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Anomalous Polarization Features of the Cyclotron Radiation Source in the NOAA 7123 Active Region: The Structure, Dynamics, and Reasons of Occurrence

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Abstract—The research results of the unique NOAA 7123 active region (April 1992) are presented; its anomalous polarization features (long-term predominance of O-mode radiation above the central part of the main sunspot) were previously revealed by VLA observations with a resolution of (2–4)" at wavelengths of 3.6 and 6.4 cm (Vourlidas et al., 1997). Additional observations in a wider band of electromagnetic radiation, including, in particular, spectrum–polarization observations performed with the RATAN-600 and SSRT radio telescopes, are considered. The analysis of these data allowed for the conclusion that the anomaly was caused by the presence of a cold substance in the upper coronal layers, starting from the height where (6–7) cm radiation was generated. A possible transportation agent of this substance—Hα filament—one of the bases of which fell on the sunspot's umbra–penumbra boundary, was found.

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INTRODUCTION

This work is aimed at studying the structural and physical parameters of the quasi-quiescent coronal plasma under a strong sunspot magnetic field of (2–4) kGs. For this purpose, we use the advantages of observing microwave sources of the S-component of solar radiation, located in the corona above active regions (ARs). At a high space–frequency resolution, we can study the coronal plasma above sunspots in very high detail, using RATAN-600 (Bogod et al., 1993), with a height accuracy of up to 100–200 km at a 1% frequency resolution (Korzhavin et al., 2010).

The case of VLA sunspot observations in the NOAA 7123 active region (April 1992) with a high spatial resolution of (2–4)" at wavelengths of 3.6 and 6.4 cm (Vourlidas et al., 1997) stands out among numerous studies on cyclotron microwave radiation sources (CMRSs) above sunspots (see the overview (Lee, 2007)). The uniqueness of this case lies in the specifics of the thin structure of the CMRS image. Among several dozen ARs observed by the VLA and the WSRT, only one case was revealed in which for >3 days the O-mode dominated anomalously over the sunspot center, notably, only at the longer wave of 6.4 cm. A narrow ring with the dominant E-mode surrounded the anomalous region. By the image (ringlike) pattern, our case is the closest to the case in (Zlotnik et al., 1998), when radiation depression was observable above the sunspot in AR 7789 in a band of (4–6) cm; however, the polarization sign was "normal" (E-mode dominance) across the entire sunspot area.

The specifics of the polarization structure of the CMRS image can be explained within a complex model of the electron temperature (T_e) and density (N_e) distribution above the sunspot. Vourlidas et al. (1997) proposed preheating with hot coronal loops, and Zlotnik et al. (1998) on the contrary proposed a radial temperature distribution, decreasing within the sunspot. Thus, the model concepts about the coronal structure turn out to be contradictory according to the CMRS observations, and the question arises what predetermines the image structure. In the case of AR 7123, for example, we would like to understand why the specifics of its polarization structure disappeared over the period April 6–9, 1992, and with what physical processes it is associated.

