GENERATION OF MAGNETIC FIELDS AND ELECTRIC CURRENTS IN THE SOLAR PHOTOSPHERE

J.C.HENOUX* and B.V.SOMOV◇
⋆ *Observatoire de Paris, DASOP, URA326,*
92195 Meudon Principal, FRANCE,
◇ *Lebedev Physical Institut, Leninskii Prospect 53,*
SU-117924 Moscou USSR

ABSTRACT. Velocities of electrons, ions and neutrals are computed in the three-fluid approximation for an axisymmetrical magnetic field. By prescribing a radial dependence of the velocity of neutrals in agreement with a downflow, the radial dependence of the magnetic field energy density is derived for a given set of values of the magnetic field at the central and external boundaries. Flux-tube cooling by advection of ionization energy is found to be significant. Vortices in the low photosphere could produce significant electric power and DC current intensity along the coronal magnetic lines of forces. The velocities of neutrals, the size and the number of flux-tubes required to power flares in plage regions, are estimated.

1. Introduction

Some authors suggested that sunspots and active regions could be superficial phenomena originating in the photosphere and at the top of the convective zone (Bumba (1987a,b), Akasofu (1984a,b,c). Inward and downward motions below the photosphere have been considered as a mean of cooling and powering the sunspot dynamics by Schatten and Mayr (1985). Ambroz (1987) found that Active Regions are formed in places where the global circulation display vorticity. And Martres et al. (1973) related sunspot formation and disappearance to the direction of rotation of the vortices. As shown below, ambipolar diffusion in the weakly ionized photosphere creates electric DC currents and the kinetic energy of the neutral component could be converted into electrical and magnetic energy as long as convection maintains the flow (Spicer, 1982).

2. Particles velocities in an axisymetric magnetic field

Assuming steady state, the balance of the forces that act per unit volume on particules k of charge q_k is expressed as

$$n_k m_k \mathbf{V}_k.\nabla\mathbf{V}_k = n_k \sum_l \mathbf{F}_{l,k} + q_k n_k(\mathbf{E} + \mathbf{V}_k \wedge \mathbf{B}) - \nabla P_k + n_k m_k \mathbf{g}. \tag{1}$$

$\mathbf{F}_{l,k}$ is the friction force acting on particule k due to particules l, and $\mathbf{F}_{l,k} = m_k \nu_{kl}(\mathbf{V}_l - \mathbf{V}_k)$. $\mathbf{B}$ and $\mathbf{E}$ are the magnetic and electric field vectors. $\mathbf{V}_k$, n_k and m_k are the velocity, density and mass of particle k. ν_{kl} is the coefficient of

J. O. Stenflo (ed.), Solar Photosphere: Structure, Convection, and Magnetic Fields, 273–277.

friction between particles $k$and l. In the case where one of the species is a neutral atom the subscript n is omitted in the friction coefficient. A velocity field $\mathbf{V}^c$ in the convective zone can create by continuity an electric field $\mathbf{E}$ in the photosphere (Hénoux and Somov, 1987). Assuming the magnetic field to be vertical in the convective zone, the electric field and plasma velocity in the convective zone are related by $\mathbf{E} = -\mathbf{V}^c \wedge \mathbf{B}$.

Restraining equation (1) to the horizontal components of the forces and using the relation between the velocity in the convection zone and the electric field we write

$$n_k \sum_l \mathbf{F}_{l,k} - q_k n_k(\mathbf{V}_k - \mathbf{V}^c) \wedge \mathbf{B_z} = -\nabla P_k - n_k m_k \mathbf{V}_k.\nabla \mathbf{V}_k + q_k n_k \mathbf{V}_{\mathbf{z},k} \wedge \mathbf{B}, \quad (2)$$

