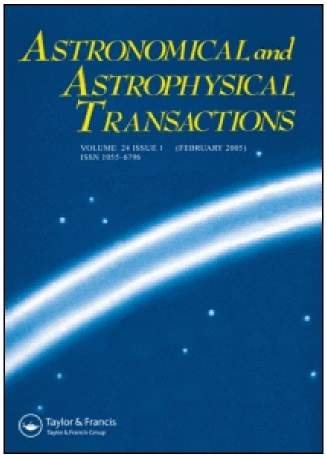

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O. Chumak [a]; H. Zhang [b]; J. Gou [b]
[a] Sternberg Astronomical Institute, Moscow State University, Moscow, Russia
[b] National Astronomical Observatories, Chinese Academy of Sciences, Beijing, PR China

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INTEGRAL PROPERTIES OF THE MAGNETIC FIELDS OF SOLAR ACTIVE REGIONS UNDER QUIET AND FLARE ACTIVITY CONDITIONS

O. CHUMAK[a,*], H. ZHANG[b,†] and J. GOU[b]

[a]*Sternberg Astronomical Institute, Moscow State University, Moscow 119899, Russia*
[b]*National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, PR China*

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The well-known problem of the correlations between eruptive processes in the chromosphere and corona and peculiarities of the magnetic field structure in solar active regions (ARs) on the photospheric level are discussed in this paper. We study the time variations in the first four moments of distribution (over the field) of four integral parameters of the magnetic field of an AR. We used Huairou (PR China) and Solar Orbit Heliospheric Observatory, Michelson–Doppler Interferometer (SOHO/MDI) measurements of longitudinal magnetic fields for ten ARs. We study the following integral parameters of an AR: total magnetic flux F_a, tilting angle A_n, complexity parameter H_u and relative total magnetic flux imbalance O_v. The distributions of these parameters show essential differences between quiet and flare productive ARs. One can observe specific differences in the distributions before and during flares. The four first distribution moments take into account these differences and so they can be good quantitative parameters of the current states of ARs relative to their flare productivity.

KEYWORDS: Solar activity, solar active regions, X-ray flares

1 INTRODUCTION

The question about correlation between the magnetic field properties of solar active regions (ARs) and their flares and solar mass ejection activity has been the subject of permanent discussion for about the last four decades and has resulted in hundreds of papers. The theoretical complexity and practical concerns of the problem have stimulated both the development of plasma behaviour theory in topologically complex strong magnetic fields and the appearance of extensive observation projects on the base of up-to-the-minute technological achievements.

As a result we know at present that, as a rule, both the frequency of flares and their importance in ARs correlate with their size and complexity (Sawyer *et al.*, 1986; McIntosh, 1990). The flare productivity of ARs correlates also with the newly arising magnetic fluxes (see for instance Wang *et al.* (1994), Nitta *et al.* (1996) and Choudhary *et al.* (1998)) and with total realignment of their magnetic fields (Patty and Hagyard, 1986; Wang *et al.*, 1998). However, strict correspondence is absent; some ARs produced large flares under the relatively simple

* Corresponding author. Email: chumak@sai.msu.ru
† Email: hzhang@bao.ac.cn

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morphology of the magnetic fields and not all ARs with a complex structure produced important flares (Patty and Hagyard, 1986; McIntosh, 1990). So, the problem is the lack of rules or indications that could strongly point to power ejections of heat and kinetic energy in the chromosphere and corona for a specific morphology of the photospheric magnetic fields. Our approach to the problem is to use the well-known solutions of force-free fields equations in the solar atmosphere (Priest, 1982). According to these solutions the radial field component B_z can be expressed by the next simple formula

$$B_z(R, z) = B_0 J_0(kR)\ \exp(-lz), \tag{1}$$

where B_0 is the field at the photospheric level, $J_0(kR)$ is the zeroth-order Bessel function, R is the radius in the cylindrical coordinate system us (distance from the source of the field), and k and l are scaling constants.

