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THE ELECTRIC FIELD, ATMOSPHERE AND EFFECTIVE TEMPERATURE OF THE SUN

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Abstract

The study of important electromagnetic effects in the solar atmosphere undertaken in previous papers is continued. It is shown that the large observed spread of effective temperatures of the sun's radiation can be accounted for by the presence of electric and magnetic fields in the solar atmosphere. The magnitude of the electric field at a level where the magnetic field is 25 gauss, calculated from the observed spread of temperatures, is found to be 0.015 volts.cm and agrees well with 0.013 volts/cm calculated earlier from the observed anomalous motions of the solar atmosphere. Gravitational equilibrium is found to be unnecessary in all regions of the atmosphere and it is shown that the "support" and stability of the chromosphere and its anomalous eastward motion are evidences of precisely the same electromagnetic mechanism. An electric field of the value given above is shown to account qualitatively for certain bright line spectra in the chromosphere of the sun. The strange observed relation between bright line spectra and rapid axial rotation of stars, just pointed out by O. Struve of the Yerkes Observatory, confirms in a striking manner some of the conclusions of this and earlier papers.

IN A series of papers it has been shown that the anomalies of the solar rotation arise from electromagnetic effects which take place in the crossed electric and magnetic fields existing in the ionized solar atmosphere. The magnitude and direction of the magnetic field is readily determined by observation, but the magnitude of the electric field is much too small to produce measurable Stark effects and must be inferred from the observed atmospheric motions. In the present paper we consider a method of calculating the magnitude of the electric field from spectroscopic data and will show that the departures of the solar radiation from that of black-body radiation lead to a value for the electric field which agrees with that calculated in earlier papers. Measurements show that the effective solar temperature calculated from the quality of solar radiation is over 1000° higher than that inferred from measurements of the density of radiation. The difference of the effective temperatures is so great that we must conclude that processes other than thermal must be present which add energy to the ions. It is clear that an electric field of sufficient magnitude might add energy to the ions during their free path so that on collision they would have energies higher than that indicated by the temperature of the region. A rough calculation shows that a radial electric field alone will not account for the observed features of the solar radiation, for if there were no solar magnetic field the conductivity of the atmosphere would be so great that electric fields would be very small. However, if we consider both electric and magnetic fields the difference in the effective temperatures is readily accounted for.

EFFECT OF CROSSED ELECTRIC AND MAGNETIC FIELDS

In earlier papers[1] we considered the effect of crossed electric and magnetic fields on the electrical conductivity, diamagnetism and mass motion of an ionized gas. It has been shown[1] that diamagnetism limits the solar magnetic field and the resulting distribution is such that the field is nearly tangential to the surface over most of the sun. The electric field, by symmetry, must be radial so that in the following we may assume for simplicity that the electric and magnetic fields are always perpendicular.

The path described by an ion in perpendicular electric and magnetic fields is a cycloid.[2] An ion starting from rest is initially acted upon only by the electric field which accelerates the ion; as the velocity increases the magnetic force at right angles to its motion increases until the ion is moving at right angles to the electric field. The magnetic force continues to act and the ion is forced by its inertia to move against the electric field, whereby it loses energy till it comes to rest. The process then repeats itself again and again. The net result of this process is that the ion progresses in a direction perpendicular to both the electric and magnetic fields and on the average does not advance in the direction of the electric field.

It is clear that in certain parts of the cycloidal path the ion has much more energy than at other points, and if the ion collides at a point in its path where its energy is large, ionizing effects will be greater than if the ion collided in a part of the path where the energy is small. In the general case the ion starts its path with a certain thermal energy and in tracing its cycloidal path it acquires and loses energy repeatedly from the electric field. If R is the radius of the generating circle of the cycloidal path, E the average electric field encountered by the ion in its path, and e the ionic charge in e.m.u., then the difference in energy W of the ion between the top and bottom of its path is

$$W = 2REe. \tag{1}$$

This energy is obviously supplied by the electric rather than the magnetic field, for the motion of the ion is always at right angles to the magnetic force and hence the magnetic field cannot transfer energy to the ion or the ion energy to the magnetic field. It is of importance to note that Eq. (1) gives the maximum energy difference and no matter how long the free path, the ion cannot acquire more. We neglect the less frequent case of successive collisions where an ion of initially large energy collides with another at a favorable point in its path and this ion in turn picks up additional energy and passes it on to still another.