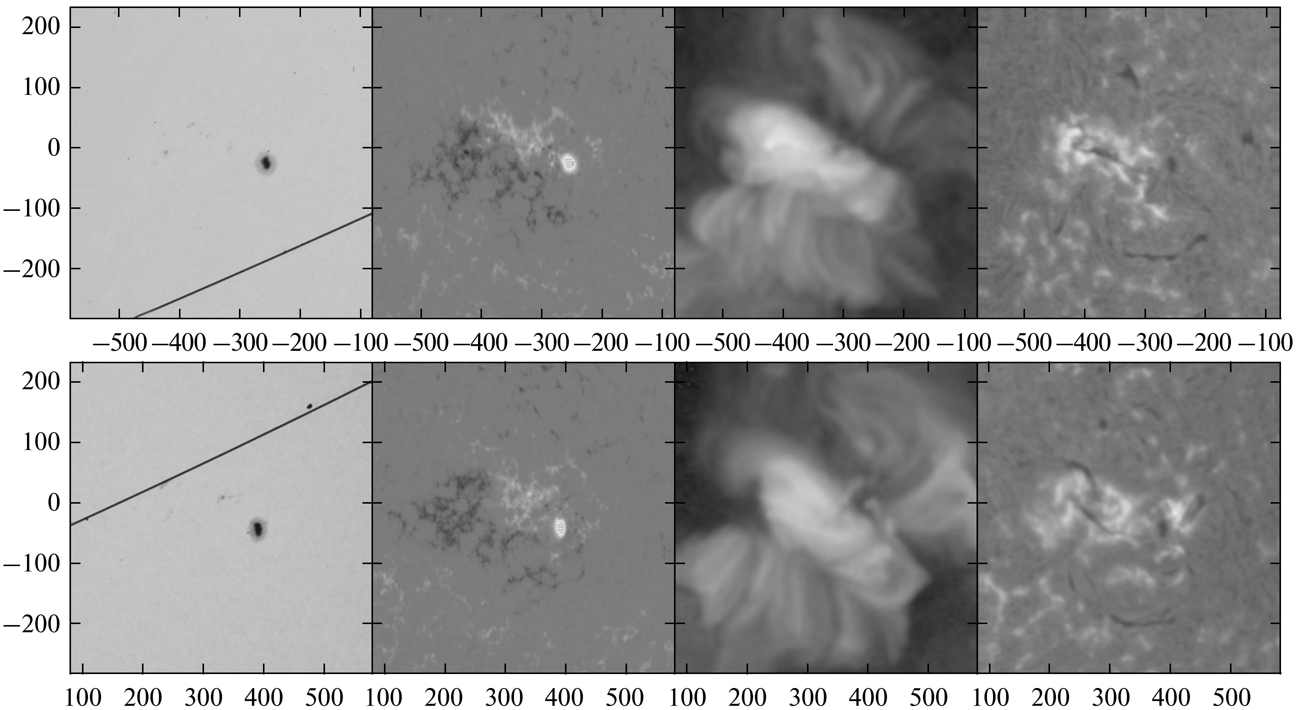

Fig. 1. Images of the NOAA 7123 active region as of April 6, 1992 (upper row), and April 9, 1992 (lower row), at various wave bands (left to right): a photoheliogram (MAS CAO), a magnetogram (Kitt Peak Obs.), soft X rays (Yohkoh/SXT), and Hα (Paris observatory).

DESCRIPTION OF THE NOAA 7123 ACTIVE REGION

By its morphological structure and by the structure of the magnetic field (MF), the NOAA 7123 low-latitude active region ($\varphi = 08$ S; the central meridian transit, April 8, 1992) refers to the ESI and B classes, respectively (see Fig. 1). The main sunspot (April 6) had a regular form with an umbra size of ~ $(11 \times 19)''$, a penumbra size of ~$(35 \times 39)''$, and an N-polarity MF strength of 2.1–3.4 kGs. The largest AR 7123 flare activity was registered during April 7–8; according to GOES, only two flares reached class ~C8. The total sunspot area decreased slowly, mainly owing to the AR tailing part.

RADIOWAVES OBSERVATIONS

The study used the materials of spectrum–polarization observations performed with the VLA, SSRT, RATAN-600, and LPR radio telescopes.

The AR 7123 2-D maps, obtained through VLA observations of parameters I and V at wavelengths of 3.6 and 6.4 cm (resolutions of 2'' and 4'') during April 3–10, 1992, were taken from (Vourlidas et al., 1997). Figure 2 shows changes in the AR polarization image structure. During April 4–6, 1992, an anomalous CMRS image feature was observed; i.e., the O-mode dominated above the sunspot center at a wavelength of 6.4 cm. Figure 2 shows it on April 6, when the AR was in its best position near the central meridian passage of the Sun. This feature disappeared during April 7 and 8, and from April 9 the CMRS acquired a "normal" image structure (see the right-hand side of Fig. 2). It is impossible to indicate the moment of change more accurately due to a lacuna in the VLA observations. At the 3.6-cm wavelength (see the lower part of Fig. 2), the usual E-mode dominance was recorded during the whole observation period.

