ISSN 0236-2457

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Published by the Eurasian Astronomical Society
and Sternberg Astronomical Institute

No. 1605, 2013 October 21

MAGNETIC FIELDS IN ON-DISC SOLAR FLARES MEASURED IN THE Hα AND D$_3$ LINES

Магнитные поля во вспышках на солнечном диске по измерениям в линиях Hα и D$_3$

Abstract. We present magnetic field measurements in two solar flares on the solar disc observed on 16 June 1989 and 29 July 2002 of importance 2B and M4.7/2N, respectively. Magnetic field strengths in the flares are studied by means of $I \pm V$ profiles of Hα and D$_3$ HeI lines. The field strengths of 1600–2600 G were measured in the former flare and 200–1000 G in the latter. We have found close positive correlation between Hα and D$_3$ HeI data: on the average magnetic field ratio between Hα and D$_3$, $B_{0.9}(\mathrm{H}\alpha)/B_{0.9}(\mathrm{D}_3) = 0.90 \pm 0.07$. Comparison of D$_3$ with well-known FeI 6173.3 line has shown that in general $B_{0.9}(\mathrm{D}_3)/B_{0.9}(6173) = 0.99 \pm 0.05$. This is an obvious evidence that our measuring technique yields reliable results. As in our previous work [3], we have found anticorrelation of the Hα and D$_3$ HeI data related to different heights of active prominences (3–14 Mm), where the field strengths were 200–2000 G. We conclude that in active prominences (a) regions of the of Hα and D$_3$ line emission can be sufficiently different and (b) probably, strong mixed-polarity fields exist here.

Резюме. Представлены измерения магнитных полей в двух вспышках на диске Солнца наблюдавшихся 16 июня 1989 г. и 29 июля 2002 г. и имевших балл B и M4.7/2N соответственно. Напряжённости магнитного поля во вспышках исследовались при помощи профилей $I \pm V$ линий Hα и D$_3$ HeI. Измеренные напряжённости поля составляют 1600–2600 Гс в первой вспышке и 200–1000 Гс во второй. Найдена тесная положительная корреляция между данными в линиях Hα и D$_3$ HeI: в среднем отношение напряжённостей поля $B_{0.9}(\mathrm{H}\alpha)/B_{0.9}(\mathrm{D}_3) = 0.90 \pm 0.07$. Сравнение D$_3$ с хорошо известной линией FeI 6173.3 показывает, что в целом $B_{0.9}(\mathrm{D}_3)/B_{0.9}(6173) = 0.99 \pm 0.05$. Это свидетельствует, что наша методика измерений даёт надёжные результаты. Как и в нашей предыдущей работе [3], найдена антикорреляция данных в линиях Hα и D$_3$ HeI, связанных с различными высотами активных протуберанцев (3–14 Мм), где напряжённости поля составляли 200–2000 Гс. Сделан вывод, что а) области эмиссии линий Hα и D$_3$ могут быть существенно различными и б) там, вероятно, существуют поля смешанной полярности.

Introduction. At present it is well known that the major part of flare energy is released in the chromosphere and corona. Namely, in these atmospheric layers one can expect the basic magnetic field transformation to other forms of flare energy. In this connection, just magnetic field measurements in the chromosphere and corona are of primary importance for the study of flares. Unfortunately, magnetic field measurements in flares are not so simple as in sunspots. First of all, solar flares occur suddenly and develop rapidly. The most interesting phases of a flare can be missed if observations are carried out in a non-continuous regime. Such non-continuous regime is usual for spectral observations, but precisely spectral observations are most suitable for magnetic field measurements in flares. As for instruments operating in the automatic regime like SOHO/MDI filter magnetograph, they yield mainly longitudinal magnetic field component, no field module. In addition, during the most powerful flares virtually all spectral lines have more or less intense flare emission. In some cases this emission distorts the magnetographic signal sufficiently and results in spurious field values and even wrong measured polarity [2, 6].

The Hα and D$_3$ HeI lines are attractive for spectral magnetic field measurements in flares owing to the following circumstances. Both lines have similar Landé factors ($g = 1.05$ and 1.06, respectively), but different temperature sensitivity: Hα produces visible emission at a lower temperature than D$_3$. This is one of the causes why Hα is visible even in weak flares on the solar disc, whereas D$_3$ appears only in bright and powerful flares. On the other hand, in prominences and limb flares occurring in the lower solar corona one can see well visible emission both in D$_3$ and in Hα. Naturally, in the latter case we can expect a wide dispersion of temperatures that can provide necessary conditions for the excitation of the emission in both lines simultaneously. In this connection, the following interesting question arises: maybe these lines, formed in volumes with different temperatures, can indicate also very different magnetic fields?

