RATAN-600 Observations of Solar Cyclotron Lines and their Interpretation

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Abstract

The data of multifrequency observations of AR 7962 on May 10–12, 1996 made in the range from 2 cm to 32 cm on reflective type radiotelescope RATAN-600 are given. The peculiarity of this sunspot-associated microwave source is a narrowband feature at the wavelength about 8.5 cm superimposed on typical frequency spectrum of the active region. Simultaneously, Nobeyama maps reveal a point-like bright source at the wavelength 1.7 cm, both sources coinciding. The observed line-like feature (the relative linewidth of which is about 0.2 and peak intensity exceeds the background radiation of sunspot-associated source by a factor of 2) can be interpreted as a cyclotron line. The life time of 3 days and brightness temperature not more than a few million Kelvin makes it possible to explain the observed line as thermal cyclotron radiation from compact source containing a hot dense plasma. High frequency radiation may be provided by bremsstrahlung from the same source. Analysis of the RATAN-600 and Nobeyama data permits one to measure magnetic field, kinetic temperature and electron density in the hot coronal loop.

Key words: solar corona — loops — magnetic field — cyclotron radiation — bremsstrahlung

1. Introduction

Existence of line-like features in the spectra of microwave sources, attributed to cyclotron mechanism of radiation, was predicted and expected rather long ago (Zheleznyakov and Zlotnik, 1980). According to theoretical analysis, individual cyclotron lines might be detectable in the solar microwave spectrum at gyrofrequency harmonics. Such cyclotron features can develop in the spectrum of the sources having various types of kinetic temperature and magnetic field distributions in the corona: in neutral current sheets, in regions where the line-of-sight magnetic field peaks at some point, in a magnetic flux tube filled with hot electrons. A system of cyclotron lines is also expected in microwave spectrum of thermal radio emission of hot X-ray kernels responsible for the so-called elementary flare bursts (Zheleznyakov and Tikhomirov, 1982). The frequency spectrum and polarization are specific for each type of distribution. This permits diagnostics of active regions by observing the fine structures of the microwave spectra.

Detection of line-like features and investigation of their sources are possible only by the spectrographs and spectropolarimeters (with high frequency resolution) combined with narrow beam antennae. Willson (1985) and Lang et al. (1987) reported the observations of a narrowband feature using the VLA at 10 closely spaced frequencies near 20 cm. Interpretation of this observation as a cyclotron line formed in the hot coronal loop, and diagnostics of magnetic field in the coronal plasma by its characteristics were proposed by Zheleznyakov and Zlotnik (1988, 1989).

In this work we declare detection of line-like feature in the spectrum of microwave radiation from an active region at the wavelength of 8.5 cm, made by radiotelescope RATAN-600, and consider its possible interpretation.

2. Observations

We present the multifrequency observations of the active region AR 7962 during May 11–12, 1996, made in the range from 2 cm to 32 cm on the reflector type radiotelescope RATAN-600. The observations were fulfilled in the antenna system with the South sector of the main mirror, Periscope mirror and the collecting third mirror in the form of parabolic cylinder (Korol'kov and Parijskij, 1979). The combined multi-wave horn was used for covering

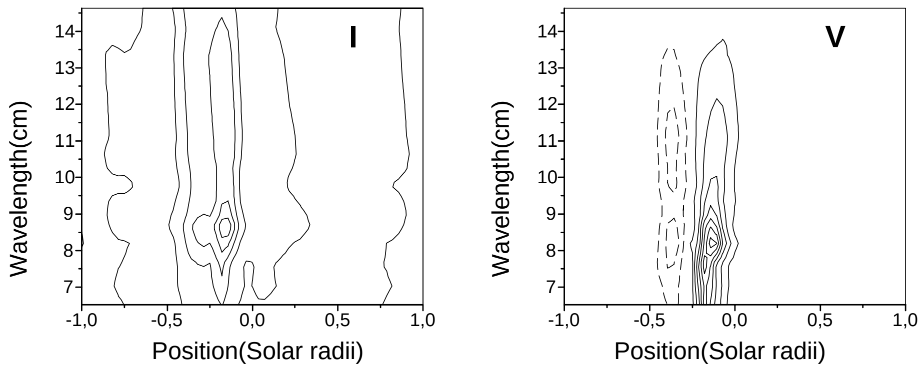

Fig. 1. A multifrequency one-dimensional scan of the source AR 7962 on May 12, 1996: *left* – Stokes parameter I, *right* – Stokes parameter V (solid and dashed lines correspond to right and left hand polarizations, respectively).

