Vol. 34 No. 11 SCIENCE IN CHINA (Series A) November 1991

THE TANGENTIAL DISCONTINUOUS SURFACE OF VELOCITY IN SOLAR CHROMOSPHERE*

HU WEN-RUI (胡文瑞),
(*Institute of Mechanics, Academia Sinica, Beijing* 100080, *PRC*)

ZHANG HONG-QI (张洪起) AND CHEN JI-MING (陈济民)
(*Beijing Observatory, Academia Sinica, Beijing* 100080, *PRC*)

Received March 2, 1990.

ABSTRACT

The data of velocity and magnetic fields in the solar photosphere (5324 Å) and the chromosphere (4861 Å) clearly show the features of tangential discontinuity of velocity in the chromosphere. The velocity fields in and near the solar active region named No. 88029 by the Huairou Station have been analyzed in detail. A lot of magnetohydrodynamic discontinuous surfaces, especially the tangential discontinuities, are shown from the observations. The calculations of the thickness of discontinuous layer and the evoluiton time of instability agree with the observational results. The variations of the flow field will directly influence the evolutions and changes of the active region as the magnetic field are coupled closely with the plasma motion.

Keywords: solar chromosphere, magnetic field, velocity field.

I. INTRODUCTION

The magnetic field and velocity field in the solar chromosphere exert a serious influence on the mass, momentum and energy transfer, and are closely related to the dynamic processes in the transition region and the corona[1]. The solar chromospheric velocity field is usually classified into three kinds, that is, the steady flow, the quasi-steady flow and transient flow. As for their subsorts[2], several theoretical models have been proposed to explain the features[3].

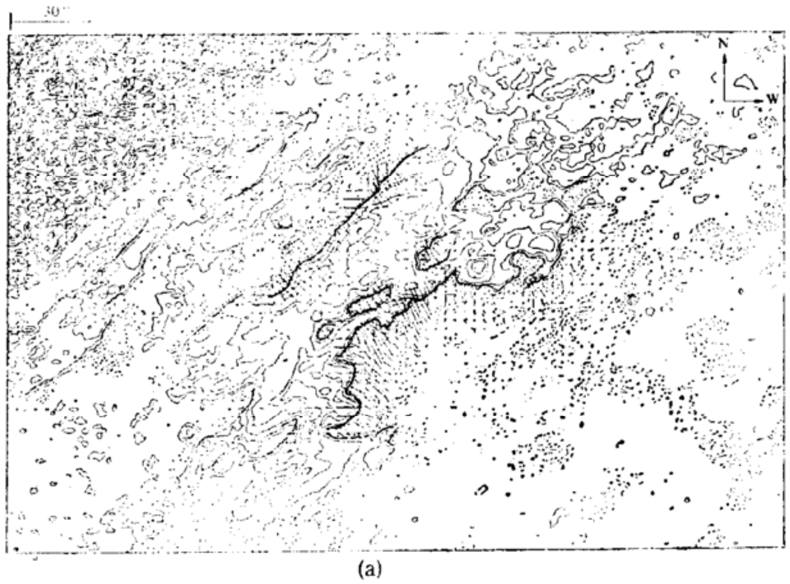
The magnetograph on the ground provided a lot of data on the velocity and magnetic fields in the photosphere[4]. The observations from the skylab and Solar Maximum Mission (SMM) satellite gave the data on the transition region and the lower corona, including the velocity measured by the Doppler measurement. The latter shows the region with a velocity greater than 4 km/s without details. It is difficult to analyze this event because of the lack of magnetic field data.

The magnetograph provided by Beijing Observatory, Academia Sinica, supports the observational data of velocity and magnetic fields at the chromosphere (4861 Å) and photosphere (5324 Å)[5], and helps study the features of mass motion in

