displacements of band centres could not be determined. But up to 1929 there is no evidence of Doppler displacements of any band centres relative to the centres of the hydrogen bands. After the disappearance of the multiple absorptions which had been present in some of the earlier stages of the nova, the band widths corresponded to velocities of approach and recession for the violet and red edges respectively of about 430 km./sec. These band widths certainly persisted up to 1929. After 1929 it is not possible to determine the band widths from the spectra available. The spectra afford no evidence of any marked increase in band widths, of noticeable structure in the bands or of displaced isolated maxima. The presence in the spectrum of isolated maxima with displacements of the order of 1000 km./sec. or of bands with centres displaced by this amount seems therefore to be extremely improbable. The ratio of the intensities of the two lines in the spectrum $\lambda\lambda$ 4944, 4989 is not in accordance with the suggested identification as displaced $\lambda\lambda$ 4959, 5007 nebular lines, for the line at λ 4944 is appreciably stronger than that at λ 4989, instead of being weaker as would be expected. If the interpretation is correct the line at λ 4944 must be a blend of N_2 with a line of other origin.

Reproductions of the spectra of February and March 1933 are given on Plate 1, together with reproductions of spectra obtained in September 1926, April and October 1928, and February 1931 for purposes of comparison. Of the two 1933 plates, that obtained in February has the better definition but is heavily fogged. The contrast has been increased by copying, the bright lines appearing stronger relative to the continuous spectrum than on the original negative. The reproduction of the March plate gives a better representation of the relative intensities on the original negative. Comparison of the two reproductions serves to show the reality of a number of the fainter bright lines in the spectrum.

The plate shows the main changes in the spectrum during the period from 1926 onwards, which have been referred to in previous papers. Reference may be made to the increase in the Balmer decrement from 1926 to 1928 and from 1929 to 1931, and to its partial decrease from 1931 to 1933; to the increase in strength of the ionised helium line at λ 4686, relative to the other lines, from 1931 to 1933; and to the development of the continuous spectrum between 1931 and 1933.

THE MAGNETIC FIELD OF SUNSPOTS.

T. G. Cowling, M.A., D.Phil.

1. It is well known that a magnetic field is a characteristic property of a sunspot. The essential features of the spot field are as follows:—*

* See Hale, *Ap. J.*, **27**, 315, 1908; *Proc. Nat. Acad. Sci.*, **8**, 168, 1922, and **10**, 53, 1924; and Hale, Ellerman, Nicholson and Joy, *Ap. J.*, **49**, 153, 1919.

(i) At the deepest visible levels the field near the centre of the spot is vertical, and of intensity about 2000 gauss.

(ii) At higher levels the field is much smaller, and the lines of force spread out from the centre of the spot in horizontal directions.*

(iii) When spots occur in pairs, the polarities of the two spots are, in general, opposite. The polarities of the leading spots in one hemisphere are, in general, the same during a sunspot cycle, and opposite from those of the leading spots in the other hemisphere; the polarities of leading spots in either hemisphere are reversed at the next cycle.

If, as seems most likely, the spot field is due to electric currents, these currents must, roughly, flow in a horizontal circuit round the spot: the radial limitation of the field must similarly be due to currents flowing in the opposite sense round a higher circuit. A possible explanation of the existence of such currents was suggested in 1919 by Sir Joseph Larmor,† on the hypothesis that gas flows into the spot column at low levels, and flows out at higher levels. If a horizontal inflow of gas occurs in a vertical magnetic field, an electric force will act on the gas, tending to cause an electric current to flow in a circuit round the axis of the spot, the magnetic effect of the current being to increase the field inside the circuit in which it flows. Larmor suggested that, if the current is sufficiently large, it may be able to maintain the magnetic field to which it is due, just as the current generated in a self-excited dynamo is used to maintain the electromagnets. Similarly, if there is a horizontal outflow at higher levels of the spot column in the presence of a vertical magnetic field, currents producing a radial limitation of the field will flow at such levels. The postulated outflow at surface levels is actually observed,‡ the velocity of outflow being of the order of 1 km./sec.; the existence of an inflow at deeper levels may be inferred.