Equation (2) leads to a system of 6 linear equations that can be solved for the radial and azimuthal components of the velocities of ions, electrons, and neutrals refered by the subscripts r and θ. These components can be expressed as a function of V_θ^c, V_r^c, $V_{z,e}$, $V_{z,i}$, the radial pressure gradients and the radial and azimuthal components of the inertial term $n_k m_k \mathbf{V}_k.\nabla \mathbf{V}_k$. Formulæ are given in Hénoux and Somov (1988,1989). In what follows, we kept in the inertial terms only the dominant contribution of neutrals and assumed $B_r = 0$. Derived from the expression of the ion and electron velocities, the azimuthal and radial current densities are

$$j_\theta = (j_z B_\theta + \frac{\partial P_n^\star}{\partial r})/B_z \quad (3)$$

$$j_r = -\frac{1}{B_z} n_n m_n \frac{V_{r,n}}{r} \frac{\partial r V_{\theta,n}}{\partial r}, \quad (4)$$

where j_z is the vertical current density and $P_n^\star$ is defined by

$$P_n^\star = P_n + \frac{1}{2} n_n m_n V_{r,n}^2 - \frac{1}{r} V_{\theta,n}^2. \quad (5)$$

Assuming that $V_r^c = 0$, the radial velocities of neutrals and ions can be written as

$$V_{r,i} = -\frac{j_\theta B_z}{\sigma B_z^2} + I_{r,i} = \frac{1}{2\mu\sigma B_z^2} \frac{\partial B_z^2}{\partial r} + I_{r,i}, \quad (6)$$

$$V_{r,n} = V_{r,i} - \frac{1}{\alpha_s} \frac{\partial P_n^\star}{\partial r}. \quad (7)$$

Here σ is the electric conductivity parallel to B, $\alpha_s = n_e(m_i \nu_i + m_e \nu_e)$ and

$$I_{r,i} \simeq -\frac{n_n m_n}{n_e e B_z} \frac{V_{r,n}}{r} \frac{\partial r V_{\theta,n}}{\partial r}. \quad (8)$$

In equation (3) $j_z B_\theta \geq 0$ and a positive pressure gradient always generate an azimuthal current and a radial magnetic field gradient. The azimuthal current is associated with a radial motion of ions, and with the neutrals moving inwards relatively to ions. Equation (4) shows that the loss of angular momentum of neutrals leads to the circulation of radial currents. These radial currents would generate

https://doi.org/10.1017/S0074180900044235 Published online by Cambridge University Press

vertical currents. It is outside the scope of this paper to compute self consistently the radial dependence of the angular momentum. From the expression of $V_{\theta,n}$ it can be shown that, except for constant B, $\partial r V_{\theta,n}/\partial r = 0$ is not a solution . We shall just assume that $rV_{\theta,n}$ decreases to zero inside the flux-tube radius. In the next section we relate the velocity of neutrals to the magnetic field gradient and to the creation of strong magnetic fields from a preexisting weak field. Then we study how vortices can lead to the circulation of radial and vertical electric currents.

3. Magnetic field concentration

From Ampère law and equation (3) we derive:

$$\frac{\partial P_n^\star}{\partial r} = -(\frac{1}{2\mu}\frac{\partial B^2}{\partial r} + j_z B_\theta) \tag{9}$$

Defining c_α as $j_z B_\theta/(\partial P/\partial r)$ and using (6), (7), (8) and (9) we obtain

$$V_{r,n}[1 + \frac{\rho_{n,i}}{x\omega_i}\frac{1}{r}\frac{\partial r V_{\theta,n}}{\partial r}] = \frac{1}{2\mu}(\frac{1}{\sigma}\frac{\partial Log B_z^2}{\partial r} + \frac{1}{\alpha_s(1+c_\alpha)}\frac{\partial B_z^2}{\partial r}), \tag{10}$$

where ω_i is the ion gyrofrequency, $\rho_{n,i} = m_n/m_i$ and $x = n_e/n_n$. By prescribing the radial dependence of the velocity field of neutrals, the radial dependence of the magnetic field can be derived. We assumed that, at $r \leq r_0$, $V_{r,n} = V_0 r/r_0$. This, together with the requirement of mass conservation ($div \rho V = 0$), imply a downflow inside the cylinder of radius r_0 with a velocity $V_{z,n} = 2V_0/r_0 H(1 - e^{z/H})$ $(z \leq 0)$. The radial dependence of the magnetic field inside the flux-tube is given by:

