

THE SPECTRUM OF CORONAL SOURCES AT MILLIMETRE AND CENTIMETRE WAVES

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Abstract. Recently recognized solar millimetre-wave off-limb sources are interpreted as a special phenomenon of long-duration post- and inter-flare emission at coronal altitudes. We present, for the first time, information about the brightness and polarization spectrum in the centimetre range for one such event of September 22, 1980 by means of RATAN-600 observations.

The brightness temperatures observed favour the interpretation of the bulk of the emission by thermal optically thin bremsstrahlung. The degree of polarization measured ($p \approx 0.1$ – 0.2 in the range 7.5 – 15 GHz) implies quite strong magnetic fields of about $\geq 300 \pm 100$ G at a height $z > 3 \times 10^4$ km above the photosphere and indicates a possible contribution of gyromagnetic radiation and/or optically thick bremsstrahlung at longer wavelengths.

1. Introduction

Sporadically occurring, long lasting millimetre-wave sources in the corona attract some interest. The phenomenon can be detected on solar radio maps at regions near the solar limb where the isophotes sometimes reveal the existence of characteristic off-limb sources. According to our knowledge, Kundu (1972) was the first to note the observation of such radiation at 3.5 mm wavelength related to a prominence, and extending to about $200\,000$ km beyond the solar limb. Almost ten years later, quite independently, special attention to mm-wave off-limb sources and their relationship to $H\alpha$ prominence was paid by Urpo *et al.* (1983). Subsequently, the characteristics of coronal mm-wave off-limb sources (CMMS) were studied by Urpo *et al.* (1986) and Urpo, Krüger, and Hildebrandt (1986) based on samples of some tens of cases. It was found that the off-limb sources may be related to flares starting up to several hours prior to the as yet only accidentally accessible mm-wave observations. Therefore, it can be suspected that coronal mm-wave sources, like long duration events in soft X-rays (LDEs, cf. Kahler, 1977), belong to a special group of long-living post-flare events forming a 'super'-gradual burst-like background of a flare/burst series.

The observed heights of the mm-wave sources range between about 50 000 and 150 000 km above the photosphere or more. Heights below 50 000 km are difficult to measure by the present mm-wave observations, due to merging with radiation of the disk as a consequence of the moderate spatial resolution.

While the first interpretation of the coronal mm-wave emission was made in terms of the anticipated optically thick bremsstrahlung from a cold ($\sim 10^4$ K) and dense ($\gtrsim 3 \times 10^9 \text{ cm}^{-3}$) source region quite in accordance with the related $\text{H}\alpha$ prominences, no observable radiation by this process could be expected in the centimetre-wave range. On the other hand, however, arguments for a possible generation of optically thin radiation from a *hot* plasma at microwaves can be obtained for several reasons:

(i) The observed association with soft (and hard) post-flare loops (Krüger *et al.*, 1989).

(ii) The observations of a time delay between the appearance of the millimetre waves and $\text{H}\alpha$ radiation (Urpo *et al.*, 1986).

(iii) The possibility of an underestimation of the brightness temperatures derived, as a consequence of the moderate angular resolution of the mm-wave observations (Urpo *et al.*, 1989).

(iv) The observation of a flux spectrum proportional to λ^2 in mm-waves for a particular case of a source at extreme height (Moiseev and Nesterov, 1984).

(v) The detection of a related emission at cm-waves (see Bogod *et al.* (1986) and the present paper).

It is obvious that a better knowledge of the radio spectrum is crucial for the exact determination of the emission process and the diagnosis of the physical source parameters. In the following we present, for the first time, information about the flux and polarization spectrum of the radiation in the cm-range associated with a coronal mm-wave source which was related to an active region behind the solar W-limb.

2. Observations

The observations were made at the large Pulkovo-type radio telescope RATAN-600 at Zelenchukskaya/Caucasus (U.S.S.R.). They refer to an off-limb source observed at Metsähovi (Finland) at 36.7 GHz ($\lambda = 8.1$ mm) on 22 September, 1980 at about 07:45 UT at a position N 15, $W > 90$ on the Sun (cf. Figure 1).

