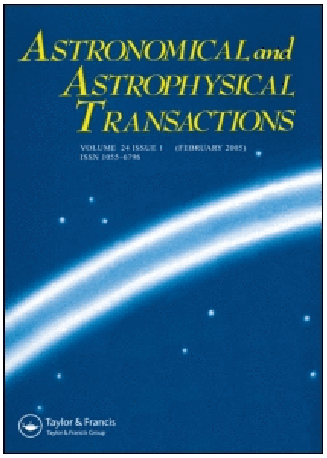

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 February 2003
To cite this Article: Krasotkin, S., Chumak, O. and Kononovich, E. (2003) 'STATE VARIABLES FOR SOLAR ACTIVE REGIONS', Astronomical & Astrophysical Transactions, 22:1, 75 - 79
To link to this article: DOI: 10.1080/1055679021000017501
URL: http://dx.doi.org/10.1080/1055679021000017501

Astronomical and Astrophysical Transactions,
2003, Vol. 22(1), pp. 75–79

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STATE VARIABLES FOR SOLAR ACTIVE REGIONS

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(Received 2 April 2002)

In this paper, several integral parameters of solar active regions are defined. The values of these parameters can be calculated from observational data. It is shown that only five of them are independent. These five parameters are sufficient for uniquely defining the active region current physical state. Such five parameters are proposed to be regarded as the state variables for solar active regions.

Keywords: Solar activity; Solar active regions

The solar active region phenomena are weakly designed in their modern understanding. For the aims of the solar active region modelling, the illegible and ill-defined qualitative categorisations without clear physical meaning and heuristic value are often used. Lack of quantitative descriptions, which could characterise active region integrity as a system, obstructs an identical understanding of the active region as a physical phenomenon. That is the reason of our attempt to solve the above-mentioned problem.

In this paper, the integral characteristics of the solar active regions are presented using the magnetograms of the observed solar enhanced areas as an example. Some of these characteristics were presented earlier in a series of works (*e.g.* Chumak, 1987; 1992; 1998). In these papers, a variety of possible integral characteristics were introduced, described and applied to the real observed examples, provided by magnetograms or several other observational 2-D data. This presented the active areas of the solar atmosphere and characterized the distribution of the magnetic fluxes Φ_i for each field point under consideration. Generally speaking, one can easily apply the same approach to the 2-D distributions of the several other observational quantities, such as radial velocity field V_i, sunspot areas, etc.

On the basis of the vector magnetograms of a certain solar photospheric area, one can calculate a set of integral parameters (or characteristics) of the region under consideration. If an observed area (usually a rectangle) includes the whole active region, and one supposes that the magnetic field is observed only over the active area, being absent outside that area, then the calculated integral parameters would characterize the mentioned active region. Let the

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ISSN 1055-6796 print; ISSN 1476-3540 online
DOI: 10.1080/1055679021000017501

Δ be equal to the smallest resolved linear element of the magnetogram, then the $\sigma = \Delta^2$ is an area of the magnetogram element defined by spatial magnetogram resolution (pixel). Let the K and L be equal to the linear dimensions of observed area (measured in pixels), then the production KL is equal to the whole number of the magnetogram pixels. Also let the $\Phi_{kl}, (k = \overline{1, K}; l = \overline{1, L})$ be equal to the elementary magnetic flux of the magnetogram element *kl*, and the Φ_0 to the magnetic field discrimination level. This level depends on the magnetograph resolution of the intensity of the magnetic field or on the adopted discrimination level, aimed to distinguish between the active region and the magnetic field background.

So the experimentally observed variables are the following:
KL – the range of observation points (pixels);
σ – pixel area;
$\Phi_{kl}, (k = \overline{1, K}; l = \overline{1, L})$ – measured values.

The magnetic field discrimination level Φ_0 is determined by magnetic field resolution of the magnetograph or our own decision.

For any element (pixel) of the magnetogram, defined by its co-ordinates k and l or by its ordinal number i, $(i = \overline{1, KL})$, we know the module of the magnetic field value $\Phi_i = \Phi_{kl}$ and the sign of its polarity (S for south and N for north). If the elementary magnetic flux is lower than Φ_0 we assume it to be zero flux. Also we can calculate the whole number of north magnetic flux elements n_N

$$n_N = \frac{1}{2} \sum_{i=1}^{KL} (1 + \operatorname{signum} \Phi_i).$$

and the whole number of south magnetic flux elements n_S

$$n_N = \frac{1}{2} \sum_{i=1}^{KL} (1 - \operatorname{signum} \Phi_i).$$

where $\operatorname{signum} \Phi_i = 1$, if $\Phi_i > 0$, and $\operatorname{signum} \Phi_i = -1$, if $\Phi_i < 0$.

