Solar coronal active structures. Theoretical approach and instrumentation

Article *in* Romanian Astronomical Journal · January 2004

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SOLAR CORONAL ACTIVE FORMATIONS

THEORETICAL APPROACH AND INSTRUMENTATION

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Abstract. This paper is proposing a new method for the investigation of active phenomena in the Sun. Here we will make use of the newest methods (self-similar particle distribution, wavelet transformation, etc.) in our effort to understand the physics that stands behind spatial and temporal evolution of the active phenomena from the solar corona, like the apparition and evolution of eruptions, eruptive prominences, "helmet" type prominences. The purpose of this paper is, with the help of the polarization theory and with one theory that initially is originating from the O spectral type stellar objects atmosphere description theory, to find the number of structures ("blobs") that are present at any moment of time in the solar corona (Brown et al. 1995). This number can prove to be a new mean of description and prediction of the solar activity evolution through the solar cycle.

Key words: Solar corona – polarization – active phenomena.

1. INTRODUCTION

Due to its complexity, the solar activity is, in the present, a hot and intriguing subject. There are existing models for explaining different solar activity manifestations but none of it is able of explaining the Sun and his manifestations in a unifying manner ... The phenomena are classified and named after their appearance not after a common phenomenological description of how and why the physical quantities (magnetic field induction, density, currents, etc.) are the observed ones (Tandberg-Hanssen 1967) … When we try to test how an physical model for a formation that is appearing somewhere in the solar atmosphere can generate formations in other atmospheric layers the model fails or, in the best case, can give in a rough manner an idea of what can happen (especially a-posteriori) ...

Rom. Astron. J., Vol. , No. , p. –, Bucharest, 2004

When we try to make long time predictions (for example, for the solar activity cycle) with activity indices (through radio and ultraviolet fluxes, sunspot or protuberance number) (Tandberg-Hanssen 1967), even that we are doing a statistical analyze, our methods are failing … So, what is to be done else than to try to give another method for solar activity studies and another index that maybe will fail also (or maybe not) to make more accurate the predictions and to better understand the Sun.

2. CONSTRUCTIVE DESCRIPTION OF THE SOLAR POLARIMETER

The constructive description of the proposed experimental device is given in the figure:

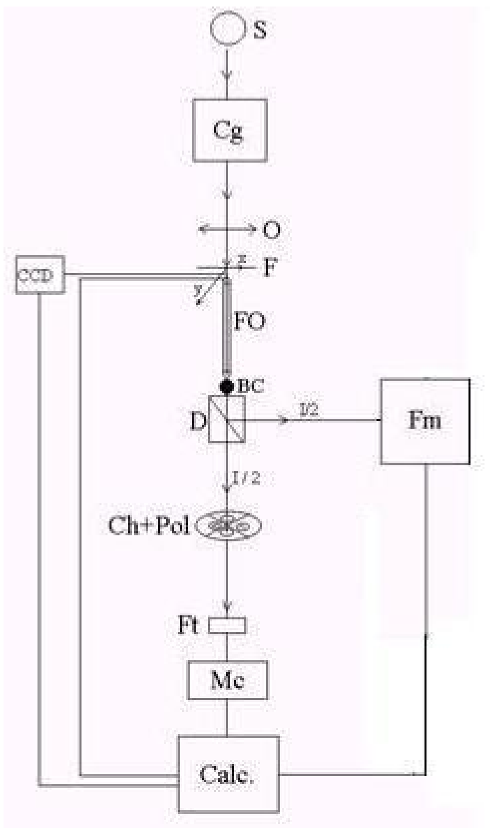

Fig. 1 The proposed experimental device. In the figure are represented the following:

S: Sun ; **Cg**: Coronagraph ; **O**: Objective lens ; **F**: The focal plane of the objective ; **„x-y”**: Pen recorder ; **FO**: Optic fiber ; **BC**: Optic coupling ball lens ; **D**: beam splitter ; **Ch+Pol**: Chopper with polarizing films ; **Ft**: Phototransistor ; **Mc**: Micro-controller ; **Fm**: Photometer ; **CCD**: CCD camera ; **Calc.**: Computer.