Surprisingly, just this case was found by the authors in two active prominences [3]. We found anticorrelation of Hα and D$_3$ data, an effect that has no analogy for photospheric magnetic fields (see, e.g., [9]). If this effect is real we can expect some unique types of strong mixed polarity fields (see Discussion in our above-mentioned paper). But, on the other hand, we should carefully check our technique of spectral measurements in order to exclude any instrumental effects.

One of possible ways of such verification is magnetic field measurements in both lines in regions with strong quasi-uniform fields, for instance, in flare knots observed over large sunspot umbra, where a quasi-uniform field could be expected. In addition, similar data are of independent interest, because they present direct measurements for different levels of the solar atmosphere.

Observations and line profiles. Observations of the flares were carried out with the Echelle spectrograph of the horizontal solar telescope of the Astronomical Observatory of the Taras Shevchenko National University of Kyiv [1]. Two solar flares, of 16 June 1989 and 29 July 2002, of importance 2B and M4.7/2N, were observed not far from the solar disc center: the cosine of their heliocentric angle μ was 0.935 and 0.92, respectively. In this work we study two Zeeman spectrograms of the flares obtained at 05:29:30 and 10:41:30 UT.

Figure 1 illustrates spectral effects in the first flare. In this figure, the left column presents Hα, middle D$_3$, and right FeII 5018.4 ($g = 1.9$). Narrow absorption lines blending the first two lines are telluric H$_2$O lines. These telluric lines can be considered as spectral benchmarks with the same wavelength in both spectra. One can see a mutual shift of the flare emission in the $I + V$ and $I \pm V$ spectra, especially in D$_3$ and FeII.

The observed Stokes $I \pm V$ profiles have the following peculiarities (Fig. 2). The Hα line has broad emission profiles (1.3–1.5 Å) with a flat top and well visible splitting of the $I + V$ and $I \pm V$ profiles, which suggests the presence of a strong (kilogauss range) magnetic field. The D$_3$ line profiles are asymmetric, with a sharp top; they have obvious Zeeman splitting, too. It is important to note that the sign of splitting is the same for both lines; in particular, it corresponds to the N polarity in the case of Fig. 2. Also, one can see that the Hα profiles

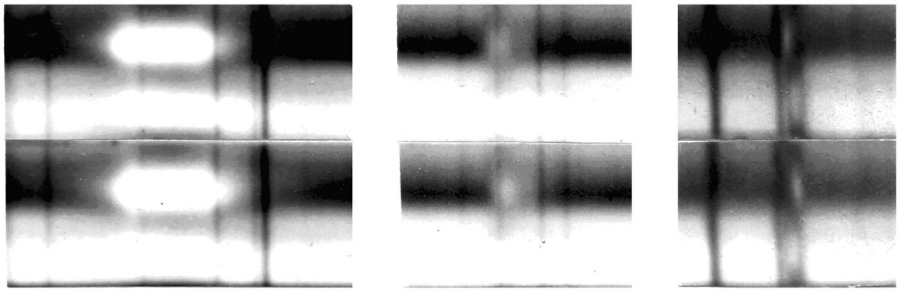

Figure 1: Fragments of the Echelle Zeeman spectrogram ($I+V$ and $I\pm V$ spectra) of the flare of 16 June 1989 showing the flare emission in some spectral lines.

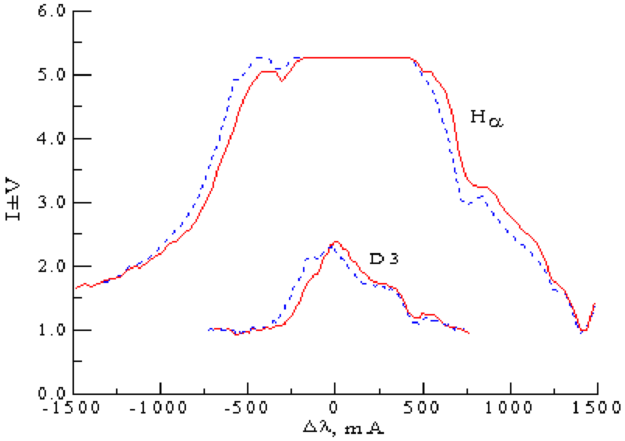

Figure 2: Observed Stokes profiles for Hα and D_3 lines in the flare of 16 June 1989 (see text).

are almost symmetric, in contrast to the D_3 line. This effect takes place due to three spectral components of this line, with $\lambda = 5875.618$, 5875.650 and 5875.989 Å [5] in the absence of a Doppler shift. Mutual blending of these components produces a smoothed summary picture of only two components: the strong component at about 5875.63 Å and the weak one at 5875.989 Å.