One-dimensional AR 7123 scans for the period April 2–11, 1992, were taken from the RATAN-600 and SSRT archives. Figure 3 shows an example of the RATAN AR 7123 scans, observed in the (2.56–7.8) cm band during April 6, 1992, and processed with conventional software. The overall structure of a one-dimensional image can be divided by Gauss analysis into the following two details: an extended detail, i.e., H (halo), and a compact detail, i.e., A, well outlined against the halo.

The RATAN scans were compared with the VLA and SSRT observations. Frequencies of 5.28 and 6.5 cm, closest to the VLA (6.4 cm) and SSRT (5.2 cm) observation frequencies, were chosen for comparison. Figure 4 shows the comparison results.

The comparison shows good agreement in the positions of the brightest details in the AR 7123 image. However, according to the RATAN-600 and SSRT

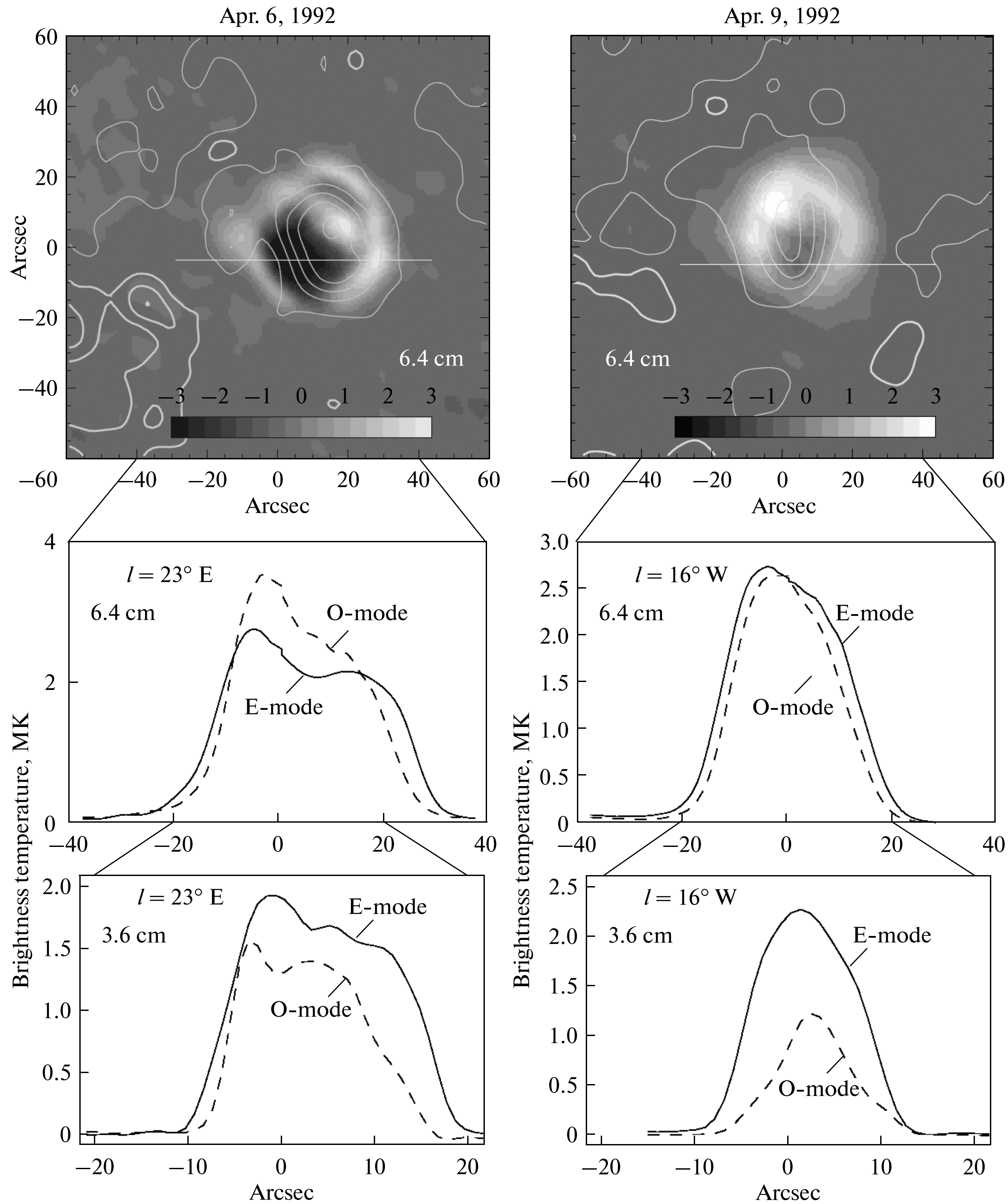