The whole number n_C of magnetogram elements where the module of magnetic flux is higher than the discrimination level Φ_0 is defined by $n_C = n_N + n_S$.

To interpret only one physical parameter we introduce a set of *integral characteristics*. The area should be measured in units of the pixel area σ.

(1) The north magnetic field flux area *NN*, measured in the pixel area σ units, is $NN = n_N$.

(2) The south magnetic field flux area *NS* (in the same units) is $NS = n_S$.

(3) The whole active region area *NC* is $NC = NN + NS = n_C$.

It is necessary to note that the above defined area values substantially depend on the value of discrimination level Φ_0. The effective area, which has no such shortcoming, will be defined below.

(4) The total north magnetic field flux *HN* is

$$HN = \sum_{i=1}^{n_N} \Phi_i^N.$$

(5) The total south magnetic field flux HS is

$$HS = \sum_{i=1}^{n_S} \Phi_i^S$$

(6) The common magnetic field flux (of both polarities) HC is $HC = |HN| + |HS|$.

(7) The magnetic field disbalance Y is $Y = (|HN| - |HS|)/HC$.

The weight of elementary magnetic flux Φ_i (in magnetogram element i) in the total magnetic flux of the same polarity (HN or HS) or in the common magnetic field HC is $P_i^N = \Phi_i^N/HN, P_i^S = \Phi_i^S/HS, P_i^C = \Phi_i^C/HC$ and the normalization condition is

$$\sum_{i=1}^{n_N} P_i^N = 1, \quad \sum_{i=1}^{n_S} P_i^S = 1, \quad \sum_{i=1}^{n_C} P_i^C = 1.$$

The north and south barycenter co-ordinates are

$$\bar{l}_N = \sum_{i=1}^{n_N} l_i P_i^N, \quad \bar{k}_N = \sum_{i=1}^{n_N} k_i P_i^N,$$
$$\bar{l}_S = \sum_{i=1}^{n_S} l_i P_i^S, \quad \bar{k}_S = \sum_{i=1}^{n_S} k_i P_i^S.$$

where l_i and k_i – coordinates of the magnetogram element i.

(8) The distance R_{SN} between the south and north polarity barycenters is

$$R_{SN} = \sqrt{(\bar{l}_S - \bar{l}_N)^2 + (\bar{k}_S - \bar{k}_N)^2},$$

and

(9) the angle ANG between the above mentioned vector and the equator is

$$ANG = \arctan\left(\frac{\bar{k}_S - \bar{k}_N}{\bar{l}_S - \bar{l}_N}\right).$$

It is necessary to note that the defined above co-ordinates are the co-ordinates of barycenters but not the geometrical centers. Respectively it is necessary to differ the distance R_{SN} and the angle ANG from the commonly used analogous parameters based on the co-ordinates of geometrical centers of the polarities.

(10) The structural entropy EN of the north magnetic flux is

$$EN = \sum_{i=1}^{n_N} l_i P_i^N \ln\left(\frac{1}{P_i^N}\right),$$

(11) the structural entropy ES of the south magnetic flux is

$$ES = \sum_{i=1}^{n_S} l_i P_i^S \ln\left(\frac{1}{P_i^S}\right),$$

and

(12) the structural entropy EC of the whole active region is

$$EC = \sum_{i=1}^{n_C} l_i P_i^C \ln\left(\frac{1}{P_i^C}\right).$$

The defined above structural entropy is the Shannon information entropy. It characterizes the ranking of magnetic flux system and depends on the magnetic fluxes distribution and on the number of pixels of the corresponding polarity or of the active region. The more concentrated is the magnetic flux, the lower is the entropy. Zero entropy corresponds to the case of the whole magnetic flux concentrated in the only one magnetogram pixel and no magnetic flux in all other pixels. The maximum possible value of entropy is ln(j) and it corresponds to the case of the magnetic flux uniformly distributed among j magnetogram pixels. The important property of the entropy is the spatial commutativity.

(13) The north magnetic field effective area SEN is $SEN = \exp(EN)$,

(14) the south magnetic field effective area SES is $SES = \exp(ES)$,

(15) and the whole active region effective area SEC is $SEC = \exp(EC)$.

(16) The north effective magnetic field strength $DSEN$ is $DSEN = HN/SEN$,

(17) the south effective magnetic field strength $DSES$ is $DSES = HS/SES$,

(18) the effective magnetic field strength of the whole active region $DSEC$ is $DSEC = HC/SEC$.

