THE ELECTRICAL STATE OF THE SUN

By Ross Gunn
Naval Research Laboratory, Washington, D.C.

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Abstract

The magnetic field due to the rotation of our galaxy is calculated, and it is shown (a) that electricity cannot be annihilated in the sun or stars; (b) that the net electrical charge on the sun or a typical star cannot exceed 1 coulomb. The electric fields, space charge and potentials of the solar atmosphere are calculated from data relating to the solar anomalous rotation and numerical values given. The negative surface charge on the sun is calculated to be of the order of 10^9 e.m.u. The problem of the maintenance of the solar electric field is touched upon.

Systematic observation of the solar surface by Mount Wilson astronomers and others has shown that many solar phenomena are of such a nature that they can be attributed to electrical and magnetic effects. The magnitude and distribution of the solar magnetic field has been determined by a laborious analysis of Zeeman spectra[1] and sufficient data accumulated to show that the solar magnetic field is not unlike that of the earth, save for its radial limitation. In 1915 an attempt was also made by Hale and Babcock[2] to determine the electric fields by measurements of the Stark effect but they could not detect fields smaller than 100 volts per centimeter and were only able to set an upper limit to the suspected electric field. Investigators have generally stated that the electrical fields in the emitting layers of the sun were negligibly small due to the high electrical conductivity and important effects arising from such electric fields were therefore absent. In the following discussion we shall endeavor to indicate the importance of the electric field and give numerical values for the electrical constants of the sun, insofar as they apply to obvious solar problems.

Separation of Charge Inside the Sun

In an important paper A. Pannekoek[3] noted that in any highly ionized gaseous region acted on by gravitational forces and in thermal equilibrium, the lighter ions diffused upward until their separation produced an electric field which opposed further separation. It is readily shown that the volume charge ρ_g expressed in e.m.u., resulting from the separation, is given by

$$\rho_g = \gamma d\mu / c^2 e \tag{1}$$

where γ is the gravitational constant, d is the density of the ionized matter,

[1] Hale, Astrophys. Jour. **38**, 31(1913); Hale, Seares, Van Maanen and Ellerman, Astrophys. Jour. **47**, 1 (1918).

[2] Hale and Babcock, Proc. Nat. Acad. **1**, 123 (1915).

[3] A. Pannekoek, Bull. Astro. Inst. Netherlands #19 (1922).

μ the mean mass of the molecules, c the velocity of light, and e the electronic charge expressed in *e.m.u.* Using data appropriate to the sun and Eq. (1) we find that the total positive volume charge inside the sun amounts to 33 e.m.u. or 330 coulombs. In another place we shall show that a negative charge of equal magnitude probably resides on the solar surface.

When the temperature is non-uniform the more mobile ions in a conductor diffuse toward cooler regions and in the equilibrium state, an electrical field is set up which prevents further diffusion. The space charge ρ_t existing when equilibrium has been attained is given (in the one dimensional case) by

$$\rho_t = -\frac{k}{8\pi c^2 e}\frac{d^2T}{dr^2} \tag{2}$$

where k is the Boltzmann constant, r the space coordinate and T the absolute temperature. Application to the interior of the sun at the present time will not be attempted for little is known about the internal solar temperature. If we follow the star models considered by Eddington[4] the temperatures are so related to gravitational forces that the space charge due to non-uniform temperatures will be of the same order of magnitude as the space charge due to gravitational forces. If, on the other hand, we should adopt Milne's[5] star model which suggests central temperatures of the order of 10^{11} degrees, it is evident that the interior space charge is likely to be large.

Annihilation of Electricity

Attempts to account for the earth's atmospheric electric current have led several writers to assume that electricity is annihilated at some definite but slow rate. Simpson[6] suggested that electricity might be generated spontaneously while Swann[7] assumed that positive electricity died constantly inside the earth but neither writer suggested where the required energy for the transformation might originate. Anderson[8] supplied the theoretical deficiency and assumed that the loss of the protonic mass supplied the necessary energy to annihilate the protonic charge. Thus he postulated a subatomic transformation in which the mass of one proton vanished for each protonic charge annihilated. Evidently if the energy corresponding to a given transformation is known then the lost mass and electrical charge can be immediately calculated. Anderson's calculations indicated that the sun was throwing off negative electricity at a rate of 4×10^{16} e.m.u. per second. This tremendous negative charge was assumed to dissipate itself through all space and finally be lost. In many respects Anderson's hypothesis is interesting in spite of the objections which will occur to the atomic physicist. We proceed to show, however, that in stars the annihilation of electricity is not probable unless the released ions leave our universe in a highly specialized and improbable manner.