The radius of the cycloidal generating circle R is given by

$$R = \frac{mv}{Be}\left[1 - \frac{2u}{v}\cos\delta + \frac{u^2}{v^2}\right]^{1/2} \tag{2}$$

where m is the mass of the ion, v the initial ionic velocity in a plane perpen-

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[1] R. Gunn, Phys. Rev. **32,** 133 (1928); **33,** 614 (1929); **33,** 832 (1929); **34,** 335, 1621 (1929); **35,** 635 (1930); **36,** 1251 (1930); **37,** 283 (1931).

[2] L. Page, Phys. Rev. **33,** 553 (1929).

dicular to the magnetic field B, u the ion drift velocity resulting from the crossed electric and magnetic fields and δ the angle between u and v. When the free paths are long and the electric and magnetic fields are perpendicular, u is given by

$$u = E/B. \tag{3}$$

A few of the ions will acquire and expend the maximum energy given by Eq. (1) and some will lose energy. To get the mean gain in energy for a typical ion we will simply take an arithmetical average and therefore we have from Eqs. (1), (2), and (3) that

$$W_1 = mvu\left(1 + \frac{u^2}{v^2}\right)^{1/2} = \frac{E}{B}\left[2mkT\left(1 + \frac{mE^2}{2kTB^2}\right)\right]^{1/2} \tag{4}$$

where W_1 is the approximate mean increase in energy and $(2\,mkT)^{1/2}$ has been written for mv. The mean increase in energy W_1 may, for convenience, be expressed in terms of an equivalent effective temperature and be equated to $3k\Delta T/2$ where k is the Boltzmann constant and ΔT is the change in effective temperature due to electrical effects. Making this substitution and transforming Eq. (4) we have

$$\frac{\Delta T}{T} = \frac{2u}{3}\left[\frac{2m}{kT}\left(1 + \frac{mu^2}{2kT}\right)\right]^{1/2} \tag{5}$$

or if we solve this for the electric field E we have

$$u^2 = \frac{E^2}{B^2} = \frac{kT}{m}\left[\left(1 + \frac{9}{4}\left(\frac{\Delta T}{T}\right)^2\right)^{1/2} - 1\right]. \tag{6}$$

In Eq. (5) we note that the difference in the effective temperatures is proportional to the square root of the ion mass. This indicates that the ions rather than the electrons are the particles effective in increasing the apparent temperature of the solar atmosphere although there is no reason why the ions cannot transfer their high energies to electrons by collision.

Departure from Black-Body Radiation

Several writers[3,4,5,6] have studied the solar radiation and found it to depart markedly from a black body distribution. At one time it was thought the departures were due to varying general absorption in the radiating layers but Milne[4] concluded that this was quite inadequate. Eddington[6] has reworked some of the data and gives 4660° for the effective temperature of the sun as calculated from the density of radiation and 5740° as the effective temperature calculated from the quality of the radiation. It is clear that the emitted light is much richer in high frequency radiation than would be the case if the sun radiated like a black body. The differences in the effective temperatures, or 1080°, is so great that the energies of some of the ions must be considerably more than that of the mean value. If we are not particularly

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[3] C. G. Abbot, Annals Astrophys. Observ. Smithsonian Inst.

[4] E. A. Milne, Monthly Notices **81,** 375 (1921).

[5] Lundblad, Nova Acta, Reg. Soc. Sci. Upsalienses **6,** #1 (1923).

