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ON THE RELATIONS OF STELLAR ELECTRICITY AND MAGNETISM TO THE PHENOMENA OF THE SUN'S ATMOSPHERE[1]

By Dr. ROSS GUNN

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NEARLY twenty years ago Hale and his collaborators at the Mt. Wilson Observatory established the existence of a general solar magnetic field. Measurements of the Zeeman displacement of certain spectroscopic lines showed that the solar magnetic field is quite large and that the sign and distribution of the field at given levels were strikingly similar to that of the earth. An unexpected anomaly was found, however, in the very rapid radial decrease of the magnetic field, which dropped from 55 gauss at an altitude of 250 km to about 10 gauss at 450 km. The observed data are consistent with the conclusion that the sun is a uniformly magnetized sphere whose axis is tipped about 6° to the axis of spin and completely surrounded by an atmosphere which somehow limits the external magnetic field by systems of electric currents. Fig. 1 illustrates in a rough manner the presumed distribution of the magnetic field within and around the sun, while Fig. 2 gives the observed magnetic field intensities in the sun's atmosphere as a function of the altitude above the photosphere.

It is well established that the pressure in the solar atmosphere, at levels that may be observed, is well below one one-hundredth of an atmosphere and that the molecules are nearly all ionized. That is to say, the solar atmosphere is a rarefied ionic gas with an

[1] An address delivered before the Section of Astronomy, American Association for the Advancement of Science, Syracuse, New York, on June 21, 1932.

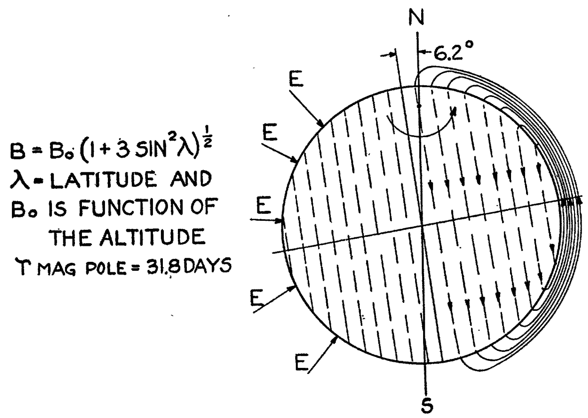

FIG. 1

admixture of neutral atoms, all immersed in a magnetic field. In an early paper we studied the effects that would be produced in a rarefied ion gas in which the ions execute long free paths as a result of thermal agitation in a magnetic field. In Fig. 3, consider an ion having a charge e that suffers a collision and starts off on its free path in a magnetic field B with a velocity v_0. The ion will be acted on by a magnetic force Bev_0, which is always at right angles to the instantaneous velocity, and this just balances the centrifugal force; hence the ion is constrained to spiral around the magnetic field. Now, the spiralling ion of mass m is equivalent to a small magnet of magnetic moment $mv_0^2/2B$ and its field is always opposed to the impressed magnetic field B, irrespective of the sign of the charge or its initial velocity. If there are N ions per unit volume, then the intensity of magnetization of the region is

$$I = -\frac{NkT}{B\left[1 + \left(\frac{R}{\lambda}\right)^2\right]}$$

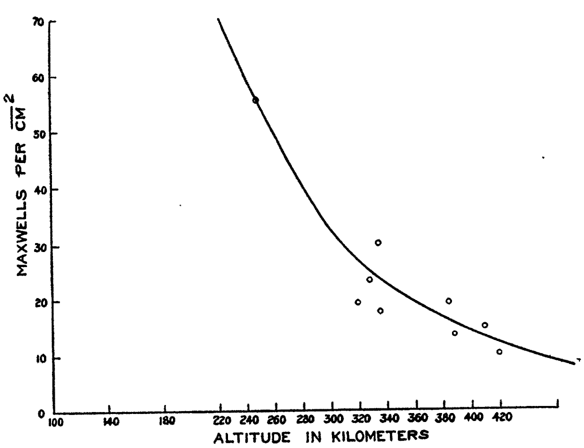

FIG. 2

and the approximate permeability of the medium is

$$\mu = \frac{1}{1 + \frac{4\pi NkT}{B^2\left[1 + \left(\frac{R}{\lambda}\right)^2\right]}}$$

