Large-scale Structures and their Role in Solar Activity
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Magnetic Field Reversal of the Sun in Polarization of Radioemission at 17GHz

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Abstract. The distribution of polarized component of the solar radio emission at wavelength of $\lambda = 1.76$ cm over the solar disk was studied using the observations of the Nobeyama radio heliograph. The latitude-time diagrams of the circular polarization were constructed for the period of the years 1992-2003. The method of averaging has been applied for the noise reduction using several images per day and a filtration of images. The high-altitude drifts of the polarized radio emission have been allocated both at latitude band of sunspots and at higher latitudes. The magnetic field reversal of the large-scale magnetic field was found as manifested in polarization of radio emission of the Sun during cycles of solar activity numbers 22-23. The analysis of polarization of radio emission for the structures of various brightness temperature has been carried out. Comparison of the radio method of analysis of the global variation of the solar magnetic fields with the phase of cycle with the results found from the optical observations confirmed its effectiveness.

1. Introduction

To understand the nature of the solar activity cycle one needs an analysis of the global magnetic field at all levels of the solar atmosphere. The Nobeyama radio heliograph has opened a new era in analysis of solar periodicity in radio wave range due to regular observations and comparatively high spatial resolution. Presence of polar activity was clearly seen at the radio waves, (Alissandrakis 1998; Shibasaki 1998; Gelfreikh et al. 2002a). The rate of differential rotation was determined and waves of torsional oscillation were revealed during 1992-2002 (Gelfreikh et al. 2002b). The measurements of the magnetic fields using radio observations are based on the theory of polarization spectrum of a radio emission (Zelesnaykov 1963; Zelesnaykov & Zlotnik 1977). For the magnetic fields outside the sunspots, such as faculae and floccules where the magnetic field strength is of the value of about $\sim$ 100 G, polarization of a radio emission is usually of several percent, (Grebinskij et al. 2000). Regular observations on Nobeyama radio heliograph allows to carry out estimation of distribution of polarization over the whole disk of the Sun for different phases of the solar activity.

In this article an analysis of distribution of the size and sign of polarization at the wave of $\lambda = 1.76$ cm for the period 1992-2003 years was carried out. Earlier, the analysis of radio emission according to Nobeyama radio heliograph already was presented in the papers on polarization of a radio emission on a disk of the Sun (Tlatov & Shramko 2002) and in the solar corona (Tlatov 2003). In this research the standard procedures were applied to increase the sensitivity in polarization radio emission and to decrease the noise level.

2. The Method of Restoration of the Daily Radio Maps

The initial data for analysis were the daily observations of circular polarization (R-L) from the Nobeyama radio heliograph presented in fits format. The radius of solar image was ~ 200 pixels and space resolution was about 10 arcsec. During the period of the 1992-2003 years nearly 3900 days of the observations had been processed. We used both the raw observations from the Nobeyama and restored maps made with one second time averaging. The latter solar maps were taken with ten minutes intervals and then averaged to get better sensitivity. The restoration of the raw observations was made using standard procedures of the Nobeyama RAO with some variations of parameters. The best results in our study were found when using ten minute averaging. However, in some cases this approach led to a low quality of the radio maps. An increase of "parasitic" (or artifact) polarization was obvious. This may be due to unfavorable connection between the structure of radio source and antenna pattern for the moment of observations. To exclude this possible effect, we prefer to use averaging of several maps taken at different moments observations during a day. Normally 40 to 50 maps with one second time averaging each were used.

