SOLAR PHENOMENA AS MHD MANIFESTATIONS

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Abstract

Nonstatic characteristics are emphasized for plasma in magnetic tubes in different parts of the solar envelope. The subjects discussed here are the role of the magnetic buoyancy on statistical properties of the magnetic field in the convection zone, a photospheric dynamo driven by a horizontal vortex motion, and the siphon action in the MHD flow forming a dark filament.

1. Introduction and Summary

In a recent IAU symposium held in Kyoto, Nariai (1980) conjectured that stellar magnetic configurations could not be in static equilibrium in general. In fact, various spatial and temporal scales associated with mechanical and thermal processes are different with and without magnetic field, and gaseous motions usually occur in realistic situations in which the magnetic field is embedded over many scale heights in nonmagnetic medium. A sunspot is often considered as an example of a quasi-static magnetic structure. However, the Evershed flow in penumbre and an inflow in umbra in the chromospheric level are observed. A large extension above the photosphere seems to prohibit a hydrostatic equilibrium of a spot field. As Semel (1980) has shown in the present seminar, a hydrostatic configuration is not the low velocity limit of a steady flow configuration because of the constraint of the continuity of matter for the steady flow. Therefore, the hydrostatic assumption is not generally justified for the interpretation of quiescent solar phenomena. Three different topics will be discussed in what follows.

The first problem concerns with the formation of magnetic ropes under the influence of magnetic buoyancy. Parker (1975) argued that the magnetic buoyancy could set an extremely serious limit on the solar dynamo. Although it was overestimated in his study (cf. Unno and Ribes 1976, Schüssler 1977), the magnetic buoyancy can still give a limit on the field strength. At least, it can be efficient for forming a rising flux rope distinguishable from fluctuations. The dimensional analysis will be given to describe roughly the state of magnetic flux ropes in the convection zone.

The second problem is on the photospheric dynamo. An empirical law found by Martres, Soru-Escaut, and Rayrole (1973) describing the relation between the time variation of the field strength and the sense of rotation of the horizontal vortex motion depending on magnetic polarity is found to be fullfilled in a number of examples in the solar collaboration observations between Meudon and Mitaka (Martres et al. 1980). This law is here claimed to be the manifestation of the magneto-activity of the photosphere where the fluid motion can reform the magnetic field in significant degree. The third problem concerns with a dark filament. A steady flow model by Ribes and Unno (1980) aimed at the fitting to the observation by Mein (1977). Drastic transitions between the chromospheric state or a dark filament and a very high-speed low density flow of a coronal cavity are regarded as a characteristic feature of the chromosphere-corona region in a siphon composed of magnetic tubes.

Three problems discussed here are different aspects of solar magnetic field in different levels in the solar envelope. A lot of solar phenomena are still left to be unexplained magneto-hydrodynamically, and a lot of theories have to be worked out in order to obtain a complete understanding of the solar magnetic field.

2. Magnetic Ropes in the Convection Zone

The characteristic time scale of the solar cycle, ω_{sc}^{-1} (=2π/period) is determined by the association of the α- and ω-mechanisms (see, Yoshimura in the present seminar), and is about 3.6 years. The maximum possible field strength B_M was predicted by Galloway et al. (1978); $B_M \sim (\nu/\nu_m)^{1/2} B_{eq}$, where ν and ν_m denote the kinematic and magnetic viscosities, and B_{eq} is the equipartition field, $B_{eq}^2 = 4\pi\rho v_c^2$. For turbulent convection, we may take $\nu \sim \nu_m$. Then, the Alfvén velocity v_A corresponding to B_M turns out to be the convective velocity v_c. Remembering that the terminal speed of a buoyant magnetic tube is estimated to be v_A by Parker (1975), we see that the time scale of lifting is about 0.1 year from the depth 10^{10} cm where $v_c \sim 3 \cdot 10^3$ cm. This means that the dynamo wave propagates before B_M is reached by means of convection and that the magnetic buoyancy sets an upper limit to the magnetic field strength in the convection zone.

Let us now suppose that this upper limit of the field strength is realized during the solar cycle. The terminal speed of rise of a flux rope w is $\sim v_A^2/v_c$, if the turbulent viscosity is taken into account (Unno and Ribes 1976). The time of rise for depth D is then given by

$$\tau_b \sim D\, v_c \,/\, v_A^2 \quad . \tag{1}$$

On the other hand, the diffusion time τ_d in turbulent convection is given by

$$\tau_d \sim D^2 / (v_c \ell / 10) \ , \tag{2}$$

where ℓ denotes the mixing length and the numerical factor of 10 takes account of the efficiency of turbulent diffusivities (cf. Nakano et al. 1979). We assume that

$$\tau_b \sim \omega_{sc}{}^{-1} \sim \tau_d \ , \tag{3}$$

where the second approximate equality is necessary for the solar cycle to be completed. Then, we obtain

$$D \sim (10^{-1}\, \omega_{sc}{}^{-1}\, v_c \ell\,)^{1/2} \quad \text{and} \quad v_A \sim 10^{-1/2}(\ell \,/\, D)^{1/2} v_c \ . \tag{4}$$

If typical values are taken at a depth of 10^{10} cm in the convection zone so that $v_c \sim 3 \cdot 10^3$ cm s^{-1}, $\ell \sim 6 \cdot 10^9$ cm, $\rho \sim 5 \cdot 10^{-2}$ g cm^{-3}, then we obtain

$$D \sim 1.4 \times 10^{10} \text{ cm} \quad \text{and} \quad B \sim 500 \text{ G} \ . \tag{5}$$

The approximate agreement of D with the assumed depth 10^{10} cm means that the magnetic buoyancy could be marginally important for the solar cycle.