[6] Eddington, Internal Constitution of the Stars.

concerned with the detailed mechanism of the radiation process, Eq. (5) of the preceding section permits a test of our prediction that the effects arise from an electric field in the solar atmosphere. Earlier work[1] showed that the mean atomic weight of the solar atmosphere in the region of the reversing layer was 6.6 if no account were taken of the electrons, or calling the mass of the hydrogen atom h, the mean mass of the ions in the reversing layer is 6.6 h. Moreover, the superposed atmospheric drift velocity u is known from astronomical data to approximate 0.5 km/sec. Substituting in Eq. (5), $m=6.6h$; $h=1.64\times10^{-24}$ gm; $u=5\times10^{4}$ cm/sec; $k=1.37\times10^{-16}$ and $T=4660°$ we find $\Delta T/T=0.197$ so that $\Delta T=920°$. This value is to be compared with the observed value 1080° and is considered satisfactory because the method of averaging to get statistical values is rough. The agreement is greatly improved if we select a mean value for the effective temperature rather than the lower value derived from the density of the solar radiation. Observation shows that the superposed drift velocity u does not change rapidly with altitude in regions which can be observed so that according to Eq. (5), ΔT also changes but little with altitude. This is consistent with the observed fact that the intensity-frequency curve decreases very rapidly on the high frequency side of the maximum. Our calculations clearly indicate that the observed spread of effective temperatures can be accounted for by the presence of electric and magnetic fields in the solar atmosphere.

MAGNITUDE OF THE ELECTRIC FIELD

In other papers[1] the relation of the mechanical motions of the solar atmosphere to electromagnetic effects was considered and it was concluded that the observed motions required that the solar atmosphere have an electric field directed radially inward and amounting to 0.013 volts/cm in the region where the magnetic field was 25 gauss. The magnitude of the electric field cannot be checked by Stark effect observations and it becomes necessary to look elsewhere for supporting evidence. The spread of observed effective temperatures provides an independent method of calculating the magnitude of the field and we turn at once to Eq. (6) which connects observed quantities with the electric field. We follow earlier work and take $m=6.6h$; $h=1.64\times10^{-24}$ gm; $k=1.37\times10^{-16}$; $T=4660°$; $\Delta T=1080°$ and $B=25$ gauss. Substitution in Eq. (6) gives $E=0.0148$ volts/cm. The agreement of this value with the earlier calculation[1] is most satisfactory and it is evident from the form of Eq. (6) that the agreement will be equally satisfactory at all other levels of the solar atmosphere. The present method of calculating the field is apparently incapable of determining the sign of the electric field, but, as we have pointed out previously, the sign inferred from the solar motions is precisely the sign observed on the earth, i.e., negative or radially inward. The agreement of the two methods of calculating the magnitude of the field strongly supports the conclusion that a solar electric field exists and that the mass motions of the atmosphere and the differences observed in the effective solar temperatures are simply different aspects of the same fundamental physical phenomena.

STABILITY OF THE SOLAR ATMOSPHERE

Eclipse spectra show that large amounts of material, notably calcium, exist high in the chromosphere and the distribution of this material is such that it cannot well be in gravitational equilibrium with a supporting gaseous pressure. Milne[7] has attempted to account for the support and stability of this material by assuming that radiation pressure was great enough to overcome the gravitational forces. His calculations show that the calcium must absorb selectively in what appears to be a highly artificial manner. A still more serious objection to his theory is the fact that once sufficient absorption is built up by special assumptions the atom will be blown away from the sun because the radiation pressure does not decrease as rapidly as gravity. Thus Milne's atmosphere is unstable.[6]

