recognize some driving field of non-electric type, which on the hypothesis of completed circuital currents need not be of great intensity.

as due to electric currents not material whirls:

It is a feature of magnetic fields that they lie close to their sources: this is on account of the inverse cube law of force. The direct and return halves, joined at their ends, of a flat cyclic current-sheet conspire in the space between them, but oppose each other outside their circuit. The magnetic field of sunspots is said to be confined to a narrow stratum: if so it could be imagined as due to opposing sheets of current at the two faces of the stratum, or to a row of parallel current vortices, such as might be sustained by radioactive discharge of electrons across the stratum*.

confined to thin strata.

The suggestion here arises, to be tested out, that as regards the Sun as a whole, the electrons may be driven differentially around its axis of rotation by repulsion (p. 448, *supra*) exerted by the outgoing radiation, simulating an electric field, as it would affect the negative electrons far more than the complementary positive ions. For on account of the Sun's rotation this outward stream of radiation is incident obliquely on the electron, after the manner of a shower of rain relative to an observer travelling across it: this Bradley aber-

Aberration-pressure of outgoing radiation,

* The general magnetic field of the Sun is found (G. E. Hale, *Astrophys. J.* 1918) to fall from 50 gauss to nothing in rising 400 km. in the atmosphere.

ration of the rays gives a backward component to the repulsion they exert: the electrons, thus repelled by the rays, would drift through the Solar mass as a negative current opposite to the direction of rotation, the positive ions also but with much smaller speeds; and this gives at any rate the right direction for the general magnetic polarity of the Sun relative to its rotation, being the same as for the Earth.

could cause electric flux.

The problem of the intense local magnetic fields of sunspots would be different. Somehow the emerging stream of Solar radiation, instead of passing out across a spot, is in part deflected round it and thus comes out perhaps more intense at its edges, as the surrounding flocculi would indicate. There might here arise a suggestion to connect the magnetic fields with gradients of temperature at the spot: the Kelvin thermo-electric effect in metals carrying currents may have its analogue for the Solar gas. In fact the density of the contained electrons may depend on the temperature: for they are more mobile at higher temperatures on account of greater speed, and so push their way down the gradient of temperature until this tendency is pulled up by their accumulation producing a countervailing electric field. Compare the partial separation of the components of a mixed gas by diffusion along a gradient of temperature, noted and investigated by Chapman. This sifting might, however, lead only to a reacting very slight distribution of electric charge in the medium, of density greater in the region of higher temperatures, which countervails it. But there may conceivably remain over a residual distribution of electromotive force, which could not be compensated by charge because of its cyclic character, yet precisely adapted to sustain currents in complete circuits. It would then be such continuing vortices of current, which may readily be intense, but not involving material whirls, that are responsible for the magnetic fields of the sunspots. The originating electric field, however it be generated, is here regarded as a local vector distribution, made up by Stokes' kinematic principle of a gradient part and a rotational part: it is the former that is compensated and neutralized by a reacting distribution of electric charge; the latter remains over and will produce strong cyclic currents. Such local current cycles associate in Amperean manner into distributions of current in larger circuits, but always without accumulation of any charge such as would choke them.

A cause of flocculi.

Kelvin thermo-electric gradient at sunspots:

mainly compensated,

but affording a residual cyclic electric field,

by Stokes' kinematic principle:

For a star as a whole a compensating Kelvin thermo-electric force $F$ would on this view be required, radial and outward from the inner higher temperatures, to maintain a steady state: it induces a feeble density of charge $\frac{1}{4\pi C^2}\left(\frac{dF}{dr} + 2\frac{F}{r}\right)$ diminishing outward, with which it is in equilibrium, and under these conditions of symmetry there is no cyclic part left to produce a closed current.

only in disturbed regions.

Estimate for Sun's general magnetic field,

Estimates may be adventured which will test the adequacy of causes such as these, to which indeed in the gaseous Solar medium we appear to be almost restricted. First we consider the Bradley aberration of the stream of issuing radiation. The repulsion of an electron, of charge $\frac{8}{5}.10^{-20}$, by unit incident radiation is $\frac{1}{2}.10^{-24}/c$: as the intensity of the outward radiation at the Sun is $7.10^{10}$, its repulsion of the electron is of the order $10^{-24}$. The mass of the electron is $9.10^{-28}$, gravity at the Sun is $3.10^4$, so its gravitational attraction is $27.10^{-24}$, about 27 times greater than the repulsion. (Cf. p. 448: Vol. I, p. 663.) The angular relative deflection, by aberration, of the rays travelling directly outward is $8.10^{-6}$. Thus the tangential force on an electron at the equator is $10^{-29}/c$, and it persists when the radial repulsion of the electrons by the radiation has become balanced by the electric field of the positive charge left behind and pulling them back.