where k is the Boltzmann constant, T the temperature of the region, R the radius of the generated helix and λ the mean free path. It is evident from these relations that the permeability of the sun's atmosphere must be less than unity—that is, the sun's atmosphere is diamagnetic. We may calculate the permeability from the approximately known ion pressures, or we may suppose that the limitation of the sun's magnetic field is due to diamagnetism and calculate the ion pressures, and compare these with observation. We here adopt the latter procedure and note that, if the observed limitation is due to diamagnetism, the permeability of the atmosphere must depart markedly

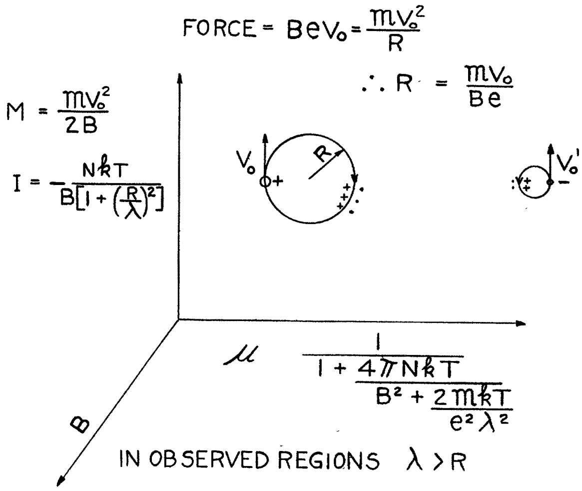

FIG. 3

from unity. We assume as a first approximation that the permeability is $\frac{1}{2}$ and calculate the ionic densities in terms of the observed values of B. We have plotted in Fig. 4 the ion densities as a function of the altitude, and, if we assume this represents an atmosphere in gravitational equilibrium, we find that its mean atomic weight is 3.3. These values are in fair agreement with later determinations by other methods. We see, therefore, that diamagnetism in the sun's atmosphere so distorts the general magnetic field that it becomes nearly tangential to the solar surface at all points except near the poles and thereby brings about the observed limitation of the field.

For nearly a century it has been known that the rotation of the sun was anomalous and that the equatorial period of rotation is considerably less than that at the pole. From the great mass of data which have been compiled, there appears to be little doubt that

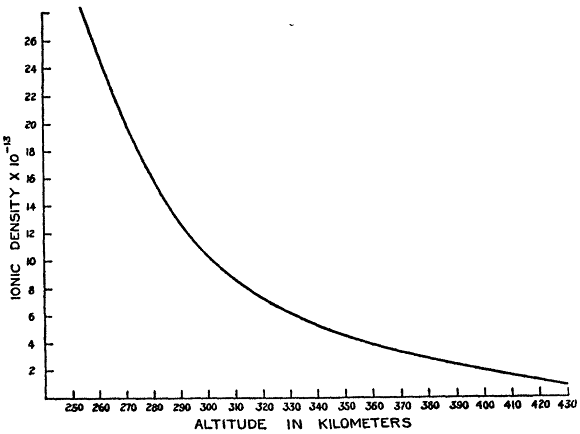

FIG. 4

not only does the rotational period change with latitude and altitude but it also changes with time. We have reproduced in Fig. 5, St. John's plot of the peripheral velocity of the sun and have indicated by the dotted curve the expected distribution if the sun rotated like a rigid body with a period of 31.8 days. The upper curve was plotted from data taken about 1907 and the next lower one about 1920. The variation of the rotational period with time and sunspot activity is shown in Fig. 6. It is to be noted that the amplitude of the fluctuation is some 8 per cent. of the total and is many times the probable error. Newall and Hahm believe that the sun rotates fastest at sunspot maximum, but their conclusion is only indifferently supported by St. John's data.

Study of the sun's rotation shows that the period depends slightly upon the object selected for observation and that the speed increases slightly with increasing altitude above the photosphere. In addition to these systematic changes there are many local variations and it is well known that even a single sunspot does not rotate at a constant speed.

