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Are short-time variations of the solar S-component emission identical with microwave bursts?

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Extended time series (time resolution about 2–3 min) of spatially resolved observations ($\geq$17 arcsec) in one dimension of solar S-component sources obtained at the Siberian Solar Radio Telescope (SSRT) at 5.2 cm wavelength allow the detection of evolutional features of the growth and decay of active regions in the solar corona. Characteristic slow flux variations with timescales of about 1–2 hours occurring during the decay phase of the radio emission in the low corona above plages and sunspots are compared with recently detected step-like flux increases on timescales of about 10–20 min followed by quasi-constant periods appearing in the initial phase of the development of active regions. Superimposed on this basic behaviour, also fluctuations at shorter timescales (or even periodic oscillations) have been observed.

As it is well known from emission-model calculations, the variations of the S-component radiation can be due to variations of the magnetic field and/or changes of the energy of the radiating particles, which is basically the same emission mechanism as for microwave bursts. Since the "S-component" is originally defined by its long timescale behaviour derived from whole-Sun flux density measurements, the presently detected small-timescale features in S-component sources require either a revised definition of S-component emission or must be considered as "burst-like".

Key words: Sun – Solar corona – activity – microwave emission

AAA subject classification: 074; 077

1. Introduction

For many years the slowly varying component (S-component) of solar radio emission is well observed in the microwave range and originates in the low coronal parts of solar active regions (Kundu 1965; Zheleznyakov 1970; Krüger 1979). The remarkable correlation between S-component fluxes and measures of sunspots early investigated (cf., e.g., Krüger et al. 1964) can be explained by the fact that magnetic fields play a dominating role in the basic emission mechanism of the S-component. This mechanism is due to thermal gyroresonance absorption which was first suggested by Zheleznyakov (1962) and Kakinuma & Swarup (1962). Based on this mechanism, models have been put forward interpreting observations of high angular resolution and providing a tool for plasma diagnostics of coronal magnetic fields and other physical parameters (Zlotnik 1968a, b; Lantos 1968; Gelfreikh & Lubyshev 1979; Alissandrakis et al. 1980; Krüger et al. 1985; Lee et al. 1995; Gopalswamy et al. 1996). Some observations, however, have shown high brightness temperatures ($T_b \gg 10^6$ K) of S-component sources not associated with large sunspots or with enhanced soft X-rays (Webb et al. 1983; Shibasaki et al. 1983) thus requiring a nonthermal origin of the emission (Chiuderi Drago & Melozzi 1984; Akhmedov et al. 1986; Chiuderi Drago et al. 1987; Bogod et al. 1992; Sych et al. 1993). These and other findings gave first indications for a possible overlapping of S-component and burst properties and for a need of a better definition separating both phenomena. Other indications emerge from a consideration of timescales as will be shown in the present paper.

In order to study the interrelation between S-component and burst features, systematic time series of observtions with high sensititvty and high spatial resolution are useful. Measurements by the Very Large Array have given evidence of microwave flux variations also in active regions without sunspots on timescales of minutes or tens of minutes suggesting a brightening and fading of individual coronal loops (Willson & Lang 1986, 1987; Benz et al. 1997). Hence it may be concluded that both extremal cases, viz. occurrence of burst-free S-component emission as well as S-component-free microwave-burst emission may be sometimes displayed. Unfortunately, the observing time at large radio telescopes like the VLA, WSRT, and RATAN-600 for solar studies is limited, and extended data displaying the evolution of solar activity over a longer period with sufficient time and space resolution are difficult to achieve. In the present paper we therefore use data of the large Siberian Solar Radio Telescope which is exclusively dedicated to solar observations and allows to obtain the required time series. The present study discusses selected observations of single active regions obtained at low solar activity in the late phase of the current solar cycle.

2. Observations

2.1. The Siberean Solar Radio Telescope

The large Siberian Solar Radio Telescope (SSRT) is a cross-type interferometer operating at 5.2 cm wavelength (5.8 GHz). Two arms (E-W and N-S) consist of 128 parabolic mirrors of 2.5 m diameter each, equidistantly spaced at 4.9 m yielding a baseline of about 625 m (for a more detailed description of the instrument cf., e. g., Smolkov et al. 1986). For technical reasons the present study is restricted to observations obtained by the E-W arm of the instrument. In this operational mode the solar disk is scanned by a fan-beam diagram. A sensitivity of about 0.05 sfu is achieved. The time and space resolution at local noon (about 05 UT) are 2 min 15 sec and 17″, respectively. The length of observation per day amounts to 6–10 hours, depending on season. In the morning and evening hours the temporal and angular resolutions are reduced to about 3 min and 30″, respectively. Observing solar active regions, the SSRT roughly resolves two types of S-component sources, viz. a sunspot component and a non-spot component outside sunspots. Using the fan-beam of the SSRT, the sunspot component is observed on the background of the non-spot component. Separating both components we infer that the level of the non-spot component can be extrapolated below the spot component level up to the boundary of the source of the whole S-component emission (cf., e.g., dotted lines in Fig. 2 c ff.).