From equation (1) one can see that, for given values of k and l, a fixed value B_z should be observed which is much higher than B_0. In other words the distribution of the field B_0 over its value corresponds to the distribution of the field over the height z. Consequently, if we take some structural parameter, which we can obtain by calculation from the radial field and which is a function of the field, then this parameter gives us the distribution of the corresponding structural characteristic over height. Therefore the distributions of the structural parameters over the field provide the possibility of monitoring, to a certain extent, the features of magnetic field topology over the whole AR volume. The first moments of these distributions can be considered as variable quantities, which characterize the current state of the magnetic field of the AR as a whole.

2 INTEGRAL PARAMETERS

In this work the distributions (over the field) of the following integral parameters of magnetic field in ARs are considered:

(i) the modulus $F_a(B)$ of the total radial magnetic flux in active region given by

$$F_a = |F_n(B)| + |F_s(B)|, \tag{2}$$

where B is the radial field, and $F_n(B)$ and $F_s(B)$ are the fluxes of the north and south polarities respectively (in 10^{14} webers);

(ii) the flux imbalance $O_v(B)$ given by

$$O_v = \frac{|F_n(B)| - |F_s(B)|}{F_a(B)}; \tag{3}$$

(iii) the tilting angle $A_n(B)$ of the magnetic axis of the group to the local parallel (in degrees);

(iv) the parameter of interosculation of magnetic fluxes of opposite polarities or the complexity parameter $H_u(B)$ given by

$$H_u = \frac{|R_n(B)| - |R_s(B)|}{R_{ns}(B)} \tag{4}$$

where $R_n(B)$ is the equivalent radius of north polarity, defined here as $R_n(B) = [N_n(B)]^{1/2}$, with $N_n(B)$ the square (number of pixels) of the n with polarity, and where $R_s(B)$ is defined similarly.

Further we calculate the first four moments for each of these distributions: *MP*, average value of the parameter P, *DP*, standard deviation of the parameter P; *KP*, asymmetry of the parameter P; *SP* excess, that is *MP* – *DP*. In this way, for each magnetogram we can correlate 16 quantitative integral characteristics of its the magnetic field. These characterize the state of the magnetic field of as AR at the observational moment and change with temporal changes of the field, of the AR.

3 SOME RESULTS

Figure 1 shows the distributions of $H_{\rm u}(B)$ for four quiet ARs as examples. The National Oceanic and Atmospheric and Administration numbers of the ARs are given in the key. From the figure we can see that the distributions have sufficiently regular behaviour without local extrema or any other peculiarities. The values of $H_{\rm u}$ are in range from 0 to 2. To determine the zero, for evaluation of the parameters, we took their average meanings calculated over eight flare non-productive ARs. These are listed in Table 1.

From the table we can see that quiet ARs are characterized by relatively small and well-balanced magnetic fluxes ($MO_{\rm v} \approx 0$), relatively small complexity ($MH_{\rm u} < 0.3$) and average tilting angle of magnetic axis to local parallel ($MA_{\rm n} \approx 30^{\rm deg}$). In Figure 2 as an example we show the typical temporal variations in the distribution of $H_{\rm u}(B)$ for AR 8210 before, during and after the flare X1.1, using Solar Heliospheric. Observatory (SUHO) MDI data. From the figure we can see that essential variation in the $H_{\rm u}(B)$ distribution can be observed from 9 h 35 min, which was approximately 4 h before the flare. Comparison of Figures 1 and 2 demonstrates considerable differences in the $H_{\rm u}(B)$ distributions in quiet and flare active ARs: the diapason of the variation in $H_{\rm u}$ increases sharply (in Figure 2 it is about 0–8.0), and a large

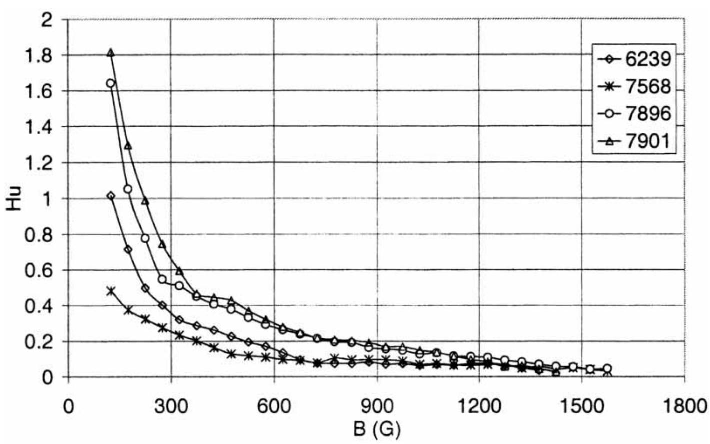

Figure 1. The example of typical distributions of $H_{\rm u}(B)$ in quiet ARs.

