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ORIGINAL ARTICLE

The Relationships of Sunspot Magnetic Field Strength with Sunspot Area, Umbral Area and Penumbra-Umbra Radius Ratio

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Abstract Stokes profile inversion is very important to get the information on the vector magnetic field. Because the magnetic fields cannot be directly observed, adopting Stokes spectrum analysis to obtain vector magnetic field has become the major technique recently. Therefore, by Stokes profile inversion, we obtained vector magnetic fields of two layers based on the numerical solution (DELO solution, Rees et al., 1989) to the polarized radiative transfer equation. We analyze the relationships of sunspot magnetic field strength with sunspot area, umbral area and penumbra-umbra radius ratio. By statistical research, it is found that the field strengths of the upper layer and the lower one decrease with the increasing penumbra-umbra radius ratio, and that the logarithmic expression is able to fit well the relationship between the maximum field strength of the upper layer and the sunspot area. Furthermore, we verify the result obtained by Ringnes and Jensen (1961) about the relationship between the maximum magnetic field strength and the umbral area, and the result obtained by Antalová (1991) of the relationship between the field strength and the penumbra-umbra radius ratio.

Keywords Sunspots-magnetic · Field-umbral · Area-radius · Ratio

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1. Introduction

Sunspots have been observed for centuries. Galileo provided the first detailed description of sunspot morphology, including the distinction of penumbrae from umbrae. However, no real further scientific progress was made until Hale's discovery, of the intense magnetic fields in sunspots in 1908. That discovery fostered a new era in solar physics. The study of magnetic structures of sunspots soon became one of the most prominent research topics in solar physics.

Based on the theory of return flux of sunspots, Osherovich and Garcia (1989) studied the relationship between the relative size of a sunspot umbra and the relative magnitude of the magnetic field at the outer edge of the penumbra. By analyzing 12 unipolar and approximately round sunspots, they found that small umbrae or, equivalently, large penumbrae (with respect to the total sunspot area) were associated with the large relative return flux and large overall magnetic field at the outer penumbral boundary.

Nicholson (1933) already pointed out the ambiguity of the relationship of the sunspot longitudinal magnetic field with a large umbral area $B_L = f(A_U)$, which was determined from an analysis of 1000 spots. Ringnes and Jensen (1961) tried to utilize several expressions to describe the relationship between the area A_U and the magnetic field strength B of single spots for several epochs in the solar cycles over the period of 1917–1956, using the magnetic field observations collected at the Mount Wilson Observatory. The best fit was obtained by utilizing the logarithmic expression $B = a \times \log A_U + b$. Brants and Zwaan (1982) determined the relationship for small umbrae ($A_U \leq 40 \times 10^{-6}$ in unit of visible hemisphere) by means of the TiI λ6064.6 Å($g_{\mathrm{eff}} = 2.0$). By making use of the scans with the microdensitometer in the two opposite directions of circular polarization on the same wavelength scale, they computed the magnetic field strength from the wavelength separation. However, they concluded that the field strength in the well-established pores and small umbrae was of little dependence on area.

Inverse proportionality between the sunspot longitudinal magnetic field B_L and the penumbra-umbra radius ratio k was found by Antalová (1991), who adopted two groups of different data. One contained 113 measurements of 74 sunspots observed from 1968 to 1976. The measurements of the sunspot magnetic fields were obtained at the Crimean Observatory. The data of the sunspot area were adopted from the Greenwich Photoheliographic Results. It was found that the maximum umbral magnetic induction B_L decreased with the increasing coefficient k. The other group consisted of 26 measurements of 15 spots observed in 1977. The data of the sunspot area were measured at the Debrecen Observatory and the sunspot magnetic induction at SibIZMIR (Siberian Institute of Earth Magnetism and Radio-wave Propagation) in Irkutsk. In spite of the different data sets, the relationships between B_L and k were the same.

