ORIGIN OF THE VARIATIONS IN THE SUN'S ROTATIONAL VELOCITY

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Abstract

The observed variations of the sun's rotation with solar activity are shown to be accounted for by changes of the electric and magnetic fields in the solar atmosphere. It is assumed that the sun's electric field arises from an electron or negative ion current flowing away from the sun's surface. The ionized atmosphere offers electrical resistance to the current and calculations show that the heat generated in the solar atmosphere is an appreciable fraction of the total radiated light energy. The electric field is thus correlated with the solar constant and since the solar constant is known to vary with the sunspot cycle, the atmospheric electric field, and hence the rotational period, must go through similar variations in magnitude. The subatomic processes which might give rise to the solar current are mentioned.

SIMULTANEOUS spectroscopic determinations of the sun's rotational velocity made at different observatories agree exceptionally well in magnitude but observations over long periods of time show that the velocities are not constant. The observed variations cannot be attributed to errors of observation or to a real change in the rotation of the entire solar mass. Newall[1] and Halm[2] have studied the observational data and definitely conclude that at times of maximum sun spot activity the sun revolves with an apparent speed that is greater by a few percent than the average; while at minimum activity, it rotates slower than the average. In addition to this type of variation there are observed temporary and local fluctuations which may amount to as much as ten percent of total superimposed velocity. These variations of velocity have been attributed to many causes, but no generally acceptable explanation has been given.

In an earlier paper[3] it was shown that the anomalies of the sun's rotation arose from the combined electric and magnetic forces acting on the ions of the solar atmosphere and that the only fundamental solar rotational period which can be observed directly, is the period of rotation of the sun's magnetic pole. With a knowledge of this fundamental period the surface velocity of the sun proper is readily calculated for any given point. To this velocity must be added the atmospheric drift which arises from the sun's magnetic and electric fields and may amount to as much as one quarter of the surface velocity. The magnitude of this superposed atmospheric velocity $\boldsymbol{u}$ is given by

$$\boldsymbol{u} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2} = \frac{E}{B} \sin \beta \tag{1}$$

[1] Newall, Monthly Notices, R.A.S. **82**, 101 (1921).
[2] Halm, Monthly Notices, R.A.S. **82**, 479 (1922).

where E and B are the electric and magnetic fields respectively, and β is the angle between E and B. We have seen that this additional velocity has the correct value and distribution to account for the anomalous rotation if the sun carries a negative charge sufficiently great to produce a radial electric field of 0.013 volts/cm at a level in the reversing layer where the magnetic field is 25 gauss.

At any given latitude and level the angle β between E and B may be considered constant and it is clear from Eq. (1) that fluctuations in the velocity of the solar atmosphere are to be expected if the ratio of E to B changes for any reason whatsoever. Observations show that the atmospheric drift at any given level and latitude may increase by as much as ten percent from a time of minimum to maximum solar activity. We may attribute this increase in the atmospheric drift velocity to: (a) an increase in E; (b) a decrease of B; and (c) a readjustment of both E and B.

The magnetic field B at any given level in the solar atmosphere is determined primarily by the magnetic permeability of adjacent layers, and we have seen[3] that due to the diamagnetic action of the atmospheric ions the effective magnetic permeability is much less than unity. The intensity of magnetization I for the region is readily calculated and it is found[3] that

$$I = -\frac{NkT}{B(1 + (R/\lambda)^2)} \tag{2}$$

where N is the number of ions per cm^3, k the Boltzman constant, T the absolute temperature, λ the ion mean free path, and B the magnetic induction. The radius R of the circle generated by the ion as it spirals about the impressed magnetic field is given by

$$R = mV/Be = (2mkT)^{1/2}/Be \tag{3}$$

where m is the mass of the ion, V its velocity and e the ionic charge in e.m.u. Making use of the usual relations it is found that the magnetic permeability μ of the solar atmosphere at any level in terms of the observed magnetic field B is given by

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

In the reversing layer observation requires a permeability much less than unity and a long ion free path. Hence it follows from Eq. (4) that $4\pi NkT/B^2$ must have a value of the order of unity. This is the approximation which has been used heretofore to determine the pressure distribution in the solar atmosphere and it was found[3] that this approximation led to a mean atomic weight for the ions constituting the solar atmosphere of 3.3, a value in fair accord with the more recent unpublished determination of Professor Menzel.[4] The important thing to note in present discussion is that

[3] Gunn, Phys. Rev. **35,** 635 (1930); **33,** 614 (1929); **32,** 133 (1928); **34,** 335 (1929).
[4] H. N. Russell, Astro. Jour. **70,** 1 (1929).

the magnetic permeability of the solar atmosphere decreases with increasing values of (N) the specific ionization.

