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Abstract

Full Text

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VARIABILITY OF THE MAGNETIC FIELD AND “HEATING” OF THE SOLAR ATMOSPHERE

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The question of the causes of the high temperature of the solar corona ($T_e \approx 10^6$ °K) remains controversial to this day. The investigations and calculations we have carried out confirm the idea, first expressed by I. S. Shklovskii ([1]), of the heating of the corona by vortex electric fields arising as a result of the variability of the Sun’ s magnetic fields.

1. A comparison of many observational facts leads to the conclusion that all phenomena of solar and coronal activity are in one way or another connected with magnetic fields. H. D. Babcock and H. W. Babcock ([2,3]) definitively proved the existence of a general magnetic field of the Sun, of dipole character, at latitudes greater than $\pm 55°$, and also studied, in first approximation, the character of local magnetic fields ($H \approx$ 1-20 gauss) at lower latitudes. All magnetic fields of the Sun are apparently variable. It follows from observations that, on the average, the decay time of a magnetic field Δt is proportional to the size of the field l and decreases with increasing field strength H, i.e.

$$\Delta t \sim l/H. \tag{1}$$

The dipole general magnetic field, in all probability, is also variable, but because of its extent ($l \sim R$) and small strength ($H_p \approx$ 1-5 gauss) it possesses the largest of the observed values of the decay time.

The following facts, in our opinion, confirm this conclusion:

a) The alternation of the magnetic polarity of spots and, apparently, of all local fields over the 22-year cycle of solar activity, as well as many other properties of spots, are most naturally explained by a change in the polarity of the general magnetic field over a period coinciding with the solar cyclicity.

b) The study of the structure of the corona from eclipse observations has long given grounds for the assumption of the existence of a general magnetic field and of its variable character. If the magnetic field of the corona is regarded as the sum of general and local magnetic fields (formed by coronal rays), then the “minimum” and “maximum” forms of the corona discovered by A. P. Ganskiy ([4]) are easily identified, respectively, with

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the maximum and minimum general magnetic field. A change of polarity may occur at the epoch of maximum solar activity. Such a possibility was indicated by S. K. Vsekhsvyatskiy ([5,6]) and G. M. Nikol' skiy ([6,7]) on the basis of a study of changes in the structural forms of the corona.

c) Direct determinations of the general magnetic field of the Sun by Hale et al., H. D. Babcock, Tissot, Kluiber, and others ([2]), carried out at different times, do not, within the limits of measurement errors, contradict the supposition stated in b).

d) The results of H. W. Babcock's study of stellar magnetism indicate that the variability of "magnetic"stars is not an exception but, most likely, a general regularity. From the published materials ([2]) it follows that the period of variability P generally decreases with increasing mean field strength at the surface of the star H_p. This conclusion agrees with expression (1) for solar magnetic fields.

2. The energy of the star' s variable magnetic field is expended as Joule heat or is carried to the surface by magnetohydrodynamic waves. To estimate the possible energy losses, on the basis of a number of considerations the value of the mean energy of the star' s magnetic field $\mathcal{E}^M$ was found,

$$\mathcal{E}^M = \int \frac{H^2}{8\pi}\, d\tau, \qquad d\tau\text{—volume element.} \tag{2}$$

a) From H. Alfvén' s model ([8]) of a dipole field (with magnetic moment $a = \frac{1}{2}H^3_{pR}$), in the case of a star with a homogeneous convective core of radius R_1, it was obtained that

$$\mathcal{E}^M = a^2/R_1^3. \tag{3}$$

For the Sun, $a \approx 7 \cdot 10^{32}$ gauss $\cdot$ cm^3 ([3]), $R_1 = 0.05R_\odot = 3.5 \cdot 10^9$ cm ([16]), and $\mathcal{E}^M_\odot \approx 10^{37}$ erg. For the star HD 153882, $H_p = 4250$ gauss ([2]), the radii R and $R_1 = 0.2R$ were taken as mean values for stars of spectral class A0 ([15]). Thus $R \approx 2.3R_\odot$ and $\mathcal{E}^M_{\text{HD}} \approx 10^{43}$ erg. The maximum field strengths inside the star ($H_{\max} = 2aR_1^{-3}$) are $3 \cdot 10^4$ gauss for the Sun, and $5 \cdot 10^5$ gauss for the star HD 153882.