The light coming from the Sun falls on the coronagraph and after that on a convergent lens, being focalized in its focal plane. The lens will be chosen in a way that to permit to see the Sun (in projection) with an optimal magnification.
The light of *I* intensity passes through a 80 μm polarization maintaining (PM) optic fiber wich is absolutely necessary in this experiment because the final purpose of the experiment is the **accurate** determination of the number of structures present in the solar corona (see section **6.**). The end of the optical fiber can be positioned in the desired place of the solar projection with the help of the pen recorder, the command being given through the computer.
At present the most popular PM fiber type in the industry is the circular SAP type (stress induced birefringence), or **PANDA fiber**. One advantage of PANDA fiber over most other fiber types is that the fiber core size and numerical aperture is compatible with regular single mode fiber. This ensures minimum losses.
The bending induced stresses in the fiber (in our application) and the temperature gradient (between -55°C and +85°C) are not modifying the polarization-state of light traveling through it (for example, the HB Polarisation Maintaining Fiber sold by “Fibercore”: http://www.fibercore.com/index.php).

The divergent beam that exits from the fiber is transformed in a parallel light beam by the optic coupling ball lens and divided in two beams of intensity *I* / 2 by the beam splitter.
After that, one of these beams is transmitted at the chopper (1st branch), on three polarizing films which are putted at a polarizing angle of 120º one from the other.
The polarization degree (see section **4.**) will be determined using the intensities found for the three polarization directions of the polarizing films putted on the chopper and for the total intensity (see section **3.**) at the coronal region where we are doing the measurement. The fourth hole practiced on the chopper lets the unpolarized light to pass and it is used as reference for the beginning of acquisition of a new data set. For this the light is transformed in electrical signals by the phototransistor. The phototransistor coupled at one micro-controller will guide the chopper speed and, also, the analog to digital signal conversion for the computer acquisition.

The deformations of the partially polarized incident light from the corona given by the used PM optical fiber can be a priori determined by analysing the behaviour of the polarization with an incoherent light source (a light bulb) by aligning the connector key with the fast axis of the fiber through "active method" or "passive method" (see the DIAMOND company products and documentation: http://www.diamond-fo.com/library/docs/PM_Technology.pdf). For this purpose, between the incoherent light source and the fiber it will be placed a polarizator which will be rotated 360^0, degree by degree. The active or passive method will be used for determining the angle of rotation of the connector key for each orientation of the polarizator placed before the fiber. For example, if at 0^o position of the input polarizator we will achive maximal extinction, at 120^o position we will achive the maximal extinction when the connector key is rotated with, let say 5^o clockwise relative to the the 0^0 position. This means that we will have to take into account (when we will do the determinations of the solar corona polarization)that the fast polarization axis of the light is rotated with 5^o anti-clockwise relative to the one "observed" by the chopper's 120^o position polarizing film.

The other parallel beam (2nd branch) will fall on the photometer which will give the value of the $I / 2$ intensity from which we will have the measure of the total intensity I .
A CCD device will be used to acquire one image of the coronal region where we do the measurements, at the beginning of the observation, each time the position of the fiber optic on the solar corona projected image is modified. The images will be stored, dated, labeled in image files in a computer for post observational analyses.

The presented polarimeter is easy to handle and very portable. The data are collected simultaneously on the two branches of the system represented in fig. 1.

3. THE TOTAL INTENSITY

The total intensity, which is affected by the interplanetary, earth atmosphere and optical instrumentation absorption, will be experimentally determined on the photometer. The total intensity, approximated as being the intensity of the solar corona, will be also given after a Baumbach type empirical relation of the form *const.*/r^n, (if we consider an spherical symmetrical corona). In this way (Baumbach 1937):

$$I(r) = \frac{A}{r^{2,5}} + \frac{B}{r^7} + \frac{C}{r^{17}}$$

where A, B, C are to be determined (for one data acquisition session) from the equality of the radial dependence of the intensity in the solar corona $I(r)$ at given r values with the photometer response at the same r values.

4. POLARIZATION DEGREE

The polarization degree P will be determined using the intensities found for the three polarization directions of the polarizing films putted on the chopper and for the total intensity at the coronal region where we are doing the measurement:
The polarized light intensities will be taken (Mariş et al. 1999):

$$I_{0^0} \equiv I_a \quad ; \quad I_{120^0} \equiv I_b \quad ; \quad I_{240^0} \equiv I_c$$

Also, the total intensity, previously computed:

$$I_t = I_K + I_F \tag{1}$$

where I_K – the intensity in the K corona in the region where we do the measurment; I_F – the intensity in the F corona in the region where we do the measurment.
The intensity of the polarized light, I_P, can be expressed as function of I_a, I_b, I_c :

$$I_P = \frac{4}{3}\left[\left(I_a + I_b + I_c\right)^2 - 3\left(I_a I_b + I_a I_c + I_b I_c\right)\right]^{1/2}$$