Fig. 2. VLA maps of the AR 7123 main sunspot (halftone, parameter V) demonstrating the polarization feature of the cyclotron radiation source above this sunspot at a wavelength of 6.4 cm (Vourlidas et al., 1997) as of April 6, 1992, and April 9, 1992. Sections are made along the lines designated on the maps.

observations in the (4.5–6.5) cm band, the R polarization prevails above the main sunspot, which is typical of the redundant E-mode for an N-polarity MF sunspot, which at first sight contradicts the VLA observations. We were able to explain these contradictions by the differences (by an order of magnitude) in the resolution of the instruments, which blurred the complex thin structure of the source (Agalakov et al., 2010). According to the RATAN-600 (6.5 cm) and VLA measurements, the integral degree of polarization agrees with a good accuracy of ~20%.

On the basis of the RATAN-600 observations over the period April 6–11, 1992, the radio flux spectra were calculated for detail A (sunspot); they are shown in Fig. 5.

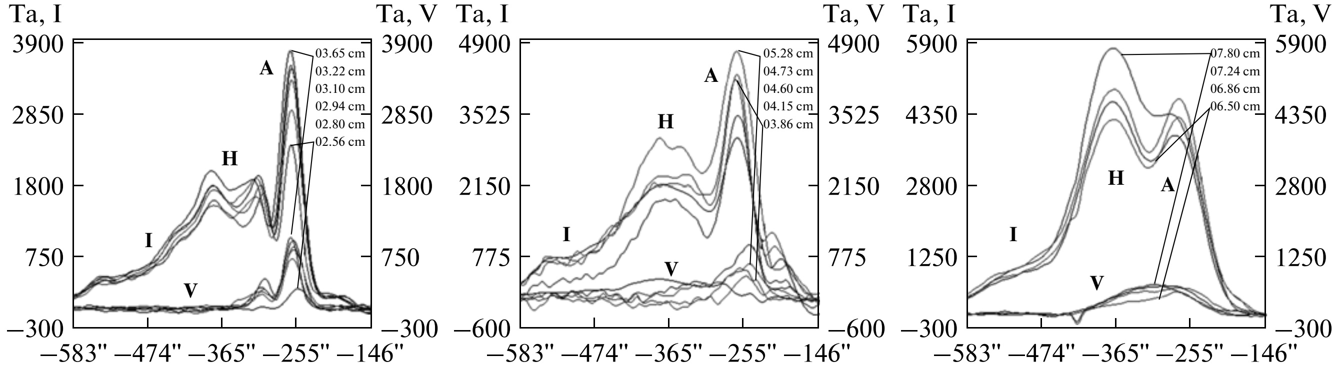

Fig. 3. RATAN scans in the band 2–8 cm (Stokes parameters I and V) according to NOAA 7123 active region observations on April 6, 1992.