The source was related to the active region McMath No. 17117 (*Solnechnye Dannye* No. 438) which disappeared two days before at the west limb due to the solar rotation. From this, and assuming a radial source extension, we obtain for geometrical reasons a *calculated lower limit* of the microwave source height of about 30 000 km above the photosphere. The *measured* mm-wave source height was found to be in the range between roughly 50 000 and 100 000 km. There is probably a connection with GRF microwave burst activity starting at about 05:45 UT. The RATAN-600 observations were available at five single frequencies, viz. 7.5, 9.3, 11, 13, and 15 GHz, observed at 09:06 UT in the form of one-dimensional fan-beam scans with a resolution of 34, 27.2, 23, 19.5, and 17 arc sec, respectively. The observations are reproduced in Figure 2(a).

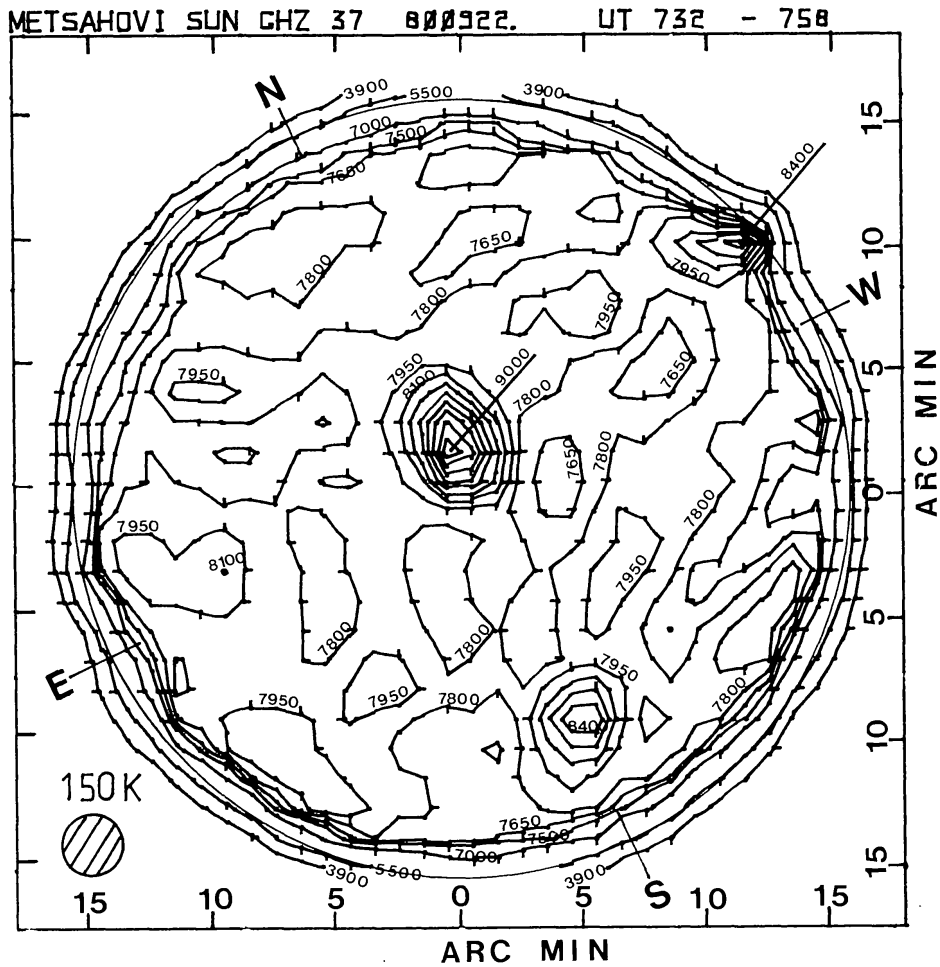


Fig. 1. Solar map observed at Metsähovi at 36.8 GHz (8.1 mm wavelength) on September 22, 1980 showing a coronal off-limb source in the N-W quadrant. Isolines express brightness temperature, the quiet-Sun level corresponds to 7800 K.