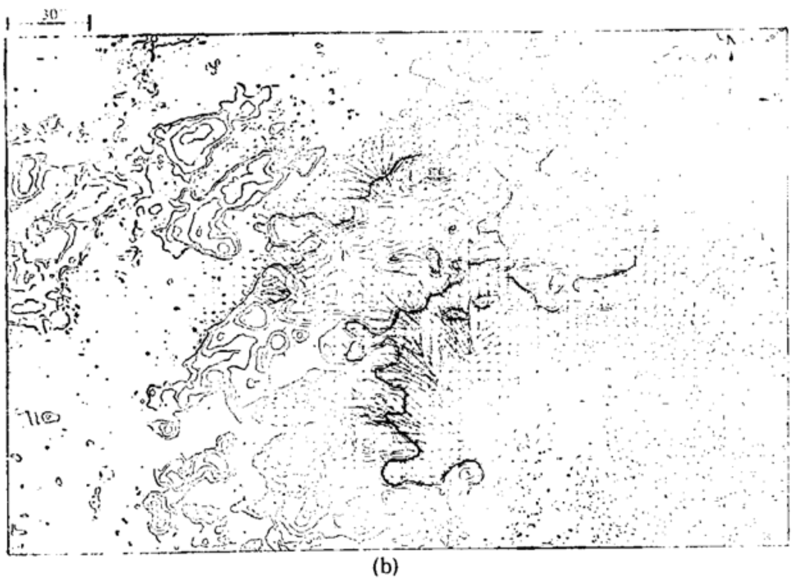
* Project supported by Academia Sinica under contract 87-64.

the chromosphere.

In the present paper, we analyze the active region 88029 named by the Huairou Station, which appeared from the east edge in March, 1988, and was described in detail in Ref [6]. Figs. 1(a), (b), (c) are, respectively, the photospheric magnetic field on March 26, 1988, the photospheric and chromospheric magnetic fields on March 27, 1988. The configurations of chromosperic fields are similar but weaker in strength in comparison with those of the photospheric field. There are clear boundaries of the photospheric fields and a larger gradient of the magnetic field near the boundary of the magnetic flux region, and obviously, the current layer between the reversed magnetic regions. Most of the magnetic fluxes emerge from the northeastern part and sink in the western part of the active region like the configuration of the bipolar region in appearance. The observation of photospheric magnetic field shows that the transverse component of the magnetic field has the same order



(a)



(b)

(c)

Fig. 1. Counters of photospheric and chromospheric magnetic field strength. N- and S-polarities are shown, respectively, by the real and broken lines, and visual fields by circular closed lines give the strength of 40, 80, 160, 320, 640, 960, 1280 and 1600 $\times 10^{-4}$T from outer to inside. The section lines give the value and direction of transverse fields.

(a) The vector photospheric magnetic field (5324 Å) at 0305 UT on March 26, 1988; (b) the vector photospheric magnetic field (5324 Å) at 0126 UT on March 27, 1988; (c) the longitudinal chromospheric magnetic field (4861 Å) at 0315 UT on March 27, 1988.

of magnitude as the longitudinal one, and however, there is lack of observation data on the chromospheric magnetic field. We can determine the angle θ_p between the magnetic field and the view direction by using the photosperic data, and then, consider it as the reference value in the chromosphere θ_{ch}. Figs. 2(a), (b), (c) are, respectively, the observational longitudinal velocities in the chromosphere on March 26, 27 and April 2, 1988. The results show that it is common that the discontinuities of the velocity field exist in the chromospheric mass motion.

II. Tangential Discontinuity of Chromospheric Velocity

The comparison of Figs. 1 with 2 shows that the magnetic field with the N-polarity extends from the southeast over 100″ to the northwest. However, the flow field is mainly downward in the southeastern part denoted by F_{N_1} with an extension of 180″, and the fluid flows mainly upward in the southwestern part denoted by F_{N_2}; the upward flow region F_{S_i} and downward flow region F_{S_j} $(j > i)$ form an interlocking pattern in the magnetic field region with the S-polarity. Fig. 1 gives roughly an arch configuration of the magnetic field from the N- to S-polarities. The fluid flows mainly along the magnetic surface from regions F_{N_2} to F_{S_j} and from F_{S_i} to F_{N_1}. As the regions F_{N_1} and F_{N_2} are larger than the magnetic region of the N-polarity, the fluid in the region which is not overlapped with the magnetic region should not be confined by the magnetic field. The similar case is found in the regions F_{S_i} and F_{S_j}. Therefore, there are many discontinuous surfaces of velocity, mostly tangential discontinuities, in active region 88029. They could be classified by their distributionsin into three catagories.

