PHOTOSPHERIC PLASMA MOTIONS IN THE MAGNETIC FIELD OF A SINGLE SUNSPOT UMBRA

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The analysis of observed velocity fields in sunspots shows that the plasma motions above a sunspot umbra do not agree with the equation of continuity. We assumed that in the temperature minimum region above a sunspot umbra there is an effective diffusion of plasma across the lines of force in the region of the magnetic field. It leads to the formation of the steady flow of plasma in the temperature minimum, *i.e.*, photosphere region. We determined the parameters in this steady flow. The calculated parameters do not contradict observational data on moving plasma in the magnetic field above a sunspot umbra.

INTRODUCTION

The most intensive motions in the solar photosphere are the Evershed motions, which are concentrated in a penumbra of sunspots, where magnetic field and velocity are mainly horizontal. Plasma motions above a sunspot umbra are attractive since they take place in the strong magnetic field oriented mainly vertically.

Earlier [5] it is found that the temperature minimum region (observation in the Fe I $\lambda\,527.0$ nm) above a sunspot umbra is the boundary above which (in the chromosphere) a vertical component of a velocity is directed upwards, but below it (in the photosphere) this component is directed downwards. The vertical velocities were taken from the observations [3, 4, 6].

Figure 1 shows the results of the analysis of the plasma motions above a single sunspot umbra. It seems that these plasma motions above a sunspot umbra do not agree with the equation of continuity.

WORKING HYPOTHESIS

We have assumed that in the temperature minimum region above a sunspot umbra there is an effective diffusion of plasma across the lines of force in a region of a magnetic field. Hotter plasma, located outside a sunspot magnetic field, getting in a sunspot umbra magnetic field, expands adiabatically along the lines of force. The expanding gas becomes cooler and heavier. Plasma falls down due to gravity action. The observed plasma motions arise in the temperature minimum, *i.e.*, photosphere region.

For the quantitative progress of this idea we used the sunspot model [1] and the solar atmosphere model [2]. The geometrical heights of these models were fitted on using the condition of the balance of a magnetic and plasma pressure in a sunspot umbra and a surrounding plasma pressure. Taking this result into account, we determined the temperature of plasma at the temperature minimum level above a sunspot umbra and the temperature at the same level outside a sunspot umbra.

A magnetic field of a sunspot umbra consists of separate magnetic flux tubes that expand with the height. We assumed that their cross-section has a round shape. Totality of magnetic flux tubes and plasma flows in them give a general structure of the observation plasma flow in a sunspot umbra magnetic field.

We suppose that the interval of heights Δh where plasma inflows in a sunspot umbra magnetic field in the temperature minimum region is 200 km. In this case we found that the mean temperature within this height interval is approximately 3500 K above a sunspot umbra and about 5000 K in the surrounding plasma.

PLASMA FLOW PARAMETERS

Plasma penetrating into the low pressure region expands. We assume that the process of the plasma expansion goes adiabatically under constant entropy. The expanding gas becomes cool down to a temperature of 3500 K (this is the mean temperature in Δh region). The temperature decrease leads to the gas pressure decrease in a sunspot umbra magnetic field by the Poisson adiabat:

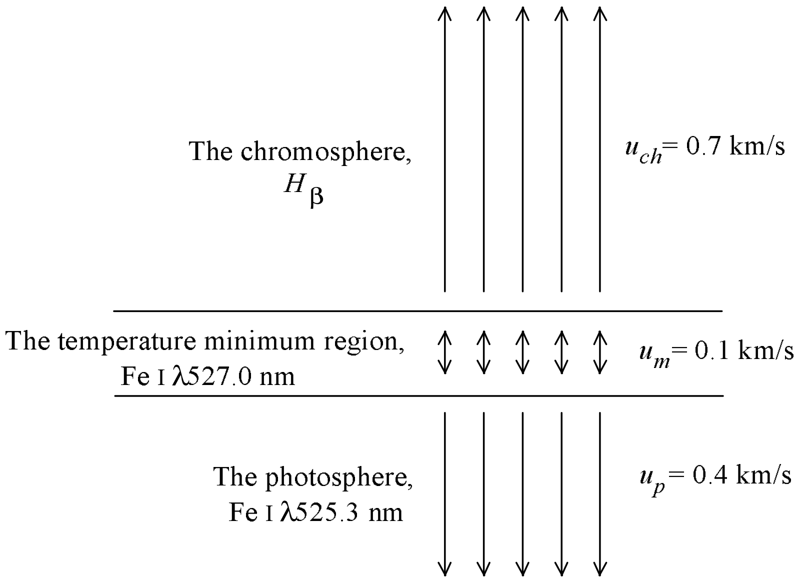

Figure 1. The scheme of vertical plasma motions above a sunspot umbra. Arrows show the direction of the vertical velocities. Their length corresponds to the mean velocity value

$$\frac{p_m}{p_a} = \left(\frac{T_m}{T_a}\right)^{\gamma/\gamma-1}. \tag{1}$$

Here, the label m marks the parameters of plasma in Δh region of a sunspot umbra; the parameters indicated by a relate to Δh region outside a sunspot umbra; $\gamma = 5/3$ is the adiabatic index.