Please note that the scanning direction of RATAN-600 which results from the transit of the Sun through the antenna diagram at local noon is inclined to the solar equator as shown in Figure 2(b) (this direction is parallel to the abscissa axis of Figure 1). For this reason the off-limb source is not positioned at the very edge of the scan but projected eastward of the emission peak at the west limb which is due to the active region McMath No. 17120 (*Solnechnye Dannye* No. 444) at S 13 W 79.

In contrast to the usual characteristics of the *S*-component sources (cf., e.g., Krüger, Hildebrandt, and Fürstenberg, 1985), no significant systematic variation of the size of the source related to frequency can be noted. Instead, for all frequencies a mean diameter of the off-limb source of 48 ± 10 arc sec (standard mean deviation of the diameters at different frequencies) is observed. Inside the relatively large scatter range of about 20 arc sec between the extremal values there are also no systematic changes of the source sizes related to the Stokes parameter *V* at the different frequencies.

Taking into account the mean source size quoted above, average brightness temperatures T_b have been derived which are plotted in Figure 3. Furthermore, the flux density S_ν measured, the degree of polarization *p*, and other characteristics are listed in Table I.

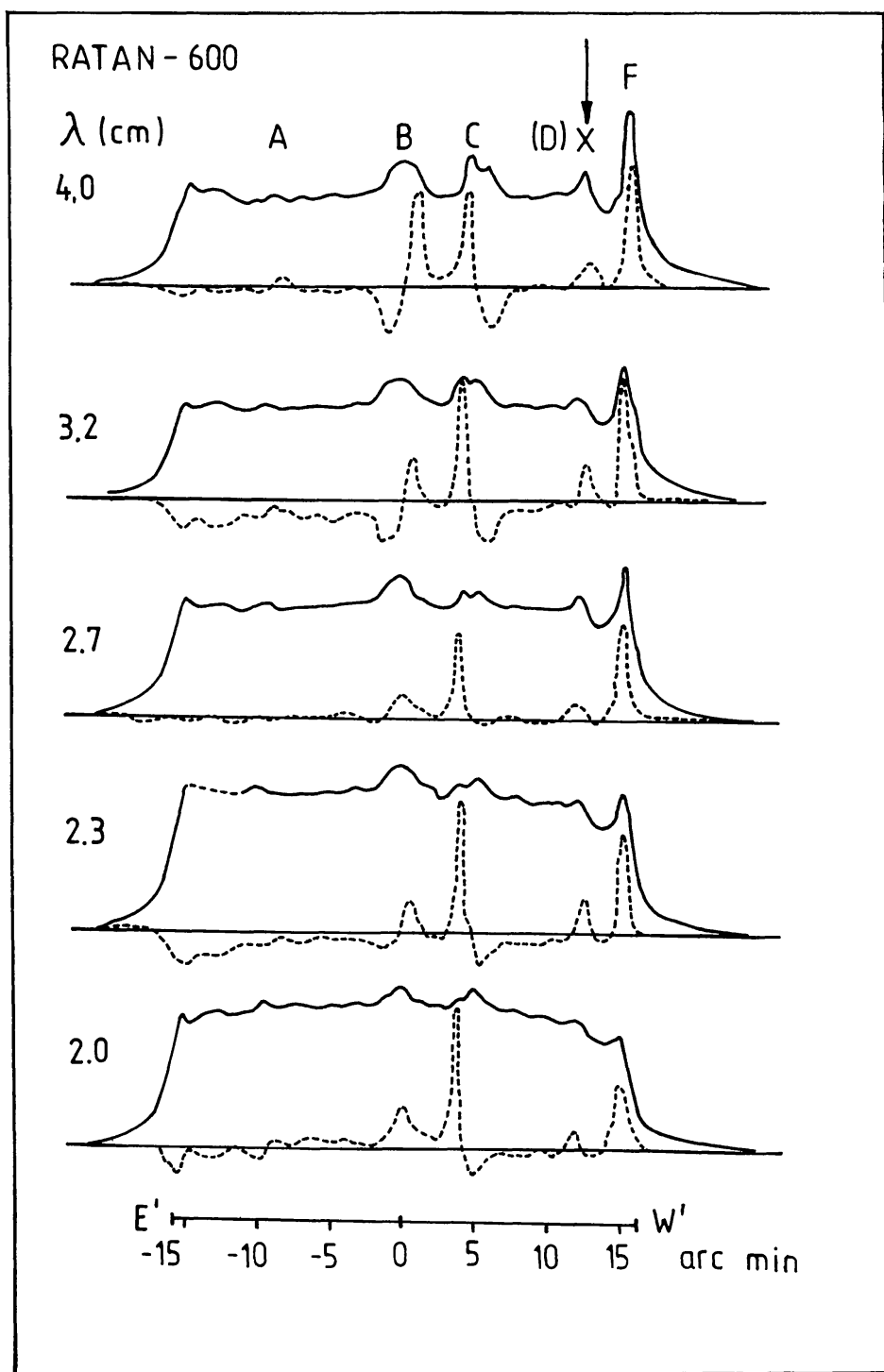


Fig. 2a. Fan-beam scans of the Sun measured by RATAN-600 at five centimetric wavelengths on September 22, 1980. Full and dotted lines refer to the Stokes parameters I and V , respectively. The coronal off-limb source related to AR 17117 (X) is indicated by an arrow. (Further peaks refer to following active regions: A – AR 17154, B – AR 17145 + 17146, C – AR 17142, D – AR 17147 (very weak), F – AR 17120.)

Error bars of T_b and p are marked in Figures 3 and 5. The evaluation of the data was based on the assumption of a two-dimensional, symmetrical gaussian source profile.

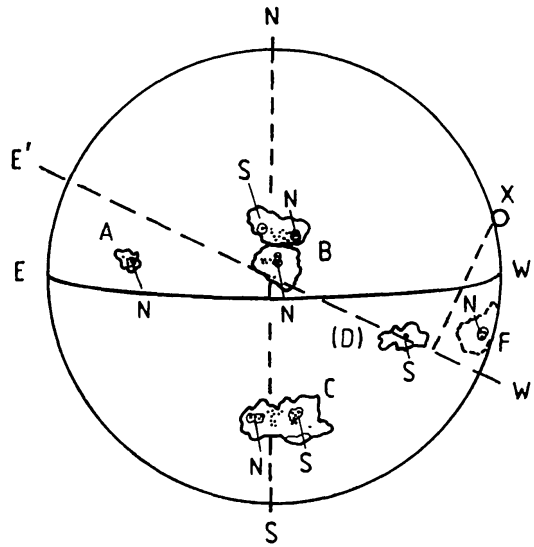


Fig. 2b. Map of the Sun demonstrating the position of main active regions labeled A, B, C, D, and F in relation to the scanning direction E'-W' of the RATAN-600 observations of Figure 2(a). X - off-limb source related to AR 17117.

