ON THE COMPLEX SPATIAL STRUCTURE OF A GRADUAL MICROWAVE BURST

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(Received 29 November 1989; in revised form 10 May, 1990)

Abstract. We present a discussion of the gradual burst event on May 13, 1985 which is based on observations of the RATAN-600 telescope at ten fixed frequencies in the range between 37.5 and 0.95 GHz (0.8 and 31.6 cm wavelength) and on time profiles of patrol observations of the Observatory for Solar Radio Astronomy at Tremsdorf near Potsdam. This up to now most complete data set allows new conclusions on the extended spectral/spatial structure of the source region.

There is strong evidence that only less than 24% of the microwave flux from this event is emitted by an excessive small-scale burst source while the bulk of the burst emission comes from a larger region consisting of two major components covered by the source area of the S-component radiation. The different components of the burst and S-component radiation are analyzed.

1. Introduction

In solar flare physics two basic groups of processes of energy release can be distinguished which are related to the impulsive and gradual phase of flares (cf., e.g., de Jager, 1983; Krüger, 1979). Apart from optical flare observations the gradual flare phase is well displayed by the (soft) X-ray and microwave emissions. The information from both wavelength regions is supplementary to each other. In contrast to X-rays, solar microwave emission is principally capable to contain information, e.g., also of the temperature range $T < 10^6$ K and on magnetic fields in the corona.

Due to the general difficulty of achieving simultaneous spectral and angular resolution, the knowledge about microwave bursts is still limited. Early interferometric observations (cf. Kundu, 1965) were in favour of a small size (< 1 arc min) of the sources of the bursts of the type gradual rise and fall (GRF) while the sizes of post-burst increase sources (PBI) have been found to be much larger (> 2.5 arc min). Both burst types form the phenomenon of gradual bursts (Wild, Smerd, and Weiss, 1963). However, the appearance of gradual bursts is much more complex than described by the simple classification schemes before. Here we present a discussion of a particular GRF event for that new spatially resolved observations are available contradicting former knowledge about the source structure of that burst type.

Solar Physics **129:** 351–361, 1990.

2. Observations

The time profiles of the main part of the microwave burst on May 13, 1985 lasting from about 07:59.5 UT till 10:30 UT are shown in Figure 1 according to solar patrol observations of the Observatory for Solar Radio Astronomy at Tremsdorf near Potsdam