Comparison of the measured magnetic fields. As in our previous paper [3], we have measured Zeeman splitting $\Delta\lambda_{\rm H}$ at a level of 0.9 peak line intensity and calibrated it in magnetic strengths using the well known formula

$$\Delta\lambda_{\rm H} = 4.67 \times 10^{-13} g_{\rm eff} \lambda^2 B, \qquad (1)$$

where $\Delta\lambda_{\rm H}$ and λ are in Å and B is in gauss (G). Such a characteristic, $B_{0.9}$, is a simple observational estimate of the local (amplitude) field in the flare volume. It is useful to remember that in a weak uniform field (when $\Delta\lambda_{\rm H} \ll \lambda_{1/2}$, where $\lambda_{1/2}$ is the line halfwidth) observed Zeeman splitting $\Delta\lambda_{\rm H}$ should be the same at different distances from the line center. As for reality, in solar flares a different case is often observed: a larger splitting of $I \pm V$ profiles nearer to line center than in far wings of the line (the so-called V effect). This effect is a direct evidence for a nonuniform magnetic field that has different values within the equivalent aperture of the instrument [3, 4]. In this case, local (amplitude) magnetic field strengths cannot be measured directly from the original observed profiles; for this purpose, the field modeling is needed, with an accurate consideration of contributions from several magnetic field components with different line profiles and their magnetic splitting. In general, this needs exact data about the physical model of the atmosphere to exclude too numerous free parameters. Since for different flares, in general, very different models of the atmosphere are expected, the true values of local magnetic fields may be obtained as a result of several consecutive approximations. On this way, the first approximation that does not require any modeling consists in direct measurements of the observed magnetic splitting in the parts of line profiles where splitting is maximum. Since maximum splitting is observed, as a rule, nearer to the core of emission profiles, parameter $B_{0.9}$ is the first step to obtaining the true values of local magnetic fields in flares.

The comparison of $B_{0.9}$ values for Hα and D$_3$ is given in Fig. 3 for both flares on the solar disc. One can see that (a) magnetic field range is 200–2700 G and (b) close positive correlation exists between the Hα and D$_3$ data, in contrast to active prominences on the solar limb (Fig. 4), where anticorrelation of analogous data was observed [3]. Similar positive correlations were found also between the Hα and D$_3$ data on the one hand and FeI 6173.3 on the other hand. The last line is the well known unblended Zeeman triplet with a large Landé factor, $g_{\rm eff} = 2.5$. The average observed strength ratios for these lines are: $B_{0.9}(\mathrm{H}\alpha)/B_{0.9}(\mathrm{D}_3) = 0.90 \pm 0.07$, $B_{0.9}(\mathrm{D}_3)/B_{0.9}(6173) = 0.99 \pm 0.05$.

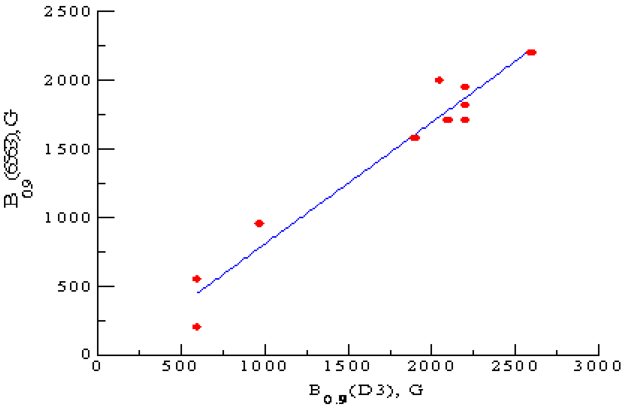

Figure 3: Comparison of fields measured in D$_3$ and Hα in both flares. Typical measurement errors are ±100 G.

Thus, from these data it follows that measured magnetic field strengths in both flares on the solar disc are virtually the same at different atmospheric levels where the FeI 6173, Hα and D$_3$ lines are formed. This is possible if magnetic fields in flare knots in the sunspot umbra are really quasi-uniform. On the other hand, these data present obvious evidence of reliability of the measuring technique used in our previous work [3]. From this point of view, one can confirm that in active prominences (a) regions of the of Hα and D$_3$ emission are rather different and (b) there exist strong mixed-polarity fields. This probably means that the magnetic field structure in the sunspot umbra and in active prominences is substantially different: we do not observe magnetic fields of opposite polarity in sunspots, but such fields are observed in active prominences at heights of 3–14 Mm.