Larmor's theory is, however, open to some objections. The currents induced in a self-excited dynamo are conducted to a point different from that at which they are set up, so that they can produce a magnetic field at the latter place. No similar conduction occurs in a sunspot, and so the current flowing in a circuit at the base of the spot reinforces the field inside that circuit, but not on it. The analogy with a self-exciting dynamo is, in any case, somewhat misleading, as the current set up in a dynamo is an alternating current, while the current required to maintain the spot field must be unidirectional and fairly steady.

2. Let us therefore consider under what conditions a steady magnetic field can be maintained by the currents it induces in an ionised gas in steady motion in it. Let ρ denote the density of the gas, and $\mathbf{c}$ its (vector) velocity at any point; also let $\mathbf{H}$ be the magnetic intensity. Then, as the state is

* This conclusion is based on the fact that the lines of certain ionised elements, originating at high levels in the spot, show small magnetic fields. The direct observations of the structure of the field are not very conclusive on the point.

† Sir Joseph Larmor, *Brit. Assoc. Reports*, p. 159, 1919.

‡ Evershed, *M.N.*, **69**, 454, 1909; **70**, 217, 1910.

steady, ρ, $\mathbf{c}$ and $\mathbf{H}$ do not depend on the time; also, by the equation of continuity of matter,

$$\operatorname{div}(\rho\mathbf{c}) = 0. \tag{1}$$

In the steady state there will in general be an electrostatic field. The density of electric charge will, however, in general be so small that it is permissible to neglect the part of the electric current arising from the convection of charged matter.* Also in calculating the galvanic current we shall for the present ignore the Hall current, perpendicular both to the magnetic field and the electric force on the gas, and consider only the direct current given by Ohm's law. The electric force on the gas due to its motion in a magnetic field is, in E.M.U., given by $\mathbf{c}_\wedge\mathbf{H}$; the electrostatic force is $-\operatorname{grad} V$, where V is the electrostatic potential, which we also suppose measured in E.M.U. Hence, if $\mathbf{j}$ is the electric current-density, and σ the conductivity of the gas,

$$\mathbf{j} = \sigma(\mathbf{c}_\wedge\mathbf{H} - \operatorname{grad} V). \tag{2}$$

Also, by ordinary electromagnetic theory,

$$\operatorname{div}\mathbf{H} = 0, \qquad \operatorname{curl}\mathbf{H} = 4\pi\mathbf{j}. \tag{3}$$

It is required to find what solutions of the above equations exist such that $\mathbf{c}$, $\mathbf{H}$ are everywhere finite.

3. The simplest way of attacking this problem is to regard $\mathbf{H}$, ρ, σ as known at all points, and to determine the corresponding values of the other variables. The current-density $\mathbf{j}$ can at once be found from (3). To determine V, take the component of the vector equation (2) in the direction of $\mathbf{H}$. The component of $\mathbf{c}_\wedge\mathbf{H}$ in this direction is zero; the component of grad V is dV/ds, where ds is an element of arc of a line of force. Hence, if j_s is the component of $\mathbf{j}$ parallel to $\mathbf{H}$,

$$j_s = -\sigma\frac{dV}{ds}. \tag{4}$$

The general solution of this equation is at once obtained. Let S be a surface intersecting every line of force, and let V be equal to an arbitrary analytic function of position on the surface. Then the value of V at any point P of a line of force which meets S in the point A is given by

$$V_P = V_A - \int_A^P (j_s/\sigma)ds, \tag{5}$$

the integral being taken along the line of force from A to P. As V is a one-valued function, if P is a second point in which the line of force meets S, the previously assigned values of V at P and A must satisfy (5). In particular, if the line of force is closed, then, taking the integral round the whole line of force,

$$\int (j_s/\sigma)ds = 0. \tag{6}$$

* For the case of the Sun's general field, Brunt (*Astr. Nach.*, **196**, 169, 1913) showed that the magnetic field arising from convection of charge is 10^{-15} of that observed. The fraction is not much different for a spot.