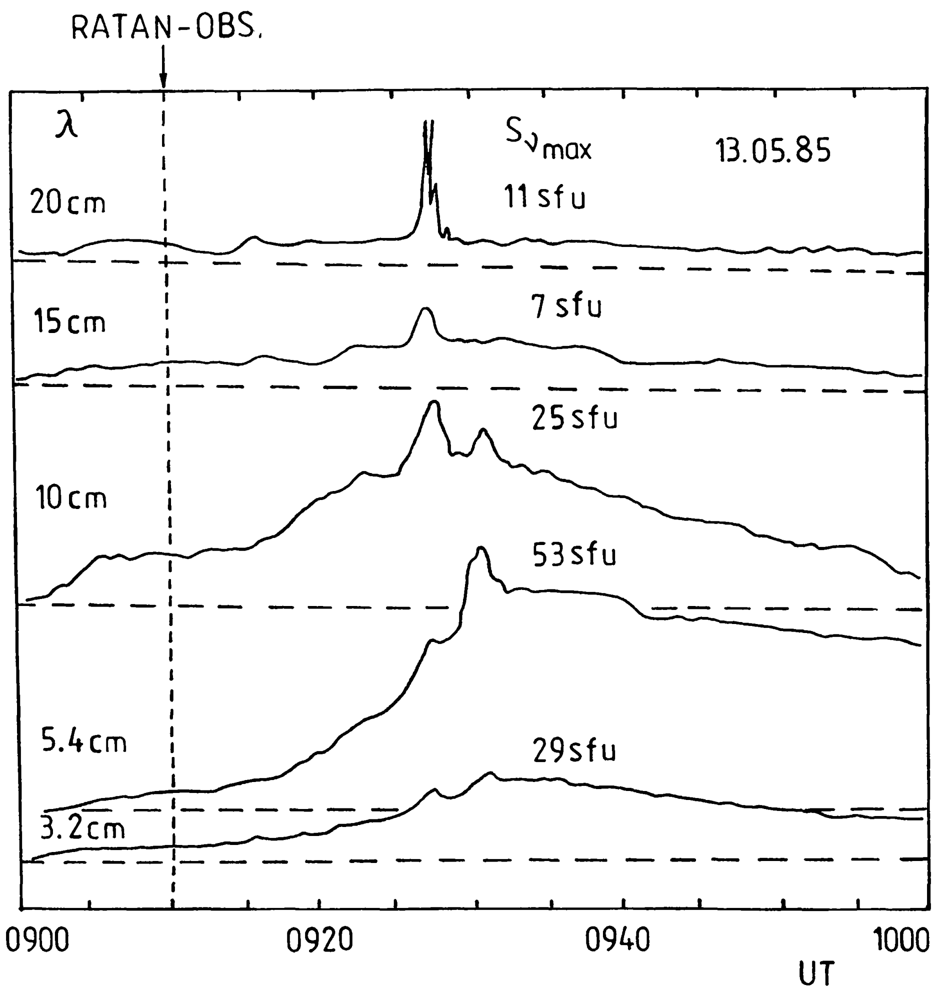

Fig. 1. Time profiles of the gradual burst event on May 13, 1985 recorded at Tremsdorf. The time of the RATAN-600 observation is marked in by the vertical broken line. Fluxes of the impulsive burst maximum are reduced to an early burst onset at 07:59.5 UT.

(GDR) in the range 3.2–20 cm wavelength. The burst originated in the active region USAF/NOAA No. 4652 (≙ SD (*Solnechnye Dannye*) No. 31/1985) at S 13, E06 as compared with optical flare observations (*Solar Geophysical Data*). The Hα flare was of importance SF and lasted from 08:03 until 08:42 UT.

This event was also observed by the large RATAN-600 radio telescope at Zelenchukskaya (Caucasus Mountains, U.S.S.R.) during the transit of the Sun through the antenna diagram at about 09:10 UT. In order to evaluate the burst emission the RATAN observations of the three consecutive days (May 12, 13 and 14, 1985) have been compared. The observations were carried out at the frequencies listed in Table I.

Figure 2 shows examples of the RATAN-600 observations at two selected frequencies

TABLE I

List of RATAN-600 observing frequencies

f (GHz)	38	15	13	11	9.4	7.5	3.6	2.6	1.4	0.95
λ (cm)	0.8	2.0	2.3	2.7	3.2	4.0	8.2	11.7	20.7	31.6
HPBW (arc sec)	7	18	21	25	30	38	83	111	190	287