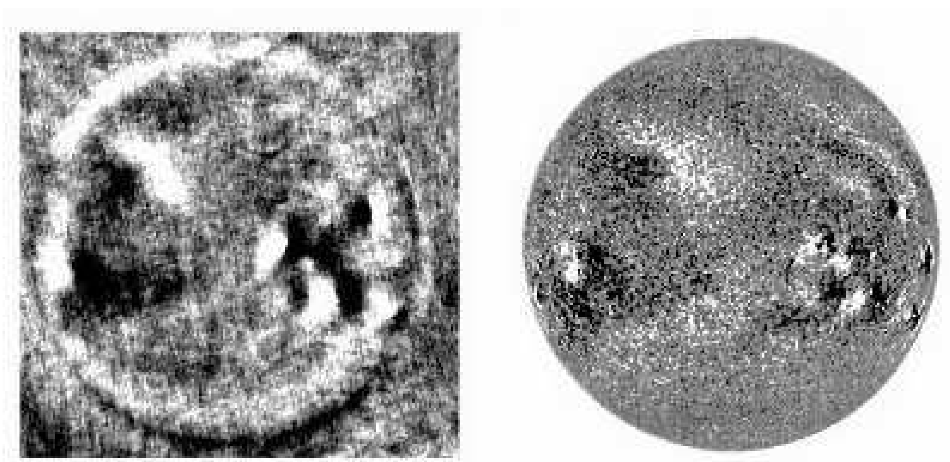

Figure 1. Left panel shows the averaged map of polarized radio emission at the wavelength of 1.76 cm for January 30, 2003. Right panel shows the photospheric magnetogram obtained at the Kitt Peak. The magnetogram was averaged to demonstrate the effects of similar spatial resolution as the radio data.

The Figure 1 shows a map obtained in this way in the channel of circular polarization for January 30, 2003. Dark and white regions reflect the positive and negative sign of polarization. For comparison, right panel shows a magnetogram obtained at the Kitt Peak Observatory for the same date. One can see a good agreement of the regions of comparatively weak fields on the both maps, different polarities including. To make the comparison of the two methods the optical magnetic maps were averaged with the 10 arc sec resolution, similar to that of the radio heliograph diagram pattern.

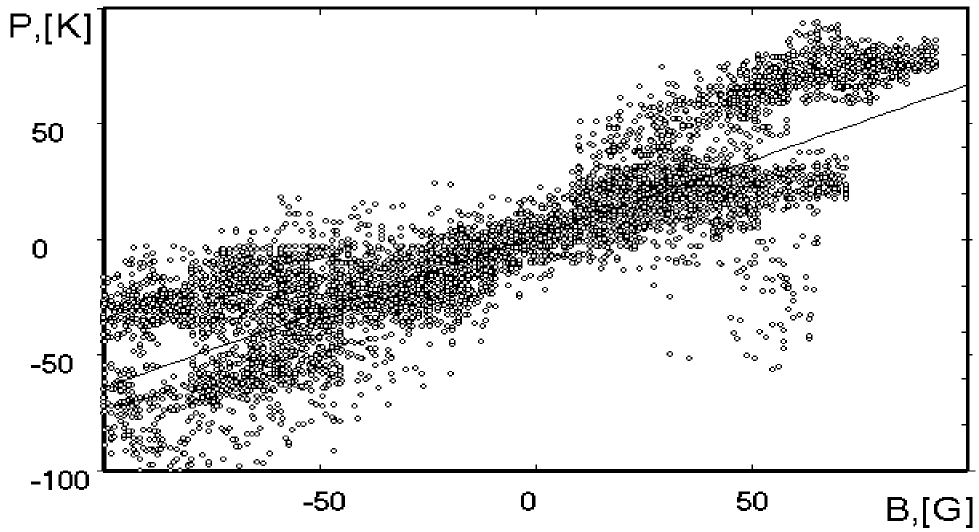

Figure 2. Regression dependence between the brightness of polarized component of the radio emission at $\lambda = 1.76$ cm and the magnetic field strength (longitudinal component) found from optical magnetograms for 30.01.2003.