as due to obliquity of radiation pressure on electrons,

The tangential acceleration of the electron against the direction of the Sun's rotation would be $\frac{1}{3}\,10^{-11}$: if the free path is $l$ this gets up a mean velocity $(\frac{1}{3}\,10^{-11}l)^{\frac{1}{2}}$ or $\frac{1}{4}10^{-5}l^{\frac{1}{2}}$, as compared with velocity $4.10^5$ due to the Sun's rotation. This mean drift involves, for a numerical density $N$ of electrons, as a circuit is open round the Sun, a current

round open circuits:

at the equator of volume density $\frac{1}{8}\,10^{-5}l^{\frac{1}{2}}Ne$. As applied to a surface atmosphere this would hardly produce a sensible magnetic field. But for a rotating star composed of gas largely ionized this backward drift of electrons would be established throughout its volume. Inside the star the intensity of the outward stream of radiation varies as $r^{-2}$ and its Bradley aberration, due to the star's rotation on its axis, varies as $r\sin\theta$: therefore the equatoreal intensity of the electronic current has to be multiplied for the interior by $(a/r)\sin\theta$ for the same density $N$ of electrons and the same $l$. For a component ring current $i$ of cross-section $\delta S$ the magnetic moment would be $i\pi r^2\sin^2\theta\,\delta S$: thus the aggregate moment would be $\Sigma\frac{1}{8}10^{-5}l^{\frac{1}{2}}Ne\,(a/r)\sin\theta\,\pi r^2\sin^2\theta\,\delta S$, of which only the order of magnitude can be estimated: taking $l^{\frac{1}{2}}N$ uniform and dividing by $\frac{4}{3}\pi a^3$ it integrates to a mean intensity of magnetization $I$ for the Sun equal to $10^{-16}l^{\frac{1}{2}}N$, giving a mean magnetic field of order $4.10^{-16}l^{\frac{1}{2}}N$. If this is to be of the order of 20 as observation indicates $l^{\frac{1}{2}}N$ would be of the average order $5.10^{16}$, which if right is far from excessive.

found to be an adequate *vera causa*,

Thus the general magnetic field of the gaseous globe of the Sun would be ascribed to a recognized cause, the interaction of its rotation and the issuing stream of radiation*. But for the magnetic Earth the stream of radiation is absent.

for a star.

* The particles gradually arrest the outward stream of radiation, producing repulsion by dispersing its momentum in all directions. They must renew the stream by fresh temperature radiation of their own, of isotropic type on average: but the kinetic effect of this (pp. 448, 673) is only diminution of their effective inertia, without any reaction of the present type involving their velocities directly.

A vortex half-ring with its ends on the Solar surface, of sectional radius $b$ and velocity of whirl of the order $v$, would be accompanied by an electric current whirl due to the stream of issuing radiation, producing a magnetic field of about the order $Nebv_0$, where $v_0$ is for the Solar intensity of radiation $2.10^{-9} v^{\frac{1}{2}} l^{\frac{1}{2}}$. For this field to be as high as $10^4$ when $b$ is $10^9$, as in some sunspots, $Nv^{\frac{1}{2}}l^{\frac{1}{2}}$ would have to be of the order $4.10^{23}$: thus if $v$ were $10^6$ the order of $Nl^{\frac{1}{2}}$ below the surface would have to be as much as $4.10^{20}$. One notes that if $l$ were small its square root would be large in comparison.

Field of a sunspot estimated.

If there is internal material circulation in the Sun, it would be accompanied by circulating electric current. If it were symmetrical round the axis of rotation, this current would contribute to the magnetic field in the Sun, without displacing its poles: Hale's discovery that the Solar magnetic pole is a few degrees away from the pole of rotation may thus point to internal circulation not symmetrical round the axis, of which there are other prominent indications.

Asymmetry of Solar field.

The cyclic electronic drifts producing the magnetic field of a sunspot would have to be sustained somehow, as above, by radiational or other effective thermodynamic energy. We can perhaps recognize at any rate whether the magnetism is essential to the existence of the spot. The opposite sides of a ring current repel each other mechanically: thus the current has expansive force and can balance a defect of pressure inside it, permitting smaller gaseous density there. In short, if we consider Hale's map of the magnetic lines of the local field, those issuing nearly radially from the region of the spot can be regarded as subject to the Maxwellian stress, tension from outside along the radius of intensity $H^2/8\pi$, and equal transverse pressure, which permits an equal defect of internal hydrostatic pressure. If the field is say $5.10^3$ this downward tension is $10^6$ dynes, which may hold down the floor of the photosphere below the mean level but only to the order of a km. if its density is comparable with a terrestrial atmosphere, if it does not concentrate the diffuse chromosphere over the spot*.

Magnetic stress in a sunspot.

* There is temptation to connect the drift of spots towards the equator and the very precisely opposed polarities even when they meet there (G. E. Hale and S. B. Nicholson, *Astrophys. J.* 62, 1925) with vortical effect of the maximal equatoreal rotation, were it not for the reversal in successive periods. Cf. Lord Rayleigh's last unfinished paper on atmospheric vortices, *Phil. Mag.* 1919; *Scientific Papers*, Vol. VI, pp. 654–7.