To determine $\mathbf{c}$, we set

$$\mathbf{c} = \mathbf{c}' + \alpha\mathbf{H}/\rho, \tag{7}$$

where $\mathbf{c}'$ denotes the component of $\mathbf{c}$ perpendicular to $\mathbf{H}$. Then $\mathbf{c}_\wedge\mathbf{H} = \mathbf{c}'_\wedge\mathbf{H}$, and so equation (2) becomes

$$\mathbf{c}'_\wedge\mathbf{H} = \text{grad } V + \mathbf{j}/\sigma,$$

whence, as $(\mathbf{c}'_\wedge\mathbf{H})_\wedge\mathbf{H} = -H^2\mathbf{c}'$, it follows that

$$H^2\mathbf{c}' = \mathbf{H}_\wedge(\text{grad } V + \mathbf{j}/\sigma), \tag{8}$$

giving $\mathbf{c}'$. The value of the quantity α of equation (7) is found from (1), which becomes, on use of (7),

$$\text{div } (\rho\mathbf{c}' + \alpha\mathbf{H}) = 0;$$

or, as div $\mathbf{H} = 0$,

$$\text{div } (\rho\mathbf{c}') = -\mathbf{H} \,.\, \text{grad } \alpha = -H\frac{d\alpha}{ds},$$

ds having the same meaning as before. The solution of this equation runs parallel to that of (4); in the notation of (5), it is

$$\alpha_P = \alpha_A - \int_A^P \frac{1}{H} \text{div } (\rho\mathbf{c}')ds, \tag{9}$$

the value α_A of α at the point A of the surface S being equal to that of an assigned analytic function of position which is such that (9) is true if P also lies on S. Thus, if the line of force is closed, taking the integral round the whole line of force,

$$\int_A^P \frac{1}{H} \text{div } (\rho\mathbf{c}')ds = 0. \tag{10}$$

Hence, for equations (1), (2) and (3) to be soluble, it is only necessary that values can be assigned to V and α on the surface S such that (5) and (9) are satisfied when both P and A lie on S, and that (6) and (10) are satisfied for any closed lines of force. For the value of $\mathbf{c}'$ given by (8) to be finite it is also necessary that

$$\text{grad } V + \mathbf{j}/\sigma = 0 \tag{11}$$

whenever $H = 0$.

4. Observation suggests that, if the magnetic field of a spot is self-contained, then the condition of affairs approximates to the axially symmetric state in which the directions of the magnetic field and of the gas motion at a point lie in the plane through that point and the axis of the spot, while the current-density is perpendicular to that plane. Let us therefore consider the axially symmetric case. Let Oz be taken as the axis of symmetry, and let ϖ denote the distance of any point from this axis, so that $\varpi^2 = x^2 + y^2$. Then V is a function of z and ϖ alone, so that the direction of grad V at any point lies in the plane through the axis and that point. On the other hand, $\mathbf{j}$ and $\mathbf{c}_\wedge\mathbf{H}$ are perpendicular to this plane; hence, by (2), grad $V = 0$, and so we can set $V = 0$.

By (1) there exists a generalised Stokes stream function ϕ, depending on z and ϖ, such that the components of $\mathbf{c}$ parallel to and perpendicular to Oz are

$$\frac{1}{\rho\varpi}\frac{\partial\phi}{\partial\varpi}, \qquad -\frac{1}{\rho\varpi}\frac{\partial\phi}{\partial z}. \tag{12}$$