The purpose of this paper is to pay more attention to the fact that the magnetic properties of sunspots are relative to their geometrical properties. Therefore, in simulating sunspots, the coefficient k, umbral area A_U and sunspot area A_S become greatly significant. Based on the verification of the former results, such as the relationship between field strength and umbral area and that between the longitudinal field strength and the penumbra-umbra radius ratio, we also obtain some new results of the relationship between the field strength and the sunspot area and that between the field strength and the penumbra-umbra radius ratio.

2. Observations and measurements

We adopt the data obtained from the Solar Stokes Spectrum Telescope (S^3T, Qu et al., 2001) at the Yunnan Astronomical Observatory of China. The spatial resolution is estimated to be about 2 arcseconds, and the spectral resolution is 15 mÅ. In this paper, we choose 30 simple and isolated sunspots observed from 2002 to 2004, and magnetic field strength is obtained from the inversion of the Stokes spectra of FeI 6302.5Å ($g_{\text{eff}} = 2.5$).

Because the magnetic field cannot be directly observed, adopting Stokes spectrum analysis to obtain vector magnetic field has become the major technique recently. In order to better reproduce the observed features, such as asymmetry, abnormal appearance of Stokes profiles, the atmosphere is usually divided into many layers. This way can reproduce the observed Stokes profiles very well, but it also suffers more from the issue of uniqueness. In order to deal with the asymmetrical Stokes profiles and suffer as little as possible from the issue of uniqueness, a two-layer model is provided to divide the atmosphere into two layers along the line of sight. To improve the calculation accuracy when using the Diagonal Element Lambda Operator solution (DELO solution, Rees et al., 1998), each layer contains more than one depth grid. In detail, the grids are outlined in terms of the local continuum opacity τ as

$$\tau_n = 2^{-4+(24-n)/3}, \; n = 24, 23, \ldots, 0$$

And the depth grid dividing the atmosphere into the two layers is $n = 15$ with $\tau = 0.5$ in the following inversion. Within each layer, the parameters are assumed to be constant.

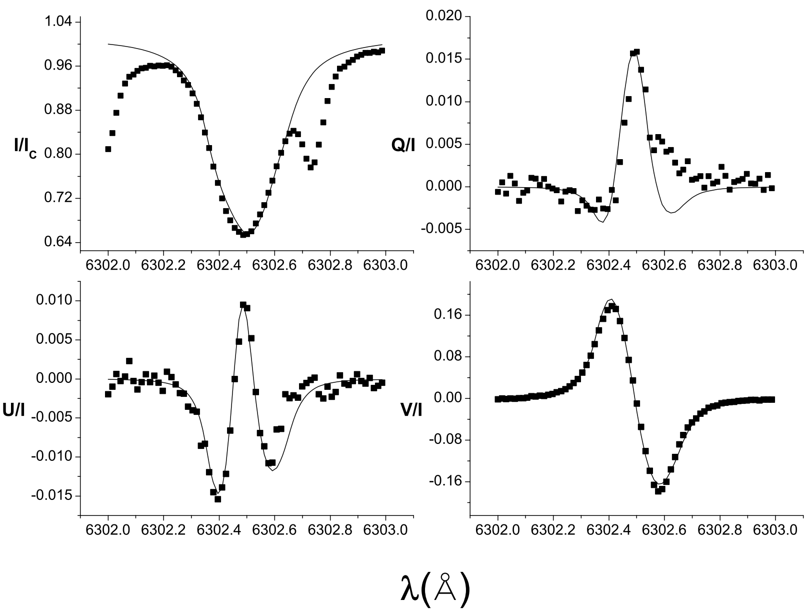

Fig. 1 The sample inversion of the full Stokes profiles of FeI λ6302.5Å. One can notice that the asymmetric feature of Stokes U/I is well reproduced, while the single valued inversion cannot do it. Abscissa denotes wavelength, in unit of Å

