THE MAGNETIC FIELD OF MASSIVE ROTATING BODIES*

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Summary

It has been known for a long time, particularly from the work of Schuster, Sutherland and H. A. Wilson, though lately little regarded, that the magnetic moment P and the angular momentum U of the earth and sun are nearly proportional, and that the constant of proportionality is nearly the square root of the gravitational constant G divided by the velocity of light c. We can write, in fact,

$$P = \beta \frac{G^{1/2}}{c} U,$$

where β is a constant of the order of unity.

For the first time, the magnetic field of a star, 78 Virginis, has recently been measured (Babcock, 1947). Using the best estimate available for its mass, radius and rotational velocity, the calculated value of the magnetic field agrees with its observed value. We have, therefore, a rough verification of the equation above for three bodies, the earth, sun and 78 Virginis, and covering a range of P and U of more than $10^{10}:1$, though only of 2,000 : 1 in measured field. It is therefore considered that the above equation must be taken seriously as a possible general law of Nature for all massive rotating bodies.

If white dwarfs are collapsed forms of stars like the sun, then they should have the same angular momentum and so, according to the equation above, the same magnetic moment. Owing to their small size, they will have a surface magnetic field of the order of 10^6 gauss. It is suggested that magnetic fields of this order may be in part the cause of the large breadth of the Balmer lines in many white dwarfs, and of the complete absence of any lines in some very dense ones. The various alternative theories of the magnetic field of the earth and sun are discussed. It is suggested tentatively that the balance of evidence is that the above equation represents some new and fundamental property of rotating matter. Perhaps this relation will provide the long-sought connexion between electromagnetic and gravitational phenomena.

1. The Magnetic Field of the Earth, the Sun and a Star

While considering the possible influence of the magnetic fields of stars in the galaxy on cosmic ray phenomena, I noticed two results which seemed to me of great physical interest. The magnetic moments P of the earth and the sun are nearly proportional to their angular momenta U, calculated from the expression

$$U = \frac{2}{5} \omega M R^2 \quad . \quad . \quad . \quad (1)$$

for a uniformly dense sphere of mass M, radius R and angular velocity ω. This proportionality can be seen from the figures in Table 1.

TABLE 1

Body	Mass M (gm.)	Radius R (cm.)	Angular velocity ω (sec.$^{-1}$)	U	H_P (gauss)	P	P/U
Earth	$6 \cdot 0 \times 10^{27}$	$6 \cdot 37 \times 10^{8}$	$7 \cdot 3 \times 10^{-5}$	$7 \cdot 1 \times 10^{40}$	0·61	$7 \cdot 9 \times 10^{25}$	$1 \cdot 11 \times 10^{-15}$
Sun	$2 \cdot 0 \times 10^{33}$	$6 \cdot 97 \times 10^{10}$	$2 \cdot 9 \times 10^{-6}$	$1 \cdot 12 \times 10^{49}$	53	$8 \cdot 9 \times 10^{33}$	$0 \cdot 79 \times 10^{-15}$

Measured values of the polar magnetic fields are also given. These are related to the magnetic moments by the expression

$$H_P = 2P/R^3. \quad . \quad . \quad . \quad . \quad (2)$$

It has long been known that the directions of rotation and of the magnetic moments of the two bodies are similarly related; in fact, in both bodies, the south magnetic poles are near the north geographical poles.

It was natural to compare the mean ratio $(P/U)_1$ of the magnetic moment to angular momentum of these two astronomical bodies with the similar ratio

$$(P/U)_2 = e/2mc = 0 \cdot 88 \times 10^7 \text{ cm.}^{1/2} \text{ gm.}^{-1/2} \quad (3)$$

for a Bohr magneton. We have

$$(P/U)_1/(P/U)_2 = 1 \cdot 08 \times 10^{-22}, \quad . \quad . \quad (4)$$

and one recognizes immediately that this numerical value is close to that of the well-known non-dimensional ratio

$$G^{1/2} m/e = 4 \cdot 90 \times 10^{-22} \quad . \quad . \quad (5)$$

of the gravitational mass of an electron to its charge in E.S.U. We can thus write

$$(P/U)_1 = \beta \frac{G^{1/2} m}{e} (P/U)_2, \quad . \quad . \quad (6)$$

where β is a small numerical constant of magnitude about 1/4; whence with (3) we find for the relation between the magnetic moment and angular momentum of both astronomical bodies

$$P = \beta \frac{G^{1/2}}{2c} U. \quad . \quad . \quad . \quad (7)$$

The simplicity of this result, either in the form (6) or (7), suggested that it must have some profound physical significance.

Stimulated thus to study the voluminous literature concerning the origin of the magnetic fields of the earth and sun, I found to my surprise that the essence of these facts had been known for many years, but had, for various reasons, dropped lately out of notice. A survey of this earlier work will be given in the next section.

Seeking a further test of equation (7), I thought at once of the possibility that the magnetic field of some rapidly rotating star might be measurable. I am indebted to Prof. S. Chandrasekhar for giving me early news of the first measurement of the magnetic field of a star that has ever been made. The measurements by Babcock[1] on 78 Virginis have now been published and give a polar field of 1,500 gauss. To calculate P and U we require its mass, radius and angular velocity. From statistical evidence on stars of similar type, the probable values of these quantities in terms of the values for the sun are found to be $M = 2 \cdot 3$, $R = 2 \cdot 0$, $\omega = 25$ (see Section 4). Table 2 gives the resulting data for the star.

TABLE 2

Body	M	R	ω	U	H	P	P/U
78 Virginis	$4 \cdot 6 \times 10^{33}$	$1 \cdot 4 \times 10^{11}$	$7 \cdot 3 \times 10^{-5}$	$2 \cdot 6 \times 10^{51}$	1500	$2 \cdot 1 \times 10^{36}$	$0 \cdot 81 \times 10^{-15}$

We find again about the same ratio for P/U, showing that (7) holds not only for the earth and sun but also for 78 Virginis. The relation between the directions of the rotation and the magnetic field is not known. This further support for the validity of (7) suggests, on one hand, that it must be taken seriously as a possible new general law of Nature, and on the other, that a more rigorous test of its validity must be made, taking into account the variation of density and possibly also of rotation inside the bodies.

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2. Previous Theories of the Magnetic Field of the Earth and Sun

Though the main dipole field of the earth is known to be of internal origin, how it is produced is still obscure. A critical discussion of the extensive literature is given by Chapman and Bartels[2] (1940). The earlier surveys by Schuster[3] (1912), Brunt[4] (1913) and Swann[5] (1923) are still of great value. Possible theories of the sun's field are discussed in a recent paper by Cowling[6] (1945).