The components of $\mathbf{H}$ in the same directions can similarly, by (3), be expressed in the forms

$$\frac{1}{\varpi}\frac{\partial\psi}{\partial\varpi}, \qquad -\frac{1}{\varpi}\frac{\partial\psi}{\partial z}, \tag{13}$$

where ψ is a function of ϖ and z, analogous to Stokes's function; it is such that the total magnetic induction across an area perpendicular to Oz, bounded by a circle with centre on Oz which passes through a given point, is equal to the value of $2\pi\psi$ at that point. Thus ψ vanishes at infinity and on Oz, while, corresponding to some pair of values of ϖ, z, it must have a maximum or a minimum value, for which

$$\frac{\partial\psi}{\partial\varpi}=0, \qquad \frac{\partial\psi}{\partial z}=0, \qquad \frac{\partial^2\psi}{\partial\varpi^2}+\frac{\partial^2\psi}{\partial z^2}\neq 0, \tag{14}$$

the sign of the last expression being positive or negative as the value considered is a minimum or a maximum.

On combining (3) and (13), the magnitude of $\mathbf{j}$ is found to be

$$-\frac{1}{4\pi\varpi}\left(\frac{\partial^2\psi}{\partial\varpi^2}-\frac{1}{\varpi}\frac{\partial\psi}{\partial\varpi}+\frac{\partial^2\psi}{\partial z^2}\right),$$

its direction being as stated above; the magnitude of $\mathbf{c}_\wedge\mathbf{H}$ similarly is

$$\frac{1}{\rho\varpi^2}\left(\frac{\partial\phi}{\partial\varpi}\frac{\partial\psi}{\partial z}-\frac{\partial\phi}{\partial z}\frac{\partial\psi}{\partial\varpi}\right).$$

Using these values in (2), we obtain the equation

$$\frac{\partial^2\psi}{\partial\varpi^2}+\frac{\partial^2\psi}{\partial z^2}-\frac{1}{\varpi}\frac{\partial\psi}{\partial\varpi}=-\frac{4\pi\sigma}{\rho\varpi}\left(\frac{\partial\phi}{\partial\varpi}\frac{\partial\psi}{\partial z}-\frac{\partial\phi}{\partial z}\frac{\partial\psi}{\partial\varpi}\right).$$

This equation is inconsistent with (14), and so is not satisfied at the point at which ψ is a maximum or a minimum. At this point, in fact, equation (11) is in general not satisfied, and so the value of $\mathbf{c}'$ given by (8) is infinite. A contradiction has thus been reached; we conclude, therefore, that it is impossible that an axially symmetric field shall be self-maintained.

5. The same argument may be put in a different way, which brings out its physical meaning better. Consider the section of the field by a plane through the axis. In this plane the lines of force are closed curves, the curves $\psi=$const., the one inside the other; these have one or more limiting points, corresponding to maximum or minimum values of ψ. At any such point, by ordinary physical considerations, $H=0$; the same may also be seen from (13) and (14).

Consider a line of force which is a closed curve of infinitesimal dimensions surrounding such a point. Let H_0 denote the mean value of H on the line of force; then the line-integral of the tangential component of **H** taken round it is $H_0 s$, where s is its length. But this is equal to the flux of electric current across the area bounded by the line of force, and, as the mean value of H in this area is less than H_0, this is, by (2), not greater than $\sigma c_0 H_0 S$, where S is the magnitude of the area and c_0 the greatest value of c in it. Thus

$$H_0 s < \sigma c_0 H_0 S.$$

This inequality cannot, however, be valid for finite values of σ and c_0, as S is an infinitesimal of higher order than s. A contradiction has therefore again been reached. We see that, in fact, the currents flowing near the limiting point are too small to maintain the field near that point; hence lines of force will steadily contract and disappear at that point.

A similar argument shows that a field which resembles an axially symmetric field in certain respects cannot, in general, be maintained by the currents it itself sets up. For example, suppose that the lines of force are closed curves all threading a limiting closed curve, and threading it in the same direction. Then the currents required to maintain the field will, near the limit curve, have a component in the direction of the curve which is at all points directed in the same sense round the curve. This component is not due to electrostatic fields, which can only make currents flow from points of high potential to points of low potential, and cannot cause them to flow round a circuit: equally it cannot be due to electromagnetic induction, by an argument similar to the above. Hence such a field cannot be self-maintained.