Table 1. Parameters of quiet ARs.

	$F_{\rm a}$	$O_{\rm v}$	$A_{\rm n}$	$H_{\rm u}$
MP	1.67	−0.004	33.04	0.241
DP	1.42	0.271	28.21	0.265
SP	0.15	−0.260	−1.01	1.791
KP	0.99	−0.015	2.63	3.310

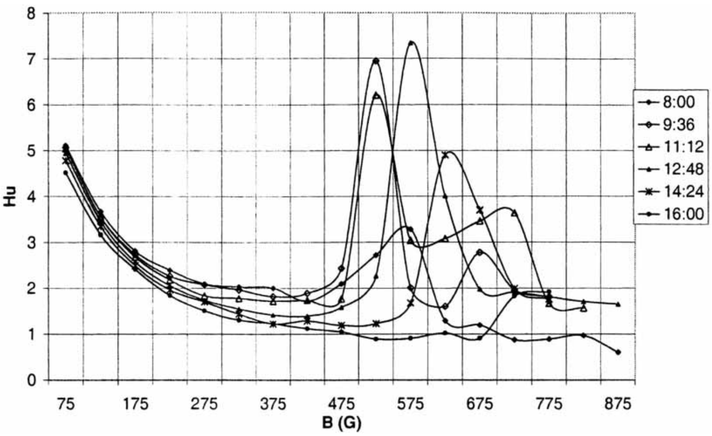

Figure 2. Variation in $H_u(B)$ distributions before, during and after flare X1.1 in AR 8210 at 13 h 31 min on 2 May 1998.

local extremum appears. Such variations in the distributions of the parameters could easily be traced from the variation in their four moments.

The investigation of temporal variation of these moments before, during and after flares was exactly the aim of this work. At present the flare situations of three ARs are considered:

(i) 6659: M19 (1N), start at 5 h 48 min on 9 June 1991;
(ii) 6891: X2.5 (3B), start at 6 h 11 min on 30 October 1991;
(iii) 8210: X1.1 (1B), start at 13 h 31 min on 2 May 1998.

The first two ARs were observed in Huairou (PR China), for AR 8210, SOHO–MDI data have been taken. Since it is impossible to demonstrate and comment on all the pictures in one paper, we give several typical examples of the temporal variations in our parameters before and during flares and also conclusions from all the obtained results. Figures 3–6 demonstrate temporal variations in the first four moments of the $H_u(B)$ distribution before, during and after flares in AR 6659 and AR 6891. The start and finish of the flares are indicated in the figures by dashed vertical lines. These figures demonstrate notable variations in amplitude in

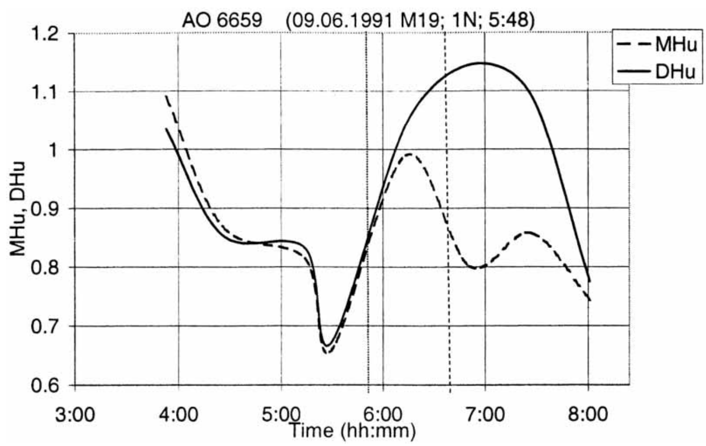

Figure 3. Temporal variations in the average value MH_u and standard deviation DH_u of the $H_u(B)$ distribution before, during and after flare M19 in AR 6659.

