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Spectral manifestations of extremely strong magnetic fields in the sunspot umbra

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Abstract

Fine peculiarities of the Zeeman effect in two big sunspots of October 29, 2003, and October 25, 2014, are analyzed. In order to search spectral evidences of very strong spatially unresolved magnetic fields, the Stokes $I \pm V$ and V profiles of the Fe I 6301.5 and 6302.5 Å lines are studied in detail. Confirmed are two effects discovered earlier by Lozitsky (2016): (a) non-parallelism of bisectors in the Fe I 6301.5 line at a distance of about ±250 mÅ from the line center and (b) the existence of weak secondary peaks in Stokes V of the Fe I 6302.5 line placed at a distance of, on the average, ±375 mÅ from the line center. Close correlation ($r = 0.77 \pm 0.06$) was found between (a) and (b) effects indicating the reality of very strong (≈8 kG) unresolved magnetic fields. For the first sunspot, the presence of the abovementioned 8-kG fields is traced along 12 Mm of the sunspot umbra. The filling factor is 0.2–0.3 here, and the relative Doppler velocities (without Evershed's effect) are from −1.7 to −3.1 km/s (plasma lifting). Similar parameters were also obtained for the second sunspot.

Keywords: Sun; Sunspot umbra; Magnetic field diagnostics; Spatially unresolved structures; 8-kilogauss fields

1. Introduction

At present, the phenomenon of extremely strong magnetic fields in sunspots has been studied insufficiently. It is well known that typical magnetic field strengths in large sunspots (⩾20 Mm) are usually from 2000 to 3000 G (Solanki, 2003; Lozitska, 2010). Magnetic fields in the range of 3500–6100 G were observed too, but very seldom (Baranovsky and Petrova, 1957; Steshenko, 1967; Livingston et al., 2006).

These values correspond to the dominant field strengths, i.e. having a filling factor of about unity ($f \approx 1$). However, a sunspot has a very fine structure of a magnetic field and velocities, with the smallest elements at the level of several tens or even several units of kilometers (Sánchez Almeida, 1998).

For such elements $f \ll 1$, and, therefore, they should give a very weak Zeeman manifestation in the spectrum. Probably, the strongest magnetic fields can exist just in such 'super-fine' structures.

This assumption arises both from observations and theory. With regard to the observations, Stenflo (1966) found that measured magnetic fields on the Sun are the stronger, the higher is spatial resolution. In the case of spatially unresolved magnetic fluxtubes, real field values in them can be determined by an indirect method only, e.g. line ratio method (Stenflo, 1973; Wiehr, 1978; Rachkovsky et al., 2005). This method gives a 'kilogauss' (kG) field range, 1.1–2.3 kG, in spatially unresolved magnetic fluxtubes outside sunspots. Quiet-Sun internetwork magnetic fields observed in the infrared Fe I 15,648 Å line show that most of the observed fields are weak, with relatively few kG

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features (Khomenko et al., 2003). In both cases, line ratio measurements and infrared observations, spectral lines with high Lande factors ($g_{eff} = 1.67–3$) were used. In practice, such lines are useless for measurements of extremely strong fields, of $\geqslant 10^4$ G range (Lozitsky, 2015). It is necessary to remember that observations of some spectral effects in lines with very low Lande factors ($g_{eff} \approx -0.01$) show that just such 'superstrong' fields could exist, at least in solar flares.

As to theory, an interesting point of view was presented by Stenflo (2000). It is based on the so-called "similarity transformations" (Alfven and Falthämmar, 1963). Stenflo (2000) wrote: "Let us assume that the linear scale is changed by a factor γ. Then Maxwell's equations demand that the time scale is also changed by the same factor. The condition that the energies are left unchanged requires that $\boldsymbol{E}l$ should not change, where $\boldsymbol{E}$ is the electric field, and l is a length. Since l scales with γ, it follows that $\boldsymbol{E}$ must scale with γ^{-1}. Then Maxwell's equations demand that the magnetic field $B \sim \gamma^{-1}$ and the electric current density $\boldsymbol{j} \sim \gamma^{-2}$, while the electrical conductivity $\sigma \sim \gamma^{-1}$ according to Ohm's equation...".