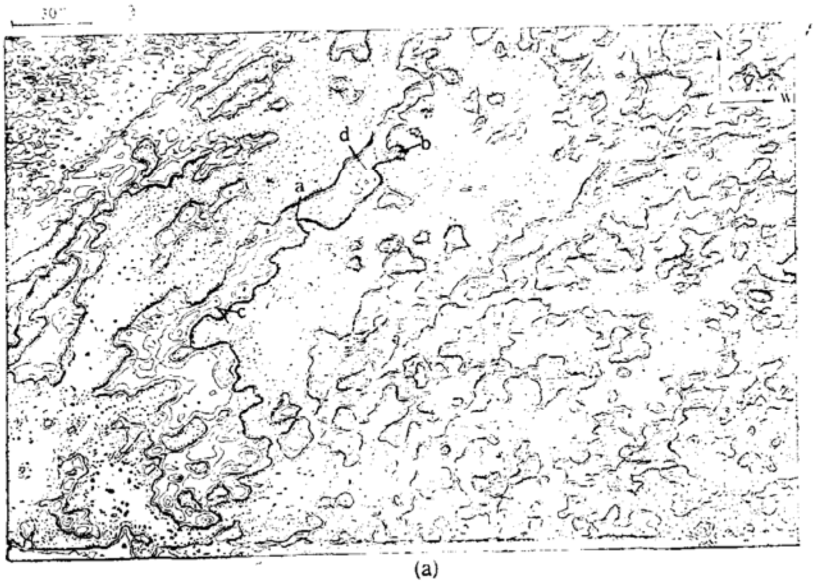
1. MHD discontinuity such as the overlapped regions of F_{N_1} and magnetic region of the N-polarity at the southeastern boundary. Both the discontinuities of velocity and magnetic field and the relationships of the discontinuity satisfy

$$v_n = 0, \quad B_n = 0, \tag{1}$$

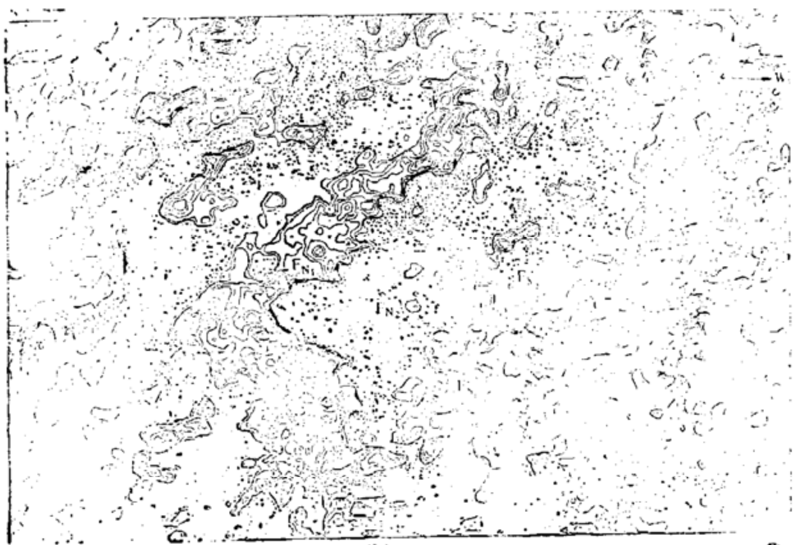
$$\left\{p + \frac{B^2}{8\pi}\right\} = 0, \tag{2}$$

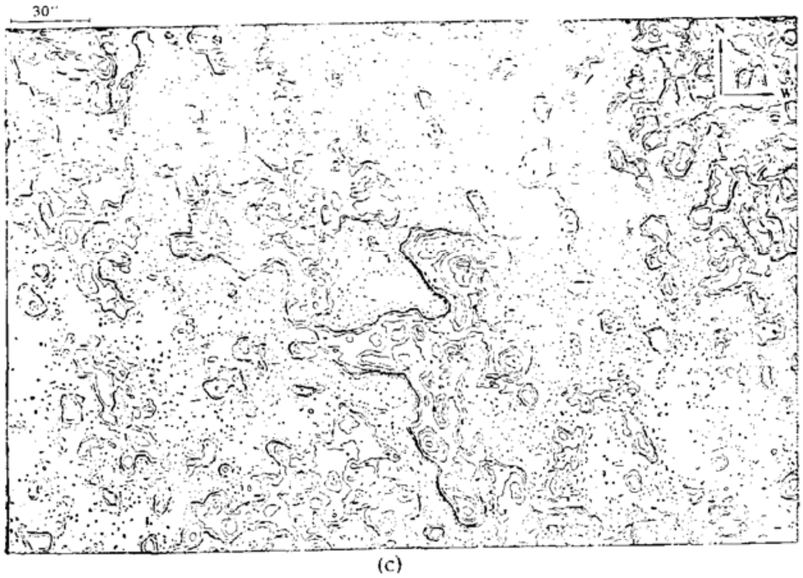
$$\{\boldsymbol{v}_\tau\} \neq 0, \quad \{\boldsymbol{B}_\tau\} \neq 0, \quad \{\rho\} \neq 0, \quad \{T\} \neq 0, \tag{3}$$