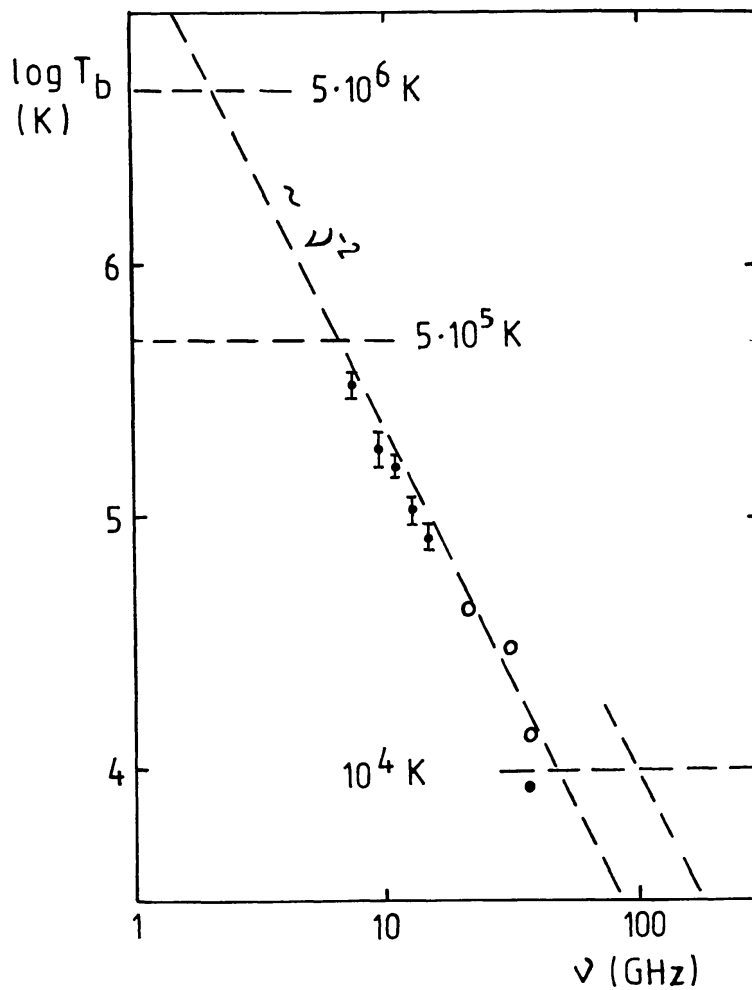


Fig. 3. Spectrum of brightness temperature T_b : black dots - off-limb source on September 22, 1980; open circles - average reduced spectrum of a sample of 48 coronal mm-wave sources after Urpo *et al.* (1989).

TABLE I

Characteristics of the observations of the off-limb source on September 22, 1980 at Metsähovi (M) and RATAN-600 (R)

(GHz)	36.8 (M)	15 (R)	13 (R)	11 (R)	9.4 (R)	7.5 (R)
(cm)	0.8	2.0	2.3	2.7	3.2	4.0
Res. ^a	2'4 × 2'4	17" × 13'	19"5 × 15'	23" × 18'	27"2 × 21'	34" × 26'
t (UT)	07:45	09:06	09:06	09:06	09:06	09:06
S (s.f.u.)	2	2.5	2.4	2.6	2.2	2.5
T _b (10 ⁵ K)	0.085	0.85	1.1	1.6	1.9	3.4
p	—	0.10	0.14	0.19	0.20	0.10

^a Angular resolution in two dimensions.

3. Discussion

The nearly constant spectrum of flux density and the corresponding ν^{-2} -dependence of the brightness temperature T_b in the frequency range observed (7.5–15 GHz) strongly favour an interpretation by optically thin Coulomb bremsstrahlung emission. The average electron density N_e can then be estimated if the average source temperature T_e and the source width Δs are known. Because observations at longer wavelengths are missing (which otherwise could provide direct information about T_e), we use, for orientation, two average values $T_e = 5 \times 10^6$ and 10^7 K in general accordance with soft and hard X-ray observations (cf., e.g., Petrasso *et al.*, 1979; Švestka, 1984; Hick and Švestka, 1987). Taking, as an example, $\Delta s = 5 \times 10^4$ km, one obtains $N_e = 7.1 \times 10^9$ and $8.2 \times 10^9 \text{ cm}^{-3}$, respectively (cf. Urpo *et al.*, 1989). These values are inside the range of densities derived from soft X-ray observations (cf. Petrasso *et al.*, 1979), but exceed those of a normal sunspot model at a height $h = 3 \times 10^4$ km (cf., e.g., Krüger and Hildebrandt, 1985) by a factor 20. The variation of T_e and N_e at different source depths Δs generally compatible with the present brightness spectrum of the RATAN-600 observations is shown in Figure 4. Calculations show that for temperatures $T_e < 10^7$, 3×10^7 , and 5×10^7 K and magnetic fields of $B < 300$, 200, and 100 G, respectively, a contribution of gyromagnetic radiation can be neglected.

The measured spectrum of the degree of polarization p shown in Figure 5 needs more detailed consideration because the dependency $p \sim \nu^{-1}$ which is expected for an optically thin plasma (where $\nu_B/\nu \ll 1$, ν_B – electron gyrofrequency) disagrees with the value of p at 7.5 GHz. There are two possibilities of interpretation:

(i) If we rely on bremsstrahlung and take an average from all frequencies measured, the magnetic field estimated via

$$B(\text{G}) = 0.178 p \nu (\text{MHz}) / \cos \theta \tag{1}$$

yields $B \geq 290 \pm 100$ G (standard deviation from the measurements at the five observing frequencies) for $\cos \theta \leq 1$, respectively. Equation (1) is valid for small optical depths $\tau_\nu \ll 1$ and small ratios $\nu_B \cos \theta / \nu \ll 1$ (cf., e.g. Krüger, 1979); application may be