The comparison of the radio polarization and optical magnetographic methods have shown that both of them result in similar presentation of the development of the global magnetic fields during the solar cycle and the distribution of the field along the solar surface. Regressive analysis (Figure 2) resulted in the following relation between the circularly polarized radio signal at $\lambda = 1.76$ cm and strength of the longitudinal component of the magnetic field found from optical magnetography:

$$V = 1.9 + 0.7 * B \quad (1)$$

3. Polarization of the Radio Emission of the Sun and its Structures in Solar Magnetic Cycle

To study polarization of the solar radio emission connected with background magnetic fields we have used Nobeyama radio heliograph observations at the wavelength of $\lambda = 1.76$ cm treated with averaging as was described above. Besides it, the received row of observations has been subjected to procedure of a filtration. For this purpose as criterion of a level of noise the average polarization above a disk of the Sun was calculated. Images in which polarization in the corona at height of 1.1R exceeded some threshold value of $\sim 100^o$ K of temperature were eliminated. Calculation of polarization was carried out over the disk of the Sun within the distance from the central meridian not more than 60^o. Thus, matrixes of monthly average values of polarization have been created in a latitude band of $\pm 80^o$. We see that in the period of minimum solar activity increased intensity of the magnetic field is observed at high heliographic latitudes.

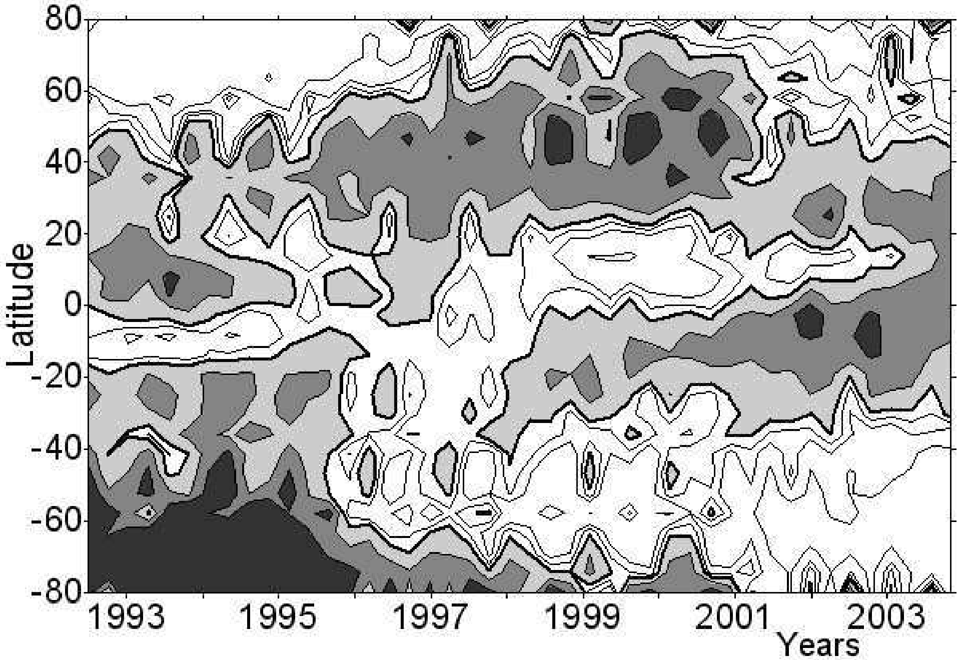

Figure 3. The latitude-time diagram of distribution of the polarized component of the solar radio emission, received for daily synthesized images, on the basis of 10 minutes Nobeyama data ($\lambda = 1.76$) cm. The regions with a level of polarization of higher than $200^o K$ in T_b^V were excluded.

The radio observations of the circularly polarized component reflect longitudinal component of the solar magnetic field. The direction of the longitudinal component of the magnetic field will determine a sign of circular polarization (V Stokes parameter). In Figure 3 the latitude-time distribution of polarization with 10 minutes data received at averaging is presented. For the best allocation of the background magnetic fields the regions with values above $200^o K$ in terms of brightness temperature of the polarized component were not taken into account. Various brightness here presents the regions from prevailing sign of the right or left polarization. It is possible to note, that distribution of polarization depends on a cycle of activity not only in the regions of formation of sunspots, but also at high-latitude regions. With the beginning of activity of the 23rd cycle, during 1996-2000 a drift of polarization of opposite sign to poles was observed. A phase of drift of polarization radio emission is close to a drift of the magnetic neutral lines during reversal of the large-scale magnetic field.