$$\mu V_{r,n} r[1+\varepsilon] = \frac{1}{\sigma}Log[\frac{B^2(r)}{B^2(0)}] + \frac{1}{\alpha_s(1+c_\alpha)}[B^2(r) - B^2(0)], \tag{11}$$

where $\varepsilon = 2\Omega/x\omega_i$ and $\Omega = V_{\theta,n}/r$. In practice $\varepsilon \ll 1$. Assuming a magnetic field of 1000 Gauss at the center of the flux-tube and using the values of the conductivity and collisional frequencies computed by Kubat and Karlicky (1986), the radial dependence of B_z in the photosphere, at the optical depth $\tau_{5000} = 1$ can be computed. Defining the radius r_0 of the flux-tube as the radial distance where B = 5 Gauss leads to $V_0 r_0 = 1.2\ 10^5$ m^2 s^{-1}. We must point out that r_0 is more an estimate of the scale-length, for the radial dependence of the magnetic field, than the exact value of the flux-tube radius r_t.

The inward radial flow of neutrals requires the existence of a pressure gradient that can be stabilized or amplified by advection of ionization energy. Assuming $r_t = r_0$, the extra power required to ionize the flux of neutrals falling inside the flux-tube per unit area is

$$\frac{dE}{dt} = \frac{2}{r_0^2}(r_0 V_0) H n \chi, \tag{12}$$

where χ is the ionization potential of Hydrogen and H is the length of the tube in the photosphere. Using the value of $V_0 r_0$ found precedently, assuming $r_0 = 40$ km, $H = 500$ km, $n = 2\,10^{17}$ cm^{-3} we obtain $dE/dt = 2.5\,10^{10}$ ergs cm^{-2} s^{-1} that is about one third of the radiation emittance of the solar surface. Consequently the resulting cooling is important and could maintain a significant pressure gradient.

4. Radial DC electric currents

Assuming no charge accumulation the vertical electric current density j_z is related to the radial current density j_r by $\partial j_z/\partial z = -2j_r/r$. Using equation (4), the integration of this equation over the flux-tube cross-section and height H, leads to the following expression of the total vertical current intensity J_z

$$J_z = J_0 + 4\pi n_n m_n \int_0^{r_t} \int_0^H \frac{V_{r,n}}{B_z\, r} \frac{\partial r V_{\theta,n}}{\partial r} dr\, dz. \tag{13}$$

Assuming $r_t = r_0$ and $V_{r,n} = V_0 r/r_0$ we derive

$$J_z \simeq J_0 + 4\pi \frac{n_n m_n}{B_z} H\, V_{\theta,n}(r = r_t) V_{r,n}(r = r_t). \tag{14}$$

Similar result is obtained by assuming that $r_0 < r_t$ and that $V_{\theta,n}$ goes to zero over a distance $\leq r_0$. Total current intensities from 10^{10} to 10^{11} Amperes are generated for photospheric velocities of 2.10^2 m s^{-1} and 6.10^2 m s^{-1} associated with horizontal magnetic field scale lengths of respectively a km to a few hundred of m (B_z =100 Gauss). However due to the high conductivity of the subphotospheric layers, most of the current shall flow in these layers. Assuming that the flux-tube extends vertically from the corona to the subphotospheric layers the current J_c flowing into the corona is

$$J_c = J_M \frac{R_b}{R_a}, \tag{15}$$

where J_M is the maximum intensity that would flow into the corona in the absence of any subphotospheric shunt and R_a and R_b are respectively the resistances of the flux-tube above and below the photosphere. From Kubat and Karlicky we estimate R_b/R_a to be close to 0.1. This reduces J_c to 10^9 - 10^{10} Amperes.