Also:

$$I_P = I_K - I_F \tag{2}$$

After solving the system composed from the equations (1) and (2) there will be obtained the values for I_K and I_F intensities.
Because the unpolarized light intensity:

$$I_n = 2I_a - I_P \pm \left[I_P^2 - \frac{4}{3}\left(I_b - I_c\right)^2\right]^{1/2}$$

and:

$$I_n = I_{nK} + I_F$$

it follows that the unpolarized light intensity of K corona I_{nK} , in the sampled coronal region, will be:

$$I_{nK} = 2I_a - I_P \pm \left[I_P^2 - \frac{4}{3}(I_b - I_c)^2 \right]^{1/2} - I_F$$

It follows that we can compute the degree of polarization:

$$P \equiv P_K = \frac{I_P}{I_P + I_{nK}} = \frac{\frac{4}{3}\left[(I_a + I_b + I_c)^2 - 3(I_a I_b + I_a I_c + I_b I_c)\right]^{1/2}}{\frac{4}{3}\left[(I_a + I_b + I_c)^2 - 3(I_a I_b + I_a I_c + I_b I_c)\right]^{1/2} + 2I_a - I_P \pm \left[I_P^2 - \frac{4}{3}(I_b - I_c)^2 \right]^{1/2} - I_F}$$

The value of P will represent a medium value for the degree of polarization over the volume observed with the optic fiber (expressed in solar radius) at the observation time t .

5. ELECTRON DISTRIBUTION

We consider that the eruptive prominences and, also the eruptions, are having an auto-similar electron distribution for a compressible turbulence spectrum at non-equilibrium with a correlation length smaller than the dynamical viscosity scale of the medium. Because of the supersonic particle injection from the photosphere (and, obviously, from the sub-photosphere region), the turbulence and the magnetic field lines reconnection will take place under this auto-correlation length. So, the structure that is resulting will have a modified value and orientation of the magnetic field induction from the ones of the original structure, a “reconnected” structure after the local correlation length (Goncalves et al. 1998).
The turbulence is a form of energy dissipation in which, generally, the energy is transferred through a cascade mechanism from a bigger to a smaller scale (sometimes backwards). As function of the physical constraints on the energy transfer, may result different scaling laws. For example, for incompressible turbulence (Moffat 1994), the constraints are the constant density energy and the constant conversion rate for energy between scales *dE/dt*. For the compressible turbulence case, which is much more frequent in astrophysics, we will need another constraints: constant life times and free falling times.
In the phase space, between different k wave numbers, the energy dissipation is taking place by a power law, which is having as consequences nonlinear phase transitions, jumps in the dynamical viscosity (also, large Reynolds numbers) and, finally, the formation of auto-correlated domains, each one with its own

characteristic length and its own value and orientation for the magnetic field induction. The minimum dissipation scale will be set by the diffusion time for the generated domains (structures) that will have to be smaller than the domains formation time (Lepine et al. 1999).
For the case of an electronic self-similar distribution sank in a random distribution (Calzetti et al. 1988):

$$N_e(r) = \overline{N_e}(r)\left[A_e r^{-\gamma} + 1 - f^2\right] \quad , \quad f < 1 \tag{3}$$

with:

$$f = \frac{KR_S^{-\gamma}}{KR_S^{-\gamma} + K'}$$

and:

$$A_e = \left(1 - \frac{\gamma}{n}\right)\frac{K^2 R_S^{-\gamma}}{\left(KR_S^{-\gamma} + K'\right)^2} = \left(1 - \frac{\gamma}{n}\right)\frac{R_S^{-\gamma}}{R_S^{-2\gamma} + \left(\frac{K'}{K}\right)^2 + 2R_S^{-\gamma}\left(\frac{K'}{K}\right)}$$

Here:

$$\gamma = n - D$$

R_S – the radius of the corona which we are able to observe with the coronagraph; n – the dimension of the considered space; D – the fractal dimension computed from the solar image at the time of the observation (and/or analyzed with the help of wavelet transformation with different weights). We will work with $n = 3$ (image without wavelet transformation) or with $n = 6$ (phase space – image with wavelet transformation (Lepine et al. 1999)). The fractal dimension D will be determined from the images taken with the CCD camera or from parts of it (at different scales) containing the region of the corona where is done the measurement (Grosdidier et al. 2001).
K and K' are proportionality constants that will take into account that the observed structures appertain to the two different distributions considered, occupying the same volume V, each one with its own correlation function in this volume:

$$N_1 = KR_S^{n-\gamma}$$
$$N_2 = K' R_S^n$$

When the correlation between electrons in the homogeny self-similar distribution is not so rigid anymore, is possible to determine empirically from the image the ratio *K* '/*K*, for the $n = 6$ (seen in analogy with the velocity structure function analysis of the phase space properties of Muzy et al. and the particular cases of Grosdidier et al.). With *K* '/*K* we can now find the value of *f* and, implicitly, of N_e (*r*). The correlation length is defined as $r_0 \equiv (A_e)^{1/\gamma}$ (Calzetti et al. 1988).
At sunspot maximum, that is when the sun is at its maximum phase, the corona has approximately a circular form and uniformly bright.
The medium electron number density $\overline{N_e}(r)$ will be fitted with a Baumbach empirical formula (Baumbach 1937):

$$\overline{N_e}(r) = 10^{-8}\left(\frac{d}{r^{1.5}} + \frac{e}{r^6} + \frac{f}{r^{16}} \right)$$

with $d = 0.036$; $e = 1.55$; $f = 2.99$. This derivation of the electron number density given in the above equation was based upon ten solar eclipse observations by averaging over the coronal features.

6. THE DETERMINATION OF THE NUMBER OF STRUCTURES PRESENT IN THE SOLAR CORONA

From the definitions of the Stokes parameters *Q, U* and of the degree of polarisation (Richardson et al. 1996):

$$P = \sqrt{Q^2 + U^2}$$
$$Q = D\tau_0 \sum_{j=1}^{N} \cos 2\alpha_j$$
$$U = D\tau_0 \sum_{j=1}^{N} \sin 2\alpha_j$$
$$\tau_0 = \frac{3\sigma N_e}{16\pi r^2}$$

where:

$$D=\sqrt{1-\left(\frac{R}{r}\right)^2}$$

and: α_j – the angle of the polarization plane for the analyzed coronal formation, j=1, .., N; σ - the cross section for Thompson scattering ; R - the radius of the Sun ; r – the distance from the Sun center to the point where we put the optic fiber (expressed in solar radius),
will result that:

$$P^2=D^2\tau_0^2\left\{\left(\sum_{j=1}^{N}\cos 2\alpha_j\right)^2+\left(\sum_{j=1}^{N}\sin 2\alpha_j\right)^2\right\}=$$

$$=D^2\tau_0^2\left\{\sum_{j=1}^{N}\cos^2 2\alpha_j+\sum_{j=1}^{N}\sin^2 2\alpha_j+\sum_{j=1}^{N}\sum_{i\neq j}\cos 2\alpha_j\cos 2\alpha_i+\right.$$

$$\left.+\sum_{j=1}^{N}\sum_{i\neq j}\sin 2\alpha_j\sin 2\alpha_i\right\}=$$

$$=D^2\tau_0^2\left\{N+\sum_{j=1}^{N}\sum_{i\neq j}\cos 2(\alpha_j-\alpha_i)\right\}=$$

$$=D^2\tau_0^2\left\{N+\sum_{j=1}^{N(N-1)}\cos 2\alpha'_j\right\}$$

From here:

$$P=D\tau_0 N^{1/2}\left\{1+\frac{1}{N}\sum_{j=1}^{N(N-1)}\cos 2\alpha_j\right\}^{1/2}=$$

$$=D\tau_0 N^{1/2}\left\{1+\frac{2}{N}\sum_{j=1}^{N(N-1)}\left(\cos^2\alpha_j-\frac{1}{2}\right)\right\}^{1/2}$$

Because:

$$\left\langle \cos^2 \alpha_j \right\rangle = \frac{1}{2},$$

for arbitrary α_j , the medium value of the polarization degree will be:

$$\overline{P^2} = (D\tau_0)^2 N\left[1 + \frac{2}{N}\sum_{j=1}^{N(N-1)}\left(\left\langle \cos^2 \alpha_j \right\rangle - \frac{1}{2}\right)\right] = (D\tau_0)^2 N \tag{4}$$

Using the binomial regression:

$$(1+\varepsilon)^{1/2} = 1 + \frac{\varepsilon}{2} - \frac{\varepsilon^2}{8} + \ldots$$

for the second term from equation (4), which can be considered <<1, and:

$$\langle \cos\alpha \rangle = 0 \quad , \quad \left\langle \cos^2 \alpha \right\rangle = \frac{1}{2},$$

we will obtain:

$$\overline{P} \cong D\tau_0 \sqrt{N}\left[1 - \frac{(N-1)}{16N}\right] \tag{5}$$