2.2. Time profiles of S-component flux decrease

In spatially resolved observations the sources of the "S-component" are recognized roughly by the steadiness (long lifetime) and relatively small amplitude of the emission. But apart from the temporally smoothed behaviour there exists a number of fine structures (time variations) of the emission which are not systematically investigated yet and of potential interest for the study of coronal energy release and magnetic fields. The present paper takes benefit from an examination of S-component sources particularly during the *declining* (post-maximum) phase in the evolution of single active regions, associated with decaying sunspots. As a rule, during this phase the radio flux does not exceed 2–3 sfu. Therefore, searching for temporal changes of the radio flux and spatial structure of the S-component sources, those active regions have been selected which just occurred near the minimum of solar activity 1994/1995. During this period a few active regions have been observed which favoured the study of small sources of the radio emission.

One of the most interesting problems concerning the declining phase of the evolution of S-component sources is the question about the physical processes leading to the decay of the sunspot component and to the disappearance of magnetic fields in the corona. For comparison, the inverse process, viz. the build-up of the sunspot component was investigated by Nefedev et al. (1993). There it was shown that the sunspot component of the S-component evolves "step-like" at timescales of the order 10–20 min (cf. Fig. 1), a feature which was not found at the declining phase of the S-component emission (cf. below).

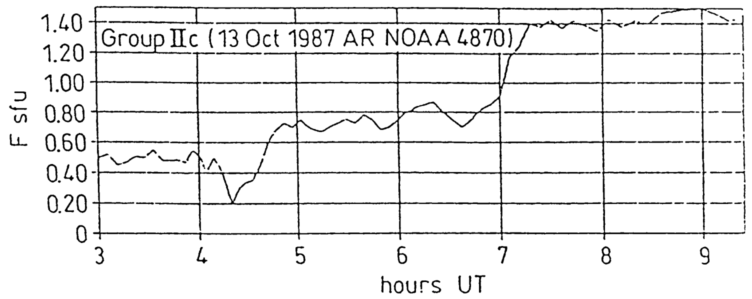

Fig. 1. Example of the flux increase (Stokes parameter I) during the rising phase of active region AR 4870 (from Nefedev et al. 1993).

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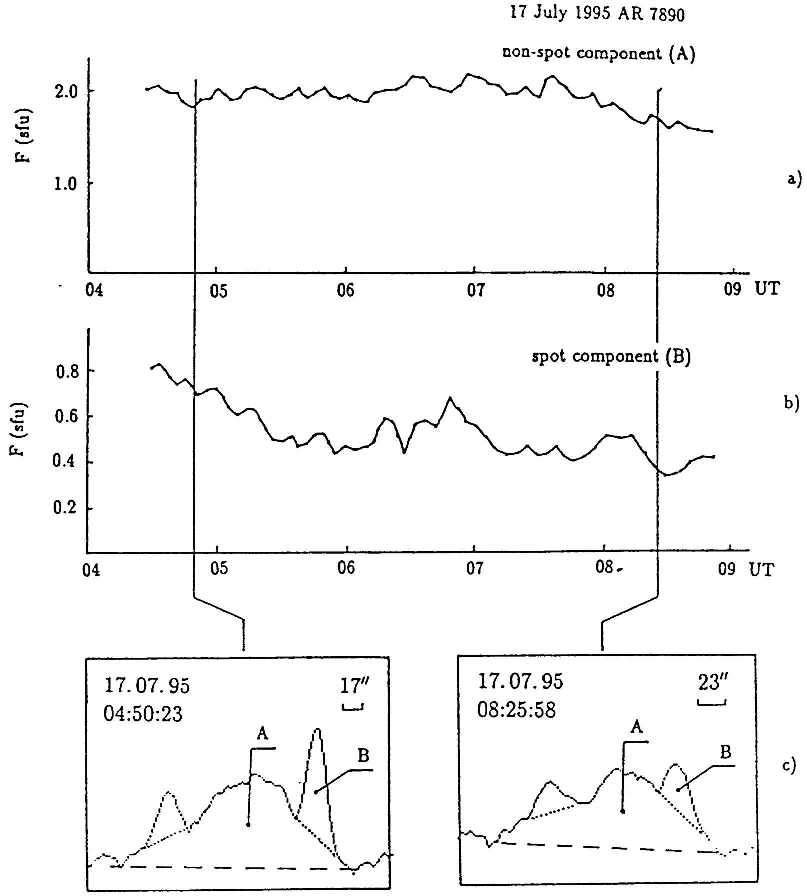

Fig. 2. SSRT observations on 17 July 1995 of AR 7890.
(a) Time profile of the radio flux of the non-spot component
(b) Time profile of the radio flux of the spot component.
(c) Scans of the brightness distribution of the whole S-component source at two different moments near the beginning and end of daily observations (cf. thin vertical lines).
Dashed horizontal lines mark the quiet-Sun level. A – non-spot component, B – spot component. The beamwidth (in arcsec) is given in the right upper half of both figures.

