Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 57 (2016) 398–407

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Indications of 8-kilogauss magnetic field existence in the sunspot umbra

V.G. Lozitsky

Astronomical Observatory of Taras Shevchenko National University of Kyiv, Observatorna 3, Kyiv 01053, Ukraine

Received 6 March 2015; received in revised form 27 August 2015; accepted 28 August 2015
Available online 4 September 2015

Abstract

We present magnetic field diagnostics in two big sunspot of different magnetic polarity observed on 18 May 2002 and 29 October 2003. In these sunspots, according to visual measurements, magnetic field strength in Fe I 5250.2 Å line was about 3500 gauss. The existence of stronger fields follows from the detailed study of fine spectral effects in I ± V and V profiles of Fe I 6301.5 and 6302.5 Å lines, such as: (a) non-parallelism of bisectors in Fe I 6301.5 line related to distance about ±250 mÅ from the line center, and (b) weak secondary Stokes V peaks on distance, on the average, ±375 mÅ from the Fe I 6302.5 Å center. Consequently, we argue that these peculiarities indicate to the fact that spatially unresolved magnetic fields exist in the sunspot umbra, their strength being about 8 kG. In small structures with such very strong fields magnetic polarity was the same as in the background field of the sunspot umbra, and Doppler velocity is about −1.9 km/s (lifting of plasma).

Keywords: Sun; Sunspots; Magnetic fields; Spatially unresolved structures; Extremely strong fields

1. Introduction

Sunspots are well-visible manifestations of solar activity with slow evolution and long lifetime. Their diameters range from a few to 150–170 mega-meters (Mm) which is much more than spatial resolution of modern solar telescopes (Solanki, 2003; Babij et al., 2011). This is the reason why they are suitable objects for magnetic field measurements. First such measurements were made by Hale (1908) using observations of the Zeeman effect in solar spectral magnetosensitive lines. It was found that in developed sunspots with umbra and penumbra typical magnetic field strengths vary as rule, from 2000 to 3000 gauss (G). In small sunspot without penumbra (i.e. pores), direct measurements give somewhat lower values, from 1100 to 2500 G (Steshenko, 1967; Solanki, 2003). It was established that magnetic field strength in sunspots, in general, increases on the sunspot diameter. Due to this fact, to study temporal changes of sunspot magnetic fields during the 11-year solar cycle, the fixation of sunspot diameter is needed (Lozitska, 2010).

It was shown that for sunspots of 22–44 Mm, the average annual strengths in umbra vary in the range of 2100–2900 G.

Sunspots, similar to other features of the Sun, have a very fine structure of magnetic fields and velocities. The most distinctly one can see this structure in the sunspot penumbra. The smallest elements of this structure are likely to be spatially unresolved, as the true size of the mentioned elements is estimated at the level of several tens or even several units of kilometers (Sánchez Almeida, 1998), whereas the best spatial resolution on modern solar telescopes is 70–100 km. Due to this fact, direct magnetic field measurements give some average parameters of magnetic fields, which may, in a general case, strongly differ from local magnetic fields. This difference should be most essential in such places on the Sun where filling factor f is much smaller than 1 ($f \ll 1$). However, in the sunspot umbra,

---

E-mail address: lozitsky_v@ukr.net

http://dx.doi.org/10.1016/j.asr.2015.08.032
0273-1177/

where $f \approx 1$ (Solanki, 2003), direct measurements give the reliable value of the local magnetic fields (Lozitska et al., 2015).

Sometimes the strongest magnetic fields in sunspot umbrae reach 4000–5000 G. Livingston et al. (2006) reported one case only where magnetic field strength was 6100 G. Recently, Van Noort et al. (2013) first discovered the field over 7000 G in a sunspot penumbra, where velocities were about 20 km/s. Excellent comparative characteristics of above articles was made by the anonymous reviewer: 'It is important to note that the magnetic field strengths in Livingston et al. (2006) and Van Noort et al. (2013) were determined by very different methods. In the case of Livingston et al. (2006) these are direct observations of Zeeman splitting in various spectral lines with large Lande factors based on the line intensity profile. In the case of Van Noort et al. (2013), they analyze full Stokes vector spectropolarimetry with an indirect Fourier technique to get information about the smallest spatial scales. The probable mechanisms behind the large magnetic field strengths are well developed in each paper. In the case of Livingston et al. (2006), very large sunspots horizontal force balance of the cool atmosphere requires additional support from a large magnetic field, while cooling also lowers the optical depth and depresses the level of the photosphere in the umbra, allow us to see larger fields. In the case of Van Noort, they also claim that the high field strengths they see in the penumbra actually originate deep between granules in the convection zone (again because the opacity is low) where field strengths should be higher corresponding to the larger gas pressure'.