Theories of the main field of the earth or sun may conveniently be divided into two classes, which may be called *specific* and *general* theories.

A *specific* theory is one which attributes the magnetic properties of a rotating body to the specific properties of the matter of which it is composed; in such a theory the magnetic moment of a massive body would depend on the specific electrical, magnetic, thermal and mechanical properties of its material, and so is likely to have quite different values for bodies in different physical conditions.

The first theory of this kind, that the earth is ferromagnetic, has long been abandoned, since the internal temperature of the earth is almost certainly well above the Curie points of any materials likely to be present. The obvious alternative is to assume the existence of an electrical conduction current in the earth. The difficulty is to find a mechanism which will maintain it. To explain the sign of the field, a positive current must flow from east to west or a negative one from west to east.

A recent attempt by Elsasser[7] (1939) attributes the current to thermo-electric E.M.F.'s arising from temperature differences in the fluid core due to convective motions. The essential asymmetry required to produce a net circulation around the axis is attributed to the action of Coriolis forces on the convecting masses. In a subsequent paper Elsasser[8] (1941) discusses the relation between the main large dipole field of the earth and the irregular part which amounts to a few per cent of the main field. The origin of both is held to be in the central core of molten metal of radius about $0 \cdot 55\, R$.

A rather similar theory by Frenkel[9] (1945) introduces in addition a self-excitation mechanism, such as had been considered by Gurevich and Lebedinsky[10] (1945) to be the origin of the magnetic field of sunspots. The first theory involving a self-excitation or dynamo mechanism was put forward by Larmor[11] (1919) and was elaborated in detail by Cowling[12] (1933) and shown to fail to explain either the magnetic field of sunspots or the main fields of the earth and sun. Cowling[6] (1945) showed, too, that thermal effects due to convection in the rotating sun give the right sign but in magnitude only 10^{-7} of the observed field. He also shows that the time of electromagnetic decay of the sun's general magnetic field is 10^{10} years, so that the field might be a relic from a different primeval state. But Lamb (for example, see Chapman and Bartel, ref. 2, vol. 2, p. 704) had shown long ago that the decay of currents in the earth would be far too quick to allow the field to be explained as a survival.

A general theory is one that attributes the dipole field to some general property of rotating matter. Already in 1891, Schuster[13], suspecting from the appearance of the solar corona that the sun might have a magnetic field, had put the question, "Is every large rotating mass a magnet?"

The only obvious atomic effect of a general character is that of magnetization by rotation, that is, the gyro-magnetic effect. This gives the right sign, but a moment 10^{10} too small (ref. 2, p. 705). But, as Schuster showed[3], any such uniform magnetization gives a total moment proportional to the volume of the sphere and so a surface field which is independent of the radius. Thus any such theory can be excluded.

In a series of papers, Sutherland[14] (1900–8) assumed that the earth's magnetic field is due to its possession of a positive volume charge compensated by a negative surface charge. He calculated the charge density required and showed that it implies electric fields inside the earth of the order of 10^8 volts per cm. He also noticed that the separation of charges, as calculated from the observed magnetic field of the earth, had about the same magnitude as would occur if gravitation were explained, on the basis of Lorentz's pre-relativity theory (for example, ref. 3), as due to a slight difference between the electric forces between two protons, two electrons, and an electron and a proton. This is, in essence, an early recognition of the numerical result explicitly stated later by Wilson[15] (1923), which expresses in a rather different way the result already given in section 1.

In 1912, Schuster gave a survey[3] of the possible theories and their difficulties, and studied in some detail one similar to that of Sutherland, depending on the assumption of unequal forces between like and unlike atomic particles. Brunt[4] (1913) surveyed many different theories and also showed that the separation of positive and negative charges in the sun's gravitational field could not produce more than 10^{-15} of the sun's magnetic field.

H. A. Wilson[15] (1923), following a suggestion of Schuster[3], showed that one obtained the right order of magnitude for the fields of the earth and sun if one assumed that a moving mass element M, measured in gravitational units, has the same magnetic effect as a moving negative charge Q measured in E.S.U. The measure M of the mass of a body in gravitational units is defined by the equation $F = M_1 M_2/r^2$ for the gravitational force between two masses. Comparing this with the expression $F = G m_1 m_2/r^2$, where m_1 and m_2 are measured in grams, we have $M = G^{1/2} m$, whence the gravitational unit of matter amounts to $G^{-1/2} = 3{,}870$ gm.

Wilson's hypothesis, expressed formally, amounted to the assumption that a mass element m gm., or M gravitational units, when moving with velocity v gives, at a distance r, a magnetic field,

$$H = -\frac{M}{cr^3}[v.r] = -\frac{G^{1/2} m}{cr^3}[v.r] \quad . \quad . \quad (8)$$

in analogy to the non-relativistic expression for the magnetic field of a moving charge Q E.S.U., which is:

$$H = \frac{Q}{cr^3}[v.r]. \quad . \quad . \quad . \quad (9)$$

From (8), we find by integration that the magnetic moment P of a sphere of mass M and uniform density ρ, radius R and angular velocity ω, is given by

$$P = \frac{1}{5}\frac{G^{1/2}}{c}\omega M R^2. \quad . \quad . \quad (10)$$

We note that (1) and (10) together give (7), apart from the constant β. The surface magnetic field at the pole is, from (2),

$$H_P = \frac{2}{5}\frac{G^{1/2}}{c}\frac{\omega M}{R}, \quad . \quad . \quad . \quad (11)$$

or expressed in terms of the density ρ

$$H_P = \frac{8}{15}\pi\frac{G^{1/2}}{c}\omega\rho R^2. \quad . \quad . \quad . \quad (11a)$$

Wilson showed that (11) gave the right ratio for the field of the sun and the earth, but numerical values about three times too great.

An alternative way of expressing this result is that the earth's magnetic field is such that would be produced if it possessed a volume negative charge density σ, given in terms of the mass density ρ by

$$\sigma \cong G^{1/2}\rho. \quad . \quad . \quad . \quad (12)$$

Angenheister[16] (1925) also stressed the fact that the assumption of an electric charge density proportional to the mass density gives nearly the correct ratio for the magnetic field of sun and earth. He clearly recognized the physical difficulties of assuming the existence of *real* charges of such a magnitude, and of the large electric fields which must accompany them, in an electrically conducting material such as the earth's core.