where the subscripts n and τ denote, respectively, the normal and tangential directions, $\boldsymbol{v}$ and $\boldsymbol{B}$ the velocity and magnetic field, ρ, T and p the density, temperature



(a)


(b)



(c)

Fig. 2. The counters of chromospheric visual velocity (4861 Å). Their values are 120, 240, 480, 1960, 2600, 3900, 5200, 6500 m/s respectively from outer to inside. The downward and upward flows are shown, respectively, by the real and broken lines.

(a) The chromospheric visual velocity field at 0144 UT on March 26, 1988.
(b) The chromospheric visual velocity field at 0237 UT on March 27, 1988.
(c) The chromospheric visual velocity field at 0141 UT on April 2, 1988.

and pressure, { } is the difference values between both sides of the discontinuous surface.

2. General hydrodynamic discontinuity such as the northern boundary of the region F_{N_1} or F_{S_2}, that has velocity discontinuity without any magnetic field. In the case of velocity discontinuity with a continuous magnetic field also, the phenomena such as the interface of F_{N_1} and F_{N_2} in the N-polarity region and that of F_{S_i} and F_{S_j} in the S-polarity region could be included in this kind of discontinuity. In this case, discontinuous relationship (1) holds, and (2) and (3) are simplified as

$$\{p\} = 0, \tag{4}$$

$$\{\boldsymbol{v}_\tau\} \neq 0, \ \{\boldsymbol{B}_\tau\} \neq 0, \ \{\rho\} = 0, \ \{T\} = 0. \tag{5}$$

3. Magnetic field discontinuity with a continuous velocity field including the boundaries of N-polarity magnetic flux in regions F_{N_1} or F_{N_2} and S-polarity magnetic flux in regions F_{S_i} or F_{S_j}. Such a boundary is similar to that of magnetostatic discontinuity, and it satisfies the relationships of (1) and (2) except (3) which is changed into

$$\{v_\tau\} = 0, \ \{B_\tau\} \neq 0, \ \{\rho\} \neq 0, \ \{T\} \neq 0. \tag{6}$$

Several typical discontinuous distributions of magnetic field and velocity are given in Fig. 3. Fig. 3(a) shows the MHD tangential discontinuity at the eastern edge of F_{N_1}, the thicknesses of vortex and current layers being roughly 1000 km. Fig. 3(b) gives the typical hydrodynamic discontinuity at the northern boundary of F_{N_1} where the magnetic field is nearly eliminated. Fig. 3(c) describes clearly the features