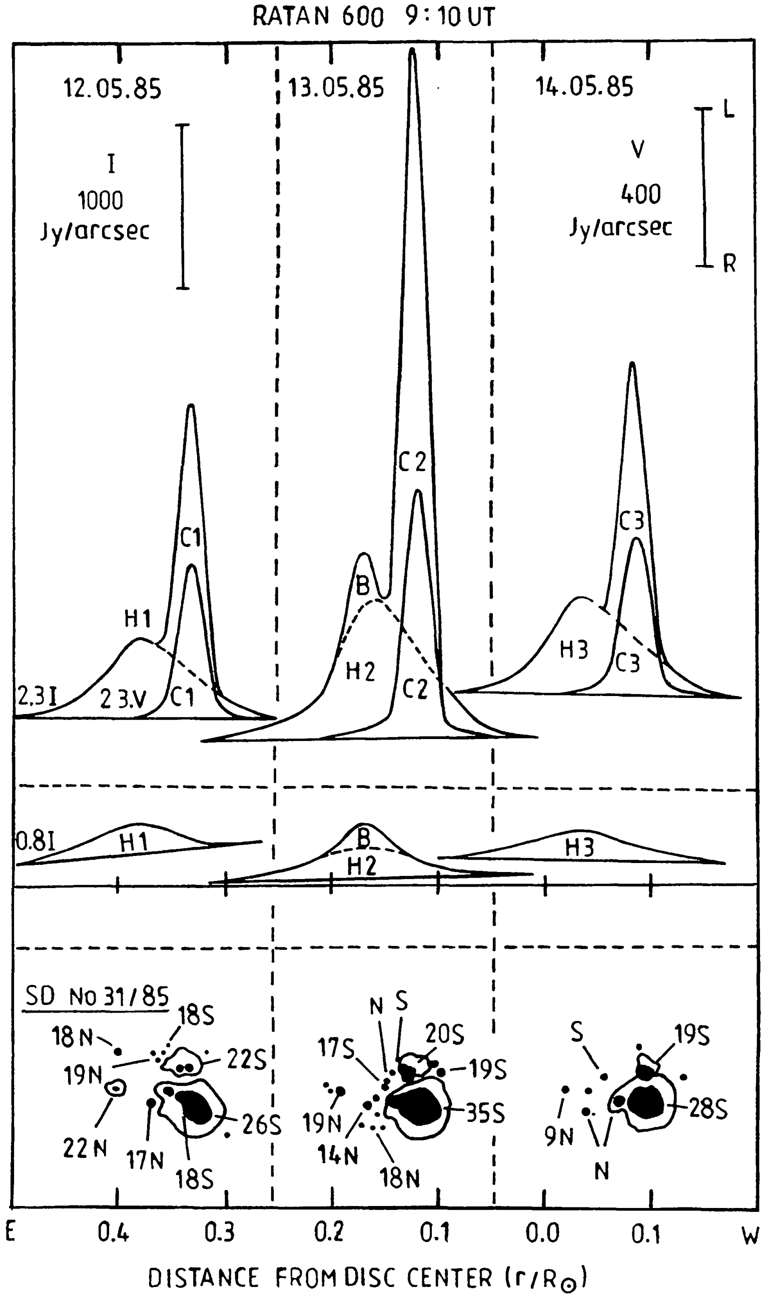

Fig. 2. Scans across AR 4652 measured by RATAN-600 on three subsequent days labeled 1, 2, and 3, respectively, at 0.8 and 2.3 cm wavelength in comparison with the photospheric sunspot configuration. Numbers on the sunspot drawings denote magnetic field strength in hG.

on the three days considered. It is evident that the source of the S-component emission of AR 4652 consisted of two main components, viz., of a left-handed circularly polarized *core/sunspot component* (C) located just above the big leading spot of southern magnetic polarity and of a *loop/halo component* (H) shifted toward the following part of the complex sunspot region. In the latter part new emerging magnetic flux of south magnetic polarity is expected to appear, though this cannot be unambigeously proven by a mere consideration of patrol observations (cf. Zirin and Marquette, 1990). During the burst time both parts of the S-component source exhibit an enhanced emission and also a smaller new source of *burst emission* (B) occurs in the neighbourhood of the component H. The separation between the components B and H is represented by the dotted line in Figure 2 derived by interpolating the best fit starting from the flanks of the H component. This procedure has been carried out at all observing frequencies and is estimated to be accurate within an error range of about $\pm 10\%$ of halo brightness temperature.

3. Discussion

3.1. Spectrum

The spectra of the observed brightness temperatures T_b of the S-component sources C and H on the three days May 12–14, 1985 labeled (1), (2), and (3), respectively, and of the separate burst source B on May 13, 1985 are shown in Figure 3. Differences between the spectra of these different components are quite obvious.

Under quiescent conditions (May 12 and 14, 1985) the part C of the S-component is peaking at about 3.2 cm wavelength. This part of the S-component radiation located above sunspots is well investigated by model calculations (cf. Gelfreikh and Lubyshev, 1979; Alissandrakis, Kundu, and Lantos, 1980; Krüger, Hildebrandt, and Fürstenberg, 1985). The decline of T_b near 4 cm wavelength can be explained by a decrease of opacity of gyro-resonance emission. An alternative explanation would require an inversion of temperature at low altitudes immediately above the leading spot (cf. Gelfreikh and Korzhavin, 1976) or other mechanisms. During the burst time the brightness temperature is rapidly increased reaching about 7.5×10^6 K at 7.5 GHz.

The loop or halo component shows a maximum brightness temperature near 1.5 GHz. Large values of T_b up to 8.5×10^6 were reached also under quiescent conditions (May 14, 1985). The spectrum clearly excludes an interpretation by mere Coulomb bremsstrahlung but rather suggests a long-lasting action of nonthermal particles. A similar case of exciting, hot S-component regions was reported, e.g., by Webb *et al.* (1983) and discussed by Chiuderi-Drago and Melozzi (1984).

