ISSN 0236-2457

ASTRONOMICHESKII TSIRKULYAR

Published by the Eurasian Astronomical Society
and Sternberg Astronomical Institute

No. 1612, 2014 July 10

COMPARATIVE CHARACTERISTICS OF THE LEADING AND FOLLOWING SUNSPOTS

Yu.S. Zagainova[1], **V.G. Fainshtein**[2], **and V.N. Obridko**[1]

[1]*Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation, Russian Academy of Sciences, Kaluzhskoe shosse 4, Troitsk, Moscow 142190, Russia. E-mail: yuliazagainova@mail.ru*

[2]*Institute of Solar-Terrestrial Physics, Siberian Division of the Russian Academy of Sciences, P. O. Box 291, Irkutsk, 664033 Russia*

Received July 8, 2014

Abstract. Magnetic characteristics of the leading and following sunspots are compared using SDO/HMI and SDO/AIA high-resolution data, and the properties of the solar atmosphere over sunspots are discussed separately for each category of sunspots.

1 Introduction

According to photospheric observations, sunspots are the features characterized by reduced temperature and brightness and by increased intensity of the magnetic field as compared to the ambient photosphere (Bray and Loughead, 1967; Obridko, 1985; Maltby, 1992). Many years of sunspot studies have given rise to the present-day notion of the solar activity, one of the most common measures of which is the Wolf number, i.e., the number of sunspots and sunspot groups observed simultaneously on the visible solar disk (Vitinsky et al., 1986).

It is known that sunspots with different properties often form sunspot groups. The westernmost spot in a group, called the leading or head spot, usually has a larger area and is located closer to the equator than the other spots. The spots of opposite polarity are called the following or tail spots. In the majority of studies conducted to date, the properties of all sunspots were considered together without separation into the leading and following ones. The publications, in which the properties of the leading and following spots are compared either in general or within one group, are relatively scarce, and they do not describe any other differences between these two categories, except the field polarity and rotation rate (see, e.g., Bray and Loughead, 1964; Obridko, 1985; Gilman and Howard, 1985). However, the recent studies based on observations in different spectral ranges have shown that the properties of the leading and following spots differ noticeably. For example, Zagainova (2011) showed that, in the declining phase of cycle 23, the umbral contrast of the leading spots in a group and solitary spots with well-pronounced umbra and penumbra observed in the $\lambda\,304$ Å line was, on the average, lower than that of the following spots; and, in both types of spots, it did not change much with the growth of the umbral area. The magnetic characteristics of the leading and following spots were also found to differ (Zagainova et al., 2014).

This paper continues the study initiated by Zagainova (2011) and Zagainova et al. (2014). Here, we compare the characteristics of the leading and following spots using high-resolution data obtained with the SDO/HMI and SDO/AIA instruments during the rising phase and maximum of cycle 24.

2 Data and methods

From the data obtained during the observation period 2010–2013, we have selected the groups in which the leading and following spots formed pairs connected by the magnetic field lines. The magnetic field was calculated using the "potential field – source surface" model by Rudenko (2001). Besides that, we selected solitary spots with a regular, circular or near-circular umbra.

To estimate the degree of UV brightness of the solar atmosphere over sunspots, we have used the contrast in line parameter known from the spectral analysis. As earlier, in (Zagainova, 2011), we studied the contrast of the sunspot umbra in the $\lambda\,304$ Å line. For this purpose, we used SDO/AIA images of the solar disk in the 304 Å channel. The sunspot contrast at $\lambda\,304$ Å was determined from the ratio $C_{304} = I_{\rm S}/I_0$, where $I_{\rm S}$ and I_0 are the counts of intensity in the sunspot umbra and in the undisturbed photosphere, respectively. The umbral area for each spot was found from the sunspot continuum images taking into account the SDO/HMI spatial resolution and was expressed in the millionths of the visible solar hemisphere.

The umbral magnetic field was analyzed using HMI observations of the vector magnetic field (http://hmi.stanford.edu/). In this work, we have analyzed the following parameters of the umbral magnetic field: $\alpha_{\rm min}$ – the minimum angle between the field direction and the normal to the solar surface at the measurement point, $B_{\rm max}$ and $\langle B \rangle$ – the maximum and the mean magnetic induction, respectively. In sunspots with the negative magnetic polarity (the field vector directed towards the Sun), $\alpha_{\rm min}$ proved to be more than 90°. To compare it with the respective angles in the positive polarity spots (the field vector directed away from the Sun), we subtracted the $\alpha_{\rm min}$ values obtained from 180°.