b) The works of Sweet ([9]), Chandrasekhar ([10]), Batchelor ([11,12]), Pikelner ([13]), Kipper ([14]), and others have shown that in a fully ionized medium possessing turbulence and even the most insignificant initial magnetic field, amplification of the magnetic field ("winding up" of the lines of force) will occur until the specific kinetic energy of the eddies and the magnetic energy are completely equalized:

$$\rho v_t^2/2 = H^2/8\pi \tag{4}$$

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(v_t—turbulent velocity, ρ—density). The process may be periodic in character, determined by the rate of energy influx from turbulent eddies, by the braking of magnetic energy into Joule losses, which in turn depend on the physical state of the medium (turbulent viscosity, etc.).

To estimate the mean energy, we shall proceed from (4), which for the whole volume leads to the expression

$$\mathcal{E}^M \approx \frac{M\overline{v_t^2}}{2}. \tag{5}$$

Here M is the mass of the star, $\overline{v_t}$ is the turbulent velocity averaged over the whole volume. The values of turbulent velocities inside stars are as yet unknown. To create a magnetic-field energy $\mathcal{E}^M_\odot \approx 10^{37}$ erg, only $v_t \approx 10^2$ cm/sec is required. Such a value of the turbulent velocity inside the Sun cannot give rise to particular objections. Assuming that the density of turbulent energy does not decrease with depth, from the known turbulent velocities at the surface of the Sun $v_{t,p} \approx 10^5$–10^6 cm/sec we obtain, according to (5), $\mathcal{E}^M_\odot \gtrsim 3 \cdot 10^{35}$–$3 \cdot 10^{37}$ erg. For the star HD 153882 (taking $v_{t,p} \approx 10^7$ cm/sec as the mean for stars of class A0 ([15])) $\mathcal{E}^M_{\mathrm{HD}} \gtrsim 10^{39}$–$10^{40}$ erg.

Since between the rotational velocities of stars and the turbulent velocities at the surface there evidently exists a linear relation, from (5) the proportionality noted by many investigators between the magnetic and rotational moments of stars becomes clear.

c) The velocity of magnetohydrodynamic waves is equal to $V = H/\sqrt{4\pi\rho}$. From (2) we find

$$\mathcal{E}^M = M\overline{V}^2/2; \tag{6}$$

$\overline{V}$ is averaged over the whole volume. The period P of variability of the magnetic field

depends on the velocity of the magnetohydrodynamic waves responsible for the variability. To order of magnitude it may be assumed that $P \approx R/\overline{V}$ and

$$\mathcal{E}^M \approx \frac{1}{2}MR^2/P^2. \tag{7}$$

For the Sun, $P \approx 22$ yr and, consequently, $\mathcal{E}^M_\odot \approx 10^{37}$ erg. For the star HD 153882, $P \approx 6^{d(2)}$ (M and R are again taken from the mean values for class A0 ([15])), $M \approx 3M_\odot$, and $\mathcal{E}^M_{\mathrm{HD}} \approx 10^{44}$ erg.

For the Sun all the estimates give values quite close to $\mathcal{E}^M_\odot \approx 10^{37}$ erg; for the star HD 153882, because averaged values of R, R_1, and M are used, the agreement is poorer.

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Let us estimate the damping time of the general magnetic field, i.e., $\Delta t = \mathcal{E}^M/D$, where D is the amount of magnetic-field energy dissipated per second. Using the expression for D found by A. Ya. Kipper (14), (4,7), after substituting the value of $\mathcal{E}^M$ from (7), we find

$$D \approx 2M\overline{V}^3/R. \tag{8}$$

Thus, $\Delta t \approx \frac{1}{4}R/\overline{V} \approx \frac{1}{4}P$, which is physically quite plausible.