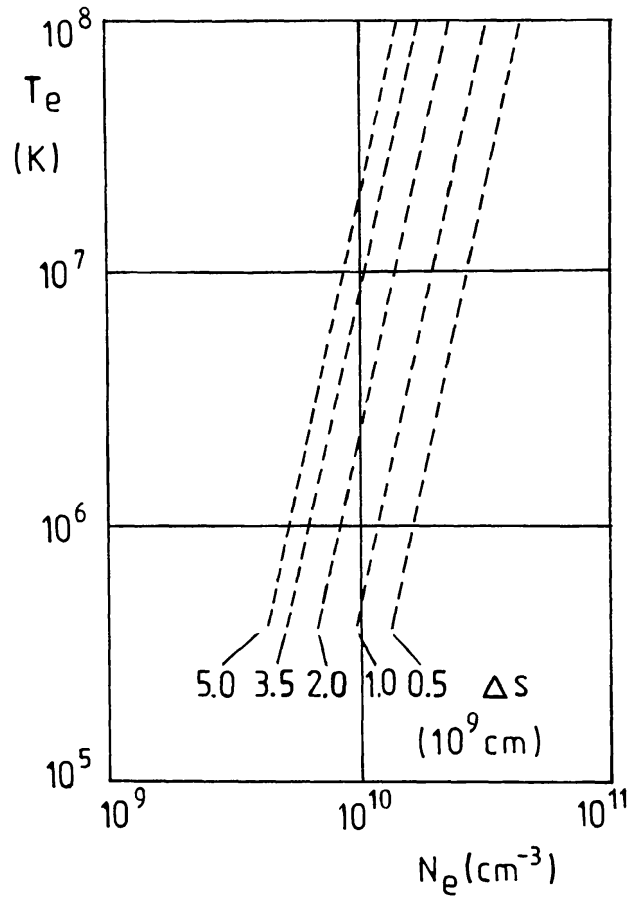


Fig. 4. Plot of the variation of the average source temperature T_e and electron density N_e in dependence on the source depth Δs applying to the optically thin bremsstrahlung spectrum shown in Figure 3.

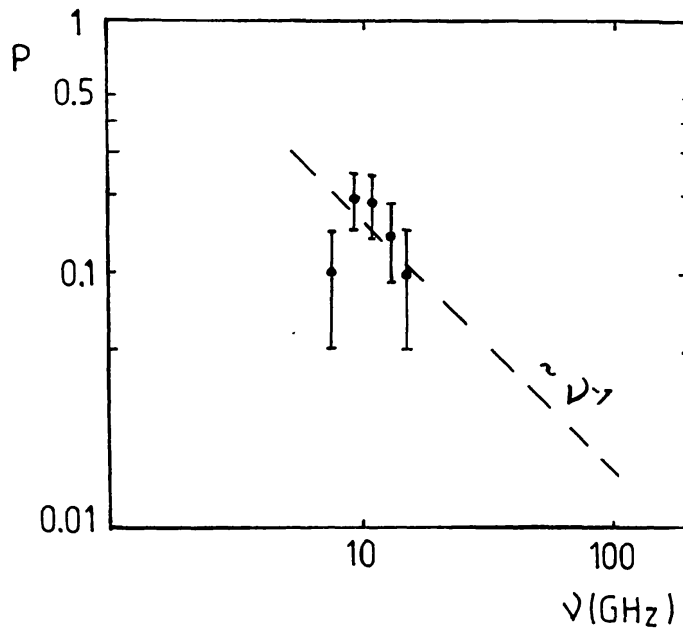


Fig. 5. Spectrum of the degree of polarization p of the off-limb source of September 22, 1980 as measured by RATAN-600.

justified to top regions of loops at the solar limb. For a potential (dipole) field where $B_{\max} = 3000$ G and the dipole depth is $z_d = 2 \times 10^4$ km, at a height $z = (3-5) \times 10^4$ km maximal values of $B(0, 0, z) = 70-200$ G result. Then the values of B derived from Equation (1) appear somewhat larger than expected on the basis of a dipole approximation.