Purely mechanical effects could hardly account for these observed motions, since a periodic change in the period of rotation would involve a periodic change in the moment of inertia of the sun. This seems highly improbable, and if such a change did take place it could not account for the observed rotation of the chromosphere faster than the lower layers. Moreover, even if we should deny the reality of the time variation and adopt Jeans' account of the variation of velocity with latitude, we are still faced with great difficulties. Jeans' postulated rapid rotation of the sun's core is inconsistent with observed magnetic data because the magnetic pole of the sun does not coincide with its axis of rotation but rotates around it once in

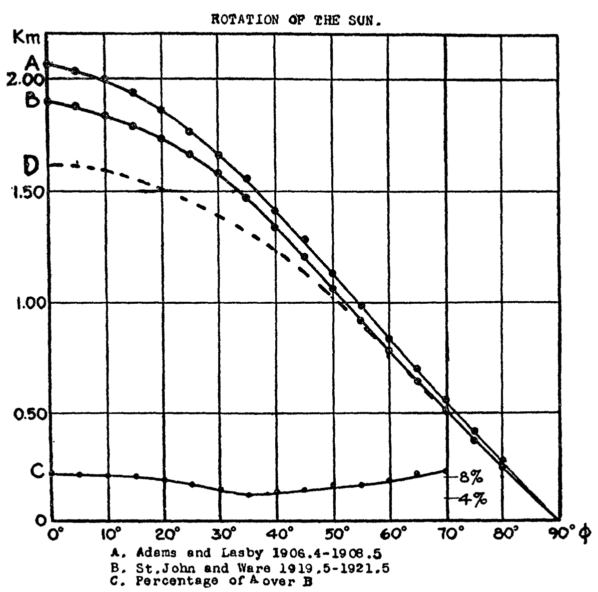

FIG. 5

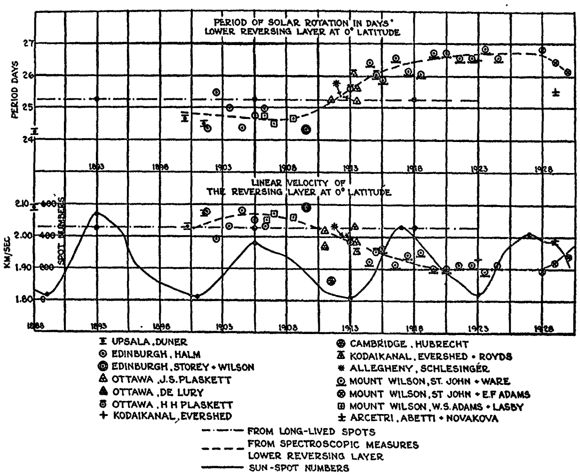

FIG. 6

31.8 days. This suggests that the sun is semi-rigid, since, if the angular velocity should increase inward, the relative motion of the highly conducting layers and the magnetic field will set up tremendous systems of electrical eddy currents which will damp out very rapidly any relative motion, the mechanism being precisely that of the classical experiment of elementary physics in which a massive copper pendulum is swung between the poles of an electromagnet.

The presence of the sun's magnetic field and its known asymmetry seems to assure us that the sun, like the earth, rotates essentially as a rigid body carrying its magnetic pole around with it once a revolution. We adopt this conclusion as a postulate. It then follows that the period of rotation of the sun proper and its associated magnetic pole is 31.8 days and is an invariable quantity. It also follows from observation that the sun's atmosphere is in motion and it rotates faster than the sun proper. That is to say, a high velocity superposed wind blows constantly to the eastward. In Fig. 5 the dotted curve shows how the surface velocity of the sun proper must change with latitude if it is quasi-rigid. The difference between the observed curves and the dotted one evidently represents the superposed atmospheric velocity, and this approximates 0.5 km/sec at the equator.

How may such a systematic motion of the atmosphere be maintained and what will be the consequences of such a motion? Evidently no simple mechanical mechanism would account for a systematic eastward motion; but our investigations suggest that the motion is a necessary consequence of electric fields in the sun's atmosphere as well as the observed magnetic field. Now it is known that the earth possesses a radially inward electric field which is greatest in regions of poor electrical conductivity, and it is perhaps reasonable to expect analogous solar electrical fields. Indeed, Hale and Babcock attempted to measure the atmospheric electric field of the sun in 1915 by means of the Stark effect but were unsuccessful because their method was not sufficiently sensitive.

