is considered. Thus it may be concluded that, since in Gunn's discussion of these effects no account is taken of departures from an isothermal steady state, neither his theory of the radial limitation of the Sun's general field nor his theory of the maintenance of the sunspot field can be accepted in its present form.

THE INFLUENCE OF A SOLAR ECLIPSE UPON UPPER ATMOSPHERIC IONIZATION.

S. Chapman.

1. In a recent lecture * I have suggested that the upper ionized layer in the Earth's atmosphere, at a height of about 220 km., is ionized by ultra-violet light, while the lower, at about 100 km. height, is ionized by neutral solar corpuscles. This hypothesis was proposed as the most likely one in the light of the available evidence, but it was not suggested that the arguments were conclusive. It is desirable to find other considerations enabling the hypothesis to be tested.

In January last Professor Appleton kindly communicated to me some passages bearing on this question from a provisional draft of a paper by himself and Mr. Naismith. They pointed out that during the solar eclipse of 1927 the radio experiments † showed a partial return to night conditions, a striking feature being that the equivalent height and the reflection coefficient of the ionized layer reached their maximum values at a time agreeing to within 1 second with that of the centre of totality. Adopting current estimates of the velocity of travel of the supposed neutral corpuscles from the Sun, they pointed out that "such a solar stream should take 4½ minutes to travel from the Moon to the Earth. During a solar eclipse, therefore, we should expect the maximum wireless effect on the lower ionized region to show itself 4½ minutes or more after totality. If there was any lag in the eclipse effect in 1927 it was certainly much less than this. We are therefore inclined to ascribe the ordinary diurnal variation of the ionization in the lower region to ultra-violet radiation, which travels the Moon's distance in just over 1 second."

2. On theoretical grounds I should expect a lag of at least some minutes in the maximum ion-reducing effect of the eclipse, even supposing an infinite speed of the ionizing agent from the Sun. This expected lag would be due to the continued recombination of the electrons, which for some minutes after the centre of totality would be likely to exceed the renewed electron-production. Hence the interpretation of the apparent absence of lag during the 1927 eclipse seemed difficult on either hypothesis as to the ionizing agent.

Further consideration, however, made it clear that, though in a different way, eclipse observations are admirably suited to settle the important question as to the source of the ionization of the lower layer. In discussing an

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* Bakerian Lecture, *Proc. Roy. Soc.*, A, **132**, 353, 1931.

† E. V. Appleton, *Journ. Inst. Elec. Eng.*, **66**, 872, 1928; also *Radio Research Board Special Report*, No. 7, 1928.

eclipse on the corpuscular hypothesis many motions besides that of the particles radially outwards from the Sun must be taken into account, such as the solar rotation, the orbital velocities of the Earth and Moon, and the rotation of the Earth. It appeared that, of these, the motions of the Moon and Earth were of principal importance, and that, in consequence of them, the Moon should cut off the supposed neutral solar corpuscles more than an hour before the ultra-violet light is stopped; the eclipse effect on the incidence of the corpuscles should in fact be entirely over before the optical eclipse begins. Thus on the corpuscular hypothesis the lower ionized layer should be subject to the influence of the eclipse long before the upper ionized layer is affected.

3. In a total solar eclipse the area of totality is always very small compared with the area of partial eclipse; the normal section of the penumbral shadow cone, near the Earth, is approximately 4000 miles in diameter, while that of the cone of totality never exceeds 150 miles. The duration of totality is very short, 8 minutes or less; while the whole duration of an eclipse may be as great as 3¼ hours at the equator near noon, or nearly 2 hours in high latitudes or near sunrise or sunset. Though there is a great difference between a total and nearly total eclipse so far as concerns spectacular effects or astronomical observations, the difference as regards their influence on the ionization of the upper atmosphere is slight. Perhaps in the past undue importance, from the standpoint of radio transmission, has been attached to the period of totality and the events happening during that period. No striking change in radio transmission marking out the few minutes of totality from the immediately adjacent periods of partial eclipse should be expected on either hypothesis as to the ionization. It seems improbable (§ 8) that the reduction in the ion-content of the layer ionized by ultra-violet light should be at its maximum during the period of totality; my calculations suggest that the minimum ion-content in the layer thus ionized may not be attained until about 15 minutes after the centre of totality.