Wilson[15] (1923) made a laboratory experiment with a swinging iron bar to test his hypothesis that a moving mass produces a magnetic field. He showed experimentally that the field given by (8), assuming that m is taken as the mass of the earth and v the relative velocity of the iron bar, did not exist. Other arguments against the hypothesis are given in Section 5.

It was probably this disproof of the existence of the field given by (8) which led to the later lack of interest in the approximate validity for the sun and earth of the result expressed by (7). This difficulty about translational, as opposed to rotary, motion had already been discussed by Schuster in 1912, and will be taken up again in Section 5.

Schlomka[17] (1933) has treated in some detail a theory based essentially on Schuster's hypothesis of unequal long-range Coulomb forces between like and unlike particles.

Haalck[18] (1937–38) attributes the required charge separation not to a difference in the Coulomb forces between electrons and nuclei, but to the short-range forces between electrons and molecules, that is, to the forces responsible for the elastic properties of materials. He assumes that such forces would lead to a charge separation proportional to some power of the radius, with a maximum at the earth's centre.

Swann[19] (1927) worked out an elaborate theory based on a small arbitrary modification of the electro-dynamical equations, chosen so as to give the required magnetic field without the unwanted electric field. However, Swann's fundamental hypothesis was that the magnetic field of a rotating body was proportional to $\rho\omega^4R^4$ rather than to $\rho\omega R^2$ as given by (11*a*). This was adopted to avoid the difficulty of translational motion by assuming that the magnetic field due to a mass element depended on certain time derivatives of its velocity, and so is zero for uniform translational motion. Swann chose this particular form since it does give correctly the ratio of the field of the sun and the earth. But it also predicts relatively large fields for rotating bodies on a laboratory scale, and these were later shown by Swann and Longacre[20] (1928) not to exist, thus refuting the theory at least for small bodies. Other objections to Swann's theory are that it is unlikely that the vector quantity P will depend on an even power of the vector ω, and that the theory in no way gives the correct numerical value of the magnetic moment except by the introduction of arbitrary parameters.

The Case for a General Theory.

Chapman and Bartels[2] (1940, vol. 2, p. 707) discuss these various theories in some detail but do not give much prominence to the particular parts of the work of Sutherland, Schuster, Wilson and Angenheister, which together establish the results already given. They sum up on the whole against a theory of the type here called a *general* theory and in favour of a *specific* theory of some type; but they do not find that any then existing specific theory is tenable. Their main reasons for the rejection of a general theory lay in the facts of the obliquity of the magnetic and rotational axes, which is 4° for the sun and 12° for the earth, and the existence of the secular variation. For the earth this means that a field amounting to some 10 per cent of the main symmetrical field would remain to be explained even if a general theory served to explain the main field. It seems to me, however, that, given a general explanation of the main field, then the convective motions, etc., that must exist in the earth's interior may well be found to modify the main field sufficiently to produce the observed field.

It is surely far more difficult to find a specific theory that will give the two striking results: (*a*) that the magnetic momenta of the sun and the earth are nearly proportional to their angular momenta—the range of variation of both being more than 10^8 to 1; and (*b*) that the constant of proportionality is nearly $G^{1/2}/c$, than it is to explain a deviation in the directions of the two axes and the existence of the secular variation.

It seems extremely unlikely that the approximate validity of equation (7) could be accidental. Its simplicity, involving as it does only the two macroscopic constants G and c, is in striking contrast to the complexity and arbitrary character of all special theories hitherto put forward, and their failure so far to provide a quantitative explanation either of the field of the earth or of the sun, far less of both.

The occurrence only of the constant $G^{1/2}/c$ multiplying the angular momentum U seems to exclude, except by way of a remarkable number of numerical accidents, the possibility that any specific properties of the rotating body, other than its size, mass and rotation, can determine its magnetic field.

If P does depend only on the macroscopic quantities M, R, ω, G, c, then dimensional considerations can be used to find the possible functional forms. Restricting our consideration to cases where P is proportional to M, we find that P can be put in the form

$$P \propto G^{1/2}c^{-1}\omega MR^2 f(\omega R/c). \quad . \quad . \quad (13)$$

For $f(\omega R/c) =$ constant, this gives our original expression (7). Since P must vary as an odd power of ω, the next likely expression is given by taking $f(\omega R/c) = (\omega R/c)^2$, giving

$$P \propto G^{1/2}c^{-3}\omega^3 MR^4. \quad . \quad . \quad . \quad (14)$$

Now our original expression gives both the observed variation of P with M, ω and R and the rough correct numerical magnitude, while the second gives neither one nor the other. It will be noticed that the second expression differs from the first by the factor $(\omega R/c) = v/c$, when v is the peripheral velocity. It is, of course, probable that at very high peripheral speeds a relativity correction involving $(v/c)^2$ would have to be introduced.

3. The Angular Momentum of a Star

As has already been explained, the approximate validity of (7) was first noted by comparing the magnetic moments of the earth and sun, assuming both to have uniform density. This, however, is far from being the case, especially for the sun, so it is necessary to take into account the central condensation of these bodies when calculating their angular momentum U.

It is convenient to introduce the ratio

$$k = I/I_0 \quad . \quad . \quad . \quad . \quad . \quad (15)$$

of the moment of inertia of a given centrally condensed sphere to that of a sphere of the same radius, angular velocity, and with a uniform density equal to the mean density of the centrally condensed sphere. Then, instead of (1), we have

$$U = \frac{2}{5}k\omega MR^2. \quad . \quad . \quad . \quad (16)$$

For the earth and major planets k is known from the work of Jeffries[21] (1924, 1937). For the sun and other stars, its value must be calculated assuming some given stellar model. First, we have the Emden polytropic gas spheres for which Eddington[22] (1926) quotes the density distributions for three values of the index n. Then there is the more recent point convective model of Cowling[23] (1935) for which new numerical calculations have been made by Blanch, Lowan, Marshak and Bethe[24] (1941) and Marshak and Blanch[25] (1946).

From their density distributions the values of k have been calculated roughly by graphical integration, leading to the figures given in Table 3, together with the ratio of the central density ρ_0 to the mean density $\bar{\rho}$.