During the burst time the whole spectrum of the H-component was even more enhanced strengthening a nonthermal origin of the halo component at the burst time. A similar interpretation of a GRF burst by nonthermal gyromagnetic radiation was proposed, e.g., by Webb and Kundu (1978) and Alissandrakis, Schadee, and Kundu (1988).

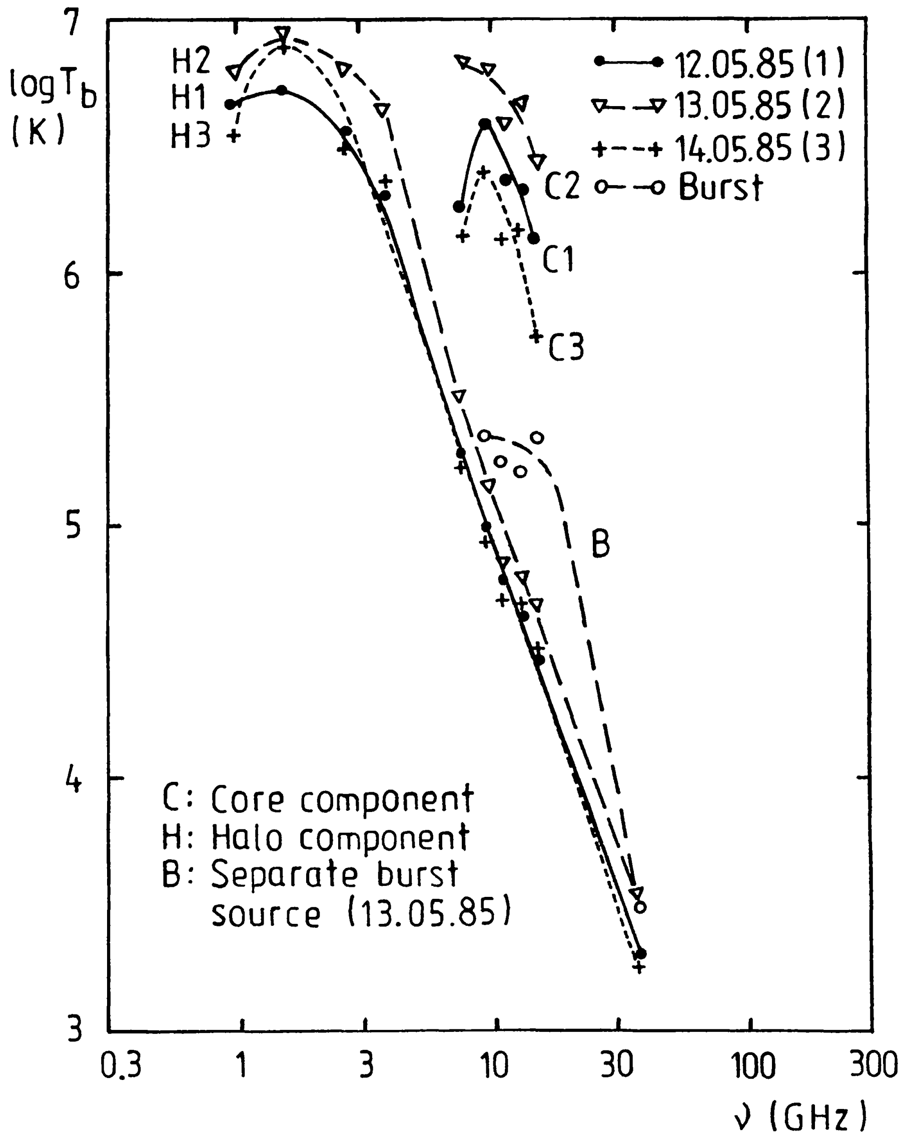

Fig. 3. Spectra of the brightness temperature T_b of the RATAN-600 observations demonstrated in Figure 2.

The only separate feature of the burst event was the low-temperature component B detectable in the frequency range 37.5–9.4 GHz reaching 3.5×10^5 K at the latter frequency. It has to be remarked that even at the frequency of the narrow spectral maximum of flux density B (1.6 s.f.u. at 15 GHz), the contribution of the component B to the burst net flux and to the gross active region flux amounts to about 24% and 12%, respectively.