4. At present we have no observational proof that neutral corpuscles are continually emitted by the Sun, but E. A. Milne * has shown that they are likely to be emitted by radiation-pressure acting upon atoms that, through chance collisions in the chromosphere, gain an upward velocity of 50 km./sec. or more. S. R. Pike † has shown also that atoms which in like manner gain a moderately abnormal *horizontal* velocity component will also be vertically (as well as horizontally) accelerated, and (unless drawn back towards the Sun by neighbouring dark areas or sunspots) will leave the Sun altogether. Their calculations agree in predicting a limiting velocity of about 1600 km./sec., attained,‡ within about 6 per cent., by the time the atoms have reached a distance of 10 solar radii from the Sun.

By chance collisions an atom in the chromosphere may acquire an abnormal velocity in any direction, but from Pike's work it may be inferred that the sheaf of corpuscular rays thus emitted from any small solar area will be

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* E. A. Milne, *M.N.*, **86**, 459, 578, 1926.

† S. R. Pike, *ibid.*, **88**, 3, 1927.

‡ S. Chapman, *ibid.*, **89**, 458, 1929.

strongly concentrated round the normal or radial direction. If v_r, v_h are the radial and horizontal components of motion of a fast-moving atom, the horizontal acceleration, tending to increase the horizontal speed, is roughly proportional to $v_r v_h$, vanishing both for purely vertical and purely horizontal motion, and having its maximum when $v_r = v_h$, *i.e.* when the atom is moving at 45° to the vertical. In that case, however, the *radial* acceleration (f_r) exceeds four times the horizontal acceleration (f_h); in fact when $v_r = v_h$ Pike found that

$$f_h = 0{\cdot}0016\ v_r g, \qquad f_r = 0{\cdot}0068\ v_r g,$$

where g denotes solar gravity (0·27 km./sec.^{2}). If

$$v_r = v_h = 50 \text{ km./sec.},$$
$$f_h = 0{\cdot}02 \text{ km./sec.}^2, \qquad f_r = 0{\cdot}09 \text{ km./sec.}^2,$$

and in 10 minutes v_r will be increased to 104 km./sec., while v_h will be increased only to 63 km./sec., the inclination of the velocity to the vertical being thus reduced from 45° to 31°. Actually the reduction will be still greater, because as v_r/v_h increases f_h/f_r decreases; moreover, Pike's formula does not allow for the decrease of f_h relative to f_r with increasing height, which would certainly occur even if v_r/v_h remained the same. It is desirable to extend Pike's calculations to consider this effect, and to determine the probable frequency distribution, at a distance of several solar radii from the Sun, of atoms moving with different inclinations to the radius through the point of emission. In so doing it seems reasonable to assume that at the outset the emission of the fairly fast particles follows the cosine law, as in the case of light; if so, 82 per cent. of the atomic velocities would initially be inclined to the radial direction by less than 45°. In this case, though I have not made detailed calculations on the point, I think it probable that 90 per cent. of the atoms will finally have velocities inclined at less than 10° to the radius.

5. An important consequence of this is that at a great distance from the Sun—as, for example, at the Earth's orbit—the particles will form a nearly parallel beam, proceeding mainly from the solar area that (at the time of emission) was near the centre of the Sun's disc. In the case of light, the beam comes nearly equally from all parts of the Sun's disc, the foreshortening of the areas near the limb compensating for the reduced emission (according to the cosine law) at oblique angles; hence the Sun's disc appears nearly uniformly bright, there being only a small darkening towards the edge. But if we viewed the Sun with the aid of optical sensations due not to light but to the neutral corpuscles, the darkening towards the edge would appear far more pronounced, and indeed only the central area of the disc, subtending an angular radius of about 15° at the Sun's centre, or having an apparent diameter about one-fourth of that of the actual disc (*i.e.* about 7′ instead of 30′), would appear bright.