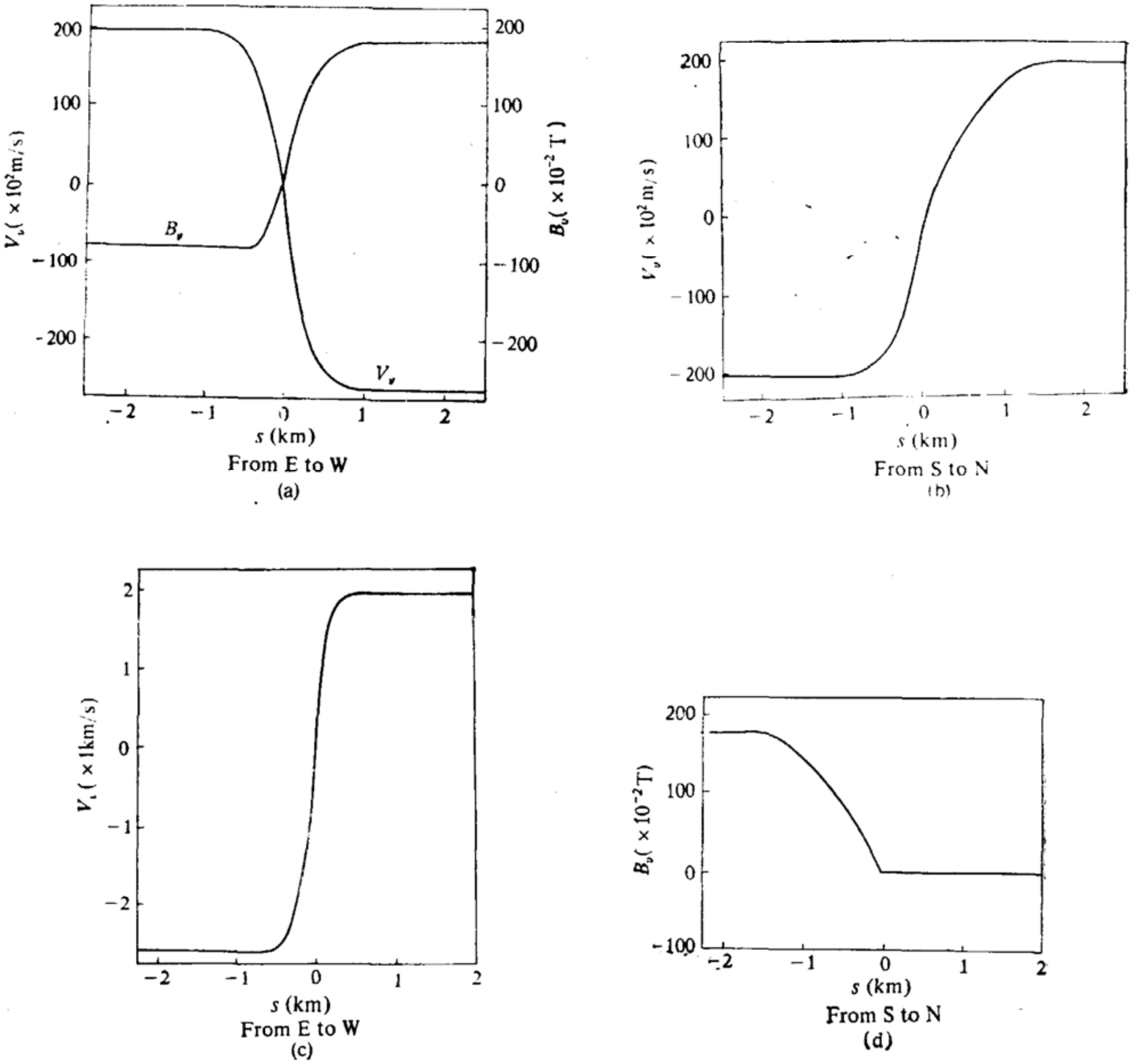


Fig. 3. Several typical tangential discontinuous distributions of magnetic field and velocity field.

(a) MHD tangential discontinuity, $\delta = 1500$ km, $\theta_p \simeq 70$; (b) hydrodynamic tangential discontinuity, $\delta = 2000$ km, $B = 0$; (c) hydrodynamic tangential discontinuity, $\delta = 1000$ km, $\theta_p \simeq 70$; (d) discontinuous magnetic field and continuous velocity, $\delta = 2000$ km, $v = 1960$ km/s, $\theta_p = 70$.

of the vortex layer by the velocity distribution on the western boundary of F_{N_1}, where the magnetic field is continuous. Fig. 3(d) gives the magnetic field distribution on the northern boundary of the N-polarity magnetic field, where the flow field is continuous.

Let us estimate the thickness of the velocity discontinuous layer. The velocity discontinuity is considered as the viscous vortex layer in the hydrodynamics. We adopt the origin of coordinate system at the point in the discontinuous surface where $v = 0$, and the direction of velocity is parallel to the direction of the z-axis and the normal direction of the discontinuous surface is along the axis. In this case, the relationship of momentum conservation gives

Here, we assume that $B_z = 0$, and all quantities depend only on (x, z). The balance is mainly between the inertial force and the viscous force inside the vortex layer, and the following relationship is obtained:

$$\rho v_z \frac{\delta v_z}{L} \Big/ \mu \left(\frac{\Delta v_z}{\delta^2}\right) = O(1), \tag{9}$$

where δv_z and Δv_z are, respectively, the velocity difference along the z-direction and that between the upstream and downstream of the vortex layer, and L and δ are, respectively, the typical scale along the velocity direction and the thickness of the vortex layer, which could be demonstrated immediately from (9) as

$$\frac{\delta}{L} = \sqrt{\frac{1}{Re}\left(\frac{\Delta v_z}{\delta v_z}\right)}, \tag{10}$$

where the Reynold number is defined as

$$Re = \frac{\rho v_z L}{\mu}. \tag{11}$$

Therefore, the typical thickness of vortex layer is proportional to $Re^{-1/2}$.