(ii) If, on the other hand, we trust in the value of p at 7.5 GHz and consider the decline of the spectrum of p at frequencies $\nu \lesssim 7.5$ GHz as real, a contribution of gyromagnetic radiation and/or optically thick bremsstrahlung appears quite reasonable.

For the purpose of a rough estimation we calculated the outcome of gyromagnetic emission and Coulomb bremsstrahlung from a homogeneous plasma sheet and used different values for the electron temperature T_e , the electron density N_e , the magnetic field B , the angle θ between wave propagation and magnetic field, and the source depth Δs . The results are illustrated in Figure 6 where T_b and p is plotted vs ν for three sets

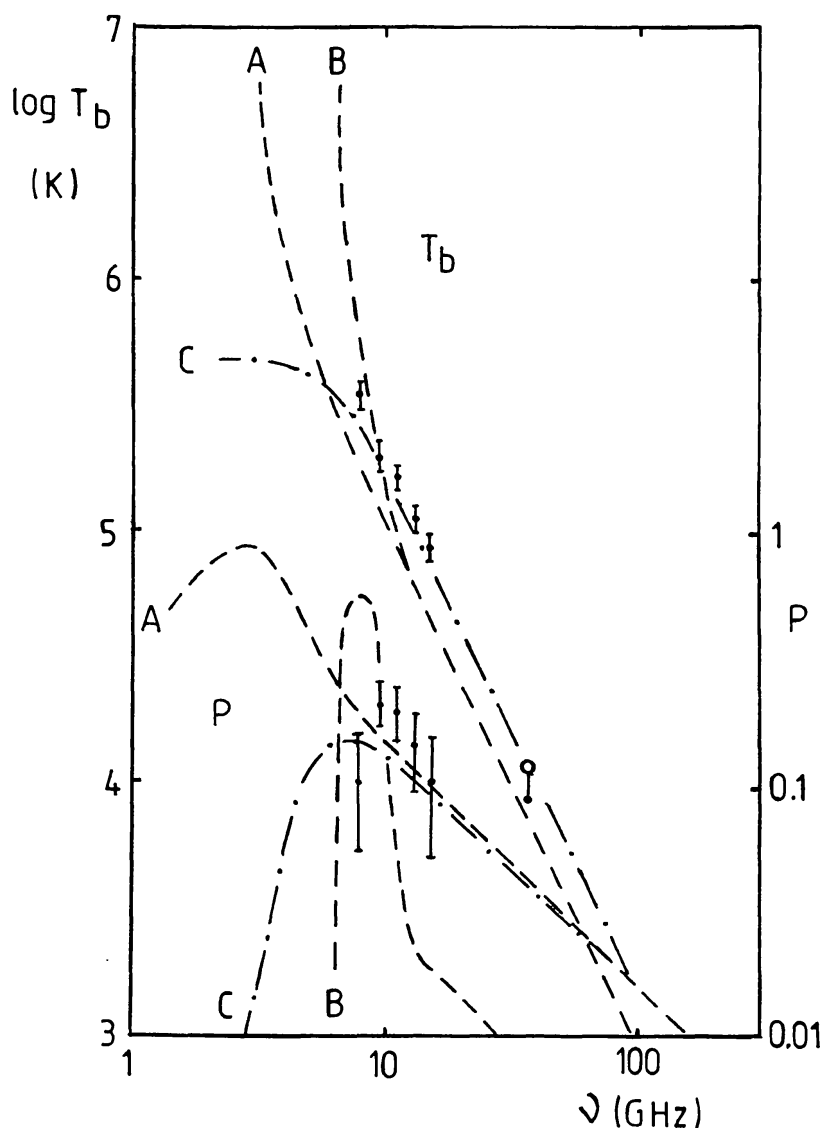


Fig. 6. Calculated spectra of T_b and p for homogeneous source models: A - $T_e = 3 \times 10^7$ K, $N_e = 10^{10} \text{ cm}^{-3}$, $B = 300$ G, $\theta = 10^\circ$, $\Delta s = 3 \times 10^9$ cm; B - same as A but $\theta = 80^\circ$; C - $T_e = 5 \times 10^5$ K, $N_e = 4.5 \times 10^9 \text{ cm}^{-3}$, $B = 300$ G, $\theta = 10^\circ$, $\Delta s = 5 \times 10^9$ cm.

of source parameters in comparison with the observations which are indicated by dots and error bars.