TABLE 3. CENTRAL DENSITY ρ_0 AND RELATIVE MOMENT OF INERTIA k OF STELLAR BODIES

	$\rho_0/\bar{\rho}$	$k = I/I_0$
Uniform sphere	1·00	1·00
Polytrope $n = 2$	11·4	0·40
,, $n = 2{\cdot}5$	24·1	0·28
,, $n = 3$	54·3	0·20
Point convective model	79·3	0·14
Earth	3·3	0·88
Jupiter	?	0·66

There is thus considerable uncertainty in the value of k for the sun. In what follows, we will assume the value 0·16 as the mean for the point convective model, and the polytrope with $n = 3$.

Non-uniform Rotation.

From considerations of stability it appears probable that the angular rotation of a gaseous stellar body cannot be uniform, but it is likely to increase inwards (see discussion by Milne[26], 1930, p. 241). On the other hand, it is known that the surface rotation of the sun is about 40 per cent slower at the poles than at the equator. Though so far there appears to be no certain way of estimating the magnitude of this effect, it is convenient to introduce a quantity defined by

$$\eta = U/U_0,$$

where U is the true angular momentum, and U_0 is the angular momentum calculated from the observed peripheral equatorial velocity, taking into account the variation of density but not the variation of the angular velocity. Then we know that η is of the order of, but probably rather greater than, unity.

I am indebted to Prof. Cowling for informing me that the mean period of rotation of the whole mass of the sun is very uncertain, but is probably not shorter than ten days, though it may be actually more than twenty-five days. This gives a limit of η between 2·5 and, say, 0·7.

We have therefore the following expression for the angular momentum of a rotating celestial body:

$$U = \frac{2}{5}k\eta\omega MR^2, \quad . \quad . \quad . \quad (17)$$

and so, with (2) and (7)

$$H_P = \frac{2}{5}\beta G^{1/2}k\eta\omega M/Rc, \quad . \quad . \quad . \quad (18)$$

where ω is the observed angular velocity of the surface at the equator. For a few stars the values of M and R are known accurately, but in general they have to be deduced statistically. The values of k and η can, of course, only be derived from some theoretical model of the interior of the star.

4. The Magnetic Field of a Rotating Star

4.1. *Babcock's Measurements on* 78 *Virginis*

It has long been known that many stars are rotating much faster than the sun, and so, on our hypothesis that equation (7) has general validity, should have large magnetic fields. But it is only quite recently that the magnetic field of any star except the sun has been measured. This has been achieved by H. W. Babcock[1] (1947) for 78 Virginis (spectral type $A2$), and, as has been explained in Section 1, it is satisfactory to find that within the rather large error of the measurement of the magnetic field and the statistical uncertainty of the estimation of the mass, radius and angular velocity, the results are in agreement with expectation, though the relation between the directions of the magnetic field and rotation is not known.

The rotational velocity of stars is measured by the broadening of spectral lines due to the Doppler effect of the light from different portions of the disk. A general account of the method is given by Elvey[27] (1930), Rosseland[28] (1936, p. 202) and Becker[29] (1942, p. 66). Stars of early spectral types O, B and A and early F are usually found to be in rapid rotation, with a most frequent peripheral velocity of about 100 km./sec., compared with the 2 km./sec. peripheral velocity of the sun (type $G0$). A small fraction have velocities of more than 200 km./sec. (see Table 4). The rotations seem to disappear rather suddenly between $F2$ and $F5$ types, and no observable rotations, that is, with peripheral velocities more than, say, 20 km./sec., have been observed for later spectral types. A few stars of the early types have, however, fine spectral lines, and this is interpreted as indicating that their rotational axes are parallel to the line of sight. It is only on such stars that the Zeeman effect can at present be measured.

Babcock's measurements on 78 Virginis give a polar field of 1,500 gauss. He assumes a peripheral velocity of 60 km./sec., and compares these figures with the field of 53 gauss and velocity of 2 km./sec. for the sun, concluding that the field is proportional to the peripheral velocity. This, however, lacks physical plausibility.

To test equation (7) we need M, R and ω. From tables given by Becker[29] (1942, p. 64) for the different spectral classes, we find for a star of type $A2$ that $M = 2{\cdot}3$ and $R = 2{\cdot}0$ in terms of values for the sun. From data on rotation given by Becker (p. 69) and reproduced in Table 4, the median peripheral velocity for A type stars appears to be about 100 km./sec. rather than the value of 60 km./sec. assumed by Babcock. The angular velocity ω must therefore be twenty-five times that of the sun, that is, nearly the same as for the earth.

TABLE 4. DISTRIBUTION OF ROTATIONAL PERIPHERAL VELOCITIES FOR STARS OF EARLY SPECTRAL TYPES, BECKER[29] (1942)

Velocity (km./sec.)	Type O, B (%)	Type A (%)	Velocity (km./sec.)	Type O, B (%)	Type A (%)
25	—	13	150	15	12
50	27	17	175	—	8
75	—	11	200	4	7
100	53	10	225	—	4
125	—	14	250	1	1

Assuming that k and η have the same values for the sun and 78 Virginis, the ratio of their polar fields, according to (11), should be proportional to $\omega M/R$, and so should have the value 29, whereas the observed value is 28. Considering the statistical nature of the data for the star shown clearly in Table 4, the closeness of the above agreement must be considered quite accidental. The direction of the magnetic field was determined, but not, of course, the direction of rotation. So no comparison of the signs of P and U is possible for this star.

4.2. *Collected Data for the Earth, Sun and* 78 *Virginis.*

In Table 5, we have given collected data for the three bodies. For the earth, the component along the axis of rotation of the dipole moment as given by Chapman[30] (1943) is used.

TABLE 5. RATIO P/U ALLOWING FOR CENTRAL CONDENSATION

	Magnetic moment $P=\frac{1}{2}H_PR^3$	k	Angular momentum $U=\frac{2}{5}k\omega MR^2$	$\frac{P}{U}$	$\beta=\frac{P}{U}\div\frac{G^{1/2}}{2c}$
Earth	$7\cdot9\times10^{25}$	0·88	$6\cdot22\times10^{40}$	$1\cdot30\times10^{-15}$	0·30
Sun	$8\cdot9\times10^{33}$	0·16	$1\cdot80\times10^{48}$	$4\cdot9\times10^{-15}$	1·14
78 Vir.	$2\cdot1\times10^{36}$	0·16	$4\cdot2\times10^{50}$	$5\cdot0\times10^{-15}$	1·16

Quite recently, one uncertainty, that of the nature and magnitude of the sun's dipole field, has been cleared up. Hale's early measurements showed a much more rapid decrease of H with height in the sun's atmosphere than would correspond to the field of a dipole. However, the work of Thiessen[31] (1946) seems finally to have established the existence of a dipole field for the sun, and gives a value for the polar field of 53 ± 12 gauss.