This near approach of the corpuscular rays to parallelism of velocity has the interesting consequence that, in an eclipse, the cone of total shielding from the corpuscles will, at the Earth, have a normal sectional diameter of about 1600 miles, little less than the diameter of the Moon itself; while there will be but little penumbra or area of partial eclipse. If the apparent radius of the emitting area, for example, were exactly one-fourth that of the whole solar disc, the penumbra would have a width of only about 500 miles, instead of about 2000 miles, as for the eclipse of the Sun's light.

I have examined the effect of the gravitational deflection of the corpuscles in diminishing the diameter of the area of total corpuscular shadow, and find it to be negligible—the reduction of diameter being only about 1 mile.

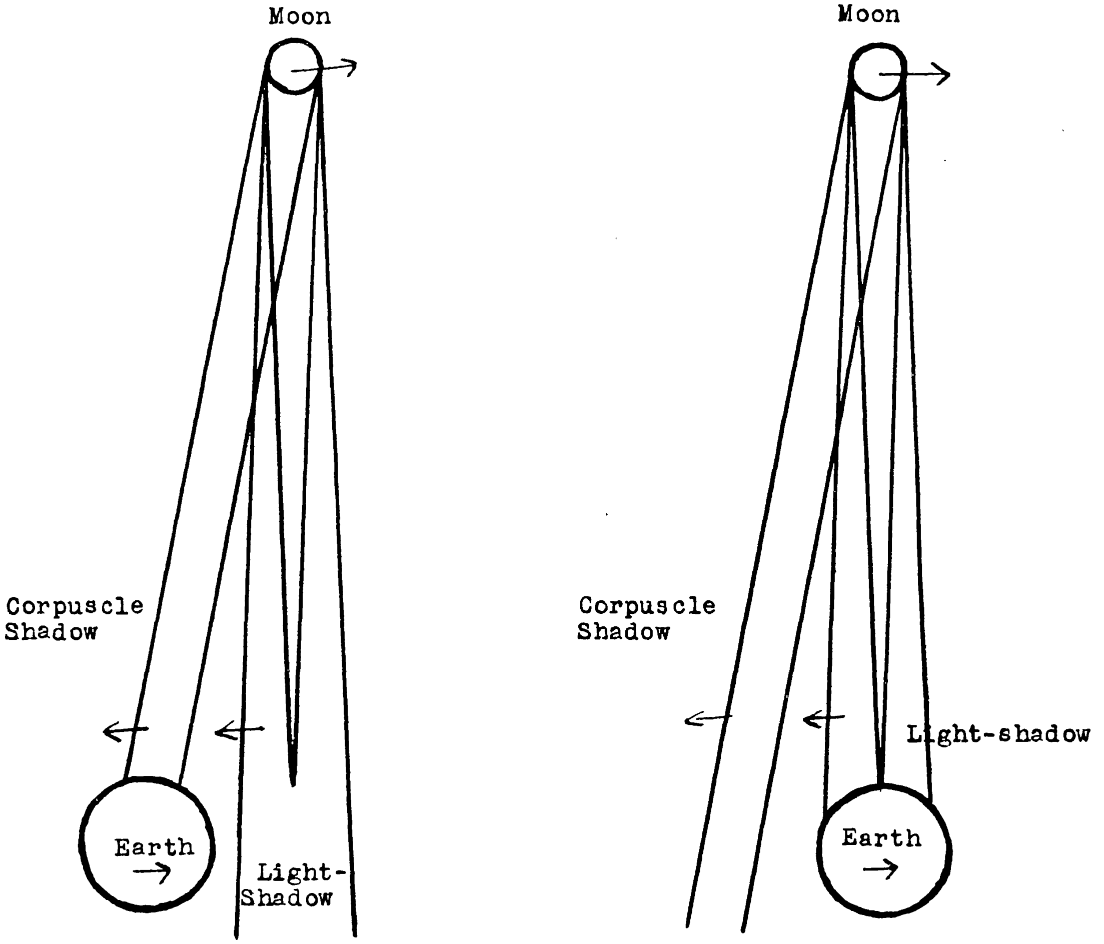
6. Thus the particles will cross the Earth's orbit in a direction nearly radial from the Sun; they are likely to have a small transverse velocity in the direction of the Earth's orbital motion, due to the solar rotation, but this velocity, at that distance from the Sun, will be only about 0·01 km./sec. and can be ignored. When the Moon is on the side of the Earth nearest the Sun it has a velocity of about 1075 miles/min. in the direction of the Earth's orbital motion. The particles therefore have an equal and opposite transverse velocity relative to the Moon, while their radial velocity is about 60,000 miles/min. (1600 kms./sec.) according to Milne. Hence it is easily seen that the shadow cylinder carved out by the Moon (treating the corpuscles as moving completely parallel to one another) will have a backward slope of approximately 1°. During the 4 minutes required for the particles to traverse the distance between the Moon and the Earth (240,000 miles), the transverse lag of the particles, or of the shadow cylinder, behind the Moon will be 4300 miles. Since the Moon, near the epoch of a solar eclipse, is moving with a velocity nearly parallel to that of the Earth but smaller by about 35 miles/min., it follows that the axis of the shadow cylinder of the particles will strike the Earth 4300/35 or 123 minutes before the axis of the optical shadow cone touches the Earth. Moreover, estimating the whole corpuscular shadow cast by the Moon as of 2600 miles diameter, it will take 2600/35 or 74 minutes for the corpuscular shadow cylinder to cross the centre of the Earth's disc.