Our study of electromagnetic effects suggests that the stability of the chromosphere does not depend on a specialized type of dance on a sunbeam but does depend on very real and sufficiently large electric and magnetic forces. Although the force on a positive ion in the solar atmosphere is vertically downward and hence in the same direction as gravity, we have seen that the ion does not move downward but on the average moves parallel to the solar surface. Thus ions executing long free paths in crossed magnetic and electric or gravitational fields are "supported" and can progress in the direction of the force field only by numerous collisions. It is therefore clear that it is not necessary to think of the very long free path ions in the solar atmosphere as being in gravitational equilibrium. To illustrate, suppose that neutral molecules of all materials are shot, undeviated by the magnetic or electric fields, by thermal processes to high altitude regions of low pressure where they immediately become ionized. The recombination coefficient will be different for different kinds of ions and those particles that remain neutral for an appreciable time will be acted on by gravity and drop to lower levels. The ions with very small recombination coefficients (calcium for example) will spend most of their life in an ionized condition and therefore will be "supported" and at the same time swept parallel to the solar surface with a velocity dependent on the ratio of the crossed electric and magnetic fields. Eventually an equilibrium condition will be reached and the supply of neutral calcium atoms will balance the loss of those dragged down by the electric field as the result of a large number of collisions and the few which are neutralized and fall under the action of gravity. We thus see that no special mechanism is necessary to account for the "support" of the chromosphere and that it is supported by precisely the same mechanism that produces its observed anomalous eastward drift.

BRIGHT LINE SPECTRA

Doubly reversed, or bright line spectra, are characteristic of certain types of stars but there have been theoretical difficulties in accounting for their presence. Eddington[6] has reviewed the subject and he concluded without attempting to make the statements quantitative, "that bright lines in the spectrum of a static star indicate that either (a) the star is greatly disturbed

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[7] E. A. Milne, Monthly Notices **84**, 354 (1924).

by "thunderstorms" or (b) it is a nebulous star." The sun can hardly be called a nebulous star and we should be able to account for certain lines of the flash spectrum by electrical excitation of the type we have considered. The electrical field will add considerable energy only to an ionized particle and more analysis will be necessary to determine the exact mechanism by which an atom is excited to radiation. In another place we have expressed the ratio of the energy added to an ion, to its thermal energy in terms of temperatures and, as a numerical example, we will calculate the ratio of the energies for a helium ion. In Eq. (5) we will take $m=6.56\times10^{-24}$ gm; $u=5\times10^{4}$ cm/sec; $T=4660°$ and we find $\Delta T/T=0.16$; that is to say, all the helium ions periodically acquire energies 16 percent greater than their thermal energies. Similarly the added energy for calcium is 50 percent while that of hydrogen is only 8 percent. Thus we are led to believe that the additional energy available is adequate to produce bright line spectra. For the purpose of this paper, which is primarily concerned with the solar electric field, the rough value given above is adequate, but it is evident that a complete study of the bearing of an electric field on the ionization equilibrium relations in stars is necessary to give a complete description of the events. Saha's[8] theory of stellar ionization will be readjusted to take account of the fields and it is expected that such a readjustment will improve the agreement of his formula with observation.

CONCLUSION

We have indicated in outline that spectroscopic data regarding the sun bear out our earlier conclusion that electromagnetic phenomena are important in the solar atmosphere. It is rather surprising that the apparent solar rotation should be so closely related to the spectral distribution of radiation from the sun but we have had a suggestion that this might be true in a recent paper by Struve.[9] Dr. Struve has noticed a remarkable correlation between the rotation of stars and their spectral class. The early type stars rotate with great rapidity and several are apparently on the verge of rotational instability. The considerations of the present paper indicate that the early type stars have electric and magnetic fields of considerable magnitude and that our sun is probably a fair representative of stellar bodies. A complete study of the sun is therefore of the greatest importance if we are to understand and correctly interpret the physical phenomena which astronomers observe.

Note added March 24, 1931:

The March issue of the Astrophysical Journal has just appeared and contains another paper by O. Struve giving observational data which is in remarkable accord with the theory developed above. Dr. Struve states "Excessive rotations, estimated at 9 or 10 (. . . 250 km/sec.), are frequent. Apparently bright lines occur preferentially in stars having rapid axial rotation."

The relation of Eq. (5) shows that the ratio of the additional excitation energy to the thermal energy is directly proportional to the superposed drift velocity u. Thus theory predicts a strict parallelism between high *apparent* rotations and bright line spectra. Struve's results appear to be a beautiful confirmation of the material of this and preceding papers.

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[8] M. N. Saha, Phil. Mag. **40**, 472, 809 (1920).

[9] O. Struve, Astrophys. J. **72**, 1 (1930).