all the range (Dikij, 1995). The diagram pattern of the radiotelescope in this case was determined by the following relations:

$$\begin{aligned} &\theta_{\text{horizontal}}(\text{arcsec}) = 0.85\lambda(\text{mm}), \\ &\theta_{\text{vertical}}(\text{arcmin}) = 0.75\lambda(\text{mm}) \end{aligned} \qquad (1)$$

In the present observations the Panoramic Analyzer of Spectrum (Bogod et al,1993; Lang et al, 1993) was used, and the spectrum was analyzed in the following subranges: 18 - 12 GHz, 12 - 8 GHz, 8 - 5.5 GHz, 5.5 - 3.5 GHz, 3.5 - 2.5 GHz, 2.5 - 1.5 GHz, 1.2 - 0.9 GHz. Each subrange is divided by 8 filters with a frequency resolution of up to 5 %.

The microwave source was associated with the complex sunspot group and has a "bipolar" structure in polarized emission. The peculiarity of the source was a narrowband feature at the wavelength about 8.5 cm, superimposed on the typical frequency spectrum of sunspot-associated microwave source. A multifrequency one-dimensional scan of the source on May 12 shown in Fig. 1 demonstrates the condensation of lines of equal intensity (left panel) near the wavelength 8.5 cm. Records of the Stokes parameter V (right panel) show that such a peculiarity was present only in the west component of the bipolar source.

The line-like feature is distinctively seen in Fig. 2, where frequency dependence of the total flux from the whole group (upper panels), as well as fluxes from two oppositely polarized components of the group (middle panels), are given. The intensity of integrated flux exceeds the background by about 50%, and the relative linewidth is about 10–20%.

Comparison of RATAN data with Nobeyama radio maps at 1.7 cm during May 11–12 (Fig. 2, lower panels) shows that the line source coincides with high frequency, bright, small-size Nobeyama source. It is confirmed also by observations during succeeding days, May 13-14, 1996: there is no signature of the narrowband feature in RATAN spectra (the spectrum itself changes its form) and the point-like Nobeyama source degraded and transformed into an extended diffuse region, was not so bright as it was on May 11-12. Matching RATAN-600 data and Mount Wilson magnetic field maps shows coincidence of the line source position with the neutral line dividing opposite polarities of magnetic field in the group.

All this implies that some anomalous compact source was present in the observed active region, which probably contained hot dense plasma resulting in the recorded properties of microwave radiation.

RATAN-600 observations do not allow us to find the source size rather reliably. However, the similarity of the line source and 1.7 cm source permits us to assume the sizes of these sources to be the same. Under these assumptions we can estimate (by the order of magnitude) the brightness temperatures of ordinary and extraordinary modes at the wavelengths around 8.5 cm. Assuming that the flux density inside the line is created by two components, namely, a small (with the size of the order of $10''$, according to Nobeyama measurements) bright source and a weaker extended source responsible for the background radiation, we obtain the background brightness temperature to be of the order of 10^6 K and the maximum line brightness temperature to be of the order of 10^7 K; the relative linewidth is about 20% and the degree of polarization is of the order of 10%.