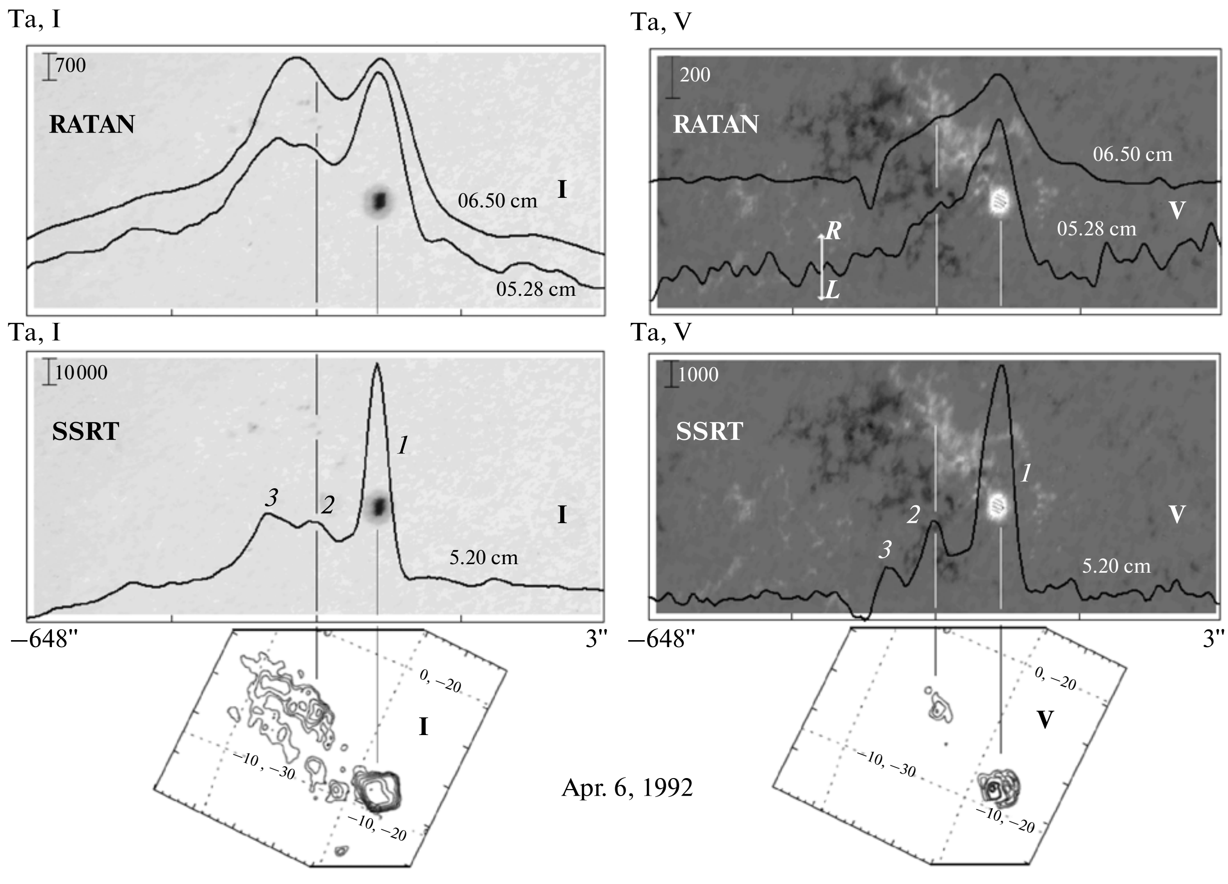

Fig. 4. Comparison of VLA, RATAN-600, and SSRT observations of the NOAA 7123 active region on April 6, 1992, superimposed on a photoheliogram (for I) and on a magnetogram (for V).

DISCUSSION

The subject of our research is the source of cyclotron radiation (detail A), located in the corona above the AR NOAA 7123 main sunspot (April of 1922). The reliability of the polarization anomaly of this source, revealed by VLA observations, was proved by the collation with independent observations made by other instruments (SSRT and RATAN-600). The question that remains is what phenomena or processes caused the change in the usual parameters of the coronal plasma above the active region and the formation of an unusual structure of the CMRS polarization image.