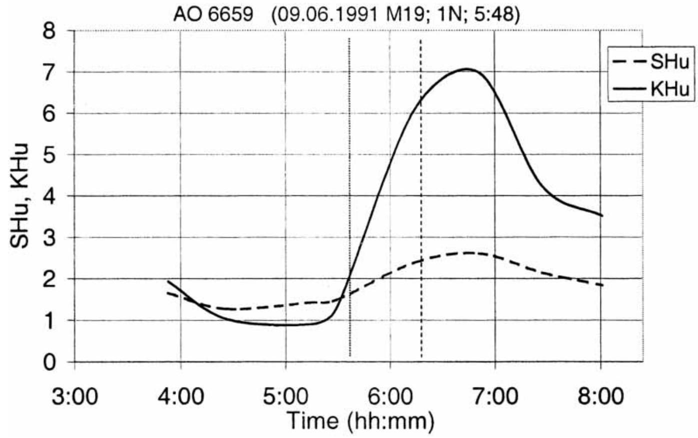

Figure 4. **Temporal variations in the asymmetry SH_u and excess KH_u of $H_u(B)$ distribution before, during and after flare M19 in AR 6659.**

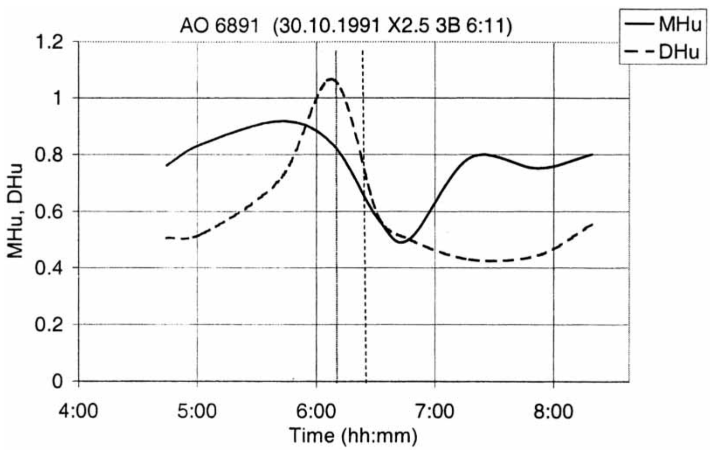

Figure 5. **Temporal variations in the average value MH_u and standard deviation DH_u of the $H_u(B)$ distribution before, during and after flare X2.5 in AR 6891.**

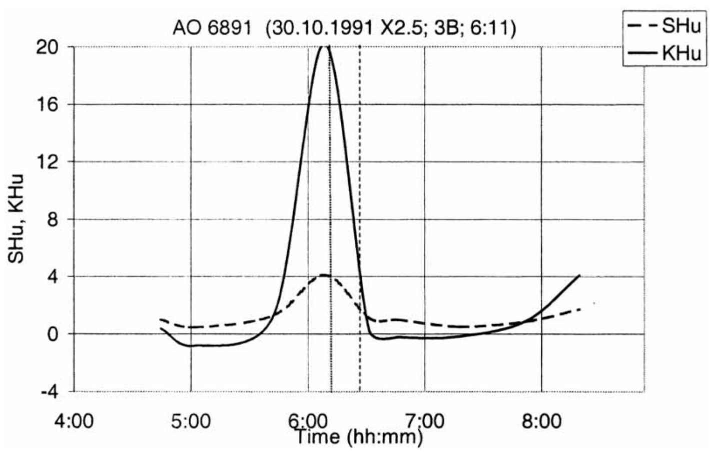

Figure 6. **Temporal variations in the asymmetry SH_u and excess KH_u of the $H_u(B)$ distribution before, during and after flare X2.5 in AR 6891.**