The same conclusion holds if, instead of being closed curves, the lines of forces are spiral curves threading on the limiting curve, and rotating round it in a fixed sense. In this case H does not necessarily vanish on the limiting curve, which is in general a line of force; but as the electric force acting on matter moving in a magnetic field is perpendicular to the field, electromagnetic induction again cannot produce a current round the limiting circuit. The conclusion is also unaffected when the Hall current is taken into account, as this current is also perpendicular to the magnetic field, and its effect becomes small compared with that of the ordinary induced current as H becomes small.

Since, then, fields possessing a general similarity to an axially symmetric field cannot be self-maintained, we are led to conclude that the magnetic field of a sunspot is not self-maintained. For the same reason the general magnetic fields of the Sun and the Earth cannot be self-maintained, as was suggested by Larmor.

6. While, however, the currents induced by the motion of gas in a sunspot are unable to maintain the magnetic field in the absence of external factors, such currents will produce a large disturbance in any external field that may be present. This suggests the possibility that the sunspot field may arise as a disturbance in the (almost horizontal) general field of the Sun. In such a case, the lines of force will not be closed curves near the spot, but will

enter the spot region from the south, and leave it toward the north; they enter the spot column near its base or near the surface according as the polarity of the spot is positive or negative.

To show that the observed field can be generated in this way we must show that equations (1), (2) and (3) can be satisfied in the finite region occupied by the spot disturbance, the magnetic field being similar to that of a spot. The analysis of § 3 shows this to be possible. If H vanishes at no point the value of $\mathbf{c}'$ given by (8) will always be finite. The electrostatic field must vanish at points outside the spot disturbance; this is ensured if a relation similar to (6) is satisfied, the line-integral being now along that part of any line of force which lies within the region considered; it is fairly clear that this relation can be satisfied by a field similar to that of a sunspot.

The electric currents required to generate the spot field will, roughly speaking, flow round the axis of the spot, as was postulated in § 1. The motion which produces these currents will, however, differ somewhat from that postulated there. Since the motion perpendicular to the magnetic field is strongly damped because of electromagnetic induction, the gas tends to move along the lines of force; on the other hand, when the gas moves across the lines of force, it tends to push these in front of it. In a spot of positive polarity the lines of force enter the spot column from the south at the base, and leave toward the north at the top; hence the motion must include an uprush of gas in the spot column, the lines of force being held up, as it were, by the moving gas on its southern side, followed by a descent of the gas, on an average at some distance to the north, the directions of the lines of force and of the motion being roughly the same. In a spot of negative polarity, on the other hand, the descending gas will be on the south side of that ascending.

A close correlation will accordingly exist between the polarity of a spot and the type of motion of the gas in it. In the formation of a spot in an undisturbed region the type of motion present may be expected to determine the polarity. The explanation of the connection of polarity with the sunspot cycle may lie along these lines. On the other hand, in the neighbourhood of a spot already existing the vertical component of the magnetic field has the opposite sign from that of the field in the spot; hence, if a new spot appears in this region, its polarity will tend to be opposite from that of the first, and the motion of gas near it will be modified accordingly.

7. There are three possible quantitative checks on the above hypothesis. First, as the lines of force in a spot are merely those which normally thread the region of the spot disturbance, somewhat displaced in position, the total magnetic flux across the cross-section of the spot column must equal the flux of the general field across the region of the spot disturbance. Now the cross-section which the spot disturbance offers to the general field can hardly be much larger than the cross-section of the spot column; hence the average intensity of the general field in the regions considered cannot be much smaller than the spot field. In the reversing layer the intensity of the general field does not exceed 50 gauss, but the intensity rapidly increases with the depth, and it is not unlikely that at lower levels the field is con-

siderably larger. For the present hypothesis to be correct, the general field must possess an intensity at lower levels not less than, say, 1000 gauss, a value which, in the absence of data to the contrary, cannot be regarded as impossible.