Figure 4 shows the spectra of the net burst fluxes, i.e., the gross flux during the burst observation minus the preburst S-component flux. For the RATAN-600 observations the S-component 'preburst' flux was estimated as the average of the quiescent flux on the two adjacent days. The spectral maxima of the flux density of the C and H components are at about 10 and 3 GHz, respectively, separated by a spectral minimum at about 7.5 GHz. The spectrum of the sum of all components measured by RATAN-600 coincides well with the spectrum derived by the whole-Sun flux patrol

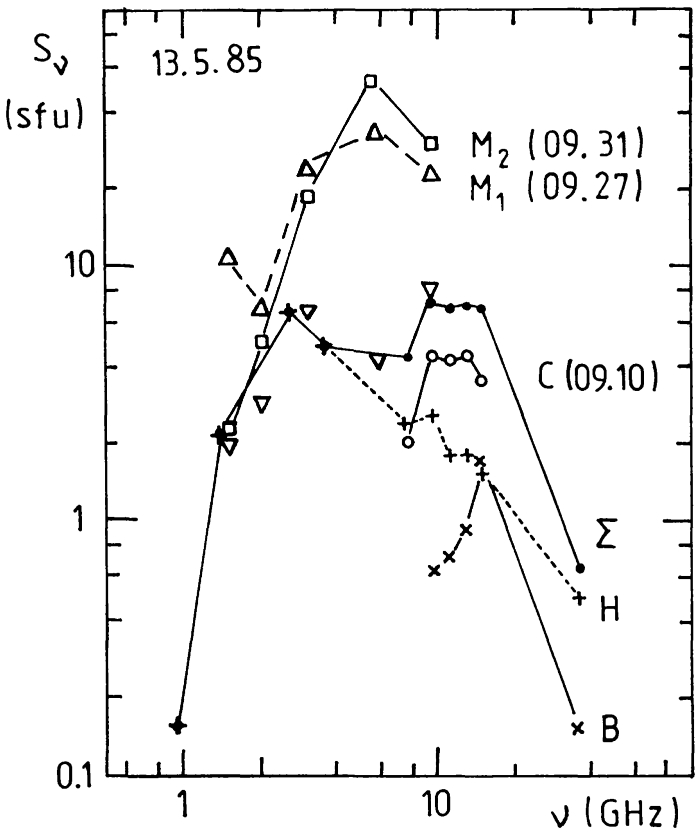

Fig. 4. Spectra of flux density of the GRF burst on May 13, 1985. (a) Tremsdorf observations: △--△ – burst maximum at 09 : 27 UT (M_1); □—□ – burst maximum at 09 : 31 UT (M_2); ▽ – burst spectrum at the time of RATAN-600 observation (09 : 10 UT). (b) RATAN-600 observations (09 : 10 UT): ×–× burst source (B); ○–○ core/sunspot source (C); + · · + loop/halo source (H); ●–● sum of the components $B + C + H$.

observations of the OSRA Tremsdorf at 09:10 UT. Furthermore, it can be noted that the flux spectra measured at Tremsdorf at the time of two maxima of the burst time profiles due to impulsive-burst emission superimposed on the GRF burst exhibit spectral maxima at about 5 and ≤ 1.5 GHz, respectively.

3.2. Localization and Burst Sizes

Figure 5 shows the positions of the centres of gravity of the different components of the microwave emission from AR 4652 in E–W-direction in dependence on frequency measured by RATAN-600 on the three consecutive days considered. For a comparison with the underlying photospheric structure, in Figure 5 drawings of the sunspot group are included in the same geometric scale. The three components B, C, and H are well separated in the high-frequency range of the RATAN-600 observations. At 15 GHz the distance between the centres of the sources C and H is about 48 arc sec whereas the HPBW is 18 arc sec at this frequency (cf. Table I).