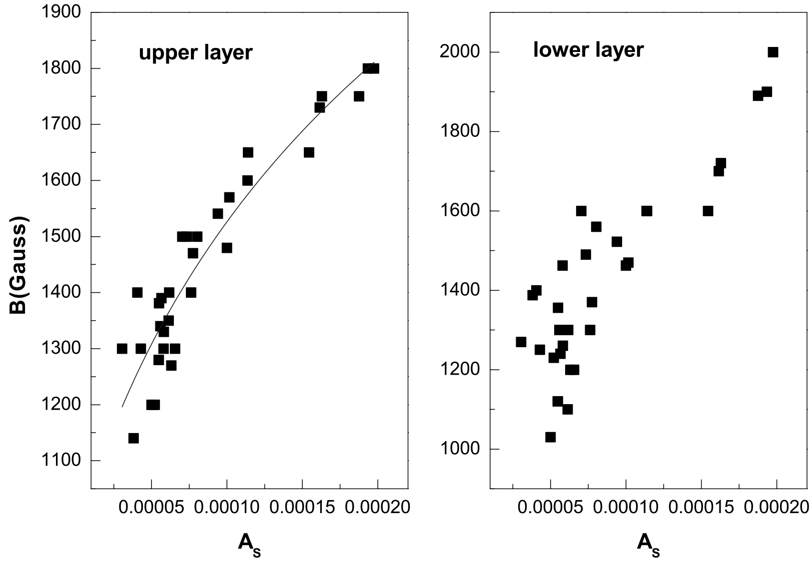

Fig. 2 The relationship between the maximal magnetic field strength B (Gauss) and the sunspot area A_S (in unit of visible hemisphere). Each scattered point represents data from one single sunspot. The relationship between the magnetic field strength of the upper layer and the sunspot area is fitted by logarithmic dependence: $B = a + b \times \ln(A_S + c)$, where $a = 6975$G, $b = 627$G, $c = 0.00007$

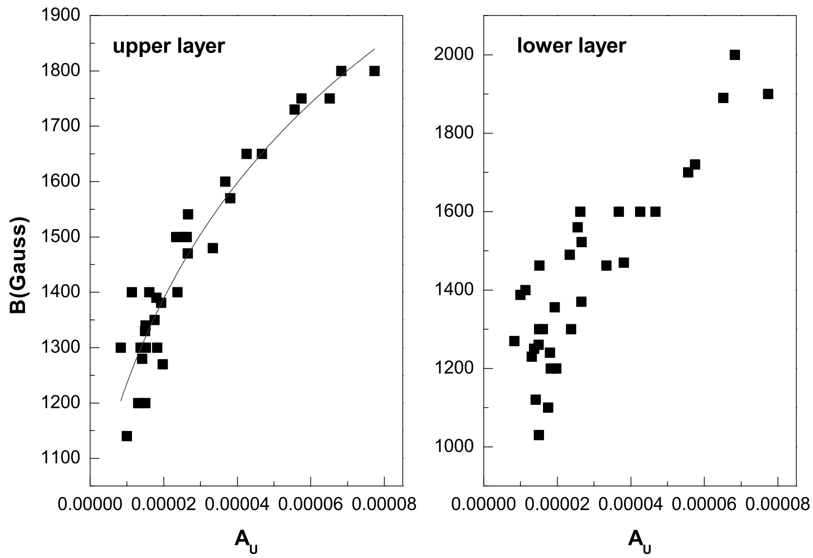

Fig. 3 The relationship between the maximum magnetic field strength B (Gauss) and the umbral area A_U (in unit of visible hemisphere). The relationship between the magnetic field strength of the upper layer and the sunspot area is fitted by logarithmic dependence: $B = a + b \times \ln(A_U + c)$. where $a = 6247$G, $b = 475$G, $c = 0.00002$

By using the Marquardt algorithm (Skumanich and Lites, 1987), we determine the magnetic field strength, inclination, azimuthal angle, line-of-sight velocity, Doppler width, line strength, damping constant, continuum source function and line source function from the Stokes profiles inversion. To obtain the maximum magnetic field strength accurately, we adopt four to seven slits through each umbra and adopt all points in the umbra along these slits.