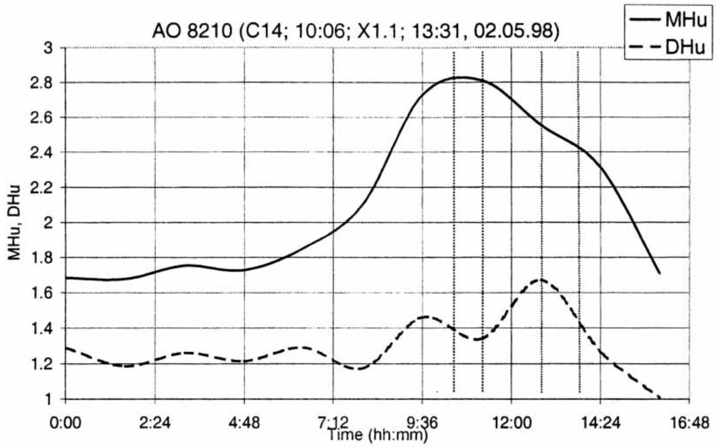

Figure 7. Temporal variations in the average value MH_u and standard deviation DH_u of the $H_u(B)$ distribution before, during and after flares C14 and X1.1 in AR 8210.

all four moments during the flares. Also, it should be noted that the forms of these curves (as well as the morphology and intensity of the flares) are different. Analysis of such differences and their correlation with features of the flares is a topic for future research.

Figure 7 is constructed from SOHO/MDI data and is analogous to Figures 3 and 5. The time step of the data (about 90 min) did not allow us to obtain the time profile of these curves in detail; however, the common tendencies of the previous case are confirmed.

Figure 8 demonstrates (on the basis of the same data) an example of temporal variations in the tilting angle of the magnetic axis of the AR during the flare period. Similar variations in tilting angle are found in all the considered cases.

The moments of the distributions of both the relative imbalance O_v and flux modulus F_a also demonstrate mainly considerable typical variations during the flare process. In fact all these temporal variations reflect magnetic field variations of the AR of very different natures; the appearance and dissipation of fluxes, the changes in flux topology, and the appearance of shear and other force-free configurations. When analysing the amplitude and character of

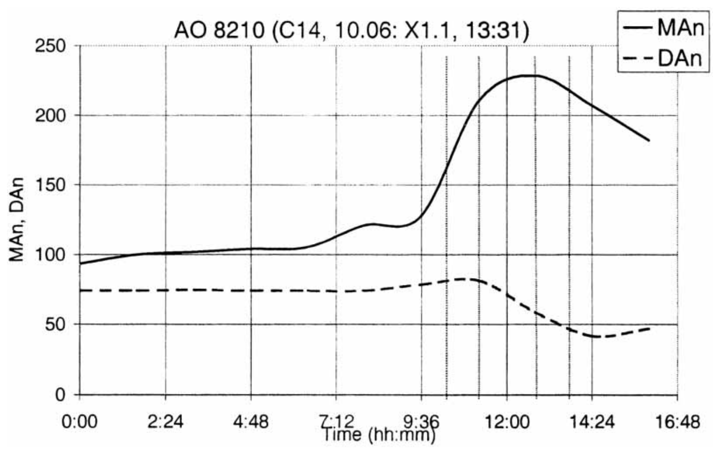

Figure 8. Temporal variations in the average value MA_n and standard deviation DA_n of the $A_n(B)$ distribution before, during and after flares C14 and X1.1 in AR 8210.

parameter variations we can judge the level of non-potential energy stored in the magnetic field of the AR and also the degree of stability of the considered configuration of the magnetic field due to the processes of cumulative energy transformation.

4 CONCLUSIONS

(1) A high sensitivity of the distributions and all the four moments of the considered integral parameters to variations in the magnetic field of the AR is found.

(2) Essential stable differences in the character of the distribution of quiet and flare productive ARs are found. These differences are reliably fixed by the first four moments of the distributions.

(3) The first moments H_{u} and A_{n} are good indicators of the level of non-potential energy cumulated in the AR, and also the level of stability of the total magnetic configuration of the AR relative to the processes, which realize this cumulated energy.

(4) The appearance of several features (local maxima in $H_{\text{u}}(B)$, strong variations in tilting angle, etc.) in the distributions of the parameters indicate a possible loss of stability of the magnetic flux structure in the AR. These may serve as precursors of a flare productive period imminent in an AR.

At the present stage of exploration, conclusions (3) and (4) are preliminary and require further examination using data with high temporal resolution.

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