The gyromagnetic radiation predicts a somewhat steeper spectrum of T_b than is observed at the low-frequency edge of the RATAN-600 observations while bremsstrahlung at lower temperatures (e.g., $T_b = 5 \times 10^5$ K) would cause an opposite behaviour. For inhomogeneous sources a superposition of both cases could give quite reasonable results. A nonmonotonic spectrum of p can be produced by both mechanisms, gyromagnetic radiation at high temperatures and bremsstrahlung at low temperatures. More refined model calculations are meaningful if more observational data will be available.

Considering the radiation at 36.7 GHz it is questioned whether optically thick radiation at $T_e \approx 10^4$ K or optically thin radiation from higher temperatures is prevailing at this frequency. Extrapolating the spectrum of Figure 3 from the cm-range towards shorter wavelengths, optically thick radiation at $T_e = 10^4$ K should be detectable at frequencies $\nu \gtrsim 40$ GHz so that the observation near 37 GHz may belong just to the transition between both parts of the spectrum. The primarily observed value $T_b = 8.5 \times 10^4$ K may be due to an moderate angular resolution of the mm-wave observations. If the source size is corrected for that value measured by RATAN-600, a good correspondence between the mm-wave and cm-wave parts of the spectrum follows (cf. Figure 3). Additionally, the reduced brightness temperatures of a sample of 48 off-limb mm-wave sources by Urpo *et al.* (1989) are introduced as open circles in the Figure 3.

5. Conclusions

We obtained for the first time quantitative information about the spectra of the brightness temperature and the degree of polarization for microwave radiation in the frequency range 7.5–15 GHz detected in association with a coronal mm-wave source (CMMS) located behind the solar limb by means of RATAN-600 observations. Results from the present study can be summarized as follows:

(1) The observed brightness temperature can be approximated by a ν^{-2} law; the source sizes are independent of frequency, the diameter is found to be about 50 ± 10 arc sec ($3.6 \times 10^4 \pm 0.7 \times 10^4$ km) for both, the I and V channels; according to the position of the parent active region on the invisible side of the Sun we obtain *geometrically* a lower limit of the source height $z \geq 3 \times 10^4$ km above the photosphere. The source height measured at 37 GHz amounts to about 5×10^4 – 10^5 km. A scatter of the diameter and source position for the V -component as measured by RATAN-600 at different observing frequencies may indicate the existence of yet unspecified local fine structures of the magnetic field.

(2) Sets of average plasma parameters being able to account for the present observations have been discussed on the basis of simple Coulomb bremsstrahlung and gyromagnetic emission models.

(3) The observed spectrum of T_b favours an interpretation of the bulk of the radiation by optically thin thermal bremsstrahlung centered at the high-frequency part of the

RATAN-600 spectrum; average values of, e.g., $T_e = 10^7$ K, $N_e = 8 \times 10^9 \text{ cm}^{-3}$, $\Delta s = 5 \times 10^9 \text{ cm}$ fit the observations of T_b on the average.

(4) According to optically thin bremsstrahlung, the measured degree of polarization yields an average magnetic field as large as $B > 300 \pm 100$ G. A possible contribution of optically thick radiation at medium temperature cannot be excluded.

(5) An interpretation of the low-frequency edge of the observed spectrum by thermal gyromagnetic radiation would not diminish the required value of B for reasonable temperatures up to $T_e = 5 \times 10^7$ K.

(6) The interpretations of items (3) and (4) appear compatible with the general outcome of soft and hard X-ray observations of post-flare sources. But in contrast to the X-rays, the radio waves are capable to contain additional information about lower source temperatures.

(7) Still broader spectral information is required for a more detailed diagnosis of the share of the single emission processes and the resulting plasma parameters.

(8) The time scale of the phenomenon (several hours) is difficult to understand by storage of main-flare released energy only, but strongly suggests excessive energy supply also during the post- and inter-flare development of coronal loops.

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