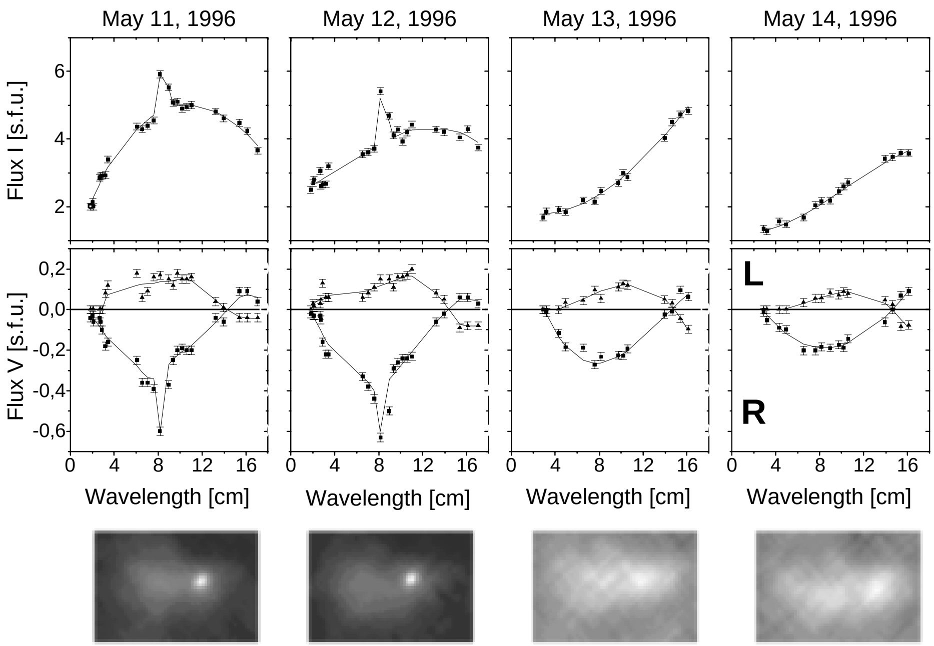

Fig. 2. Dependence of the total flux from the whole source (upper panels) and fluxes from two oppositely polarized components of the group (mid panels) on the wavelength and the Nobeyama radio maps at 1.7 cm (lower panels) during May 11-14, 1996.

3. Model and Radiation Mechanism

Looking for a model and mechanism of the observed radiation, we must bear in mind both RATAN and Nobeyama sources. Since the source existed for a rather long time (more than 2 days), it is reasonable to assume a thermal origin, not associated with non-thermal and coherent mechanisms. It implies that the contrast of compact source against the background radiation of the active region as a whole is due to specific values and distributions of kinetic temperature, electron density or magnetic field. The brightness temperature $\sim 10^7$ K makes plausible kinetic temperature in the source of line-like emission to be of the same order, while the temperature in surrounding plasma is, probably, a few times lower. As for electron density and magnetic field, we consider two possible models of the source: in the first one the narrowband feature at 8.5 cm is associated with the cyclotron mechanism while the bright source at 1.7 cm is due to bremsstrahlung; the second one explains the observed features in both the frequency bands as bremsstrahlung.

3.1. Cyclotron origin of line-like emission

Let us assume that magnetic field at a height of the source is strong enough, so that the frequency corresponding to wavelength 8.5 cm can be one of the low harmonics of the electron gyrofrequency. In analysing different magnetic structures capable to form cyclotron lines, we have to take into account that the bandwidth of the cyclotron line is determined by either the Doppler effect or magnetic field inhomogeneity. If it originates from neutral current sheet (as well as in magnetic field configuration containing maximum at a certain height), the bandwidth is determined mainly by Doppler broadening and/or does not exceed the value $\Delta\lambda/\lambda \sim 2\sqrt{2}\beta_T \cos\alpha$ (where $\beta_T = (\kappa T/mc^2)^{1/2}$, and α is the angle between the magnetic field and the line of sight). For kinetic temperature $T < 10^7$ K and $\alpha \sim 45^o$ (for estimations of α see below) the relative bandwidth is about 5 %, while the observed value is not less than 15–20%. Therefore, we have to leave aside the above configurations of magnetic field and consider formation of the line in the source with inhomogeneous magnetic field.

Moreover, considering such an important observational fact that only a single line was recorded (but not a set of lines at multiple frequencies), we can unambiguously conclude that it may be merely the third harmonic. This restriction is defined by well known properties of gyroresonance layers in the coronal plasma: harmonics with the numbers $s \geq 4$ are optically thin, but harmonics $s = 2, 3$ are optically thick. So, if the observed line had been due to the second harmonic in the hot source, its radiation would have been absorbed in the layer $s = 3$, located in the weaker magnetic field higher in the background corona. Further, if the hot source had contained magnetic field corresponding to harmonic $s = 4$ at the wavelength 8.5 cm, then it would have been impossible to explain the absence of the line-like emission at the wavelength 11.3 cm, corresponding to the third harmonic. This is because the optical thickness of the layer $s = 3$ is much greater than that of $s = 4$, so if the noticeable radiation at the fourth harmonic had been present, the spectrum would have necessarily contained the line $s = 3$ at 11.3 cm. Thus, the observed radiation is due to the third harmonic of the gyrofrequency and we can find magnetic field in the line source:

$$B = \frac{2\pi mc^2}{3e\lambda} \sim 400\,\mathrm{G}, \tag{2}$$

where e and m are the charge and mass of electron, and c is the speed of light.