The azimuthal force acting on neutrals is $F_\theta = -j_r B_z$. The work made by this force per unit of time is $dW/dt = -j_r B_z V_{\theta,n}$. From this expression and from equation (4) the total power that is taken out of the kinetic energy of neutrals in the dynamo region to generate electric currents can be derived and is

$$P_v = -\pi n_n m_n \int_0^{r_t} \int_0^H \frac{V_{r,n}}{r} \frac{\partial (r V_{\theta,n})^2}{\partial r} dr\, dz. \tag{16}$$

The same assumptions as for deriving equation (14) lead to

$$P_v = -\pi n_n m_n H r_t V_{r,n}(r = r_t) V_{\theta,n}^2(r = r_t). \tag{17}$$

Due to the shunt of the subphotospheric layers the power available in the corona P_c is only one tenth of P_v.

The total intensities observed in active regions and the total power required in order to power one powerful flare (10^{24} Joules) per week, in an area of 10^8 km^2 (radius R

$= 5600$ km), are of about 10^{11} Amperes and 10^{18} watts. These values can be reached in plages if many concentrated flux-tubes are present in the flaring area. About 10^6 flux-tubes of cross section ≈ 1 km^2, surrounded by vortices with velocities close to 2. to 5. 10^2 m s^{-1}, are required to give a power of 10^{18} watts. This imply a filling factor of only 10^{-2}. The net total D.C. Current intensity J_c depends of the sign of V_θ and, if there is a net loss of angular momentum over the active region, it could easily be as high as requested. The requirements on the filling factor would be relaxed in quiet sun area.

5. Conclusion

We have shown that, in the hypothesis of axial symmetry, any mechanism that could create a radial pressure gradient, in a region with a low preexisting magnetic field, would increase the magnetic energy density by creating azimuthal currents. By a cooling of the flux-tube by advection of ionisation energy, the initial radial pressure gradient could be increased. This effect may lead to the formation of concentrated magnetic flux-tubes. The annihilation of the kinetic energy of vortices in the low photosphere could produce significant electric power and current intensity in the corona.

6. References

Akasofu, S.I. (1984a) 'Vortical distribution of Sunspots', Planet.Space Sci., Vol.33, No.3, 275

Akasofu, S.I. (1984b) 'Sunspot pair formation by the photospheric dynamo process' Planet.Space Sci., Vol.32, No.10, 1257

Akasofu, S.I. (1984c) 'An essay on Sunspots and Solar Flares', Planet.Space Sci., Vol.32, No.11, 1469

Ambroz, P. (1987) 'The global horizontal circulation on the Sun', Bull. Astron.Inst. Czechosl., 38, 110

Bumba, V. (1987a) 'Magnetic Fields of the Sun and Stars', 10^{th} European Regional Astronomy Meeting of the IAU, The Sun, Vol.1,3(1987)

Bumba, V. (1987b) 'Does the solar dynamo act in Sunspot Groups', 10^{th} European Regional Astronomy Meeting of the IAU, The Sun, Vol.1, 59

Hénoux, J.C. and Somov, B.V. (1987) 'Generation and structure of the electric currents in a flaring activity complex', Astron. & Astrophys., 185, 306

Hénoux, J.C. and Somov, B.V. (1988) 'Electrodynamic conversion of energy: Magnetic field amplification in the solar photosphere' Adv. in Space Res., in press

Hénoux, J.C. and Somov, B.V. (1989), submitted to Astron. & Astrophys.

Kubát, J. and Karlický, M. (1986) 'Electrical conductivity in the solar photosphere and chromosphere, Bull. Astron. Inst. Czechosl., 37, 155

Martres, M.J., Soru-Escaut, I., Rayrole, J. (1973) 'Relationship between some Photospheric Motions and the Evolution of Active Centers', Solar Phys., 32, 365

Schatten, K.H. and Mayr, H.G. (1985) 'On the maintenance of Sunspots: An ion hurricane mechanism', Ap.J., 299, 1051

Spicer, D.S. (1982) 'Magnetic energy storage and conversion in the solar atmosphere', Space Science Reviews, 31, 435