The succession of shadow regions will therefore be as indicated in fig. 1, where, however, the angles and dimensions are incorrectly drawn to emphasize the points it is desired to bring out.

Taking a section of the shadow regions at the distance of the Earth's orbit, the distances are shown approximately in fig. 2 for a typical case. The distances are given in miles and also in minutes, at the rate of 35 miles per minute, representing the rate of travel of the shadow system relative to axes through the Earth's centre but not rotating with the Earth.

Owing to the Earth's rotation the actual time of passage of the shadow system past any terrestrial station will depend on the latitude, season and time of day at which the eclipse occurs at the station. At the equator near noon, for example, the peripheral speed of a point on the Earth, in the direction of the Earth's orbital motion, is 16 miles/min., so that the relative rate of motion of the shadow system is only 19 miles/min.; hence the corpuscular shadow system, about 2600 miles wide in all, would take about 135 minutes to traverse the station. But in high latitudes and near sunrise or sunset the component of the peripheral speed in the direction of the

Earth's orbital motion is much smaller, and the shadow system will therefore move with correspondingly greater rapidity. The sequence of events can be easily calculated for any given height above the Earth (a factor of which the importance in the case of the 1927 eclipse was pointed out by Dr. E. H. Rayner), for any actual eclipse, along the lines here indicated ; all that is worth doing in this general discussion of the question is to indicate the main features in a typical case.



Corpuscular eclipse in progress, before light-eclipse begins.

Light-eclipse in progress, after corpuscular eclipse is over.

Fig. 1.

7. If the lower ionized layer owes its ionization to corpuscles of the kind here considered, the production of new ions will cease during the passage of the corpuscular shadow cylinder (ignoring the slight penumbra). Hence during this period the ion-content will steadily fall and minimum ion-content will occur at the *end* of the corpuscular eclipse. With the renewal of the corpuscular bombardment the ion-content will again begin to increase.

The total decrease in ion-content will depend on the duration of the eclipse (varying according to the season, time of day and the latitude), on the initial ion-content, and on the coefficient and mode of recombination. The probable order of magnitude can be roughly indicated in one or two typical cases. At the equator at noon the duration t of the eclipse is about 2 hours or 7000 seconds; if the maximum electron-content n_0 is 10^6 per c.c., and the coefficient α of recombination (according to the law αn^2) is 10^{-9}, the electron-content n will be reduced to $n_0/(1+\alpha n_0 t)$ or $n_0/8$. At a station in a higher latitude or at a time near sunrise (or sunset), where t is only 1 hour and where n has the value 10^5 at the outset of the eclipse, the reduction will be only in the ratio $1/1{\cdot}35$; but if at the given time the value of n would normally be rising rapidly, the effect of the eclipse would be to produce this moderate decrease of n in place of the normal rapid increase; in this case the effect of the eclipse might persist throughout the day and even be perceptible next morning. A corpuscular eclipse occurring near sunset would only accelerate the normal reduction of ion-content then experienced, and would therefore have a less important and less enduring influence on atmospheric ionization.