From (5), knowing the medium value of the polarization degree determined in **4.** , it will be possible to find the number of structures N , or the number of structures N' in the phase space, in the analyzed part of the corona and at the distance $r = r_s$. The obtained number can be compared with the number of structures observed either in the CCD image of the corona, either in the wavelet-transformed image (in the studied region of it). This is a consistency test for the theoretical method and for the results because the number of structures resulted from computation can't be smaller than the observed one. The dependency $N(r)$ will be the best fitting function of the $N = f (r)$ points, sampling the corona at different r distances, in radial direction from and to the position r_s where we are having interesting formation (or formations) which we want to study.
Using a modified Richardson relation (Richardson et al. 1996):

$$\frac{dN}{dN_e} = \frac{dN(r)}{dr}\left(\frac{dN_e(r)}{dr}\right)^{-1} = \frac{(1-\gamma)N_0(r)\left[\overline{N_e}(r)\right]^{-\gamma}}{\left[N_{e,\max}(r)\right]^{1-\gamma} - \left[N_{e,\min}(r)\right]^{1-\gamma}}$$

Here, the expression of $dN(r)/dr$ will be the derivative with respect to r of the previous determined $N(r)$ fit.
$dN_e(r)/dr$ is the derivative of equation (3). The minimum and maximum values for the electronic densities $N_{e,\min}(r)$ and $N_{e,\max}(r)$ will be computed from (3) in the approximation that it is existing, in the coronal field of view of the coronagraph, a region with the radius $r_{\text{optic fiber}} \times R_{\text{Sun in projection}} / R_{\text{Sun}}$ where $K'/K = 0$ (the optic fiber "catches" just one formation; this is more probable in the higher corona than in the lower one) and where $K'/K = 1$ (the optic fiber "catches" many formations, for which the self-similarity is indiscernible due to the lack of resolution; this is more probable in the lower corona than in the higher one). So:

$$\frac{dN(r)}{dr}\left(\frac{dN_e(r)}{dr}\right)^{-1} = \frac{(1-\gamma)N_0(r)\left[\overline{N_e}(r)\right]^{-\gamma}}{\left|\left[N_{e,K'/K=1}(r)\right]^{1-\gamma} - \left[N_{e,K'/K=0}(r)\right]^{1-\gamma}\right|}$$

Knowing $\gamma (= n - D)$ and the electronic density variation determined as above, it will be possible to extract the radial dependence of the total number of formations $N_0(r)$ present in the solar corona at any moment of time.
Integrating over the radius of the field of view we will be able to get the total number of formations present in the corona at any moment of time:

$$N_0 = \int_{r_{\min}}^{r_{\max}} N_0(r)dr$$

This value can prove to be a solar constant or a slowly varying parameter (a secular variation?). This time dependence must be experimentally verified to see if N_0 is or not constant and, if it isn't, if it's having a periodic variation, which is this period (weeks, mounts or even years) and if we can correlate it somehow with the solar cycle in a useful way for the solar activity and space weather predictions. We must not exclude the possibility that N_0 is having random time dependence and no physical meaning. This remains to be seen after the interpretation of the experimental data.

Acknowledgement: I want to express all my gratitude to Prof. Mircea Rusu from the Faculty of Physics, University of Bucharest for his support, advices and shared scientific expertise in imagining (and soon constructing) the solar polarimeter.

REFERENCES

Baumbach, S.: 1937, Astron. Nachr., **263**,121
Brown, J.C., Richardson, L.L., Antokhin, I., Robert, C., Moffat, A.F.J., St.-Louis, N.: 1995, A&A, **295**, 725
Calzetti, D., Giavalisco, M., Ruffini, R.: 1988, A&A, **198**, 1
Goncalves, D.R, Jatenco-Pereira, V., Opher, R.: 1998, ApJ, **501**, 797
Grosdidier, Y, Moffat, A.F.J., Blais-Ouellette, S., Joncas, G., Acker, A.: 2001, ApJ, **562**, 753
Lepine, S., Moffat, A.F.J.: 1999, ApJ, **514**, 909
Mariş, G., Ţifrea, E.: 1999, *Eclipsele*, Bucharest, Ed. Tehnică, 134-138
Moffat, A.F.J.: 1994, RvMA, **7**, 51
Moffat, A.F.J.: 1994, ApJ, **421**, 310
Muzy, J.F., Bacry, E., Arneodo, A.: 1993, Phys. Rev. E, **47**, 875
Richardson, L.L., Brown, J.C, Simmons, J.F.L: 1996, A&A, **306**, 519
Tandberg-Hanssen, E.: 1967, "Solar Activity", Blaisdell Publishing Company