The second check is that no impossibly large velocity of the gas in a spot shall be required for the currents induced in the moving gas to be able to produce a disturbance in the general field of the magnitude observed. Suppose, for example, that a current flowing round the axis of the spot is responsible for its field. If the radius of the circuit in which it flows is, say, 10,000 km., to produce a field of 2000 gauss at its centre a current of $10^{12}/\pi$ E.M.U. must flow round the circuit; if the cross-section of the circuit is taken as a square of side 1000 km.,* this corresponds to a current-density of about 3×10^{-5} E.M.U. The conductivity at the base of the spot is taken to be 10^{-9} E.M.U., in agreement with the values found in a previous paper.† Thus the electric force producing the above current is 30,000 E.M.U., which is the force acting on matter moving with a velocity of 30 cm./sec. in a field of 1000 gauss. Hence no impossibly large velocities are required to produce a disturbance of the type suggested. It may equally be seen that no impossibly large velocities are required for currents to appear at the top of the spot column large enough to cause the vertical limitation of the field.

The third check is that no impossibly large mechanical effects shall arise in the production of the spot field. In the above a current of density 3×10^{-5} E.M.U. was supposed to flow in the presence of a magnetic field of 1000 gauss; in consequence, a force of magnitude 3×10^{-2} dynes/cm.^{3} acts to retard the motion of the matter across the field. If this force acts at all points inside a circuit whose cross-section is a square of side 1000 km., to overcome it there must be a pressure 3×10^6 dynes/cm.^{2} greater on one face than on that opposite. Hence the pressure at the level of this circuit must be larger than 3×10^6 dynes/cm.^{2}. This is considerably higher than current estimates of the pressure at the base of a spot, and confirmation of this value by other methods is required. If, however, the present hypothesis is valid, the mechanical effect of the currents producing the spot field is extremely important; probably it is one of the chief factors determining the magnitude of the velocities appearing in the spot.

If the motion of gas across the field at the top of the spot column causes currents to be set up which produce the radial limitation of the field, this motion will likewise be retarded. Here pressure cannot maintain the motion, as the pressure required would again have to be of the order of

* The values adopted here for the depth of the base of the spot column, etc., differ greatly from those given by earlier workers on sunspot theory, *e.g.* Milne suggests a depth of, say, 25 km. These estimates must, however, be greatly increased when the effect of an abundance of hydrogen on the molecular weight and specific heat are taken into account, and a value exceeding 1000 km. is probable. The parallel estimates of the pressure at the base of the spot require a similar correction.

† *M.N.*, **93**, 90, 1932. The value in question is a mean of those for σ_1 given in the fourth, fifth and sixth rows of the table on p. 96.

3×10^6 dynes/cm.^{2} at least. It is possible, however, that the currents in question are due to a vertical motion under gravity across horizontal lines of force. If the cross-section of the circuit in which the currents flow is equal in area—though not necessarily in shape—to the circuit in which the spot field is set up, a current-density of the same order as that at the base of the spot will be necessary, and so there will again be a retarding force of 3×10^{-2} dynes/cm.^{3} on the moving gas. For gravity to be able to balance this, the density of the gas must be 10^{-6} grm./cm.^{3}, a value far higher than the commonly accepted figure of 10^{-8} grm./cm.^{3} for the base of the reversing layer. Even if the magnetic field in the region considered is taken to be only 100 gauss instead of 1000, we still obtain the high value of 10^{-7} grm./cm.^{3}. This would appear only to be possible if the currents causing limitation flow at a level lower than that of the reversing layer near the spot; this presumably implies that the visible levels in a spot are lower than the visible levels of the surrounding photosphere. The observational evidence on this point is conflicting and uncertain.*

8. In conclusion we may indicate what effect the Hall current has, on this theory, on the spot field. The ratio of the Hall conductivity to the ordinary conductivity will be small at the base of the spot, if the above estimate of the pressure at the base is valid; at the surface, however, the ratio is greater than unity, and even when the effect of electrostatic fields in hindering the flow is taken into account the Hall current will be of the same order as the direct current.