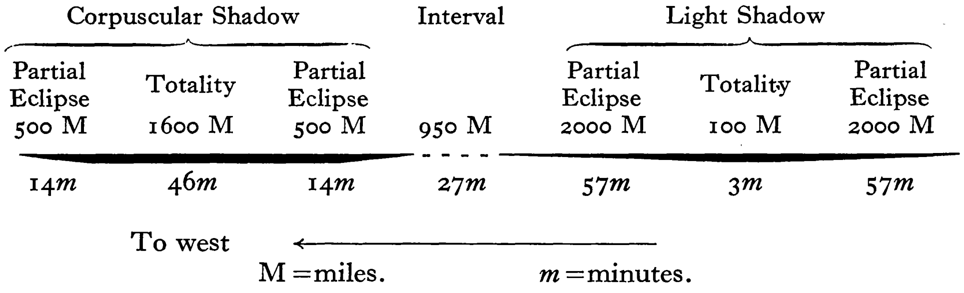


Fig. 2.

8. The influence of the eclipse of the Sun's ultra-violet light is rather different from that of the eclipse of the supposed solar particles, owing to the much greater penumbra in the former case. The reduction in the amount of ion-producing radiation q follows a more gradual course, of the form shown in fig. 4 (*a*), instead of (as in the corpuscular case) as in fig. 3 (*a*), where the eclipse is total for a much larger fraction of the whole eclipse. Hence the influence on the ion-content will be correspondingly smoother, as shown in fig. 4 (*b*), than in fig. 3 (*b*) for the corpuscular case. The curves are drawn for an eclipse occurring near noon, when q is nearly stationary; similar curves for morning or afternoon eclipses can easily be drawn. I have made some rough calculations of the lag of the minimum of n after that of q, and found that it may be of the order of one-eighth of the duration of the eclipse (partial and total), though it depends on many factors that differ from one eclipse to another, and also on the recombination coefficient and the initial values of n and q. As stated in § 3, this time lag is about 15 minutes for an eclipse lasting 2 hours.

To sum up, the effect of the eclipse of the Sun's ultra-violet light will be to reduce the ionization of the atmospheric layer or layers which it ionizes;

this reduction will be gradual, and greatest about 15 minutes after totality (or maximum phase in the case of a partial eclipse). The reduction will be experienced over a wide area, and the area and time of totality will not be distinguished from neighbouring regions and times by any marked discontinuity or gradient of ionization. The effects will depend greatly on the time of day at which the eclipse occurs, and also upon the latitude. Calculations of the expected effects must be made for each individual eclipse, as no one investigation can cover all cases even roughly. In such calculations the inclination of the Moon's orbit to the ecliptic must, of course, be taken into account. It must be remembered also that the interval between the corpuscular and the optical eclipse is not definitely calculable, since we do not know the speed of the corpuscles. If the radio observations show any signs of a corpuscular eclipse, besides throwing light on the origin of the ionization of the lower layer they will afford valuable information as to the speed of the particles.