Effective area is equal to the number of pixels in case the measured magnetic flux has a uniform distribution, providing its entropy being equal to the entropy of the real observed distribution.

(19) The structural parameter XSE is $XSE = (\sqrt{SEN/\pi} + \sqrt{SES/\pi})/R_{SN}$ and characterizes a spatial mergence of the north and south magnetic fluxes.

This parameter characterizes the degree of isolation or mutual penetration of the magnetic fluxes of both polarities. In the numerator of this ratio, there is a sum of circle radii of the equivalent effective areas of north and south magnetic fluxes. In the denominator of this ratio, there is a distance R_{SN} between the barycenters of north and south magnetic fluxes. The case of the $XSE < 1$ corresponds to the situation of β-configuration of active region (according to Mt. Wilson classification), the case $XSE \approx 1$ corresponds to the situation of γ-configuration, and the case of $XSE > 1$ corresponds to δ-configuration of active region.

(20) The length LNL of the magnetic field neutral line (the polarity inversion line) expressed in the number of pixels, in which the magnetic field changes its polarity, is

$$LNL = \sum_{k=2}^{K-1} \sum_{l=2}^{L-1} \delta_{k,l}$$

where

$$\delta_{k,l} = 1, \text{ if } \operatorname{signum}(\Phi_{k-1,l-1} \times \Phi_{k+1,l+1}) < 0 \text{ and}$$
$$\delta_{k,l} = 0, \text{ if } \operatorname{signum}(\Phi_{k-1,l-1} \times \Phi_{k+1,l+1}) > 0.$$

(21) The summarized gradient GR of magnetic field along the neutral line is

$$GR = \sum_{l,k \in LNL} \frac{(\Phi_{k-d,l-d} - \Phi_{k+d,l+d})}{2d}$$

where d is the distance from the neutral line (in pixels), where the gradient value is determined. The values of the last two parameters depend essentially on their determination algorithm.

(22) The density of gradient DGR along the neutral line is $DGR = GR/LNL$.

In spite of the fact that some integral characteristics are the combinations of the others (for example, *HC* and *Y* are the combination of *HN* and *HS*) together they help to understand better some properties of the active region.

It is very important to find the minimal set of parameters that unambiguously and quantitatively characterize the active region. The above-defined parameters, called *integral characteristics of an active region*, form a space of state of the active region. The sequence of an active region of individual states forms in this space a trajectory of the active region states. It is very important for the observational data analysis to choose a set of linearly independent parameters, which form the orthogonal basis in the space of active region state. The solution of this problem also helps to solve the problem of the active region classification.

By means of factor analysis, the problem of choosing the quasi linearly independent parameters was solved on the basis of more than 1000 magnetographic observations of the 10 active regions, observed in 1989. To present the variability of the 90% of the 22 parameters, it is necessary to just use 4-D orthogonal basis, so the embedding space is 5-D. It is necessary to note that we have managed to choice not linearly independent, but quasi linear independent basic parameters. This shortcoming was donated in order to obtain physically clear basic parameters.

We propose to use the following 5-D quasi-orthogonal space: *the common magnetic flux HC* of an active region, *the disbalance Y* of the north and south magnetic fluxes, *the distance* R_{SN} between the barycenters of the south and north magnetic fluxes, *the effective area SEC* of an active region, and *the summarized gradient GR* of the magnetic field along the neutral line. The cross-table illustrating the values of the explained variability (squared coefficient of correlation) is shown below.

	HC	*Y*	*RSN*	*SEC*	*GR*
HC	1	–	–	–	–
Y	0.00	1	–	–	–
RSN	0.11	0.00	1	–	–
SEC	0.32	0.004	0.12	1	–
GR	0.00	0.02	0.04	0.12	1

The linear independence of *the common magnetic flux HC* of an active region and *the disbalance Y* of the north and south magnetic fluxes is a result of their definitions. The correlation between *the common magnetic flux HC* of an active region and it's effective area is evident because the higher the magnetic flux, the higher *the effective area SEC* of an active region. The correlation between *the common magnetic flux HC* of an active region and *the distance* R_{SN} between the barycenters of south and north magnetic fluxes is expected to be 11% because it is clear. When the active region (and its *magnetic flux HC*) is small, the distance R_{SN} may be also small or may be large, and when the magnetic flux is large the distance may be only large. The same reasons help to find the similar correlation between the *effective area SEC* and the distance R_{SN}. In future, it is necessary to find the different types of active regions and to analyze the above mentioned relations between basic parameters for different active region types. Only the great number of observations of different active regions can help in the solution of this problem.

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