3 Results

We compared the umbral contrast in the $\lambda\,304$ Å line for the leading and solitary spots (hereinafter referred to as $C_{304-\rm ls}$ and $C_{304-\rm ss}$), on the one hand, and the following spots ($C_{304-\rm fs}$), on the other, in the rising phase and at the maximum of cycle 24 (2010–2013) (Figure 1). One can see that, the same as in (Zagainova, 2011), the contrast of the leading/solitary and following spots is, on the average, different; and for both categories of sunspots, it depends weakly on the umbral area, S. However, the mean contrast for both categories of sunspots proved to be higher than reported in (Zagainova, 2011). This may be due to two factors: (1) the use of data from different instruments with different spatial resolution, and (2) the use of data obtained in different phases of solar activity. The results presented in this paper refer to the rising phase and maximum of cycle 24 characterized by some abnormal features (e.g., Akhtemov et al., 2014), while the results reported by Zagainova et al. (2011) refer to the declining phase of cycle 23. It is possible that the sunspot contrast C_{304} in cycle 24 was also abnormal.

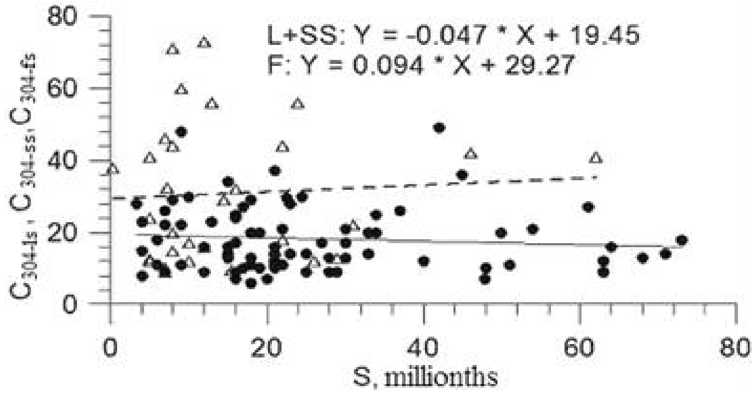

Figure 1: The contrast in the λ304 Å line as a function of the umbral area for the leading and solitary spots (L+SS; circles) and for the following spots (F; triangles). The straight lines are the regression lines.

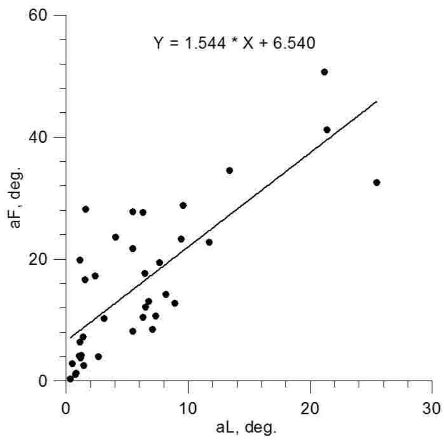

Figure 2: Relation between the minimum angles between the field direction and the normal to the solar surface in the umbrae of leading ($\alpha_{\rm min-L}$) and following ($\alpha_{\rm min-F}$) spots.

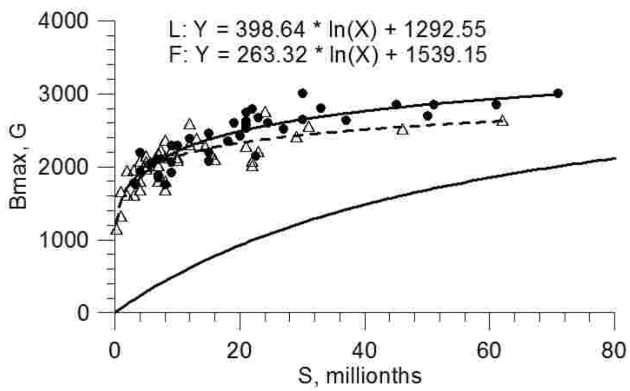

Figure 3: $B_{\rm max}$ as a function of the umbral area in the leading (L; circles) and following (F; triangles) spots. The dashed and the thick solid lines are the corresponding regression lines. The thin solid line illustrates the Houtgast and van Sluiters dependence between the magnetic induction and sunspot area (Bray and Loughead, 1964).