The conservation of the magnetic energy should also be considered. The decrease of B by rising motion is estimated to be $w|B|/D$. The increase of $|B|$ results from poloidal field stretched by the differential rotation $\Delta\Omega$. Then we have

$$|B_p| \sim |B|\, w \,/\, (D\Delta\Omega) \sim |B| \,/\, (\tau_b \Delta\Omega) \sim 20 \text{ G} \ .$$

Fluctuations must be inherent in the turbulent convection. Then, the increased buoyancy associated with fluctuations of larger field intensity will give rise to the formation of the flux tube. There is also the excess buoyancy due to the thermal inhomogeneity resulting from the differences in the superadiabatic temperature gradient and in the turbulent thermal conductivity in a magnetic tube (Unno and Ribes 1976). The latter thermal effect may be effective for the breaking up of a flux rope into the thickness of the order of a scale height, e.g., $6 \cdot 10^4$ km. The total magnetic flux of an active region would then be $\sim 10^{23}$ M_x. The enhancement of the magnetic intensity of a flux rope can be made in upper convection zone where the Alfvén velocity is fairly large and the hydraulic concentration becomes effective (Parker 1976).

3. Photospheric Dynamo

In the photosphere, ion motions are governed by collision with neutral atoms that are the main constituent of the medium. Electrons, on the other hand, are more tightly bound to the magnetic field. These properties are essential to the photospheric dynamo (Sen and White 1972). Note, however, that the MHD processes in the photosphere are not independent of the situation in the convection zone as emphasized by Heyvaerts (1974) and Kaburaki (1975, 1979).

The polarity-helicity rule of a magnetic vortex (Martres et al. 1973) seems to be a typical representation of the photospheric MHD behavior. The magnetic field changes in time as if an electric current opposite in direction to the vortex motion is increased in the periphery of the magnetic region. Figure 1 shows the electric field E and the current j_r that are considered as common between the photosphere and the convection zone. The interpretation of the law is described elsewhere (Unno, Tanaka, and Semel 1980). The essential point is that electrons move with $v_{\theta,c}$ which is the rotating velocity of a deeper layer in the convection zone, while ions move with v_θ of the photospheric medium.

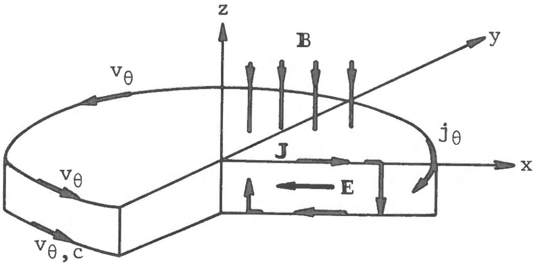

Fig. 1

The empirical law will then be explained by an increase of $(v_{\theta,c}-v_\theta)$ with time. The vortex motion may be brought by a large scale turbulent motion. Then, there will be the difference in time scale of the angular momentum transport between the photosphere and deeper layers. At a phase of large v_θ, the magnetic field is twisted and the torque exerted on the photospheric medium will decrease v_θ more rapidly than $v_{\theta,c}$ statistically.

4. Continuous Flow Forming a Dark Filament

Many MHD phenomena are observed in the chromosphere-corona regions. Flows are present in sunspots, faculae, spicules, moustaches, prominences, coronal arches, etc. Unresolved magnetic structures are discussed by Ribes (1980) and by Semel (1980) in the present seminar. Here, we regard a dark filament as a representative MHD event showing a drastic change in the thermal condition of plasma. Recently, Ribes and Unno (1980) constructed an analytical model of a dark filament and attempted to reproduce Mein's (1977) observational results by the parameter fitting. The model exhibits the physical characteristics similar to the Kippenhahn-Schlüter (1957) model within the filament, except that the matter is continuously replenished. The matter must be suspended by the magnetic field, if the free-fall of several 10^2 km s^{-1} should be avoided. The matter supply is due to a sudden condensation of an extremely rarefied high-speed plasma in the surrounding coronal cavity within a helmet structure. Also, the evaporation of filament matter into the coronal cavity should occur as the reverse process. Such discontinuous transition is controlled by the thermodynamics of the transition layer, and this is a characteristic feature of MHD in the chromosphere-corona region (cf. Leroy in the present seminar).

The model fitting to Mein's (1977) observation shows that the speed of flow should change from 0.2 km s^{-1} at the chromospheric foot point of a magnetic arch to 450 km s^{-1} into the coronal cavity, although uncertainties are involved. Also, the pressure at the foot-point is required to be ten times as high as the normal chromospheric pressure. The problem turns out to be the formation of a coronal cavity composed of a very high-speed low-density plasma. Low lying magnetic configuration (multiple component) may be particularly important, since it would provide high pressure and a geometry necessary for accelerating a Bernoulli flow along a magnetic tube.

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