For the sunspot with magnetic field at the photosphere $B_{\mathrm{ph}} \simeq 2000$ G and the size $d \sim 10^9$ cm it means (under the assumption of dipole character of the magnetic field) that the source was located at the height $h \sim 8 \cdot 10^8$ cm. The observed linewidth $\Delta\lambda$ is determined by magnetic field inhomogeneity along the line of sight. In the same approximation the geometrical size of the source can be estimated as

$$\frac{\Delta h}{h + d} = \frac{1}{3}\frac{\Delta\lambda}{\lambda} \simeq 0.07 \tag{3}$$

or $\Delta h \sim 10^8$ cm, which conforms to the known data on the thickness of coronal loops. Note that this value is greater than the geometrical thickness of the gyroresonance layer $L_3 \simeq 2\sqrt{2}\beta_T \cos\alpha L_B \sim 3 \cdot 10^7$ cm. In order to estimate the optical thicknesses of gyroresonance layers in the source with such parameters we need to know the angle α between the magnetic field and the line of sight. It is important that a weak polarization of observed radio emission requires great values of optical thicknesses τ_{3_o} and τ_{3_x} of the layer $s = 3$ for both ordinary and extraordinary modes. It imposes some restrictions on the angle α: the waves must propagate at a rather great angle to the magnetic field, otherwise the layer $s = 3$ may be transparent for ordinary mode, that results to marked polarization. However, the condition $\tau_{3_{o,x}} > 1$ is easily satisfied for a wide range of values of α. In this paper we accept the value $\alpha \sim 45^o$ (see the discussion below).

The next step of qualitative modeling is finding of the electron density and the size of the source. In the hot plasma (at the temperature $T \sim 10^7$ K) the condition $\tau_{3_{o,x}} > 1$ is easily satisfied even with usual coronal densities N_e and typical magnetic field scales. Restriction from above is imposed by the absence of the fourth harmonic in the observed spectrum (at the wavelength 6.4 cm). Restriction from below is connected with providing a high level of bremsstrahlung at the wavelength 1.7 cm.

We begin with the observed size of the Nobeyama source $l \simeq 10''$ and find electron density providing observed brightness at 1.7 cm. Under assumption of spherically symmetric source its size along the line of sight is the same, that is $l \sim 7 \cdot 10^8$ cm. The optical thickness of the radiating layer can be estimated according to the known relation for bremsstrahlung:

$$\tau_b \sim 10^{-6}\frac{N_e^2\lambda^2 l}{T^{3/2}}, \tag{4}$$

where N_e is expressed in units of $10^9\mathrm{cm}^{-3}$, T is in 10^6 K, l is in 10^8 cm, λ is in cm. Estimations of τ_b at temperature $T \sim 10^7$ K and thickness $l \sim 7 \cdot 10^8$ cm give required electron density $N_e \sim (1 - 3) \cdot 10^9\mathrm{cm}^{-3}$ and corresponding brightness temperature $T_b \sim (10^4 - 10^5)$ K, which is enough to create the observed contrast at 1.7 cm.

An optical thickness of the third harmonic at the temperature $T \sim 10^7$ K, electron density $N_e \sim (1-3) \cdot 10^9$ cm^{-3} and magnetic field scale $L_B \sim 10^9$ cm is undoubtedly great enough. Indeed, using the known relations for optical thickness of gyroresonance layers (see, for instance, Zheleznyakov, 1970; Zlotnik, 1968):

$$\tau_{3_{o,x}} \simeq 0.04 N_e T^2 \lambda L_B \frac{\sin^4\alpha}{\cos\alpha}(1 \mp \cos\alpha)^2, \tag{5}$$

(where all values are written in the same units as before), we obtain $\tau_{3_o} \sim (0.3 - 1) \cdot 10^2$ and $\tau_{3_e} \sim (0.3 - 1) \cdot 10^3$ for $\alpha = 45^o$. However, the harmonic $s = 4$ in such a source is not negligible, namely, according to relation

$$\tau_{4_{o,x}} \simeq 0.7 \cdot 10^{-4} N_e T^3 \lambda L_B \frac{\sin^6\alpha}{\cos\alpha}(1 \mp \cos\alpha)^2, \tag{6}$$