The position of component C is clearly above the umbra of the big leading sunspot as it is well known for the sunspot component of S-component emission. The position of the component H is expected at higher (loop-like?) levels in the corona. Due to the

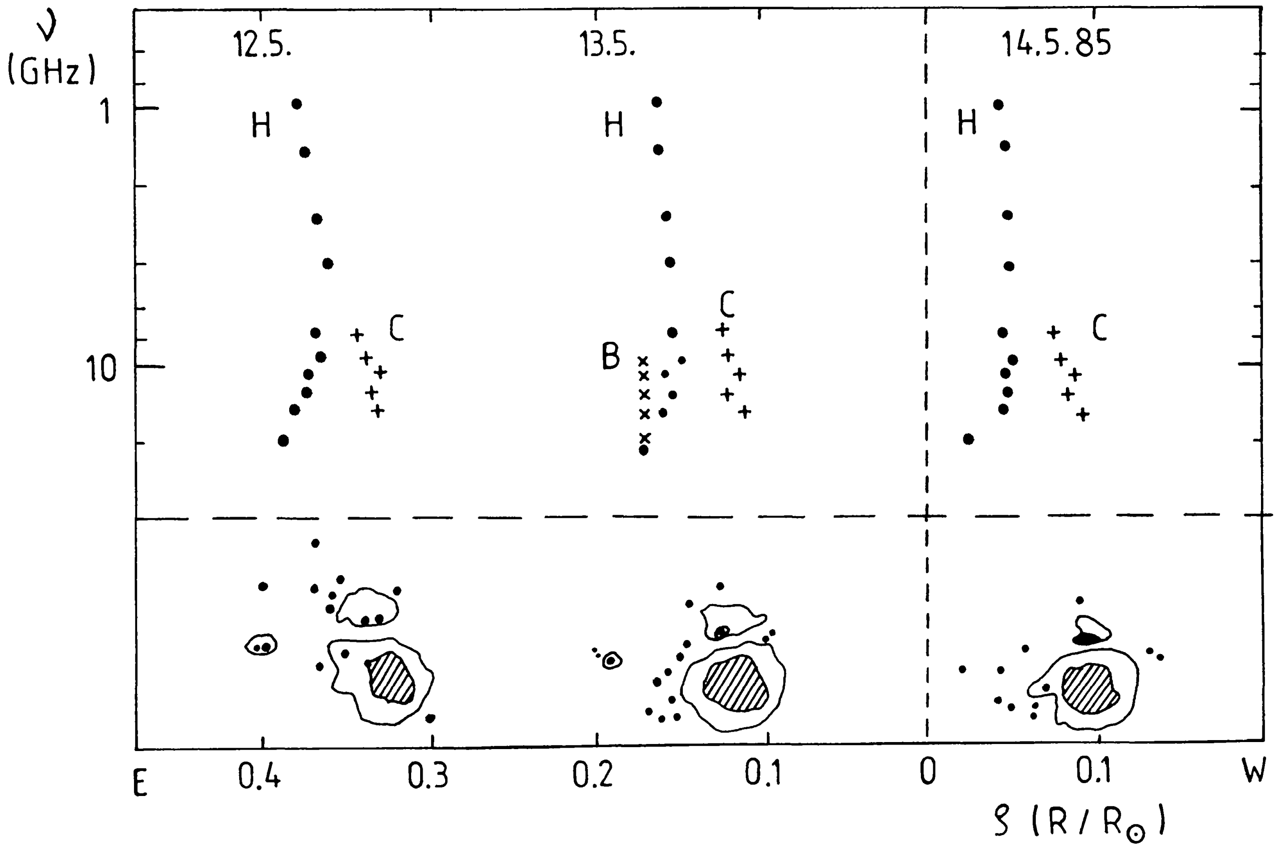

Fig. 5. Plots of the central points of the positions of the components *B*, *C*, and *H* in dependence on frequency, measured by RATAN-600, in comparison with the position of sunspots.

successive decrease of the angular resolution at the lower frequencies of RATAN-600, the sources *C* and *H* are expected to merge below 7.5 MHz.

It may be interesting to note that measurable emission at 38 GHz (8 mm wavelength) preferably corresponds with the location of the component *H* so that it cannot be excluded that this mm-wave emission originates high in the halo region rather than merely in the footpoints of coronal loops.