To answer this question, we studied the AR 7123 dynamics and structure by observations in the radio, optical, and X-ray bands (see Figs. 1–6) over the entire period (April 2–11, 1992) of the AR presence on the

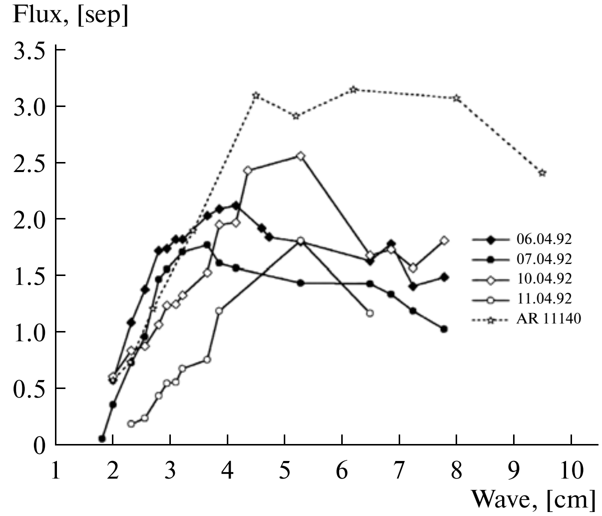

Fig. 5. RATAN spectra of the microwave radiation flux of the sunspot detail of the NOAA 7123 active region according to observations over the period April 6–11, 1992. A spectrum with a similar detail in NOAA 11140 (Korzhavin et al., 2012) is given here for comparison.