Using vector magnetic-field data, we determined and compared the properties of the umbral magnetic fields in the leading and following magnetically conjugate sunspots (Figure 2). It was found that, in ~84% of the sunspot pairs analyzed, the minimum angle between the field direction and the normal to the solar surface in the leading spots is smaller than in the following ones. For the sunspots that meet this condition, $\langle\alpha_{\rm min-L}\rangle \approx 6.91^\circ$ in the leading spots and $\langle\alpha_{\rm min-F}\rangle \approx 16.42^\circ$ in the following ones. These values are much smaller than Zagainova et al. (2014) obtained using magnetic-field calculations under potential approximation. Besides, a positive correlation with a coefficient of ~0.75 is revealed between $\alpha_{\rm min-L}$ and $\alpha_{\rm min-F}$ at $\alpha_{\rm min-L} \le \alpha_{\rm min-F}$. And, finally, this work corroborates the conclusions drawn by Zagainova et al. (2014) that a weak negative correlation exists between $\alpha_{\rm min-L}$ and $\alpha_{\rm min-L}$, on the one hand, and the sunspot umbra (S) and the maximum magnetic induction ($B_{\rm max}$), on the other.

We have compared the relation between $B_{\rm max}$ and S for the leading and following spots (Figure 3). According to the Houtgast and van Sluiters dependence for $B_{\rm max}(S)$ (Bray and

Loughead, 1967) and as shown by recent measurements of the vector magnetic field (Jin et al., 2006), the magnetic induction in the sunspot umbra increases with the increase of the umbral area in the entire known range of S. Our analysis has shown that (1) the nature of the $B_{\max}(S)$ variation differs in the leading and following spots, and (2) in both categories of sunspots, a rapid increase of $B_{\max}$ with the increase of S ends in a kind of "quasi-saturation", when the further increase of S has little effect on $B_{\max}(S)$. Note also that quasi-saturation for the following spots begins at smaller values of S and $B_{\max}$.

Our analysis has revealed a negative correlation between $\alpha_{\min-\mathrm{L}}$ and $C_{304-\mathrm{L}}$, as well as between $\alpha_{\min-\mathrm{F}}$ and $C_{304-\mathrm{F}}$ provided that the sunspots under consideration satisfy the conditions $\alpha_{\min-\mathrm{L}} \leq \alpha_{\min-\mathrm{F}}$ and $C_{304-\mathrm{L}} \leq C_{304-\mathrm{F}}$. It turned out that with the increase of the $\alpha_{\min}$ ratio for the leading and following spots the ratio of the umbral contrast at $\lambda 304$ Å in these spots decreases. It was also found that the dependence between the contrast, C_{304}, and the sunspot umbral area is very weak.

References

Akhtemov Z.S., Andreeva O.A., Rudenko G.V., Stepanian N.N., and Fainstein V.G.. Bull. Crimean Astrophys. Observ. **110**, 108 (2014).

Bray R.J. and Loughead R.E., *Sunspots* (London: Chapman & Hall, 1964; Russ. transl. Moscow: Mir, 1967).

Gilman P.A. and Howard R., ApJ, **295**, 233 (1985).

Jin C.L., Qu Z.Q., Xu C.L., Zhang X.Y., and Sun M.G., Astrophys. and Space Sci. **306**, 23 (2006).

Maltby P., in: *Sunspots: Theory and Observations; Proceedings of the NATO Advanced Research Workshop on the Theory of Sunspots, Cambridge, United Kingdom, Sept. 22–27, A93-47383 19–92*, p.103 (1992).

Obridko V.N. *Sunspots* (Moscow: Nauka, 1985).

Rudenko G.V., Solar Phys. **198**, 5 (2001).

Vitinsky Yu.I,, Kopecký M., and Kuklin G.V. *Statistics of the Sunspot Formation Activity in the Sun* (Moscow: Nauka, 1986).

Zagainova Yu.S., Astron. Rep. **55**, 159 (2011).

Zagainova Yu.S. et al., Astron. Rep., in press (2014).

Сравнительные характеристики ведущих и ведомых солнечных пятен

Ю.С. Загайнова[1], В.Г. Файнштейн[2] и В.Н. Обридко[1]

[1]*ИЗМИРАН, Троицк, Москва, 142190, Россия*
E-mail: yuliazagainova@mail.ru

[2]*ИСЗФ, п/я 291, Иркутск, 664033, Russia*

Резюме. На основании данных высокого разрешения SDO/HMI и SDO/AIA проводится сравнение магнитных характеристик ведущих и ведомых солнечных пятен. Отдельно для каждой категории пятен обсуждаются свойства солнечной атмосферы над пятнами.