3. Obviously, not all the energy of the magnetic field "damps" inside the star; part of it is carried to the surface. Since the energy losses of the solar corona are estimated as 10^{28} erg/sec, then, provided that 1/10 of $\mathcal{E}^M_\odot$ is damped in the Sun' s atmosphere, the energy balance of the corona will be ensured. The dissipation of magnetic energy in an ionized gas has been considered by a number of investigators (1,17–19), etc. The amount of magnetic-field energy ε converted into Joule heat in 1 cm^3 in 1 sec,

$$\varepsilon = \sigma_\perp E^2 \tag{9}$$

(where $\sigma_\perp$ is the electrical conductivity in the direction perpendicular to the magnetic field, and E is the electric-field strength), is determined from Maxwell' s equation $\operatorname{rot} \overline{E} = -\frac{1}{c}\frac{\partial H}{\partial t}$ and is approximately equal to

$$E \approx -\frac{1}{c}\frac{\Delta H}{\Delta t} \cdot \frac{l}{4}; \tag{10}$$

l is the size of the region occupied by the varying magnetic field.

Consideration of the damping time Δt of various magnetic fields (using (1)) leads to an average value $l/\Delta t \approx 10^5$ cm/sec, which is comparable with the velocity of magnetohydrodynamic waves at the surface of the Sun. Taking a rather low value for the change in field strength, $\Delta H \approx 1$ gauss, we obtain for chromospheric conditions a value of the electric-field strength $E \geq 10^{-7}$ CGSE. Such a value is confirmed by several methods.

The processes of electrical conductivity in the direction perpendicular to the magnetic field have been sufficiently studied only for a completely ionized gas. The presence of neutral atoms in the plasma substantially changes the course of the electrical-conductivity processes. The electrical conductivity may increase by several orders of magnitude in comparison with a completely ionized gas at the same electron densities and temperatures.

For the general case the electrical-conductivity processes were considered by Cowling and Piddington. Using the equation (25) derived by Cowling (19), we obtained

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$$\sigma_\perp = \frac{n_e e}{H} \frac{(KK_i + F^2)K_i}{(KK_i + F^2)^2 + K_i^2}; \tag{11}$$

here

$$K = \frac{8n_e r_{ie}^2}{3eH} \left\{ \frac{2\pi kT m_i m_e}{m_i + m_e} \right\}^{1/2}; \qquad K_i = \frac{8n_a r_{ai}^2}{3eH} \left\{ \frac{2\pi kT m_a m_i}{m_a + m_i} \right\}^{1/2},$$

where the indices i, e, a denote quantities referring, respectively, to the ion, the electron, and the neutral atom; F is the relative specific density of neutral atoms; r_{ie} and r_{ai} are the effective radii of collision of the corresponding particles; the remaining notation is standard. (Because of the smallness of r_{ae} for collisions of an electron with a neutral atom and the small mass of the electron in comparison with the mass of the atom, the quantity K_e was neglected in deriving formula (11).)

We have carried out an investigation of the coefficient $\sigma_\perp$ for the conditions of the solar chromosphere and corona (in (15) averaged data were taken for the distribution of densities, temperatures, etc.). Because of the great uncertainty of the function $H(R)$ and the approximate character of many quantities, the numerical data obtained can be used only for approximate calculations. Thus for the inner corona one obtains $\sigma_\perp \simeq 10^8$ CGSE, and in the chromosphere $\sigma_\perp \simeq 3 \cdot 10^{10}$ CGSE. Estimates of the energy received by a column (with cross section 1 cm^2) of coronal and chromospheric matter from the varying general magnetic field of the Sun give

$$\int \varepsilon \, dl \simeq 10^5 \text{ erg/cm}^2 \cdot \text{sec},$$

which agrees with the energy losses in coronal matter (1).

The electrical conductivity reaches a maximum in the upper chromosphere and then decreases sharply as $F \to 0$. This can explain the existence of a sharp boundary between the chromosphere and the corona. A partially ionized gas as it were "burns out" in the presence of a variable magnetic field, turning into a highly heated coronal gas. The close coexistence and mutual penetration of relatively cold chromospheric and hot coronal matter, the close connection of the regions of emission of the "yellow" coronal line λ5694 (Ca XV, $P_i = 814$ eV) with prominences and active regions of the chromosphere, find their natural explanation. The boundaries of prominences must be regarded as regions of the most intense "heating" and transformation of chromospheric matter into coronal matter or, conversely, when a steady magnetic field penetrates into the corona, as regions of cooling and condensation of coronal matter into chromospheric matter.

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