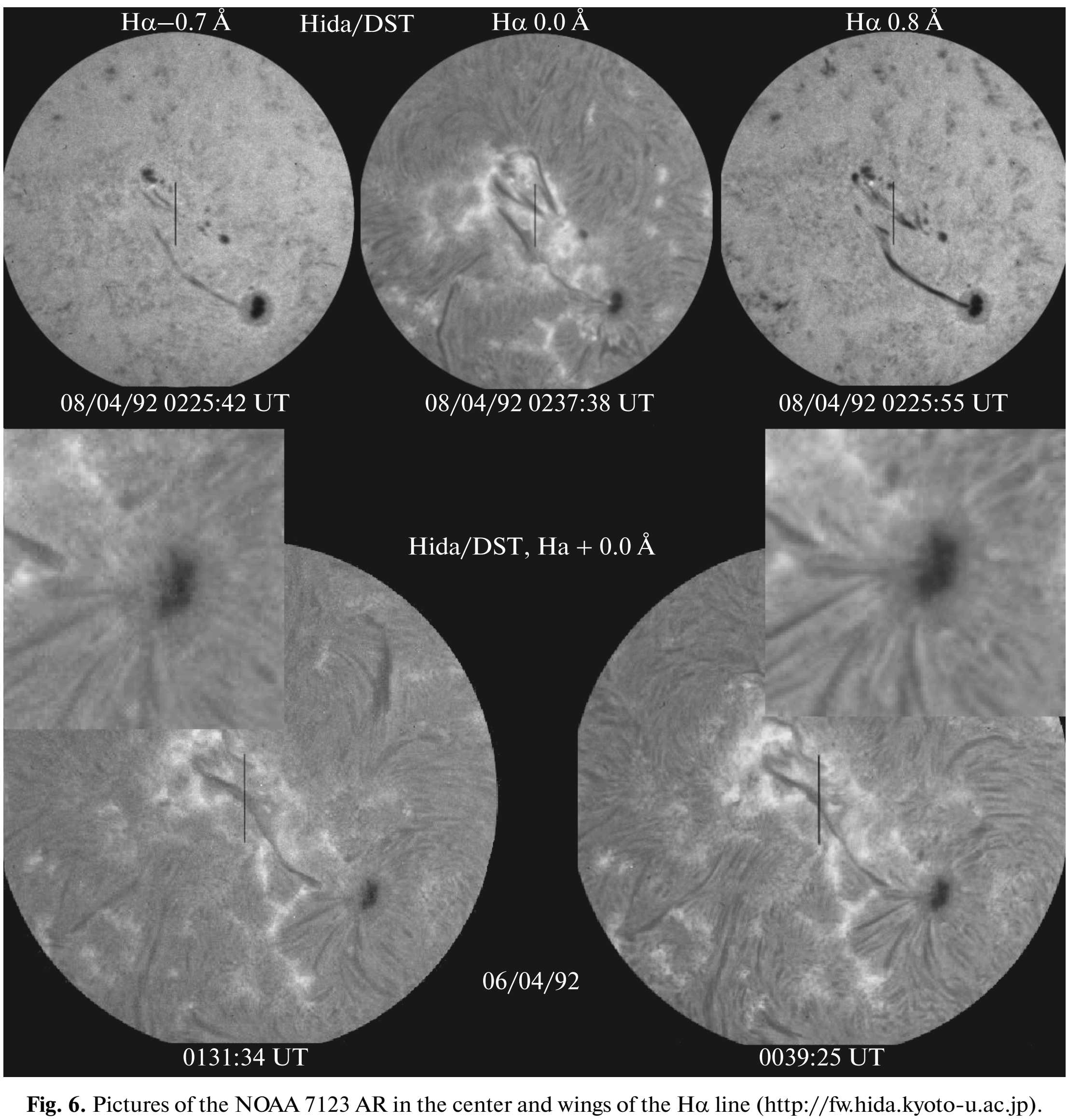

Fig. 6. Pictures of the NOAA 7123 AR in the center and wings of the Hα line (http://fw.hida.kyoto-u.ac.jp).