The umbral area A_U and sunspot area A_S are measured according to the MDI continuum and Active Regions images of BBSO, while the projections of the spots are considered. We define umbrae and penumbrae according to the continuum intensity. At the same time, we also consider the magnetic field in defining umbrae and penumbrae.

The uncertainty about the magnetic field strength ranges from 100 to 300 G. There is also the uncertainty about the umbral area in the extreme cases; it is mainly due to the subjective discrimination between the umbra and the penumbra, which also results in the errors of the penumbral-umbral radius ratios.

3. Results

At first, we show one sample fitting of Stokes profiles of FeI 6302.5Å in Fig. 1. We select the data observed in 2002. In each panel of the figure, the dotted line represents the observed Stokes profile, and the solid line the fitting curve. It is evident that the observed profiles are well fitted, especially the asymmetry of Stokes U/I. It is noteworthy that in the first panel, the lines near 6302.0Å and 6302.5Å are two O_2 telluric lines.

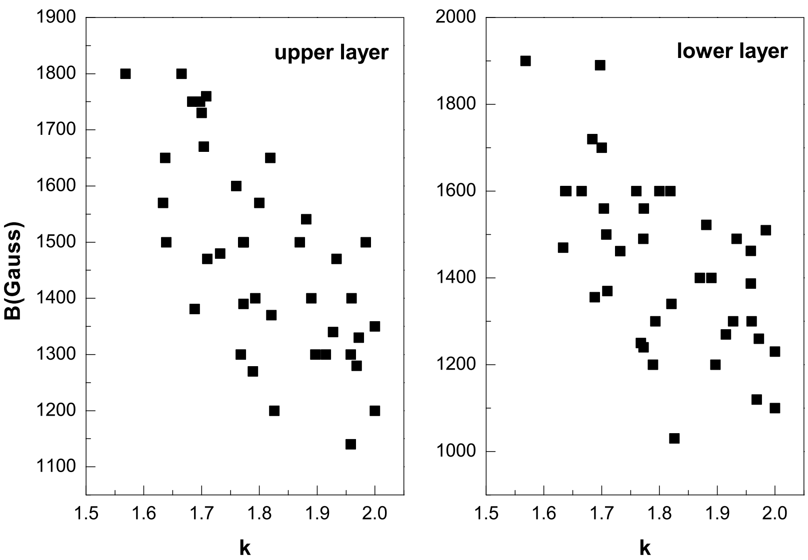

Fig. 4 The relationship between the maximum magnetic field strength B (Gauss) and the penumbra-umbra radius radio k

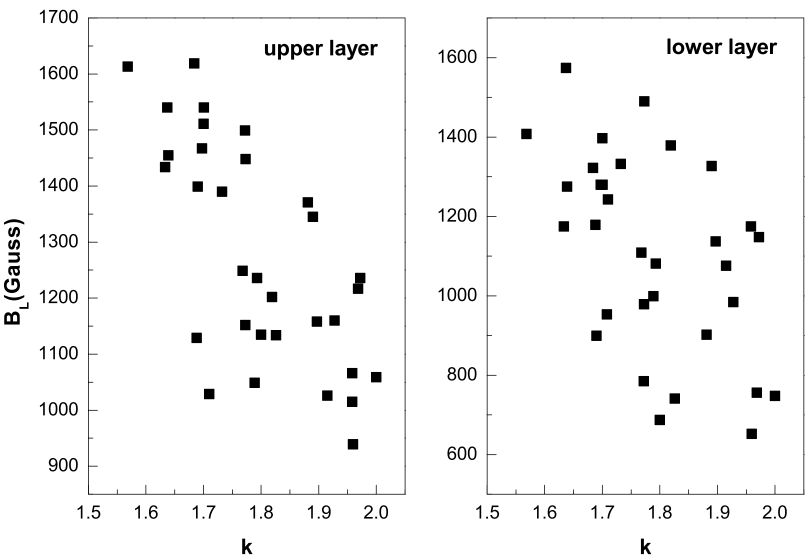

Fig. 5 The relationshup between the longitudinal magnetic field strength B_L (Gauss) and the penumbra-umbra radius radio k

Figure 2 shows the relationship between the maximum magnetic field strength of sunspot and the sunspot area. We try employing the logarithmic expression to describe the relationship between the field strength of the upper layer and the sunspot area: $B = a + b \times \ln(A_S + c)$, and find $a = 6975G \pm 2566G$, $b = 627G \pm 333G$ and $c = 0.00007 \pm 0.00009$. While the field strength of the lower layer and the sunspot area don't show the logarithmic relationship, from the figure, one also can clearly see that the magnetic field strength of the lower layer increases with the increasing sunspot area.