In the last column of Table 5 are given the values of β, calculated from (7) by inserting the observed values of P and U and taking $G^{1/2}/2c = 4\cdot31 \times 10^{-15}$ cm.$^{1/2}$ gm.$^{-1/2}$. It will be noticed that β is nearly unity for the sun and 78 Virginis, but about 0·3 for the earth; the latter fact had been originally noticed by Wilson[15] (1923). Alternatively, β can be obtained directly from the expression

$$\beta = \frac{5}{2}H_PRc/k\omega MG^{1/2}. \quad . \quad . \quad . \quad (18a)$$

This equation is convenient as showing the effect on β of errors in the various quantities.

It is noteworthy that the close proportionality between P and U for the earth and sun, found on the assumption of uniform densities (Section 1), is destroyed by taking into account the central condensation of the sun and the stars.

In Table 6 the observed relative values of H_P for the three bodies are compared with the values calculated from (7), assuming that the angular momenta are calculated from equation (1) for uniform density, and equation (16) for centrally condensed spheres.

TABLE 6. OBSERVED AND CALCULATED POLAR FIELD

	H_P (observed) gauss	H_P (observed) relative	Uniform density $\frac{M\omega}{R}$	Central condensation k	Central condensation $\frac{M\omega R}{R}$ (rel.)
Earth	0·61	1·0	1·0	1·0	1·0
Sun	53±12	86	121	0·16	20
78 Vir.	1500	2450	3500	0·16	550

4.3. *Possibility of Further Tests on Stars of the Main Sequence.*

Clearly, further measurements of the magnitude and direction of the magnetic field of highly rotating stars are of great importance to test the theory. Babcock[1] (1947) has stated that it might be possible to find the relation between the directions of H and ω on a visual binary. As shown in Table 4, some stars of the early spectral classes, rather similar to 78 Virginis, have rotational velocities about 2·5 times as high (see also Struve[32], 1930, Westgate[33], 1933, 1934). Such stars should therefore have a polar field of about 4,000 gauss.

The maximum magnetic field is set by the Roche Limit giving the maximum angular velocity ω_m for stability. This is given by

$$\omega_m = 1\cdot52\, G^{1/2}\,\bar{\rho}^{1/2}, \quad . \quad . \quad . \quad . \quad (19)$$

where $\bar{\rho}$ is the mean density (Jeans[34], 1928, p. 246). This suggests that angular rotations up to some four times that of 78 Virginis are possible, thus giving a maximum field for this type of star of about 6,000 gauss. If we insert ω_m from (19) in (11*a*), we see that the maximum possible field H_m of a star is proportional to $\bar{\rho}^{3/2}R^2$. From the variation of $\bar{\rho}$ and R with spectral type (ref. 1, p. 62), we see that H_m varies rather slowly with spectral type along the main series. Relative to the value for the sun ($G0$), we find $H_m = 1\cdot2$ for ($M0$) and 0·5 for ($B0$) type. These later types, though apparently not normally rotating fast, are capable dynamically of giving greater fields than early types.

The most satisfactory test would, of course, be on a star for which the magnitude and direction of both the magnetic field and angular velocity could be measured directly, rather than having to rely on a statistical argument for the determination of the rotation, as for 78 Virginis. It seems that this might, in principle, be done by measuring both the Zeeman effect and the Doppler effect of the light from the nearly eclipsed edge of the rear component of an eclipsing binary. But probably the experimental difficulties would be very great.

4.4. *The White Dwarfs.*

The white dwarfs should also have a large field if they are rotating with comparable angular velocities to the sun, owing to the high values of the ratio M/R on which the field depends (equation 11). The values for several white dwarfs of this ratio, which is also the ratio governing the red shift, are between twenty and thirty times that of the sun (Russell[35], 1945, p. 760), and so should give a field of about 1,300 gauss. If, however, for example, the dark companion of Sirius has the same angular velocity of rotation as Sirius itself, that is, eight days, its magnetic field would be about 5,000 gauss.

It has been suggested by Kuiper[36] (1941) that possibly white dwarfs have angular *momenta* comparable with that of the sun, as would be expected if they are formed by the collapse of such stars. Now Sirius B has nearly the same mass as the sun but only a fiftieth of its radius. If its angular momentum is equal to that of the sun, so will be, according to our hypothesis, its magnetic moment. Consequently its magnetic field will be 50^3 times as great; that is, its equatorial field will be 3×10^6 gauss.

Now the most prominent lines in the spectra of white dwarfs, and often the only lines, are the hydrogen Balmer series. These lines are, however, much broader than for normal main sequence stars. This greater breadth is generally ascribed to pressure broadening, that is, to the Stark effect due to atomic collisions, which should be exceptionally great in these stars owing to the high pressure associated with the very intense gravitational fields. It appears from the discussion by Kuiper[36] (1941) that a rough quantitative explanation on these lines is possible.

It is, however, interesting to note that a magnetic field of a few million gauss will also produce a broadening of the observed magnitude. For the double Zeeman separation of a normal triplet of the wave-length of $H\gamma$ is nearly 2×10^{-5} A./gauss, so the breadth of the Zeeman pattern should be about 60A. It must be remembered that owing to the Paschen–Back effect the Balmer lines will give nearly the normal triplet. Since the polar field is twice the equatorial field, this calculated breadth will approximately represent the double width to half intensity of the light from the star as a whole. Sirius B itself seems to have rather finer Balmer lines than 60A., and also some metallic lines. However, a number of white dwarfs, for example, 40 Eridani B and Wulf 1346 have Balmer lines of widths of about 50A. (Kuiper[36], 1941). Thus it cannot be considered unplausible to suppose that the line widths of white dwarfs are markedly greater than main sequence stars, not only because of a large Stark effect but also in part because of a large Zeeman effect. The comparison given by Kuiper of the spectra of 40 Eridani B with a comparison star shows that the line width of the latter, probably to be attributed to pressure broadening, would be enough to obscure the typical double-triplet structure of a Zeeman pattern in the white dwarf.

Many of these stars show a rather fine central core to the broad Balmer lines which is difficult to explain as due to Stark effect; and it is possible that this is caused by the undisplaced components of the Zeeman pattern, which will be the same all over the disk.

It is perhaps significant that most of the white dwarfs which are believed to be still smaller than Sirius B show no Balmer lines at all (Wulf, 489, 457, 219) or very shallow ones (AC. 70, 8247). One star, Ross 627, is anomalous in this respect, as it has rather fine lines but is nevertheless believed to be very dense.