The components *B*, *C*, and *H* are characterized by quite different source sizes which are shown in Figure 6. The burst source *B* is expected to be compact with a size of about 20 arc sec. Like component *B*, also component *H* is almost independent of frequency. However, the component *H* has a much greater size than *C* reaching about 1.5 arc min (average value 94 arc sec). This source size is evidently larger than the top region of a coronal loop and also greater than reported by Kundu (1965) as being typical for GRF bursts. In contrast to the components *H* and *B*, the diameters of the component *C* depend on frequency and are comparable with the HPBW of RATAN-600. Such behaviour is in accordance to model calculations of the sunspot-related *S*-component emission (cf., e.g., Krüger, Hildebrandt, and Fürstenberg, 1985).

3.3. Polarization

On all three days considered, the component *C* exhibits lefthanded circularly polarized emission in the range 15–9.4 GHz. Ranging between 10 and 40%, the degree of

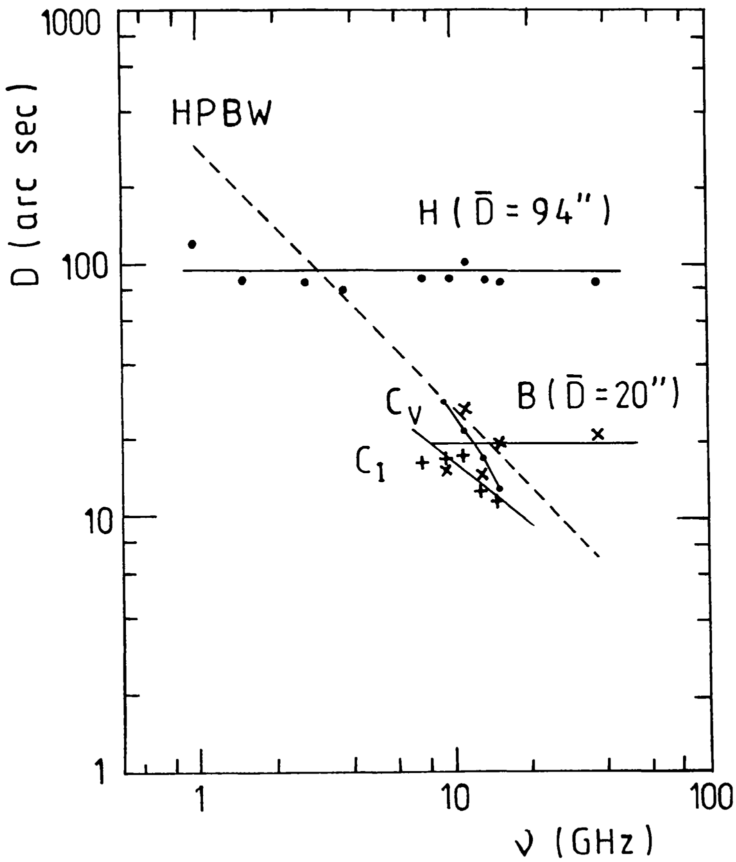

Fig. 6. Sizes of the sources *B*, *C* (for Stokes parameters I and V), and *H* of the event on May 13, 1985 in dependence on the observing frequency of RATAN-600.

polarization *p* increases from 11 to 15 GHz which is well expected for gyromagnetic radiation. However, there occurs also an increase of *p* towards 9.4 GHz which is difficult to explain. During the burst time the degree of polarization is reduced by a factor ≤ 0.5 in comparison with the polarization of component *C* on the adjacent days.

In comparison to the component *C*, the state of polarization of the component *H* is much weaker and rather complex. In the whole range of the spectrum observed we find at least three reversals of the sense of polarization, viz., between 11 and 9.4 GHz, 9.4 and 3.7 GHz, and between 1.4 and 0.9 GHz, even in absence of interfering burst radiation. During the burst time the degree of polarization decreased at short cm-waves.

Concerning the component *B* very weak left-handed polarization seems to be indicated which, however, is strongly masked by the *H*-component.

The polarized part of the source *C* (Stokes parameter V) appears little bit more extended than the source displayed by Stokes parameter I (cf. Figure 6). This behaviour is quite in accordance with the effect expected from a polarized ring around the source caused by emission at the third harmonic of gyrofrequency.