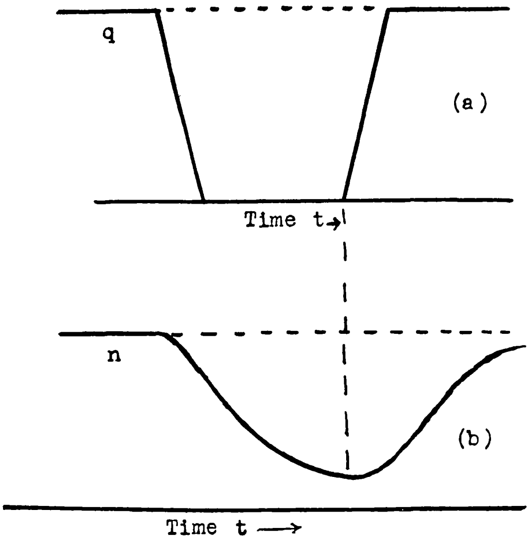


FIG. 3.—*Corpuscular eclipse.*

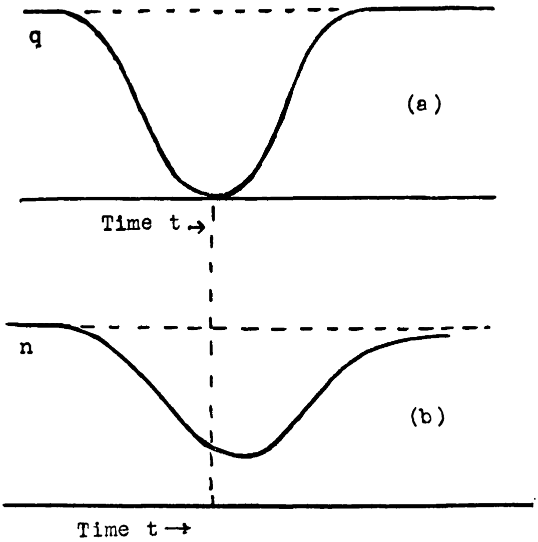


FIG. 4.—*Light eclipse.*

9. Some remarks may be made about the eclipse of 1927 June 29, which passed over the lower ionized layer above England between 0520 and 0522 G.M.T. If this lower layer be ionized by corpuscles, the corpuscular eclipse must have commenced about 2 hours before optical totality—that is, at or about sunrise; the sunrise effects might therefore not be experienced in the eclipsed region until the corpuscular eclipse was over. For some time before even the partial optical eclipse began, the layer should have been increasing in ion-content, though this would be still much below the normal value at that time of day. The greatest eclipse effects on the upper ionized layer must have been experienced further to the south, probably over the English Channel, owing to the much greater altitude of the layer; the times of totality along this belt would be correspondingly slightly earlier.

The radio observations made on the day of the eclipse and the adjacent days for signals travelling in several directions relative to the eclipse track showed some notable features nearly coinciding in time with the brief interval of totality. In the valuable account and discussion of the observations it was remarked * that "they constitute fairly strong evidence of a definite effect produced by the eclipse on the transmissions. At all these stations there is an outburst of variations during the half-hour of maximum observation, the centre of the outburst coinciding roughly with the time of totality." It is stated, however, that "unfortunately the possibility of this occurrence being somewhat of a coincidence cannot be entirely ruled out, as shown by the appearance of an outburst of the same nature (though certainly not quite so definite) on the day after the eclipse—about half an hour earlier."

I understand from Professor Appleton that this doubt extends only to part of the observations, and that he is inclined to interpret the 1927 eclipse results as showing that ultra-violet light is responsible for an important part of the ionization of the lower layer, if not for all of it.

It seems desirable in any case to take the opportunity afforded by the 1932 eclipse to settle the question definitely, and (though I cannot speak with expert knowledge on the experimental side) the best way would seem to be by measuring the changes in the maximum electron density, using the methods developed by Professor Appleton for this purpose.†

Note added during Proof-correction.—While writing the foregoing discussion, it had escaped my notice that the large time-interval between the corpuscular and optical eclipses would, owing to the diurnal rotation of the Earth, be accompanied by a considerable space-interval; the corpuscular eclipse track will lie to the east of the optical eclipse track, the interval in longitude corresponding approximately to the time-interval. I am indebted to Dr. Jackson and Professor Sampson for calling my attention to this important point.

Owing to the short time now available for preparation for observations of the 1932 August eclipse, I have asked Mr. J. C. P. Miller to add a map and brief description of the corpuscular eclipse track, calculated on the assumption that the corpuscular speed is 1600 km./sec. I am indebted to the Department of Scientific and Industrial Research for a grant for payment for this assistance.

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* "Wireless Observations during the Eclipse of the Sun, 1927 June 29," Dept. of Sci. and Ind. Research, *Radio Research Board Special Report*, No. 7, 1928, p. 22.

† E. V. Appleton, *Nature*, 1931 February 7.