In the spectrum of (AC. 70, 8247) there are two shallow lines more than 100 A. in breadth and centred on 4480 A. and 4140 A. If these are identified with $H\gamma$ (4341) and $H\delta$ (4102) and their breadth attributed to Zeeman effect, the required magnetic field is about 10^7 gauss. Taking Kuiper's estimate (ref. 36, p. 234) of the radius as 0·004 of that of the sun, the magnetic moment and so the angular momentum of the star relative to the sun will be $(10^7/25) \times (0{\cdot}004)^3 = 0{\cdot}024$. It is, however, possible that the observed shallow lines do not represent the whole absorption line but only the finer central core. In this case the real breadth will be considerably larger than 100 A., and so the angular momentum also will be larger—thus bringing it nearer to that of the sun.

Clearly, polarization measurements on the spectra of the white dwarfs are urgently needed, and calculations of the line profiles which would result from the combination of the Zeeman effect in large fields with pressure broadening.

I am indebted to Prof. H. H. Plaskett for pointing out that there is one white dwarf, Wolf 489 (see ref. 36, p. 211), which lends support to the explanation of the broadening by Zeeman rather than Stark effect. This star is unusual in being of a later colour type (G8) and so should show strong lines of ionized calcium. In fact, it shows no lines at all. Since Ca^+ lines are very much less influenced by the Stark effect than hydrogen lines, it is difficult to explain their absence as due to the Stark effect. Thus the Zeeman effect, to which the H and Ca^+ lines are equally sensitive, provides a more plausible explanation.

Since the Zeeman breadth $\Delta \lambda_Z$ is proportional to the surface magnetic field and so, according to (2) and (7), to U/R^3, while the Doppler breadth $\Delta \lambda_D$ is proportional to the peripheral velocity and so to $U/M.R$, the ratio $\Delta \lambda_Z/\Delta \lambda_D$ is proportional to M/R^2 and so is independent of the rotation. For very small and dense stars the Zeeman breadth becomes greater than the Doppler breadth. For Sirius B, $\Delta \lambda_Z$ is about twenty times $\Delta \lambda_D$. The two breadths will be equal for a star of about the sun's mass, which has a radius about five times that of Sirius B. The period of rotation of Sirius B, if it has the same angular momentum as the sun, is fifteen minutes, and its peripheral velocity 100 km./sec. Owing to the high density, the limiting period set by the Roche limit is about forty seconds.

4.5. *The Major Planets.*

Another interesting possibility is that Jupiter might have a measurable field. Take the value of k as 0·66, as given by Jeffries[21], with $R = 7{\cdot}0 \times 10^9$ cm., $\bar{\rho} = 1{\cdot}35$, $T = 9{\cdot}8$ hours, we find from (18a) that the polar field is about 30 gauss, using the value of β for the earth, and 120 gauss with the value for the sun. Probably such a small field would be unmeasurable, as the only spectral lines available are apparently the absorption bands of methane and ammonia; the low temperature 150° abs. would, however, help by making the lines narrow.

5. Theoretical Discussion

5.1. As has already been explained, early attempts to explain the magnetic field of the earth on the lines of a general theory tentatively assumed that the earth was in some way electrically charged. Since the earth has a very small external electric field, it was necessary to assume that the net charge was zero, and so a separation of positive and negative charges within the earth was postulated. To explain the sign of the magnetic field, it was necessary to suppose that the negative distribution was displaced outwards. A special case of such a distribution (Sutherland[14], 1904) is that of a uniform positive volume charge combined with negative surface charge of equal total magnitude.

A charge separation theory of this type has the great merit of explaining very simply the existence of a magnetic field due to a rotating body, and the absence of a magnetic field due to pure translational motion. Provided, however, that the normal laws of electro-magnetism are assumed, it is quite impossible to believe in the existence of a real charge-separation of the required magnitude. This is given by (12), and for the earth is of the order of 10^{-3} E.S.U., or 10^6 electrons per unit volume. But such a charge distribution implies an electric field inside the earth of the order of 10^8 volts/cm., which is greater than the dielectric strength of any known material. In the sun its non-existence is still more obvious. Since the conductivity both of the central core of the earth and of the ionized matter in the sun are relatively high, any such charges which were produced by any static E.M.F. would very rapidly be conducted away. Chapman[37] (1928) and Cowling[6] (1945) have calculated that the conductivity of the matter at the sun's centre is of the same order as that of copper at normal temperature.

Actually there will, of course, be some separation of positive and negative charges in an ionized gas in a gravitational field, due to the large difference in mass between the electrons and the positive ions. Pannekoek[38] (1922) and Rosseland[39] (1924) have treated this question (see ref. 22, 1926) and have proved from the Maxwell–Boltzmann equation that a charge density of magnitude

$$\sigma_e = G\rho\mu/e, \quad . \quad . \quad . \quad . \qquad (20)$$

when μ is the mass of the positive ions and e is the electronic charge, will be produced by the tendency of the electrons to move to regions of higher gravitational potential.

For the sun, the mean molecular weight is about 2·2 in terms of the hydrogen atom. Comparing (20) with (12), we see that the ratio of the charge density and so the electric field, due to this separation of electrons and ions in the gravitation field, to the charge density and electric field necessary to explain the magnetic field of the earth, is about 10^{-17}. Essentially the same result was obtained earlier by Brunt[4] (1913) in a less general form. The sign of the charge distribution is the same as that required to explain the magnetic field, that is, the negative charge is outermost.

Cowling[40] (1929) has pointed out that when an ionized medium in a gravitational field is moving at right angles to a magnetic field, then the electric field due to the separation of the charges is considerably greater than that given by (20). It is still, however, far too small to explain the observed magnetic moments.

If the normal electro-magnetic equations are assumed valid, it is clear that no adequate real charge separation can exist. Thus some alteration in the fundamental equations seems inevitable. Further, it is difficult to believe that any possible alteration of the electro-dynamical equation can allow the existence of a real charge density in the earth and sun of the required magnitude. Still, it is possible that the charge separation theories of Schuster, Schlomka and others, which depend on the hypothesis of lack of exact equality between protons and electrons, etc., may repay further study.

Another type of alteration of the electro-magnetic equation is that proposed by H. A. Wilson, who postulated that a mass in moving with velocity v, even though electrically neutral, produces a magnetic field given by (8).