[4] Eddington, Internal Constitution of the Stars (1926).
[5] E. A. Milne, Monthly Notices **91,** 4 (1930).
[6] C. G. Simpson, Monthly Weather Rev. **44,** 121 (1916).
[7] Swann, Jour. Franklin Inst. **201,** 143 (1926).
[8] W. Anderson, Zeits. f. Physik **42,** 475 (1927).

The system of stars embraced by the Milky Way stretches far out into space and forms our galactic system. The motions of the stars in this system, their masses, radiation, numbers and distribution are known and if electrical charges are constantly given off by each member of the galactic system, observable magnetic effects should be measured on the earth. We will assume that when ions are thrown off by a star the ion preserves its angular momentum about the gravitational center of the galaxy as it finds its way to outer space. Thus the systematic motion of the stars about the center of the galactic system is shared by the electricity which has been thrown off by them.

The systematic motion constitutes an electrical convention current and will produce a magnetic field. In the present connection we need only the order of magnitude of the effect and a rough calculation which directs attention to the physics of the problem will readily serve. Let us suppose that the entire negative charge in the space outside the stars but inside the galaxy, is compressed into a ring of radius equal to the mean radius of the system. Then the magnetic field H at the center of the system is

$$H = 2\pi Q\omega \tag{3}$$

where Q is the total free charge and ω is the mean angular velocity about the center of the system. The earth is not at the center of the system but it is difficult to see how its position and motion could change the value of the magnetic field at the earth by more than an order of magnitude.

The angular motion of our galaxy is known from astronomical data and Q is determined by calculating from the total radiation of the galactic system, the rate of release of negative electricity. We must note further that the time the released electricity remains in the system proper must be at least as great as the time it would take light to traverse the path. Thus

$$Q \geqq Ir/c \tag{4}$$

where I is the total current thrown off by all stars of the galaxy as calculated by Anderson's hypothesis, r is the mean radius of the galactic system and c the velocity of light. The mean star of the galaxy has a mass 1.6 that of the sun and there are roughly 10^{10} of them,[9] so that we may assume that the total current I of the system is 10^{10} that of the sun or 10^{26} e.m.u.[10] Taking $r = 10^3$ parsecs, $\omega = 10^{-13}$ rad/sec and combining Eq. (4) with Eq. (3) we find that the magnetic field at the center of the galaxy is of the order of 10^{25} gauss.

Such a large magnetic field seems absurd and we conclude that observation demands either that the charges which leave a star, leave in a very special manner, or else that annihilation of positive charge in stars does not occur. The evidence is such that we believe Anderson's and other similar hypotheses must be abandoned.

Net Solar Charge

An upper limit may be set for the net charge which the sun may carry if we are willing to assume that the sun is a star typical of the average star of

[9] Russell, Dugan and Stewart, Astronomy (1927).

[10] R. Gunn, Phys. Rev. **32,** 133 (1928).

our galaxy. Magneticians have been collecting precise data on the variations of terrestrial magnetism for a great many years but there is no evidence of which we are aware that suggests that there may be an extra-terrestrial magnetic field which would be observed to have a period of a siderial day. Certainly such a field would have been found if it was as great as 10^{-3} gauss and probably a field much smaller would be noticed. We may then assume that if a galactic magnetic field exists its value H is probably less than 10^{-3} gauss.

If the stars of our galaxy (of which the sun is typical) carry free electrical charges, then certainly their ordered motion in our galaxy will give rise to a magnetic field. In Eq. (3) we substitute for Q the product of the total number of stars n, by q the mean charge on each, and write the inequality

$$q \leqq H/2\pi\omega n. \tag{5}$$

Substituting the appropriate numerical values in Eq. (5) we find that the mean charge on each star of our galaxy cannot be greater than 0.1 e.m.u. or one coulomb. In the present case there is no question regarding the motion of the charges for they are attached to the stars. When we reflect that the total surface charge of the earth is of the order 10^5 coulombs we see that stars are neutral to a high degree of approximation. We note in passing that measurements show the earth is probably neutral as a whole. These considerations lead us to assume that the sun as a whole is electrically neutral.