According to this criterion, we can expect very strong magnetic fields in very small spatial scales. For instance, if the size of a structure decreases by two orders, then the magnetic field strength increases in this structure also by two orders. Thus, from this point of view, we can expect that $10^4–10^5$ G fields are possible but in very small structures.

We should point some difficulties in finding such superstrong fields in spots.

Firstly, due to a low filling factor, we can expect very weak photometric effects comparable with noise fluctuations in intensity. In some cases, $f \approx 0.2–0.3$ (Lozitsky, 2016), but, generally speaking, it is not known how unique such cases are. In particular, there is no certainty that all of the great sunspots include areas of particularly strong fields with a relatively high filling factor.

Second, the spectral manifestations (i.e., Zeeman σ components) of especially strong magnetic fields can be very narrow – as in flares and in sunspots (Lozitsky, 2015, 2016). Such spectral peculiarities can be identified erroneously as random noise fluctuations.

Third, not entirely clear is the range of relative radial velocities in the relevant structures with particularly strong fields. Van Noort et al. (2013) found essential velocities (20 km/s) of plasma lowering in places with very strong ($B > 7$ kG) fields. In the areas of 8-kG magnetic fields of the sunspot umbra, the Doppler velocity was found to be negative (plasma lifting) and one order smaller, about 2 km/s (Lozitsky, 2016). When magnetic fields reach 7–8 kG and the Doppler velocities reach 20 km/s, the Fe I 6301.5 and 6302.5 lines should be considered as mutually blended. Of course, this complicates the diagnostics of very strong fields.

Fourth, the Fe I 6301.5 and 6302.5 Å lines are blended by the telluric lines of 6302.000 and 6302.764 Å, and by the molecular line 6302.090 (in the sunspot umbra). In this connection, space observations (e.g., with Hinode) are especially appropriate.

This paper is a direct continuation of the study published earlier by Lozitsky (2016). To remind, the preliminary indications about the 8 kG fields in the 5 Mm area of the spot umbra were found there. In this study, we are expanding the scope of the search for the specified fields of over 5 Mm of the same sunspot and, additionally, we are investigating another great sunspot with the same purpose.

2. Observations and profiles of lines

We studied magnetic fields in two large sunspots which were observed on October 29, 2003 and October 25, 2014. The observations were carried out with an Echelle spectrograph of the horizontal solar telescope of the Astronomical Observatory of the Taras Shevchenko National University of Kyiv (Kurochka et al., 1980; Lozitsky, 2016). These spots were the largest in the active regions NOAA 10,488 and 2192, and had the diameters of the penumbra of 70 and 72 Mm, respectively. The first spot was in the leading area of the 10,488 group, whereas the second, in the tail area of the 2129 group. In this second sunspot, three cores of various sizes and shapes existed inside a common penumbra. We analyzed here the largest umbra of about the 22 Mm diameter, with a nearly round shape. During the observations, the $I + V$ and $I - V$ spectra were recorded using ORWO WP3 plates. Exposures were 30 s and started at 12:53:50 UT for the first sunspot and at 11:03:00 UT, for the second one.

The magnetic fields in the sunspots were investigated using the Fe I 6301.5 and 6302.5 Å lines. These lines have the nearest heights of formation in the atmosphere but different effective Lande factors, $g_{eff} = 1.669$ и 2.487, respectively (Zemanek and Stefanov, 1976). In the first approximation, these lines can be viewed as one and the same line with two discrete Lande factors, with their ratio of 1.5. This is highly valuable in the line ratio method (Stenflo, 1973) which makes it possible to study spatially unresolved magnetic fields.

The following peculiarities are observed in the $I \pm V$ profiles (Figs. 1 and 2):

(a) the Fe I 6302.5 Å line has partly separated Zeeman π- and σ-components in both sunspots, whereas the Fe I 6301.5 Å line blended these components;
(b) the splitting of $I \pm V$ profile bisectors in the Fe I 6301.5 Å line is different at different distances from the line center, especially in the first sunspot (October 29, 2003). Namely, this splitting has the maximum in the line core, and the minimum, in the middle wings, and the second maximum, in the far wings. It should be noted that, by theory, in a homogeneous field the splitting of bisectors should be monotonous, without the second maximum (Lozitsky, 2016);