By adopting the chromospheric temperature as 10^4 K, the gas is partly ionized, and the chromospheric atmosphere consists mainly of neutral hydrogen. The viscous coefficient of molecular hydrogen is $\mu_H = 845$ g/cm • s at room temperature, so it gives $\mu_H = 4878$ g/cm • s at a temperature of 10^4 K. We adopt the chromospheric density $\rho = 10^{-12.5}$ g/cm^3, the ratio of velocity differences $\Delta v_z / \delta v_z = 4$, $v_z = 2000$ m/s, $L = 1000$ km, from which the thickness of the discontinuous layer is derived:

$$\delta = 1755 \text{ km}. \tag{12}$$

This estimated value agrees well with the observed results given in Fig. 2. These analyses show that many velocity tangential discontinuities in the chromosphere are similar to the viscous vortex layer in the hydrodynamics.

III. Instability of Chromospheric Tangential Discontinuity

The tangential discontinuity is absolutely unstable. The perturbation perpendicular to the magnetic field could be restrained by the magnetic rigidity. However, the magnetic field has no stabilization effect on the perturbation along the direction of the existing magnetic field. The relative effect of magnetic stabilization depends on the relative amount of the Alfvèn velocity and velocity difference Δv_z. In the chromosphere, the Alfvèn velocity associated with the magnetic field of $0.02T$

is

$$v_A = \frac{B}{\sqrt{4\pi\rho}} = 1.0 \times 10^3 \text{ km/s}, \tag{13}$$

where we adopt $\rho = 10^{-12.5}$ g/cm. This velocity has the same order of magnitude as the chromospheric velocity in the direction of view. It shows that the magnetic field is strongly coupled with the plasma motion.

For the incompressible model with uniform basic states in both upstream and downstream, the dispersion relations of MHD tangential discontinuity for the linear wave of small perturbations may be written as[7]

$$\omega = \frac{1}{\rho_1 + \rho_2} \cdot \left\{\rho_1 \boldsymbol{k} \cdot \boldsymbol{v}_1 + \rho_2 \boldsymbol{k} \cdot \boldsymbol{v}_2 \pm \sqrt{\frac{\rho_1 + \rho_2}{4\pi}[(\boldsymbol{k} \cdot \boldsymbol{B}_1)^2 + (\boldsymbol{k} \cdot \boldsymbol{B}_2)^2] - \rho_1\rho_2(\boldsymbol{k} \cdot v_1 - \boldsymbol{k} \cdot \boldsymbol{v}_2)^2}\right\}, \tag{14}$$

where ω is the frequency of the wave, $\boldsymbol{k}$ the wave number, and subscripts 1 and 2 denote, respectively, the value of basic state for the upstream and downstream. The amplitude of perturbation will increase with time and show the evolution of instability if the root in the relationship (14) is negative and there is an imaginary part of ω. The instability condition requires

$$|\boldsymbol{k} \cdot \Delta \boldsymbol{v}| > \sqrt{\frac{\rho_1 + \rho_2}{4\pi\rho_1\rho_2}[(\boldsymbol{k} \cdot \boldsymbol{B}_1)^2 + (\boldsymbol{k} \cdot \boldsymbol{B}_2)^2]}. \tag{15}$$

The perturbation modes perpendicular to the magnetic field ($k \perp B$) is stable, and in this case, the root of (14) equals zero; all perturbations along the other directions satisfying condition (15) are unstable. Generally, it is believed that the plasma moves along the magnetic surface in the solar atmosphere. In this case, the velocity perpendicular to the magnetic surface is required to be zero, but the velocity need not be parallel to the magnetic field everywhere in the magnetic surface. The perturbations which are not completely perpendicular to the magnetic field may excite instabilities.