At present, it is unknown why and how often such extremely strong fields occur. Steshenko (1967) observed the field of 5350 G in a relatively small area ($\leqslant$2 arc sec) of the umbra of a great sunspot, whereas outside this area the magnetic field was much weaker. Taking into account that both penumbra and umbra have very fine structure, it is most likely that the extremely strong fields ($\geqslant$7 kG) can occur in sunspot umbra too.

As to spectral manifestations of such a case, we can expect a complicated picture of the Zeeman effect, with superposition of, at least, two components with different magnetic fields and filling factors: the first (background) component has a lower magnetic field but a bigger filling factor, while the second (subtelescopic) one has stronger magnetic fields but a smaller filling factor. In principle, the true physical parameters of both components could be determined on the basis of comparison of observed profiles with theoretical ones calculated for different models of magnetic field, velocity and atmosphere.

The simplest case is when Zeeman splitting $\Delta\lambda\mathrm{H}$ in a small-scale (spatially unresolved) component is much bigger than spectral half-width $\Delta\lambda 1/2$ of magnetosensitive line ($\Delta\lambda\mathrm{H} \gg \Delta\lambda 1/2$). In this case, two discrete and fully separate Zeeman pictures are observed in one and the same spectral line which corresponds to different magnetic fields and velocities. This allows for obtaining reliable magnetic field parameters in each component independently from any assumption about models of the magnetic field and atmosphere.

In a more complicated case $\Delta\lambda\mathrm{H} \leqslant \Delta\lambda 1/2$ in both magnetic components (Gordovskyy and Lozitsky, 2014). This case also calls for a two-component model, but the problem is that the number of free parameters of such a model is too high, about ten. This leads to using some simplest assumptions that lead to ambiguity of final conclusions (Rachkovsky et al., 2005).

An alternative approach is to use, for comparison, a simple theoretical one-component model, and to analyze the deviation of observations from such a model. For this purpose, the consideration of bisectors of $\mathrm{I} \pm \mathrm{V}$ profiles proves to be a very convenient and simple method (Lozitsky, 2015). This method is used in the present study. Also, a second (more direct) method is employed here, namely the search of spectral manifestations of full Zeeman splitting ($\Delta\lambda\mathrm{H} \gg \Delta\lambda 1/2$) in a spectral line with a large Lande factor.

2. The instrument

The observations were made with Echelle spectrograph of horizontal solar telescope of Astronomical Observatory of Taras Shevchenko National University of Kyiv, AO KNU (Kurochka et al., 1980). The optical scheme of this instrument is given in Fig. 1.

In this Figure: M_1 and M_2 – coelostat flat mirrors with diameters of 310 and 350 mm, respectively, M_3 – the main telescope mirror, with the diameter of 300 mm and focusing distance of 12,500 mm, M_4 – throwing-back-mirror with the diameter of 150 mm, $\lambda/4$ – a quarter-wave plate, *ES* – enter slit of the spectrograph, P_1 – splitting-beam-prism made of Iceland spar, M_5 – collimator's mirror with the diameter of 150 mm and focus of 6000 mm, *G* – Echelle diffraction grating. This grating measures 100 × 150 mm, has 50 strokes per mm and diffraction angle 30°. In order to separate the different diffraction orders (from 31 to 56 in visual band), the glass prism P_2 is used with the refraction angle of 12°. M_6 is the camera's mirror with the diameter of 500 mm and focus of 6500 mm, and *PP* is a photoplate. This instrument can simultaneously record the solar spectrum from 3800 to 6600 Å with the spectral resolution of nearly 200,000 (i.e. 30 mÅ) in the green region and with the temporal resolution of about several seconds. The spatial resolution of observations depends mainly on image vibration and equals, as rule, 2–3 arc sec during the morning observations. As rule, typical equivalent length of the spectrograph exit slit is about 35 arc sec, i.e. 25 Mm.

Although the spatial resolution of observations on the instrument is low, it has the following advantages:

(a) a wide spectral range, from 3800 to 6600 Å, of the simultaneous recording; for this goal large (180 × 240 mm and 240 × 240 mm) ORWO WP3 photo-plates are used;