the optical thicknesses at the above parameters are $\tau_{4_e} \sim 2 - 6$ and $\tau_{4_o} \sim 0.2 - 0.6$. It implies that in the microwave spectrum from the source with chosen parameters the polarized line-like radiation must be detectable at the wavelength 6.5 cm, that does not fit observations. Hence, parameters of the compact source must be changed in order to suppress the fourth harmonic radiation. However, we are not allowed to change them arbitrarily: the kinetic temperature T cannot be lower than observed brightness temperature, and electron density cannot be decreased markedly (otherwise Nobeyama data will not be fitted). The two free parameters contained in (6) that may be decreased are magnetic field scale L_B and angle α. Indeed, in estimations above we described magnetic field by vertical dipole buried under the photosphere, and believed that the magnetic field in the coronal loop and considered compact source at its top does not differ from that in surrounding atmosphere above the sunspot. Such an idea is suitable for elementary rough estimations but is hardly adequate to real magnetic fields in complex sunspot groups. Bearing in mind the necessity to suppress the fourth harmonic we can assume that the magnetic field scale in the loop may be markedly less than accepted above value $L_B \sim 10^9$ cm. It is possible that the total magnetic field consists of two components - longitudinal one (along the loop axis), which is bound with the feet of the loop, and azimuthal one, which is due to a current along the loop. In this case the magnetic field scale may coincide or be less than the transverse size of the loop. It is quite enough to put $L_B \sim 10^8$ cm in order to make the fourth harmonic undetectable in the spectrum of the source with chosen temperature and electron density.

Note that the transverse size of the loop itself cannot be decreased arbitrarily: the thin loop does not give enough bremsstrahlung to fit Nobeyama data. One possible way is to choose electron density greater than $3 \cdot 10^9 \mathrm{cm}^{-3}$ and the sizes L_B and l small enough. Since $\tau_b \propto N_e^2 L$ and $\tau_{3,4} \propto N_e L_B$, and, generally speaking, magnetic field height scale L_B and the size l of the region with enhanced tamperature and electron density may differ, one can achieve necessary decrease of τ_4 with no reduction of the bremsstrahlung level at the short wavelength.

Another way to select parameters fitting observation is to choose a plausible angle α. It is seen from (5)-(6) that when α is small enough, we can satisfy simultaneously both conditions $\tau_{3_o} > 1$ and $\tau_{4_e} < 1$ necessary for providing a single non-polarized line attributed to the third harmonic.

Anyway, the above analysis shows that the line-like feature observed by RATAN-600 at 8.5 cm can be understood as the thermal cyclotron radiation from compact source located somewhere in the coronal loop. The kinetic tamperature and electron density in this source are enhanced compared to the surrounding plasma in the loop. The high frequency radiation from the same source detected by Nobeyama radio telescope is attributed to bremsstrahlung mechanism.

3.2. Bremsstrahlung origin of line-like emission

It is known that narrowband line-like features can result not only from the cyclotron emission mechanism but also from bremsstrahlung mechanism (Kuznetsov and Syrovatskii, 1980, Zheleznyakov and Zlotnik, 1988). If $N_e \sim 10^9 \mathrm{cm}^{-3}$ and $T \sim 10^7$ K, the values adopted above, bremsstrahlung from a layer of thickness $l \sim 10^8 - 10^9$ cm will play a negligible role compared to the 8.5 cm cyclotron radiation; but if the plasma density if higher, the bremsstrahlung may become more important.

If the plasma density along the line of sight reaches a maximum N_{max} at some point, a maximum will also appear in the frequency dependence of the optical thickness; it will happen at the wavelength $\lambda_p = c/f_p$ corresponding to plasma frequency $f_p = \sqrt{e^2 N_{max}/\pi m}$. If the inhomogeneous layer has a higher temperature than the ambient plasma, then under plausible conditions the bremsstrahlung spectrum may develop a relatively narrow line.

We have calculated a bremsstrahlung line for a thermally homogeneous layer of thickness $l = 10^8$ cm, temperature $T = 10^7$ K, and an electron density law $N_e = N_{max} \cosh^{-2}(h/l)$, with $N_{max} = 1.5 \cdot 10^{11} \mathrm{cm}^{-3}$, basing on expressions published in (Zheleznyakov and Zlotnik, 1980c). The density N_{max} at the midpoint of the layer has been so chosen that the wavelength λ_p coincides with the 8.5 cm wavelength in the line center, while the thickness and temperature adopted for the layer provide the best fit to RATAN observations.