We shall now discuss the growth rate $1/\gamma$ of perturbation, which is defined as the reciprocal of the imaginary part of frequency $1/\omega_i$, for a typical sort of tangential discontinuity. For simplicity, we analyze the intersurface of F_{N_1} and F_{N_2} or F_{S_i} and F_{S_i}. Therefore, we assume

$$\boldsymbol{B}_1 = \boldsymbol{B}_2 = \boldsymbol{B}, \quad \rho_1 = \rho_2 = \rho.$$

Correspondingly, Formula (14) is reduced to

$$\frac{\omega}{k} = \frac{\boldsymbol{k} \cdot (\boldsymbol{v}_1 + \boldsymbol{v}_2)}{2k} \pm \frac{i}{k}\sqrt{\left(\frac{\boldsymbol{k} \cdot \Delta \boldsymbol{v}}{2}\right)^2 - \frac{(\boldsymbol{k} \cdot \boldsymbol{B})^2}{4\pi\rho}}. \tag{16}$$

The growth rate of perturbation is, then, given:

$$\frac{1}{\gamma}=\frac{\lambda}{2\pi\sqrt{\left(\frac{\boldsymbol{e}_k\cdot\Delta\boldsymbol{v}}{2}\right)^2-\frac{(\boldsymbol{e}_k\cdot\boldsymbol{B})^2}{4\pi\rho}}},\tag{17}$$

where $\boldsymbol{e}_k$ is the unit vector of $\boldsymbol{k}$, and λ is the typical wavelength. Formula (17) shows that the larger the typical scale of the configuration, the faster the perturbation growth for the smaller-scale perturbation. This feature agrees with the observation.

We calculate the growth rate of perturbation in detail. Formula (13) gives the typical chromospheric Alfvèn velocity as 1.0×10^3 km/s. The typical velocity distributions shown in Fig. 2(b) show that the chromospheric velocity has the same order of magnitude as the Alfvèn velocity in the chromosphere. The fastest growth rate of perturbation is given for the case of $\boldsymbol{e}_k\cdot\boldsymbol{B}=0$:

$$\left(\frac{1}{\gamma}\right)_{\max}\simeq\frac{\lambda}{\pi\left|\boldsymbol{e}_k\cdot\Delta\boldsymbol{v}\right|}.\tag{18}$$

We discuss the photospheric fields to show clearly the variation of the perturbation. Adopting $\boldsymbol{e}_k\cdot\boldsymbol{v}=6$ km/s, $\lambda=10^4$ km, we obtain the typical time in an order of magnitude 10^3 s. The growth rate may be $1/\gamma=10^4$ s for the perturbation propagating along the magnetic field if $\Delta\boldsymbol{v}$ is parallel to $\boldsymbol{B}$. The observed results of the photospheric velocity show that the configuration of tangential discontinuity may be changed into a period of several hours. This agrees with the estimated growth rate of the disturbance.

The velocity distributions in Fig. 2 show that there are significant variations near the boundaries of the flow regions that are characterized as discontinuous layers; the velocity distributions are not uniform near the boundaries, and there are many vortex pairs with a great speed, which is often associated with the distortion of boundaries. These features may be considered as the instability evolution of the perturbation and the result of instability. The larger-scale velocity discontinuity that is one order of magnitude larger than the Earth's scale such as the active region observed on March 26, 1988, has presented a lot of data for analysing the configuration and the motion of plasma.

It should be noted further that the observed magnetic and velocity fields are given in the direction of view. The real direction of the magnetic field could be demonstrated by the observed longitudinal and transversal components of the fields. The visual magnetic field is not perpendicular to the solar disk, but is obviously inclined. The evolution of perturbation described by Formula (14) introduces the variations in configurations at different levels of the solar atmosphere including the horizontal level in the chromosphere even for the case of relatively strong magnetic field.

IV. Interaction of Magnetic and Flow Fields in Active Region

The relationship between the configurations of the magnetic field and the characteristics of the flow field is important observationally and theoretically as it is associated with fundamental dynamic processes such as the emergence of magnetic flux tube into the solar atmosphere and the evolution and dispersion of the flux tube.