We have considered in earlier papers the effects produced in an ionized atmosphere like the sun's if subject to electric as well as magnetic fields and showed that, when the electric field is at right angles to the magnetic field (which symmetry and observation demand in the case of the sun) an important and perhaps a surprising electromagnetic effect results. A mass motion is imposed on the ion bank such that its velocity u in regions of low pressure depends only on the ratio of the magnitudes of the impressed electric field E to the impressed magnetic field B. The paths described by the ions and the more general vector expression for the magnitude of the superposed mass velocity, which we will refer to as an electromagnetic wind, are given in Fig. 7. The magnitude

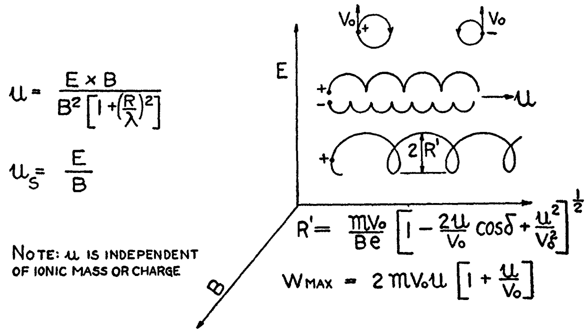

FIG. 7

of B is known in most of the reversing layer, and, by the use of the calculated values for u derived from direct observations, we can readily calculate the electric fields that must exist in the sun.

We first calculate the law of variation of the apparent angular velocity as a function of latitude and compare it with the observational data. The mean drift velocity u imposed on both kinds of ions which execute long free paths in crossed electric and magnetic fields is given by

$$u = \frac{E}{B}\sin\beta$$

where E and B are in e.m.u. and β is the angle between E and B. Take B positive northward in the reversing layer at the equator and E radially outward, then a positive value of u corresponds to a westward superposed atmospheric motion. According to Mt. Wilson data, the magnetic field at a given level and latitude λ is given by

$$B = B_o\,(1 + 3\sin^2\lambda)^{\frac{1}{2}}$$

where B_o is the value of the equatorial field at the level considered. Thus combining the foregoing relations, the superposed angular velocity of drift is

$$W = \frac{E\sin\beta}{B_o\,R_o\,[(1+3\sin^2\lambda)\;(1-\sin^2\lambda)]^{\frac{1}{2}}}$$

where R_o is the radius of the sun. The magnetic and electric fields are virtually at right angles throughout the region of observed data so that we may set sin $\beta = -1$, and for not too large values of λ; the last equation may be expanded to

$$\Omega = \Omega_o - (E/B_oR_o)\;(1 - \sin^2\lambda)$$

and this agrees with the observed form of the variation of angular velocity with latitude. Putting in the correct constants and carrying through the calculations, we find that the required electric field is radially inward and in the same direction as the earth's electric field. The field is greatest in regions of poor electrical conductivity; amounts to 0.013 volts/cm in a typical region of the reversing layer and, within the limits of the reliability of our data, decreases logarithmically with altitude much as the earth's electric field is observed to do.

No complete theory of the electric field of the sun has been worked out, and indeed present theories of the earth's electric field are highly unsatisfactory. However, the underlying physics of the problem is such that almost any theory would predict larger values for the electric field, as more and more energy traversed the atmospheric layer. That is to say, the electric field derives its energy from the thermal energy dissipated in the region. Thus, in general, we should expect the sun's electric field to be a more or less variable quantity whose magnitude would be related to the activity of the sun. It is well known that the sun is a variable star of small range, and our examination of electromagnetic effects in its atmosphere shows that radiation changes should produce, indirectly, changes in its apparent rotation.