To determine a ratio of plasma density, ρ_m, in the magnetic flux tube of a sunspot umbra in the temperature minimum region to density of surrounding plasma, ρ_a, we used the perfect gas low:

$$\frac{\rho_m}{\rho_a} = \frac{p_m}{p_a}\frac{T_a}{T_m}. \tag{2}$$

The effective diffusion of plasma leads to the formation of the quasi-stationary downwards flow. The plasma inflowing in a magnetic field through the lateral surface of Δh region transforms into the vertical downwards flow of gas in a sunspot magnetic field:

$$2\pi r_d \Delta h \rho_a u_d = \pi r_d^2 \rho_m u_m, \tag{3}$$

where u_d is the velocity of plasma diffusion in a magnetic flux tube, r_d is the radius of a magnetic flux tube in the temperature minimum region. According to equation (3), the equation for the velocity of plasma diffusion in a magnetic flux tube is:

$$u_d = \frac{1}{2}\frac{r_d}{\Delta h}\frac{\rho_m}{\rho_a}u_m.$$

The increase of the deep of the temperature minimum region level above a sunspot umbra as well as the increase of Δh region leads to the decrease of plasma diffusion velocity.

In that magnetic flux tube plasma moves downwards from the level of the temperature minimum to the photosphere along the magnetic field with the converging lines of force. In the steady state the mass of gas, which passes per a unit time through the flux tube cross-section, is constant along the flux tube, in our case from the temperature minimum region to the photosphere level. In this case the equation of continuity is:

$$S_m \rho_m u_m = S_p \rho_p u_p, \tag{4}$$

where the parameters indicated by index p are related to the photosphere.

The cross-section of the magnetic flux tube increases with the height because of the divergence of the lines of force. We assume that, to a first approximation, the angle of the divergence of the lines of force in the flux tube is a constant. Then, on the basis of the simple geometric considerations, we get:

$$\frac{S_m}{S_p} = \left(1 + \frac{\Delta z}{r_d} \tan \alpha\right)^2 , \tag{5}$$

where Δz is the difference of heights taken from the temperature minimum region up to the photosphere, α is the angle of divergence of the lines of force in the magnetic tube.

According to equations (4) and (5), we find an expression for the determination of changing plasma density in steady flow along the flux tube:

$$\frac{\rho_m}{\rho_p} = \frac{u_p}{u_m} \left(1 + \frac{\Delta z}{r_d} \tan \alpha\right)^2 .$$

The change of the temperature in plasma moving along the magnetic flux tube is defined on the basis of the Bernoulli equation:

$$\frac{u_m^2}{2} + w_m = \frac{u_p^2}{2} + w_p, \tag{6}$$

where w is specific enthalpy. A potential energy of the unit plasma mass is not included in the Bernoulli equation. This is connected with the fact that we know velocities of the moving gas in both cross-sections of the flux tube.

Since for a perfect gas

$$w = \frac{\gamma}{\gamma - 1} \frac{P}{\rho} = \frac{\gamma}{\gamma - 1} RT,$$

equation (6) yields

$$T_m - T_p = \frac{\gamma - 1}{2\gamma R} \left(u_p^2 - u_m^2\right) . \tag{7}$$

Here, R is the specific gas constant. Equation (7) determines the change of the plasma temperature in the steady flow from the temperature minimum region to the photosphere.

The ratio of the observational velocities in the temperature minimum region and in the photosphere, u_m/u_p, and also the ratio of the plasma temperature in the temperature minimum region above a sunspot umbra and the plasma temperature at the same level outside a sunspot umbra, T_m/T_a, are given in Table 1. On the basis of these data we determined all the parameters in the steady flow of plasma. The results of the calculations are presented in Table 1.

Table 1. The ratio of the parameters in a steady adiabatic and isentropic flow

T_m/T_a	p_m/p_a	ρ_m/ρ_a	u_m/u_d	u_m/u_p	ρ_m/ρ_p	$T_m - T_p$, K
0.70	0.44	0.61	0.67	0.25	2.22	3.6

Thus, the data on the temperature in the temperature minimum region above a sunspot umbra and at the same level outside a sunspot umbra and the vertical velocities at the both levels permit us to determine all the parameters of plasma and their change in the steady adiabatic isentropic plasma flow.

CONCLUSION

The diffusion of plasma in a magnetic field across the lines of force is possible if plasma pressure in a magnetic field is weaker than the pressure of surrounding plasma. From the data of Table 1 one can see that the ratio of these pressures is 0.44. Plasma density in the region of a magnetic field is less by a factor of 0.61 than the density outside the magnetic field. The shift of the plasma diffusion region in the deeper atmosphere layers or the expansion of the diffusion region leads to the decrease of the plasma diffusion velocity. This leads to the decrease within the magnetic flux tube of both, plasma pressure, p_m/p_a, and density, ρ_m/ρ_a. The plasma diffusion velocity exceeds the vertical downward velocity of plasma in the temperature minimum region above a sunspot umbra. While we do not know a type of plasma instability which leads to the effective plasma diffusion in a magnetic field across the lines of force. However, a fine structure of a magnetic field promotes a rise in plasma diffusion in magnetic structures. A fine structure of a magnetic field does not influence the parameters of the plasma moving stationary and isentropically downward along the lines of force. Because of an increase of velocity with the depth in plasma moving downwards, from the temperature minimum region to the photosphere, the plasma density, ρ_m/ρ_p, decreases more than two times. At the same time the plasma mass, inflowing per unit time in the magnetic flux tube at the photosphere level is the same as at the temperature minimum level. The moving plasma becomes cooler less than by 4 K. This is no surprise, since the plasma moves with the velocity which is small in the comparison with the local sound velocity in the plasma.

The calculated parameters do not contradict observational data on moving plasma in the magnetic field above a sunspot umbra.

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