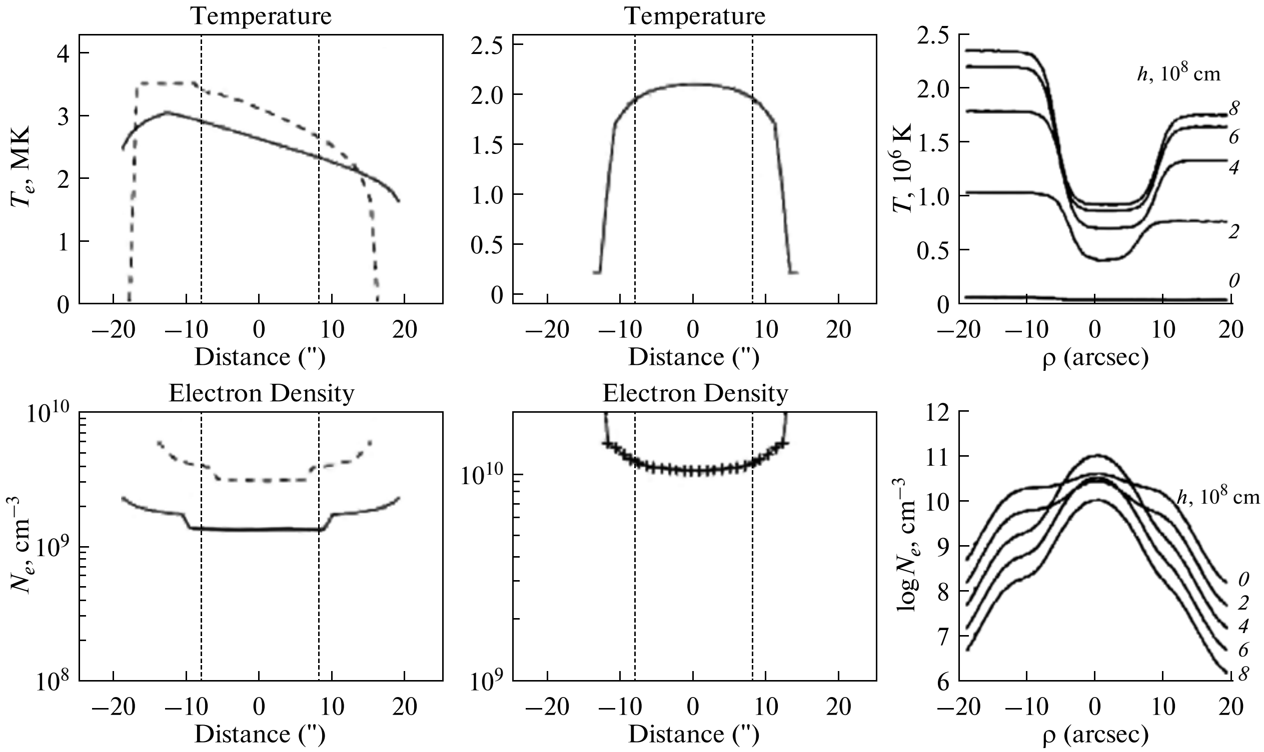

Fig. 7. Models (T_e and N_e) of cyclotron radiation sources above sunspots: the left and middle columns were taken from (Vourlidas et al., 1997, Fig. 11) for waves of 6.4 and 3.6 cm, respectively; the right one is from (Zlotnik et al., 1998, Fig. 2).

solar disk. An analysis of the observation results showed that, during the above period, the AR radiation in general degraded gradually which in no way explains the special features of the VLA polarization image of the radiation source above the main sunspot. The only clue to the cause of the features observed was an AR image in the Hα line (see Fig. 6), showing a filament, one end of which was projected on the area of the sunspot's umbra–penumbra boundary.

The main point demonstrated by Fig. 6 is the direction of the matter movement in the filament. Observations in the line wings show that **the cold substance flow into the sunspot umbra.**

Another result important for interpretation is the spectral characteristics of the AR 7123 umbra source (see Fig. 5). They were revealed through collating the RATAN-600 observations with the spectrum of another sunspot source (AR 11140, January 2011 (Korzhavin et al., 2012)) similar to the source in AR 7123 studied here. The differences lie in deficient radiation at long waves (a drop in the 5–8 cm range), recorded in the spectrum of the AR 7123 sunspot source during the existence of the image anomaly (April 3–6). At the same time, this effect was absent at short waves. Simultaneously, a process of general degradation of radiation in time was under way (especially noticeable by the time of observations on April 11).

Vourlidas et al. (1997) interpreted their results by including hot loops in the source model (see Fig. 7), but we did not find loops in our study. We think that the special features of both the images and the spectrum of the cyclotron radiation source above the AR 7123 sunspot can be explained in a different way, i.e., not preheating the plasma from below but cooling it from above. Most likely, a model of this source should be close to the model described in (Zlotnik et al., 1998) by its nature but, unlike it, with a more significant plasma-cooling effect above the sunspot center right to the sign reversal of the coronal temperature gradient. Vourlidas et al. (1997) also introduced this assumption, since the O-mode is hotter than the E-mode in their model but only at the 6.4-cm wavelength (see Fig. 7).

This implies that the cooling of the plasma from the top does not penetrate deep and affects only the upper coronal layers. At the level of radiation generation at shorter waves (3.6 cm), the normal distribution of the coronal temperature remains unchanged with height.

GENERAL RESULTS

When studying the anomalous cyclotron microwave radiation source (CMRS) above the NOAA 7123 AR sunspot (April of 1992), VLA, SSRT, and RATAN-600 observations in the microwave range with a high space and frequency resolution yielded the following results.

(1) The Hα filament was identified, and one of its bases was projected on the sunspot umbra when the CMRS anomaly existed.

(2) It was revealed that within a few days the spectrum of the CMRS fluxes differed by a decreasing intensity of radiation in the long-wave region of the spectrum (>5 cm).

(3) Unlike Vourlidas et al. (1997), an assumption was made during interpretation that the special features of the CMRS spectrum, as well as the special features of the thin structure of the CMRS image, can be explained not by the presence of hot loops but, on the contrary, by the cold plasma, inflowing into the sunspot umbra from the Hα filament.

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