Magnetic fields of the sun have not been measured above 500 km, but there is no reason to suppose that the field vanishes above this level and, indeed, the fact that the chromosphere rotates somewhat faster than the upper reversing layer guarantees that some such mechanism as considered above must be operative. The observations of the superposed motion give only the ratio of the electric to magnetic field and indicate that this ratio increases with increasing altitude until coronal regions are reached. Even in these regions there is evidence of faster rotation than in the chromosphere, so that we may suppose that here also the ion pressures and field intensities permit the existence of electromagnetic winds. It may be seen, therefore, that we can account for substantially all the observed features of the anomalous rotation of the sun if we grant that the sun has an atmospheric electric field not unlike the electric field of the earth. In

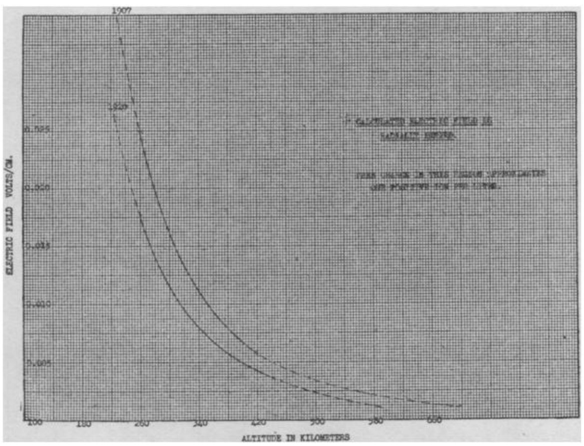

FIG. 8

Fig. 8 the estimated electric field has been plotted as a function of altitude on the assumption that the magnetic field remains constant. The upper curve corresponds to conditions existing about 1907 and the lower curve about 1920.

The existence of a simple mechanism, which we know is operative on the earth and which explains completely the sun's very unusual and complicated atmospheric motion, seems to establish a strong presumption for the existence of such a solar electric field.

Calculations show that the electric and particularly the magnetic forces acting on the atmospheric ions are far greater than those of gravity or radiation pressure. Thus, since the sun's atmosphere is highly ionized, we should expect its stability to depend primarily on electromagnetic forces. However, in the solar atmosphere we must recognize two highly differentiated types of particles acted on by forces of quite different magnitudes. The neutral atoms are acted on only by gravitation and radiation pressure so that they are free to diffuse where they will, and thermal processes will cause great numbers of them to be shot to high altitudes of low pressure where their chance of becoming ionized is increased tremendously. Once the particles are ionized the forces acting on them are increased hundreds of times and they are constrained to spiral around the impressed magnetic field and advance to the eastward as a result of their interaction with the electric field. When the ion recombines to form a neutral atom, it is again free to be acted on by gravity and it may fall to low levels. A single atom will spend some of its time in the ionized state and some in the neutral state. In general, we may expect to find particles which spend a very large fraction of their total life in the ionized state, high in the chromosphere, while those which recombine easily will spend most of their time in the neutral state and will therefore drop to regions low in the reversing layer. By considering the ionization potentials, recombination coefficients and masses of all the ions, we could easily build up a complete equilibrium theory of the chromosphere. These data are lacking and we only point out here, that, although the electric force on a positive ion is in the same direction as the gravitational force and hundreds of times larger, yet the net motion of the ion is not downward but is tangential and to the surface and moves eastward. Thus, the ion is "supported" and we see that magnetic and electric fields qualitatively account for the observed motion and stability of the sun's atmosphere. On the basis of such a theory we need not be surprised to find the arc spectra of a given element as well as the spark spectra at high levels; for there is no reason to suppose that a captured neutralizing electron will go to its lowest energy level immediately, but it may just as readily drop by steps, yielding the spectrum of a neutral atom.

It is, perhaps, of interest to note also that stability of the type we have considered would be little disturbed if the star rotated so fast on its axis that its surface acceleration approached zero. Thus, since some rapidly rotating nearly unstable stars are observed to retain their atmosphere, we infer that magnetic fields must be a common property of stars.

Several writers have studied the solar radiation and found it to depart markedly from black body radiation. Eddington, in his reexamination of the available data, estimated the sun's effective temperature as calculated from the density of radiation to be 4660°, while the temperature corresponding to the quality of the received radiation is 1080° higher or 5740°. Thus the solar radiation is far richer in the high energy region of the spectrum than the total received radiation would lead us to expect. It is well known, also, that the emission spectra of hydrogen and helium are strong in eclipse spectra and we are led to inquire if these phenomena are not directly related to the sun's electric field.