3.4. Relation to the Source Development

The optical counterpart of the present event was a subflare occurring as a member within a sequence of subflares in an active region characterized by a complex magnetic structure and a strong S-component emission. At dm-waves the maximum brightness temperature of the halo component increased under quiescent conditions from 5×10^6 K on May 12, 1985 to 8.5×10^6 K on May 14, 1989. As mentioned before, the present observations are compatible with an origin of the 8 mm-radiation in the halo region.

Source heights of a persistent radiation at 8 mm wavelength of the order 100000 km above the photosphere have been also observed in the case of coronal mm-wave off-limb sources (CMMSs) reported by Urpo, Krüger, and Hildebrandt (1986), and a connection to active regions producing noise storms, at metre waves and long duration X-ray events (LDEs) as well as coronal mass ejections (CMEs) could be stated (Krüger *et al.*, 1989). It may be worthwhile to note that during the burst on May 13, 1985 also a noise storm was in progress at metre waves. An association between noise storms and LDEs or enhanced microwave emission was also stated by other authors (cf. Lantos *et al.*, 1981; Rapley, 1982; Bratova, Gelfreikh, and Gnezdilov, 1983).

Considering the RATAN observations of the present GRF event it should be noted that the observations refer to the rising (pre-maximum) phase of the burst and thus no effect of PBI cvan be expected. The reported start of the event at 09:02 UT (*Solar Geophysical Data*) refers to the onset of a renewed enhancement of radiation; more probable is, however, the start of the event already at 07:59.5 UT where a small, long lasting flux increase can be detected in the time profiles of microwave patrol observations coinciding with a subflare in the same active region. The present event exemplifies the fundamental difficulty of the separation between changing S-component and gradual burst radiations related to the question of detected or not detected (sub)flare signatures.

4. Interpretation and Diagnostics

Summarizing the results of the present observations the following features are to be remarked which may be important for the interpretation of GRF bursts.

(1) An isolated compact centre of the burst source B was located above the following part of the active region where a complex magnetic structure possibly indicates the presence of emerging magnetic flux. However, source B emits only a small part of the microwave emission of the whole event.

(2) The core and halo regions of the source of the S-component were strongly affected by the burst and produce the main part of the burst emission. Unusually large brightness temperatures were observed for the C and H components outside the burst time as was mentioned also in other cases (cf., e.g., Webb *et al.*, 1983).

(3) In spite of the wide range of observing frequencies available, the burst component B could be detected only in the wavelength region 0.8–3.2 cm exhibiting a spectral maximum of 1.6 s.f.u. at about 2 cm wavelength a the time of the RATAN observation. The diameter of source B amounted to 20 ± 5 arc sec.

(4) The polarization of the burst emission was (weakly) left handed at cm-waves in agreement with the leading spot (and probably emerging flux) polarity.

(5) The spectrum of component C does not exclude an inversion of the temperature immediately above the leading spot at low altitudes (cf. Gelfreikh and Korzhavin, 1976). An influence of nonthermal electrons on the components C and H is clearly indicated.

The present observations allow to reconsider the old question of distinguishing the GRF source characteristics from those of the post-burst increase (PBI) which by mere analysis of the time profiles of single-frequency whole-Sun flux observations can be hardly done. Kundu (1965) noticed a remarkable difference in the source diameters of both burst types. Here we could find that, apart from a small volume of the source B, by some dynamical process which sometimes also includes impulsive phenomena, a large source volume in horizontal and vertical direction is occupied by the GRF emission.

5. Conclusions

The considered burst event occurred within a series of subflares in an active region of a complex magnetic structure and strong S-component emission. Hot parts of the S-component ($T_b \geq 5 \times 10^5$ K) are spatially difficult to separate from burst radiation. They evidently indicate the presence of neutral sheets of a complex magnetic field configuration generated by shear or emerging magnetic flux in the following part of the active region. Both, the halo region (about 1.5 arc min diameter) and the core region (about 20 arc sec diameter) of the S-component are clearly affected by the burst emission while the initial burst component, which was spatially separated from the pre-existing S-component sources, governs only a small part of the whole burst emission.

The present observation suggests a close connection not only between impulsive and gradual burst components, but also show a close connection between the burst occurrence and S-component activation. A quantitative analysis of the emission process and a consideration of the dynamic processes leading to a spectacular expansion of the burst source should be the subject of a separate study.

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