It seems well established that the value of the solar constant[5] increases by three percent from sunspot minima to maxima and that the radiation in the ultraviolet may increase by as much as thirty percent. This increase in radiation increases the specific ionization and decreases the permeability which in turn reduces the magnetic field at a given level. This reduction of the magnetic field increases the velocity of the atmospheric drift and at sun spot maxima we find, in accord with observation, that the solar rotational velocity is a maximum. It seems unlikely that this effect alone will account for the entire observed changes even though it is of the correct sign. We shall see that variations of the electric field appear to be of more importance in causing the observed changes in the rotational velocity.

In an earlier paper on the anomalous solar rotation[3] it was shown that the observed atmospheric motions demanded the existence of an electric field in the reversing layer which is directed radially inward and which has an equatorial value of 0.013 volts/cm at a representative level in the reversing layer. No attempt was made to account for the presence of this field, although the calculations showed that the potential difference between the sun and free space amounted to at least 10^6 volts and the phenomena giving rise to the electric field must therefore be quite energetic. The required electric field may arise from some unknown cause but at the present time it seems correct to assume that the presence of the electric field is evidence of a current of electrons or negative ions which flow constantly outward from the sun to free space. In order to calculate the total electric current discharged by the solar atmosphere on our assumption it is necessary to note that diamagnetism confines the entire solar magnetic field to the solar atmosphere, and ions which eventually leave the sun, no matter where they leave the surface, must drift across the magnetic field and not along it. We have seen[3] that the electrical conductivity of long free path ions moving across a magnetic field was very much smaller than the conductivity for ions moving in zero field or moving parallel to the magnetic field. In the present case we will not be greatly in error by taking the mean conductivity nearly equal to the conductivity of a typical level in the reversing layer near the equator. In this region the ions necessarily move across the magnetic field, and the usual expression for the electrical conductivity is reduced by a large factor dependent upon the ratio of the mean free path to the radius R of the ion path. If we take ion pressures in the reversing layer which are consistent with earlier work it seems likely that the electrons within the layer contribute but slightly to the electrical conductivity[3] and that the current is carried almost entirely by ions. The electrical conductivity (σ) of highly ionized stellar matter has been worked out by Chapman[6] who gives a mean value for the conductivity in the reversing layer of 1.7×10^{-11} e.m.u. This value is probably too large at the specific level in which we are interested, for here the magnetic field appreciably

[5] Report Astro. Observ. Smithsonian for 1923, p. 109.

[6] Chapman, Monthly Notices R.A.S. **89**, 54 (1928).

affects the conductivity of the ions as well as the electrons. We can do no better at the present time than adopt the foregoing value although it may be considerably in error. The mean current density i of negative charge flowing away from the sun is simply $i=\sigma E$ where $\sigma=1.7\times10^{-11}$ e.m.u. and E is 1.3×10^{6} e.m.u. Thus the current density in this region is roughly 2×10^{-5} e.m.u. per cm^2 and if we assume this special region to be representative of the whole surface, the total solar current amounts to 1.3×10^{18} e.m.u.

The potential difference between free space and the base of the reversing layer has been calculated[3] and found to approximate 1.5×10^{14} e.m.u. Moreover an extrapolation has been made extending down to the solar surface proper and the potential difference between the surface and free space was found to be 6.6×10^{15} e.m.u. This value may be taken as an upper limit and is based on the rather doubtful assumption that the drift velocities of the deep atmospheric layers are identical with the drift velocities in the reversing layer.

The solar atmosphere offers electrical resistance to the outward flow of current and the heat generated in the reversing layer by this process is radiated away into free space. The total electrical power dissipated in the form of heat in the solar atmosphere is simply the product of the total current and the potential difference. Thus the total electrical power dissipated in the reversing layer is 2×10^{32} ergs/sec and the total electrical power dissipated in all the surface layers cannot exceed 8×10^{33} ergs/sec. Since the total solar radiation is 3.8×10^{33} ergs/sec, we are driven to conclude that electrical heating effects in the solar atmosphere regulate to a certain degree the amount of light energy radiated into free space. The calculations which have been made are not sufficiently precise to warrant the conclusion that electrical heating effects are the only effects of major importance but they do indicate clearly that electrical phenomena may control to a marked degree the amount of energy transferred from the sun's interior to the solar atmosphere.