The discussion of the active region shows that a large-scale chromospheric mass flows upward near the neutral line of the longitudinal magnetic field, and spreads obviously to the following magnetic region with the N-polarity of the dipole active region, the discontinuous surface at visual velocity is formed there. There are small-scale structures which overlap on the large-scale pattern near the neutral line. The chromospheric mass seems to flow obviously downward to the region concentrated with strong magnetic field[6]. The upward flowing process transfers not only the heated gas but also carries the magnetic flux tube from the deep layer of the sun to the solar surface, where the complex magnetic structures exist. It seems that the downward flowing gas carries the relatively cold medium from the solar atmosphere to the deep layer of the active region in the region of strong magnetic field. The gaseous temperature and density in the flux tube are decreased, and then the stronger magnetic field is concentrated. On the other hand, the instability of the chromospheric tangential discontinuity distorts the configuration of magnetic field and breaks through the magnetic active region. The vortex pairs observed on both sides of discontinuity are removed with a typical time scale of 2—3 h, and the configuration of the discontinuous surface is deformed. This is seemingly the configuration variations of the magnetic field induced by the instability of velocity discontinuity in the chromosphere.

The discontinuous surface of the chromospheric velocity occurring on March 26, 1988 was nearly broken in the middle and became fragmentary structures on April 2, 1988, as shown by chromospheric velocity distributions in Fig. 2(c). The observed magnetic field reveals that the structure of the photospheric magnetic field has undergone a relatively large change[6]. In addition to the variation of small-scale magnetic structures in local region, the successive magnetic field of the dipole active region is separated into two pieces. The magnetic force-line emerges from the two following N-polarity regions and sinks mostly into the forward S region. Its structure is similar to that of the mass flowing pattern in the corresponding region of the chromosphere. The result of the evolutionary magnetic configuration is different from that occurring on March 27, 1988.

We have to emphasize that the evolution of the magnetic field in the active region is influenced strongly by the velocity field. The evolution of the magnetic field in the active region such as the distortion and fragmentation induced by the instability of tangential discontinuity is discussed in detail.

V. Conclusion

By using the persistent flow in a larger area occurring from the eastern edge of the solar disk on March 27, 1988, as a sample, the features of chromospheric discontinuities are analyzed. For the lack of descriptions on the flow features at a velocity similar to the Alfvèn velocity persisting several days in a large area, this paper discusses generally the plasma motion. Further statistical and morphological analyses are needed.

We study the interactions between the chromospheric magnetic and velocity fields using the magnetographic data obtained at the same time by Beijing Observatory, Academia Sinica. It is usually assumed that the plasma motion in the active region is confined to the magnetic flux tube, which coincides with the streaming tube, and their boundaries are tangential discontinuities. The present paper states that the actual flow field is more complex than the simple pattern. The area of the flow region is much larger than that of the magnetic flux region. Moreover, various kinds of boundaries and discontinuities are introduced. The interaction between the complex magnetic field and the flow field suggests a challenge to the simplified model of theoretical calculations.

The analyses in the present paper assume the zero normal velocity at the boundary of magnetic surface, i.e. $v_n = 0$, and give the configurations of tangential discontinuities. This assumption is reasonable from the aspect of theoretical estimations on the thickness of vortex layer and the evolution of instability. Experimentally, this assumption has not been checked by observations. The discontinuity will be the front of shock wave if $v_n \neq 0$, which is important for the transfer of chromospheric mass, momentum and energy.

The existence of MHD tangential discontinuity in the chromospheric active region suggests a new mechanism of the evolution of active region. The instability might cause the deformation, fragmentation and disappearance of the discontinuity. The variations in the flow field and its region morphology are associated closely with the variation of the magnetic field, and the region of magnetic flux may be either concentrated to have the magnetic field increased or dispersed and eliminated. The analyses in the present paper reveal a strong influence of the flow field on the evolution of the active region.

It could be seen that the magnetographic data obtained by Beijing Observatory, Academia Sinica, support such advanced information on some new phenomena. Further information on the transverse components of chromospheric magnetic and velocity fields is urgently needed. The theoretical model of this paper seems rather simple, and the research awaits the survey such as the theory of non-uniform field and nonlinear theory of instability.

References

[1] de Bussac, G., *IAU Symp.*, Clermont-Ferrand, 1976, 36.
[2] Athay, G., in *Solar Active Region* (Ed. Orrall, F. Q.), Colorado Univ., 1981, p.83.
[3] Priest, E. R., *ibid.*, 213.
[4] Athay, G., *Solar Phys.*, **100**(1985), 257.
[5] 艾国祥、胡岳风，天文学报，**27**(1986)，173.
[6] 张洪起等，北京天文台台刊，1989，14: 1.
[7] 胡文瑞，宇宙磁流体力学，科学出版社，1987.
[8] 史忠先，太阳耀斑(胡文瑞等编著)，科学出版社，1983.