Solar Atmospheric Electricity

The highly ionized regions of the solar surface which can be observed are known to be regions of low pressure and the ion free paths are therefore very long. An early paper[11] showed that when ions execute long free paths in crossed electric and magnetic fields, ions of both kinds were swept in a direction perpendicular to both the electric and magnetic fields with a velocity which depended only on the relative magnitude of the crossed fields. This effect is of the nature of a mass motion and is of great importance because it connects directly the easily observable mechanical motions of an ionized region with the magnitudes of the impressed electric and magnetic fields. In a series of papers[11] the above electromechanical effect was shown to account quantitatively for the observed anomalous solar rotation, if the sun possessed an atmospheric electric field which was strikingly similar to the field observed on the earth.

The superposed drift velocity $\boldsymbol{u}$ of an ionized atmosphere is given by

$$\boldsymbol{u} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2[1 + (R/\lambda)^2]} \tag{6}$$

where $\boldsymbol{E}$ and $\boldsymbol{B}$ are the electric and magnetic fields respectively, R the radius of the spiral generated by an ion as it is constrained to move about the impressed magnetic fields and λ is the mean free path. We calculate R from

[11] R. Gunn, Phys. Rev. **35,** 635 (1930); **36,** 1251 (1930); **37,** 283 (1931).

$$R = \frac{mv^1}{Be} = \frac{(2mkT)^{1/2}}{Be} \tag{7}$$

where m is the mass of the ion, v^1 the component of its velocity perpendicular to the magnetic field B, and e the ionic charge in e.m.u. In the atmospheric levels of the sun which we can see, λ is large compared to R and if we agree for simplicity to consider only the motions at the solar equator, Eq. (6) takes the simpler scalar form.

$$E = Bu \tag{8}$$

where E is now the radially inward electric field, B the northward magnetic field and u the eastward atmospheric ion drift measured with reference to the surface of the sun proper. The eastward superposed drift u is readily determined from

$$u = u_0 - a\omega \sin \phi \tag{9}$$

where u_0 is the measured velocity of the observed point whose colatitude is ϕ, a is the solar radius and ω is the angular velocity calculated from the rotation of the sun's magnetic pole. The magnetic field B can be measured directly by the Zeeman effect, so that E can always be calculated for all observed levels. The drift velocity u is known to change with altitude, solar activity and to be subject to large local fluctuations. As we have seen elsewhere[11] the fluctuations are probably due to variations in E rather than B.

In a typical region of the reversing layer the magnetic field is observed to be 25 gauss and the difference of velocity of the surface proper and that actually measured or u is 5×10^4 cm/sec. By aid of Eq. (8) we find the electric field in this region is 0.013 volts/cm. Similarly where the magnetic field is 55 gauss the electric field is 0.027 volts/cm. Now the difference in altitude between these two points is roughly 8×10^6 cm, according to Mt. Wilson data, and we can estimate the volume charge by a one dimensional Poisson's equation. Thus

$$\rho_a = -\frac{u}{4\pi c^2}\frac{dB}{dr} \tag{10}$$

where ρ_a is the atmospheric volume charge in e.m.u. and the other quantities are those defined before. From Eq. (10) and the foregoing observational data we find that over a small interval the space charge in the solar reversing layer is $+1.66 \times 10^{-23}$ e.m.u./cm^3 or on the average there is one singly charged free positive ion per liter.