This hypothesis, however, is certainly untrue, if v is interpreted as a relative translational velocity. For example, an observer in an aircraft moving at 500 km./hr. relative to the earth can be considered as at rest with the earth moving past him at the same velocity. Thus, according to (8), he should observe a magnetic field of the order of 1 gauss and with a direction quite different from the actual field of the earth. Again Wilson disproved this relation by a laboratory experiment.

There is also, of course, a theoretical objection to the existence of any magnetic field associated with the translational motion of a neutral mass. For the normal Lorentz transformations for free space show that the magnetic field given by (8) can only exist if the assumed 'neutral' mass has an electric charge $Q \sim G^{1/2}m$; this contradicts the assumption that the mass is uncharged.

We must conclude, therefore, that a neutral mass with a pure translational velocity does not produce a magnetic field according to (8). However, for the purpose of explaining equation (7), it may not be necessary to assume that (8) is true for pure translational motion. If, for example, the velocity of a mass element δm is interpreted as that velocity relative to an observer which is produced by the absolute rotation of the body, then one can use (8) to explain (7) without necessarily concluding that a neutral mass in pure translational motion produces a magnetic field. We conclude, therefore, that equation (8), with an additional multiplying factor β, may possibly provide a tentative explanation of (7), provided v is defined as the relative velocity due to rotation as measured with reference to the inertial frame of the universe, that is, by the equation $v = [\omega.R]$, when ω is the measured absolute rotation and R the radius vector from the centre of gravity.

It is not, however, clear to me whether it is, in fact, possible to retain (8) for rotational motion and deny it for translational motion without some far-reaching alteration in the electro-magnetic and dynamical equations. No difficulty occurs in the application to a single rigid rotating body, but how to avoid difficulties in connexion with the orbital motion of, say, the planets or a double star is not so clear. As has already been pointed out, this difficulty does not occur on the hypothesis of a real charge separation. For here we have two equations of type (9), one with Q and H positive and one with them negative. It is the cancellation of the magnetic fields from the opposite charges which give a magnetic field for rotational but not for translational motion. The problem is whether one can obtain the same result with the single equation (8). If this proves impossible, then one may be forced back on some theory equivalent to the assumption of virtual electric charges, that is, charges which produce a magnetic field but not an electric field. A hint of how this might be done may possibly be obtained from considering the field of the neutron.

At the time of the first attempt to explain the magnetic field of the earth, no magnetic fields were known except those associated with a movement of electric charges or with a time variation of electric intensity. This is no longer the case, since it is now known that the neutron has a magnetic moment. This amounts to 1·80 Bohr nuclear magnetons, and the magnetic moment and spin vectors (angular momentum) are opposite in direction, as they are for the earth or sun. In some current meson-field theories, the difference between the magnetic moments of the neutron and proton are attributed to the existence of virtual mesons, thus bringing in virtual but not real electric charges. Possibly this might be taken as a hint that the magnetic field of a massive rotating body might be attributed to such a virtual charge separation. The observed linear variation of H with ω shows that such a virtual charge separation cannot be the result of the rotation but must be a property of a massive body at rest.

Since the ratio P/U for a neutron is about 10^{-3} of that for a Bohr atomic magneton, it can be seen from (6) that there is no obvious numerical relationship between P/U for a massive body and P/U for a neutron, unless one quite arbitrarily introduces such a non-dimensional ratio as $e^2/hc = 1 \cdot 16 \times 10^{-3}$.

It seems at present impossible to find an explanation of the fact that $\beta \cong 0 \cdot 3$ for the earth and about unity for the sun and 78 Virginis. The screening effect of ferromagnetic materials in the earth's crust could not possibly give an effect so large as 1 per cent. It is, of course, possible that the fault lies with the values of k and η assumed for the sun and 78 Virginis. If the products $k\eta$ were in reality three times as large as assumed, the discrepancy would be removed. But so also would be the attractive feature that β is nearly unity for the sun and 78 Virginis.

An alternative possibility is that the difference is due to some small effect of the *specific* properties of terrestrial or stellar matter, superimposed on the *general* mechanism responsible for the existence and order of magnitude of the main field. One might, perhaps, attribute the difference of the value of β to, say, the proportion of free electrons in the matter, or to the ratio of protons to neutrons.

Clearly the experimental result (7) and its hypothetical explanation (8) are to be considered as holding only for the non-relativistic case. When peripheral velocities comparable with c occur, modifications are clearly to be expected.

In general, it seems very probable that a satisfactory explanation of equation (7) will not be found except within the structure of a unified field theory. In this connexion equation (6) may be of special significance in view of the important part that the non-dimensional rate $G^{1/2}m/e$ must play in any such theory.

5.2. *The Magnetic Field of an Asymmetric Body.*

We have implicitly assumed so far that the static magnetic field given by (7) for a sphere must ultimately be expressible as an integral over all parts of the body. Though equation (8) represents one differential form which gives the observed result for a sphere, apart from the numerical factor β, we must inquire if there are likely to be solutions of a different type. For the following reasons this seems unlikely. First, the fact that, for a sphere, H is found experimentally to vary as ρ (see equation (11a)), implies that H must be expressible as the vector sum of contributions δH from each mass element considered separately. For if, for example, δH for a mass element depended not only on δm, but, say, also on the gravitational potential at the element, then H for the whole body would not be a linear function of ρ. If, therefore, we assume that each mass element gives an independent contribution to the total field, then (8) appears the only form which will give the observed linear dependence of H on ω.

It is possible, of course, that the correct solution is of the form of (9) rather than (8), where δQ is interpreted as some form of virtual charge taking both positive and negative values. If this is so, then δQ for any volume element may depend on the whole configuration of the body, as it would for a real charge separation, and not only on δm.

Until this question is settled, it is not possible to calculate the magnetic field of an asymmetric body, such as a massive ellipsoid rotating, say, about its shortest axis. This is of importance in connexion with possible laboratory experiments, as it might prove technically easier to measure the alternating field which one would expect from such an asymmetrical body, rather than the static field of a symmetrical one.

The general question then arises as to whether one can, in fact, extrapolate (7) and (8) to the laboratory scale. Though (7) holds experimentally roughly over a range of U of more than $10^{10} : 1$ for the three astronomical bodies, does this justify the necessary extrapolation of $10^{28} : 1$ from the earth to the case, say, of a bronze sphere of 1 metre diameter rotating at 100 r.p.s., which should give a field of about 10^{-8} gauss (see next section).

The physical conditions of the material of such a laboratory sphere differ so widely from that of the earth, not only in respect of size, but also of temperature, pressure and tension, ratio of gravitational to centrifugal forces, etc., that little can be concluded until a consistent theory of (7) has been found.