4. Discussion

The polarized component of the thermal radio emission of the solar plasma is generated by two mechanisms: cyclotron radiation at the first few harmonics of the electron gyrofrequency and bremsstrahlung (free-free emission). As far as the emission at $\lambda = 1.76$ cm is concerned, one can expect the cyclotron emission only above large sunspot when the magnetic field strength in the corona or CCTR is as high as 2000 G. So, most of the brightness distribution of the polarized components effects presented above are due to thermal bremsstrahlung emission.

In this case an optically thick isothermal layer generates nonpolarized radio emission. The polarized component analyzed in this study may be due to two main effects: gradient of temperature in the chromosphere, where main part of the observed emission is generated and the emission of optically thin coronal structures. In the latter case the source of the radiation may be isothermal but the optical thickness for the two types of circular polarization (ordinary and extraordinary modes) is different.

The degree of polarization with good accuracy for the quasi longitudinal propagation may be presented as (Gelfreikh 2004):

$$P = n\frac{f_B}{f}cos\alpha, \tag{2}$$

where f_B - electron gyrofrequency and α - direction of the magnetic field. Here n is logarithmic index of the spectrum (assuming that brightness temperature $T_b \propto \lambda^n$). So, for the Nobeyama observations ($\lambda = 1.76$ cm) longitududinal component of the magnetic field is

$$B_l = \frac{61}{n}P\% \tag{3}$$

For the case of the optically thick chromosphere we need spectral observations to estimate n. As far as we have none, we shall use an assumption $n = 1$(typical in this wavelength range for the quiet sun). We also assume $T_b^I = 10000°$ having in mind that most of analyzed here regions of the solar surface are of low activity and excess of brightness temperature above the quite level is low. Then we get

$$T_b^V \approx 1.66B_l \quad or \quad B_l \approx 0.60T_b^V \tag{4}$$

The coefficient in this formula (0.6) is in a very good agreement with that (0.7) in Eq. (1), reflecting regression analysis of connection magnetic fields found from optical magnetography with the radio polarization analysis. So we have come to the conclusion that the radio maps of the circularly polarized component at $\lambda = 1.76$ cm really may be considered as magnetograms of the longitudinal component of the solar magnetic fields, naturally referring to the chromosphere level. Now, coming to the Figure 1, we see that optical and radio magnetograms generally present very similar magnetic structure for the whole solar surface.

At the same time some differences in the magnetic structure seen on the radio and optical magnetograms do present. Also of interest is the fact that at regression equation for $B_{optical} = 0$ we get $T_b^V \neq 0$. We can propose three different sources for these differences of the two methods of the solar magnetography: (1) Our data refer to different levels of the solar atmosphere: chromosphere or low corona (radio) and photosphere (optical). (2) The corresponding value of the B_l to T_b^V in fact depends on spectral index n, we have assumed to be constant. Similar problems certainly are present and in optical magnetography (calibration coefficient depends on the local form of the spectral line). (3) Some artifacts ("parasitic effects") are difficult to exclude.

The most significant result of the paper is certainly development of the solar cycles (number 22 and 23) in the structure of the global magnetic fields of the sun at the chromospheric level presented at the Figure 3. This covers the ten year period for 1992-2003 years. Such detailed radio analyses of reconstruction of the magnetic field in the chromosphere in the period of replacement of one 11-year cycle to another is a new step in the solar physics. At this stage of development of the new radio approach to the problems we may confirm by quite independent observational method the main laws of the events: the inversion of the sign of polarization and high activity (stronger magnetic fields) at polar region at the period of minimum activity at lower heliographic altitudes.

To get principally new information from the new method of an analysis of the global magnetic cycle of the sun certainly one needs longer period of observations certainly covering the whole (e.g. 23rd) cycle, some spectral analysis of the microwave observations including.

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Part VI
Eruptive Phenomenon