We encounter a serious handicap at the start of our investigation, for, if appreciable electric fields actually exist in the sun's atmosphere, then it can never be in thermodynamic equilibrium and we have no right to use the powerful thermodynamic method developed by Saha to determine the state of ionization or excitation of the solar atoms. This complicates the problems we face, because we have then to work out the detailed processes of excitation and ionization. This has been done only for one or two simple cases so that for the present we must be content with a purely qualitative description of the effects.

Although it is probably not permissible to use equations based upon thermodynamic equilibrium in the sun's atmosphere, many investigators have done so. They find, for example, by these methods that, in the case of hydrogen, the calculated numbers of atoms that must be in a state to account for the H_α line must be increased by a factor of 800 if it is to agree with the number calculated from the observed line contours, whereas the numbers for H_δ must be multiplied by 25,000. From the form of the relations we can see that the discrepancy between the observed and calculated number will increase as the ionization and excitation potentials of the selected state increase. Thus, we find in the case of the line λ4686 of ionized helium that the calculated numbers of atoms in the required state must be multiplied by a factor something like 10^{40} to represent correctly the observed abundance. It is clear that something is seriously wrong with the methods employed. Dr. Menzel, of the Lick Observatory, notes that most of the difficulties can be resolved if, in the modified Saha relations, we insert a value of 18,000° for the solar temperature. There is some evidence for believing that such temperatures may exist in localized regions, but it could hardly exist generally throughout the sun's atmosphere. Thus we are forced by the observational data to believe that the mean temperature of the sun does not depart greatly from 5,000°, yet that some auxiliary mechanism is operative in its atmosphere which produces excitation and ionization corresponding to far higher temperatures. This is about the situation that we would expect to exist were the solar atmosphere permeated by electric fields of the calculated magnitude.

One might suppose that an ion describing a free path in an electric field would gain energy proportional to the product of the electric field and the length of the free path; but in the presence of a magnetic field this is not the case, as the ion is constrained to describe a curved cycloidal path. The lower curve of Fig. 7 shows the trajectory of a typical ion. It is clear that the maximum distance that the ion can travel in the direction of the electric field is 2 R^1, where R^1 is specified by the equation in Fig. 7 and hence the maximum energy W_m that can be added to or subtracted from a typical ion by the impressed electric field even if the free path is infinitely long is given by

$$W_{max} = 2\ m\ V_o\ u\ (1 + \frac{u}{V_o})$$

in which m is the mass of the ion, v_o is its initial velocity and $u = E/B$. Thus in the sun's atmosphere we have substantial equipartition for the neutral molecules, whereas the ions take on and lose successively energies specified by the foregoing relation. We note that the excess or deficiency of energy depends on the mass of the ion and calculate that the electric field does not particularly disturb the energy distribution of the electrons but does greatly modify the energies of the ions. In Fig. 9 we have plotted