It may be noted that the separate ranges of R, ω and ρ for the three astronomical bodies are about 220 : 1, 25 : 1, and 14 : 1, respectively. The extrapolation to a laboratory sphere involves an extrapolation of $1 : 10^{-7}$ for R, and $1 : 10^7$ for ω.

5.3. *Possibility of Laboratory Test.*

Assuming that the extrapolation is justified, we can calculate the maximum field from a sphere of given material. Giving β the value $0 \cdot 30$ as for the earth, the polar field of a rotating sphere is found from (11a) to be—

$$H_P = 1 \cdot 07 \times 10^{-15} \rho \omega R^2. \quad . \quad . \quad (20)$$

In this expression we have to insert the maximum possible value ωm rad./sec. consistent with the maximum safe tensile stress S gm./cm.^{2}; using for this the value for a disk given by Svedberg (1940), which can be put in the form

$$\omega m = 50 \ S^{1/2} \rho^{-1/2} R^{-1}, \quad . \quad . \quad (21)$$

we find

$$H_P = 5 \cdot 4 \times 10^{-14} S^{1/2} \rho^{1/2} R. \quad . \quad . \quad (22)$$

We thus see that $H_P \propto R$, hence the advantage of a large body rotating correspondingly slowly. Taking $\rho = 8$, and, for example, $S = 3 \cdot 0 \times 10^6$ gm./cm.^{2} or 43,000 lb./sq. in., we find:

$$H_P = 2 \cdot 6 \times 10^{-10} R. \quad . \quad . \quad . \quad (23)$$

For a 1-metre sphere ($R = 50$ cm.), the maximum speed is 100 r.p.s. and $H_P = 1 \cdot 3 \times 10^{-8}$ gauss. For a 10-metre sphere, the speed is only 10 per sec. and the field is $1 \cdot 3 \times 10^{-7}$ gauss. If it should turn out that the correct value of β to take is that for the sun rather than that for the earth, these fields would be multiplied by three.

If an asymmetrical body of the same maximum linear dimensions were used, then one would obtain a smaller field than that given by a sphere; but the fact that it would be alternating might permit detection of this smaller field more easily than is possible for the static case.

The only experiment which appears to have been carried out to attempt to detect the magnetic field of a rotating body is that of Swann and Longacre[20] (1928), who spun a copper sphere of 10-cm. radius at 200 r.p.s. According to (20) the field should be about 10^{-9} gauss. The experimental method was only sensitive enough to show that no field so large as 10^{-4} gauss was produced.

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BRITISH ECLIPSE EXPEDITION TO BRAZIL

IN consequence of the aeroplane disaster at Dakar in the early hours of April 13, the British expedition to observe the total eclipse of the sun of May 20 at Araxa in Brazil has been cancelled.

The programme approved by the Joint Permanent Eclipse Committee of the Royal Society and the Royal Astronomical Society comprised four items.

The profiles of the chromospheric lines were to be observed using a Michelson echelon grating. The apparatus devised provides for a succession of short exposures at several points of the sun's limb to study the variation of profile and intensity with height above the sun as the moon successively masks off the lower layers. Some indication was hoped for of transition from photospheric temperatures to the high excitation temperatures now attributed to the coronal regions.

The corona was to be photographed in its own green monochromatic radiation through a large aperture (13·5-cm.) Fabry–Perot étalon to gain information on internal motions or rotation and to determine the profile of the green line accurately, also with a view to temperature assessment. The plates of the étalon had a separation of just over 1 mm. and were aluminized to give a resolving power of some 400,000. The coronal image would be crossed by arcs of circular fringes the displacement or distortion of which would reveal the motions. These two instruments were designed by Dr. J. A. Carroll, now deputy for research and development to Controller of the Navy and scientific adviser to the Board of Admiralty, during his occupancy of the chair of natural philosophy at Aberdeen.

In addition, it was planned to determine the darkening towards the limb by using one of the infra-red photo-cells, developed at the Admiralty Research Laboratory, with suitable recording gear.

Observations to measure solar radio noise at a frequency of about 60 megacycles/sec. were also planned with the collaboration of the War Office and Ministry of Supply, apparatus having been prepared by Dr. J. S. Hey and Major S. J. Parsons.

Dr. Carroll had been asked to take charge of the expedition, its organisation and preparation by the Joint Permanent Eclipse Committee, assisted by Dr. A. Hunter from the Royal Observatory, Greenwich, and one or two others, depending on what could be organised in the time available. During the period of preparation, he succeeded Mr. A. P. Rowe in the chief scientific post at the Admiralty, and it was impracticable for him to give the time required for preparation of, and participation in, the expedition as originally contemplated. The specialized nature of the equipment made assistance hard to find. Dr. Alan Baxter, who had been on Prof. Carroll's staff in Aberdeen, was familiar with it and had participated substantially in its design and development there for use in Omsk in 1936, but he had become a principal scientific officer in the Royal Naval Scientific Service. The Board of Admiralty took the view that, in the circumstances, it was reasonable that they should advance pure scientific research by making their scientific officers' services available to the expedition. The remaining expert optical member required for the team was Mr. J. H. Strong, of the Spectroscopy and Astrophysics Department of the Imperial College of Science and Technology.

During the last few months of 1946 and the first three of 1947, the equipment was assembled, modified and tested by this team in a room made available at the Admiralty Research Laboratory and with assistance from the Laboratory's workshops. The intention was that the gear and three observers, Dr. Baxter, Dr. Hunter and Mr. Strong, should proceed by sea in time to give them a clear month on the site, they being joined about ten days before the eclipse day by Dr. Carroll and Major Parsons. Various factors, among them the fuel crisis in Britain, caused the last ship which could be relied upon to reach Rio de Janeiro in time to be one due to sail on March 11. This was only known a few days beforehand, and it was barely possible to complete testing, dismantle all instruments, pack them and get them on board, particularly as the fuel cuts and the weather had seriously slowed up the later stages of the work. However, the gear, with the exception of the Fabry–Perot étalon and certain parts of an image rotator used in the echelon spectrograph, was dispatched, and arrangements made for the three observers to go out by air a month later. In attempting landing at Dakar while the airfield there was fog-bound, the aeroplane carrying the observers broke up, Dr. Baxter being killed instantaneously, Mr. Strong receiving injuries which at first were thought not dangerous but later proved fatal (see p. 667). Dr. Hunter escaped with severe cuts and abrasions. An emergency party