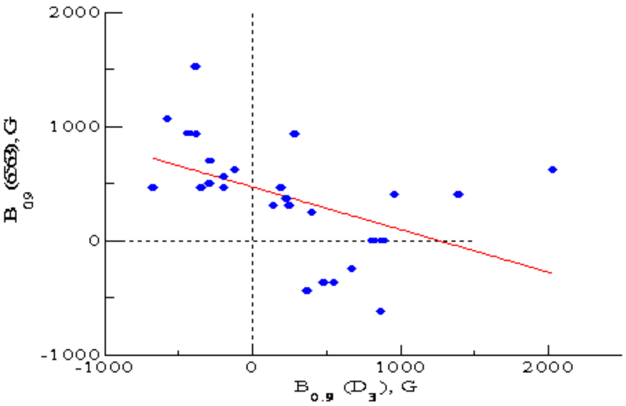

Figure 4: Comparison of measured fields for two active prominences according to [3].

Discussion. The present study as well as some results published earlier reflect a paradoxical situation with the problem of magnetic fields in flares. On the one hand, just such "kilogauss" fields are required for the flare energy release. On the other hand, such fields are "too strong" for the chromosphere and corona, and it should be understood why and how such fields appear in these atmospheric layers. Let us illustrate these points using simple estimations.

In 2012 Prof. A.A. Soloviev (Pulkovo Observatory, Russia) presented at the conference in the Taras Shevchenko National University of Kyiv the following considerations [7]. It is well known that solar flares have energies 10^{26}–10^{32} erg, and the typical volume of energy release associated with bright flare kernels is $(10^9)^3$ cm^3 $=$ 10^{27} cm^3. If a weak field of 10 G exists in above-mentioned volume, then the total energy store is $E = (B^2/8\pi) \times V \approx (100/25) \times 10^{27} \approx 4 \times 10^{27}$ erg, which is much less than 10^{32} erg. If the magnetic field is stronger, 100 G, then the total energy reserve is 4×10^{29} erg, also less than 10^{32} erg. If the magnetic field is of the kilogauss range, $\sim$ 1000 G, then the total energy store is 10^{31} erg, also less than 10^{32} erg. In addition, as it is well known from observations and theory, all magnetic fields do not "burn out" during the flare (probably, $\approx$ 10% of the total magnetic energy). Thus we should assume that stronger fields, of the $\sim 10^4$ G range, must exist in flare volume in order to provide the flare energy!

Furthermore, these very simple estimations were made under the assumption that the magnetic field is the same in the entire flare volume. Obviously, this is an unrealistic approximation: actual solar magnetic fields are very nonuniform, with very fine, filamentary nature. From this point of view, local magnetic fields must be yet stronger, maybe of the $\sim 10^5$ G range.

There are the following very acute problems: how is it possible to concentrate such "superstrong" fields taking into account a huge difference of gas and magnetic pressures?

In fact, a magnetic field of 70–90 kG [4] has a magnetic pressure at a level of 10^8 dyn/cm^2. For comparison, in the upper photosphere the gas pressure is about 10^4 dyn/cm^2, but in the corona and chromosphere it is only 10^{-1}–10^2 dyn/cm^2. The difference between the magnetic and gas pressures reaches 4–9 orders of magnitude! It is incredible that such fields occur in the chromosphere and corona; probably they exist in the convective zone and emerge in the solar atmosphere before the flare.

But even in this case we can expect that magnetic field structure in regions with "superstrong" fields is extremely peculiar to suppress a huge pressure difference, even in a short time.

Obviously, very strong fields cannot occur in the simplest case of an untwisted magnetic flux tube. Stronger fields should exist in twisted force-free magnetic structures. It was shown that a theoretical interpretation of "superstrong" magnetic field phenomena can be offered within the framework of the linear force-free model [8]. This model invokes Bessel functions of the zeroth and first order, J_0 and J_1, and has a multipolar periphery and magnetic field up to $\sim 10^4$ G with discrete values near the tube axis. For a field of 10^4 G, a large number of discrete layers with opposite magnetic polarity are required within one small-scale structure. Perhaps multicomponent emissions and multicomponent magnetic fields [4] are observational manifestations of precisely such structures.

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Received September 19, 2013