The introduction of an electrical mechanism to account for the transfer of energy from the interior of a star to its surface and hence, by radiation, to free space would profoundly modify many present astrophysical conceptions. It seems likely that the electrical effects will account for certain puzzling discrepancies which are now found in a comparison of the physical properties of different stars. A discussion of these astrophysical consequences must be postponed.

As a direct result of our conclusions in regard to the electrical energy dissipated in the solar atmosphere, we see that a direct relation exists between the amount of light energy radiated by the sun and the electric field produced in the reversing layer. Thus if the solar atmospheric current is increased by some subatomic or other process the radial electric field will increase, as will the total radiation. Observation shows[5] that at sun spot maxima the solar constant increases by a few percent, which indicates that the solar electrical field must have increased. The resulting increase in the electric field increases the superposed drift velocity of the solar atmosphere and this in turn increases the apparent observed rotational velocity. The above theoretical discussion suggests that the electric field and hence the superposed drift velocity is approximately a linear function of the solar radiation, if we consider small variations. This is in complete accord with observation and is reliable evidence for the physical reality of the theory.

We have no direct clue to the phenomena which take place inside the sun and give rise to the outward negative atmospheric current. It is certain that similar phenomena give rise to the observed atmospheric current of the earth and because the potential differences encountered are so great it seems likely that the current systems arise from some subatomic transformation. G. C. Simpson[7] has suggested that electricity might be generated spontaneously within the earth while Swann[8] has considered the effects arising from the death of positive electricity. Swann did not discuss the important question of the origin of the energy for such a transformation. Unless the law of conservation of energy is entirely ignored, the death of electricity must be accompanied by the absorption of energy during its transformation, for death of the charge is electrically equivalent to its transfer to infinity. This requires energy and unless this energy is supplied by subatomic processes it seems clear that death cannot take place. W. Anderson[9] has avoided the above difficulties and he accounts for the earth's electric field by a single postulate. Anderson notes that the solar radiation must arise in some manner from the annihilation of matter and instead of assuming that the proton and electron vanish simultaneously with resultant radiation, or that the charge alone vanishes, he assumes that the proton's mass and charge both vanish while the associated electron wanders off into free space giving rise to certain solar and terrestrial phenomena. By this postulate Anderson was able to calculate the total solar current from the total solar radiation since one electron must appear for every proton annihilated and he found the total current to be 4×10^{16} e.m.u. Comparison of this value with 130×10^{16} e.m.u. computed above suggests that Anderson's postulate may yield the correct results, for the numerical value of the conductivity which has been chosen here, is probably too great. This postulate also connects directly the solar radiation with the solar electric current and therefore changes in the total radiation should be accompanied by rotational changes.

In his discussion of the source of solar energy Jeans[10] suggests that the energy arises from purely radioactive transformations of a material having a higher atomic weight than uranium. If this is the case it is not unlikely that the transformation results in a residue of electrons and perhaps several electrons may be released by the conversion to radiation of the mass of a single equivalent proton. By incorporating such hypothesis in the author's theory, the above numerical values can be brought into accord with solar radiation data. So far as can be determined at the present time, the author's postulate, or that of Anderson, cannot be shown to be inconsistent with any

[7] G. C. Simpson, Monthly Weather Review **44,** 121 (1916).

[8] Swann, Jour. Franklin Inst. **201,** 143 (1926).

[9] W. Anderson, Zeits. f. Physik, **42,** 475 (1927).

[10] Jeans, Astronomy and Cosmogony.

known fact. These postulates do, of course, readily account for the earth's observed electric field as well as that of the sun.

The anomalies of the solar rotation and its fluctuations, in the light of this and previous work, must be attributed primarily to the solar magnetic field and some special mechanism which gives rise to moderately large electric fields in the solar atmosphere. The electric fields are not so large that they could be detected by their Stark effect, and it is important to investigate carefully the less direct proofs of their existence. The theory is noncommittal in regard to the origin of the electric fields but the rough agreement between the present calculations and the values given by very simple and not unreasonable postulates are suggestive of some mechanism whereby subatomic transformations result necessarily in the release of negative electricity.