The space charge increases rapidly as we go deeper and deeper into the sun and if the magnetic field and drift velocity were known at all levels the surface charge and total atmospheric charge could be determined. The solar astronomical data giving the intensity of the magnetic field as a function of the altitude are not very reliable on account of the difficulties of measurement and there is even sharp disagreement as to the scale of altitudes in the reversing layer. In an earlier paper[11] a semi-empirical relation was employed to represent the magnetic field as a function of altitude and the constants so chosen as to fit observation over a limited range. Precise analysis requires appeal to direct observational data for it is unlikely that the radial distribution of the magnetic field is as simple as our assumed formula indicates. We will assume that the magnetic field at any level in the solar atmosphere is given[11] approximately by

$$B = B_0 \exp\left[-\frac{zHg(r - a)}{2kT} \right] \tag{11}$$

where B_0 is the magnetic field of the sun at the "surface proper," z the mean atomic weight of the atmospheric ions, g the acceleration due to gravity, H the mass of the hydrogen atom and $(r-a)$ the altitude above the sun. Relation (10) becomes by aid of Eq. (11)

$$\rho_a = \frac{uzHgB}{8\pi c^2 kT} \tag{12}$$

so that the total atmospheric volume charge in a prism 1 cm² in cross-section is given by

$$\int_a^\infty \rho_a dr = uB_0/4\pi c^2 \tag{13}$$

and since on the whole the sun is neutral and there is no external electric field it follows that the surface charge on the sun proper is equal and opposite to the positive space charge. Following earlier work[12] we use 12,000 gauss for B_0 and calculate the total positive charge in a prism 1 cm² extending from the sun outward and get $+5.3\times 10^{-14}$ e.m.u. The surface charge is equal and opposite. The total negative surface charge of the sun is therefore 3×10^9 e.m.u.

We can use Eq. (11) to determine the potential difference between the surface proper and free space if we combine it with Eq. (8) and integrate.[11] Let ϕ_1 be the potential difference, then

$$-\phi_1 = \int_a^\infty E dr = u\int_a^\infty B dr \tag{14}$$

which by aid of Eq. (10) becomes

$$\phi_1 = \frac{2uB_1 kT}{zHg} \tag{15}$$

where B_1 corresponds to a level where the atmospheric electrical conductivity begins to drop off rapidly due to the solar magnetic field[11,12] and it amounts to about 280 gauss.[11] Substitution of the approximate values in Eq. (15) shows that the sun proper is negative with respect to free space by 1.5×10^6 volts. The foregoing values, calculated by aid of semi-empirical formula cannot be expected to be precise for we have made the assumption that the equatorial

[12] R. Gunn, Phys. Rev. **33**, 614 (1929); **34**, 1621 (1929).

drift velocity was the same constant at all altitudes. In the region of the reversing layer where the constants were made to fit the known points the equations are more reliable.

Maintenance of the Solar Electric Field

The electrical conductivity of the solar atmosphere is high even in the reversing layer where the magnetic field greatly reduces the mobility of the ions.[10] It is readily shown that the solar atmosphere would discharge itself in 10^{-10} seconds if no mechanism was provided to maintain the current. We are therefore faced with precisely the same problem that has puzzled physicists for years in connection with the earth's electric charge. As in the case of the earth we may now assert that the sun is neutral to a high degree of approximation and we may further maintain that electricity does not continuously leave the sun. These restrictions narrow down the investigation to fairly definite problems and several have been examined keeping always in mind that the mechanism of replenishment should also be capable of modification to fit the earth. Even though the mechanism in the sun must be quite simple compared to that on the earth, no definite conclusion has been reached. The extreme variability of the electric field as indicated by the atmospheric motions suggest that local conditions may affect the field greatly somewhat in the manner that an electrical storm disturbs the earth's local electrical state. Young[13] had the idea long ago that the solar atmosphere "rained" condensed metallic particles and brought charges down with them. While the idea is tempting because of present ideas regarding the maintenance of the earth's charge it has several weak points and cannot be made quantitative. It has been shown[11] that the electrical energy dissipated in the solar atmosphere is an appreciable fraction of the total radiated energy and any mechanism which will account for the field must be a moderately efficient one.

Conclusion

Our study has shown that the rather artificial postulate of the annihilation of charge is inconsistent with observation and that to a high degree of approximation the sun is electrically neutral. Our calculations show that the separation of charge in the solar atmosphere is considerable and that the resulting distribution of electric field is remarkably similar to that observed on the earth. In a typical equatorial region of the reversing layer the electric field is radially inward and amounts to 0.015 volts/cm, a value far too small to be detected by measurements of the Stark effect. In the present paper the fields have been calculated from data derived from the observed solar atmospheric motions. In a forthcoming paper the electric fields will be calculated from certain spectroscopic data and the values obtained shown to be consistent with the present estimates.

[13] Young, The Sun.