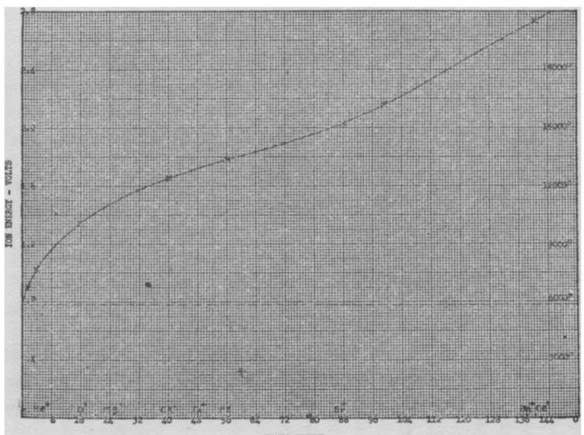

FIG. 9

the maximum energies of ions of different atomic weights on the assumption that the initial velocity of the ion is the mean thermal velocity and that the electric field has the values just calculated. After some collisions special ions will start off with an even higher velocity and a small but finite number of the particles will have their maximum energy increased by perhaps more than twice that indicated by the curve. The energies have been expressed both in electron volts and in terms of the temperature that ions of the same energy would be in thermal equilibrium. Thus in the solar atmosphere we have an ionized gas which is in anything but thermodynamic equilibrium. Many ions have very low energies and absorb energy readily, while some have very high energies that can be passed on by collision and produce abnormal excitation in other atoms. For example, the maximum energy of a calcium ion is as great as it would be if it were in thermal equilibrium at 12,000° while a barium ion would approximate 20,000°. We note particularly that the energy of an ion changes continuously during its flight and its energy at collision depends on its position and trajectory. The neutral atoms and electrons are not particularly disturbed by the electric fields and except for their collision with ions of excessive energy, they would approach an approximate thermodynamic equilibrium. The problem of working out the detailed equations of equilibrium between excitation and deexcitation of all the different kinds of ions in the solar atmosphere is an imposing one and will probably not be solved for some time. It does appear, however, that electric fields in the solar atmosphere will account qualitatively for the observed anomalous characteristics of the sun's radiation, because such fields make possible the selective excitation of the more energetic radiations without disturbing in any important manner the mechanisms which are responsible for the general radiation.

Our studies of the relations of electricity and magnetism to the properties of the sun's atmosphere have demonstrated that electric and magnetic effects play, perhaps, a major rôle in determining the observed phenomena. While it can not be said to be proved beyond doubt that electric fields exist in the sun's atmosphere, yet the internal evidence and the interrelation of much data makes the existence of such fields seem probable. Much additional data are needed to completely test our results, and it is sincerely hoped that the solar eclipse of 1932 will be of material aid in this respect.

ON THE LOCOMOTION OF SNAKES[1]

By Dr. WALTER MOSAUER

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DURING the years 1929–1931 an investigation dealing with ophidian locomotion and its anatomical basis was carried on in the Department of Anatomy, University of Michigan. Since the publication of the voluminous thesis embodying the results of this work has met with considerable delay, it seems advisable to publish a brief abstract at this time.

The anatomical structures involved in locomotion are the skeleton of the trunk and tail, their musculature and integument. All three show special modifications fitting them for their task.

The vertebral column of a snake consists of a very great number of single pieces, sometimes as many as several hundred; each vertebra articulates with a neighboring one at five points. The shape of the articulating surfaces restricts the possible movements to two main planes, *i.e.*, to the frontal plane, permitting of lateral flexion, and to the sagittal plane, permitting of dorsal and ventral flexion. Moreover, movements in both planes can be so combined as to allow the snake the multitude of graceful windings that makes the ophidian vertebral column the most remarkable instance of mobility in this organ, although rotation about the long axis is wholly impossible. X-ray photographs were used to determine the degree of flexibility in the main planes; it was found in several different species to be about 25° for lateral flexion between successive vertebrae, about 13° for ventral flexion, while the maximum of dorsal flexion varied from 12° to 18°. The ophidian vertebral column, considered as a mechanical unit, is of an admirable perfection. It permits of almost unrestricted movements in the frontal and sagittal plane, avoiding any loss of energy in the production of these movements by the impossibility of rotation. Moreover, it is very resistant to strain and stress in the long axis, thus making for high efficiency in transferring the locomotor forces from one small section of the body to the whole.

Each vertebra from the second to the last trunk vertebra articulates with two ribs that are attached to it by clublike enlarged extremities, while their other ends are free between the muscle sheets. The vertebrocostal articulation, while it was generally considered as a ball and socket joint, actually functions as a hinge joint, a ginglymus, in which movements are possible in one oblique plane only, due to the peculiar shape of the articulating surfaces. Consequently, the free end of a rib when moved forward is also lifted; when moved backward, it is depressed. This seems to be of significance in locomotion.

The myology of the body of snakes is at the same time simple and complicated. It is simple because, due to the loss of the extremities, the appendicular muscles have disappeared, except for a few rudiments.

[1] Abstract of a lecture delivered before the Western Society of Naturalists, Berkeley, California, December, 1931.