The results are the following: the source with adopted parameters is optically thin at 8.5 cm relative to bremstrahlung, and the line profile looks like a casp (see Fig. 3 in Zheleznyakov and Zlotnik, 1980c). It means that, first, the brightness temperature $T_b \sim 10^7$ K cannot be reached and, second, the expected linewidth cannot be reconciled with observed values (for instance, expected brightness decreases by the factor of 3 at a relative distance of 0.01 from the center of the line, unlike the observed value of 0.1). Evidently, the brightness of 1.7 cm radio emission is quite sufficient to provide the observed contrast of point-like source on the Nobeyama map. As for the 8.5 cm source, its optical thickness and, correspondingly, brightness temperature may be increased up to the observed values if the size of the source along the line of sight is much greater than above value $l \sim 10^8$ cm. But since the observed size of the Nobeyama source does not exceed $5 \cdot 10^8$ cm, it is hardly believed that the region of enhanced density has the size much more than 10^8 cm. Besides, the bremsstrahlung -line profile, with its sharp cusp, cannot be brought into agreement with the observed profile even if the size of the source and optical thickness are great enough in order the effects of saturation take place in the center of the line.

4. Conclusions

It has been proved that radio telescope RATAN-600 has detected line-like emission in the microwave spectrum of an active region. RATAN's archives contain some other records with narrowband features on the spectra of microwave sources associated with active regions. These data are being checked and re-checked now in order to exclude possible influence of calibration effects in different frequency channels. The data chosen for our paper are more reliable, first, because of rather high intensity of line-like radiation compared to background, and, second, because of existence of counterpart on the Nobeyama map.

Thus, the source of the line emission at 8.5 cm coincides with a point-like source on the Nobeyama map at 1.7 cm. The qualitative analysis shows that the observed fine structure around 8.5 cm can be understood as a cyclotron radiation at the third harmonic of the gyrofrequency in a dense hot small-size source located somewhere in the coronal loop, while enhanced high frequency radiation at 1.7 cm from the same source is due to bremsstrahlung. The observed parameters permit us to estimate magnetic field $B \simeq 400$ G, kinetic temperature $T \simeq 10^7$ K, electron density $N_e \simeq 3 \cdot 10^9 \mathrm{cm}^{-3}$, the transverse size of the loop $l \sim 5 \cdot 10^8$ cm and magnetic field scale $L_B \sim 10^8$ cm. Analysis shows that the bremsstrahlung line can hardly be reconciled with the observed data.

It should be noted that we left aside a mechanism of the background radiation; it will be discussed elsewhere. But since the line source is assumed to be located higher in the corona than the background one, and the line source turns out to be optically thick, the specific mechanism of background radiation is not important for interpretation of the line radiation.

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References

Bogod V.M., Vatrushin S.M., Abramov-Maximov V.E., Tsvetkov S.V., Dikij V.N. 1993, ASP Conference Series, 46, 306

Dikij V.N. 1995, IEEE Asia-Pacific Workshop on Mobile Telecommunication, Hyon Son, Korea Institute of Communication Sciences, Kyongju, Korea, 173

Korol'kov D.V., and Parijskij Yu.N. 1979, Sky and Telescope, 57, 4

Lang K. R., Willson R. F., Smith K. L., and Strong K. T. 1987, ApJ 322, 1044

Lang K.R. et al 1993, Ap.J., 419, 398

Syrovatskii S.I., and Kuznetsov V.D. 1980b, in Radio Physics of the Sun (IAU Sympos. No. 86), ed. Kundu M., Gergely T., D. Reidel Publ.Co., Dordrecht, 445

Willson R. F. 1985, ApJ 298, 911

Zheleznyakov V.V., and Tikhomirov Yu.V. 1982, Solar Phys. 81, 121.

Zheleznyakov V. V., and Zlotnik E. Ya. 1980a, Astron. Zh. 57, 778 (Sov. Astron. 24, 441)

Zheleznyakov V.V., and Zlotnik E.Ya. 1980b, in Radio Physics of the Sun (IAU Sympos. No. 86), ed. Kundu M., Gergely T., D. Reidel Publ.Co., Dordrecht, 87

Zheleznyakov V. V., and Zlotnik E. Ya. 1980c, Astron. Zh. 57, 1038 (Sov. Astron. 24, 595)

Zheleznyakov V. V., and Zlotnik E. Ya. 1988, Sov. Astron. Lett. 14, 195