The left panel of the Fig. 3 demonstrates the logarithmic relationship between the maximum field strength of the upper layer and the umbral area: $B = a + b \times \ln(A_U + c)$, where $a = 6247G \pm 1553G$, $b = 475G \pm 173G$, $c = 0.00002 \pm 0.00002$. However, the field strength of the lower layer increases with the increasing umbral area. and they don't display the logarithmic relation.

From the Fig. 4, we can obviously find that the magnetic fields of the upper layer and lower one decrease with the increasing coefficient k. Furthermore, the same inverse proportionality relationship between the maximum longitudinal magnetic field strength and coefficient k also is displayed in the Fig. 5. Because the longitudinal field strength is calculated in observer's reference frame, we transformed the measured results into heliographic coordinates (Hagyard, 1986).

4. Conclusions

From the measurement of FeI λ6302.5Å, we conclude that the relationship between the maximum magnetic field strength B of the upper layer and the sunspot area A_S is the logarithmic expression $B = a + b \times \ln(A_S + c)$. At the same time, the obtained relationship between the maximum field strength B of the upper layer and the umbral area A_U is also logarithmic: $B = a + b \times \ln(A_U + c)$. Although the magnetic field strength of the lower layer with the sunspot area and the umbral area can't be fitted by logarithmic expression, it increases with the increasing sunspot area and umbral area. Furthermore, both longitudinal field strength B_L and maximum field strength B decrease with increasing coefficient k.

Because we divide the atmosphere into two layers, we obtain the two kinds of relationships, that is to say, the relationship between sunspot geometrical properties and the magnetic fields of the upper layer and the relationship between sunspot geometrical properties and the magnetic fields of the lower layer. Our conclusions about sunspot geometrical properties and the magnetic field of the upper layer effectively support the standpoints of Antalová (1991) and Ringnes and Jensen (1961). At the same time, our results about sunspot geometrical properties and the magnetic fields of the lower layer also support the viewpoint of Antalová (1991). However, ours are different from those of Brants and Zwaan (1982). Those are brought on perhaps due to the following reasons. At first, the methods of the data processing are different. Brants and Zwaan (1982) utilized the microdensitometer scans in two opposite directions of circular polarization on the same wavelength scale, and then computed the magnetic field strength from the wavelength separation between the medians of the line cores. However, the method is only applied to the case of strong field. Furthermore, the filter-based magnetograph makes use of the weak field approximation, so it is only applied to the case of weak field. Therefore, our results are reliable because we apply the Stokes spectral inversion method, which can be applied to not only the case of strong field but also that of weak field. Secondly, the adoptive spectral lines are different. Because different spectral lines have different sensitivities to the magnetic field and form in different layers, the results obtained with different spectral lines may be different too.

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References

Antlová, A.: Baicz **42**, 316 (1991)
Brants, J.J., Zwaan, C.: Solar Phys. **80**, 251 (1982)
Hagyard, M.J.: Solar Phys. **107**, 239 (1987)
Nicholson, S.B.: PASP **45**, 51 (1933)
Ringnes, T.S., Jensen, E.: An **7**, 99 (1961)
Rees, D.E., Murphy, G.A., et al.: ApJ **339**, 1093 (1989)
Skumanich, Lites: ApJ **322**, 473 (1987)
Osherovich, V. A., Garcia, H. A.: ApJ **336**, 468O (1989)
Qu, Z.Q., Zhang, X.Y., et al.: Solar Phys. **201**, 241 (2001)