The Hall current arises because the motion of electrons across the lines of magnetic force is retarded more than that of the ions, and so its direction is that of the motion across the lines of force. Hence at the surface it flows first outward, then downward. The consequent magnetic field at higher levels is in a direction round the axis of the spot in a negative sense; if this is superposed on the field already postulated, lines of force, instead of entering or leaving the spot in directions roughly passing through the axis of the spot, will be spirals round the axis, right- or left-handed as the polarity of the spot is negative or positive. Since the outflow from the spot tends to be along the lines of magnetic force, this suggests that the observed vorticity of a spot should be right-handed for a spot of positive polarity, left-handed for a spot of negative polarity. A correlation of vorticity with polarity is not actually observed; Hale suggests, however, that this is no evidence that such a correlation does not exist, as the vorticity observed on $H\alpha$ spectroheliograms corresponds to a high level, and may differ from that at a lower level.†

Summary.—The theory proposed by Sir Joseph Larmor, that the magnetic field of a sunspot is maintained by the currents it induces in moving matter, is examined and shown to be faulty; the same result also applies for the similar theory of the maintenance of the general field of Earth and Sun.

* G. Hale, *The Study of Stellar Evolution*, p. 71, 1908; J. and M. A. Evershed, "The Spectrum of Sunspots," *Mem. Kodaikonal Obs.*, 1909. For these references I am indebted to Mr. H. W. Newton. A problem related to this is discussed by Miss Moore in *Ap. J.*, **75**, 298, 1932.

† Hale, Ellerman, Nicholson and Joy, *loc. cit.*

The possibility that the sunspot field may arise as a disturbance in the general field is examined, and it is shown that several of the properties of the spot field are explicable on this hypothesis. Observation must, however, ultimately decide on its validity.

In conclusion, I should like to record my gratitude to Professor Chapman for the interest he has shown in this work and for his advice.

University College, Swansea :
1933 *October* 27.

THE NUCLEI OF TWO PLANETARY NEBULÆ.

G. G. Cillié, M.Sc.

1. *Object of the Investigation.*—Group-parallaxes of planetary nebulæ by van Maanen * and determinations based on galactic rotation by Zanstra † indicate radii for these objects of the order of 5000 astronomical units. Many nebulæ are approximately in equilibrium under the action of gravitation and radiation pressure from the nucleus, combined in some cases with rotation. This indicates that the nuclei are very massive.

Menzel pointed out ‡ that, apart from the above evidence, the less marked galactic concentration of planetary nebulæ compared with other O type stars indicates that they are no farther away than these stars. The relative faintness of their nuclei compared with the O type stars Menzel attributes to their much smaller surface areas, and using Plaskett's dimensions for the O type stars he showed that the nuclei of planetary nebulæ have high mean densities, probably of the order 10^5 gm./c.c.

The probable white dwarf character of these stars was recently demonstrated along similar lines by Zanstra,§ who in addition had at his disposal their effective temperatures as given by his theory of nebular luminosity.

The same suggestion has been put forward by Milne || in his theory of stellar structure. According to this theory a nova outburst is the result of a collapse of a star on to itself, with the consequent setting free of a large amount of gravitational potential energy. This sudden increase in the luminosity causes the atmospheric layers to be blown off, leaving the star to settle down to a much denser configuration. Milne then tentatively suggests that planetary nuclei are old novæ and therefore probably have high mean densities.

The above hypothesis, that the nuclei of planetary nebulæ are white dwarfs, is capable of an observational test. If at the surface of a star the gravitational potential is high, the absorption lines in its spectrum are displaced towards the red according to the general theory of relativity. This is of

* van Maanen, *Mt. Wilson Contributions*, **18**, No. 406, 1930 ; **19**, No. 463, 1933.
† Zanstra, *Zeits. f. Astrophys.*, **2**, 329, 1931.
‡ Menzel, *P.A.S.P.*, **38**, 295, 1926.
§ Zanstra, *M.N.*, **93**, 131, 1932.
|| Milne, Halley Lecture, 1932.