We investigated the declining phase of six active regions observed by the SSRT. A list of these active regions together with their related sunspot areas (taken from Solar Geophysical Data in units of 10^{-6} of the solar half-sphere) is shown in Table I. From this table it can be seen that for these active regions the sunspot area basically decreased during the considered time interval almost monotonously.

An inspection of the S-component (sunspot and outside-spot) sources shows the existence of characteristic peculiarities of the temporal variations of the radio flux and spatial structures for all six active regions which will be discussed in the following.

For illustration, we consider the S-component sources of AR 7890 on 17 July 1995 (Fig. 2) and of AR 7668 during the period of 12, 14, and 15 February 1994 (Figs. 3–5). During these days the related sunspot areas decreased. Spatially resolved pictures of the S-component sources are given in Figs. 2–5 (bottom) where scans of the radio brightness distribution of the total intensity I at the beginning and end of the daily observing period are presented.

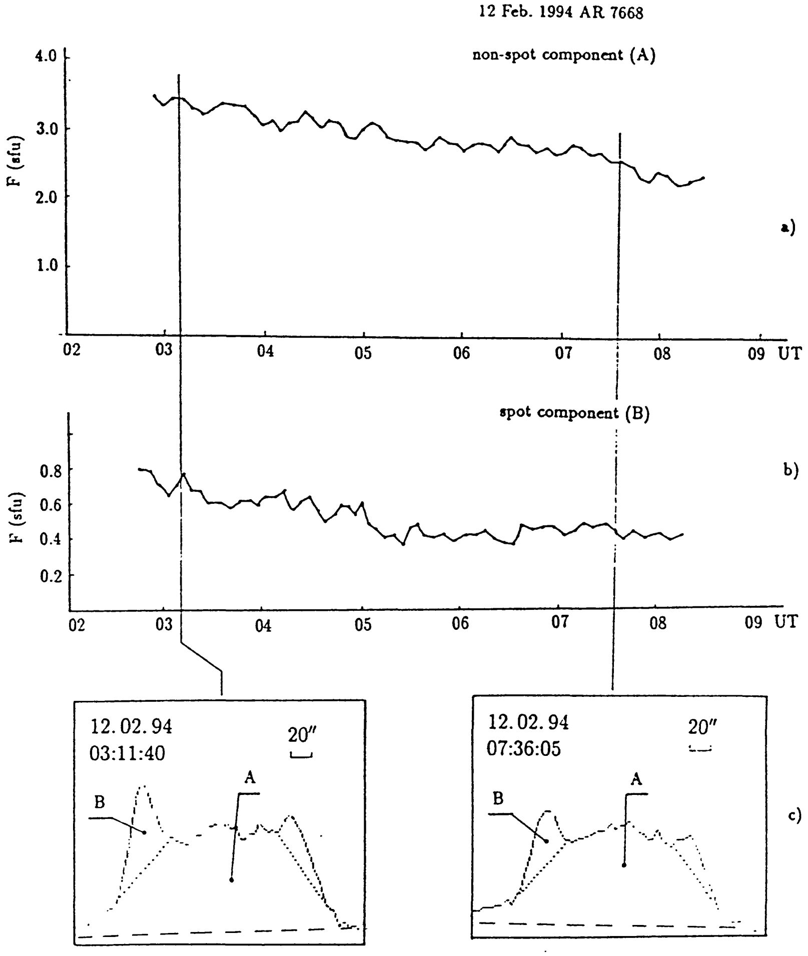

Fig. 3. The same as Fig. 2, but for 12 February 1994, AR 7668.

Table 1. List of observed S-component sources

AR 7668	11 Feb. 94	12 Feb. 94	13 Feb. 94	14 Feb. 94	15 Feb. 94
	Sp 300	Sp 200	Sp 100	Sp 80	Sp 30
AR 7692	21 Mar. 94	22 Mar. 94			
	Sp 40	Sp 30			
AR 7767	21 Aug. 94	22 Aug. 94			
	Sp 80	Sp 40			
AR 7770	24 Aug. 94	25 Aug. 94			
	Sp 70	Sp 50			
AR 7890	16 Jul. 95	17 Jul. 95	18 Jul. 95		
	Sp 150	Sp 100	Sp 90		
AR 7896	6 Aug. 95	7 Aug. 95	8 Aug. 95		
	Sp 50	Sp 30	Sp 0		

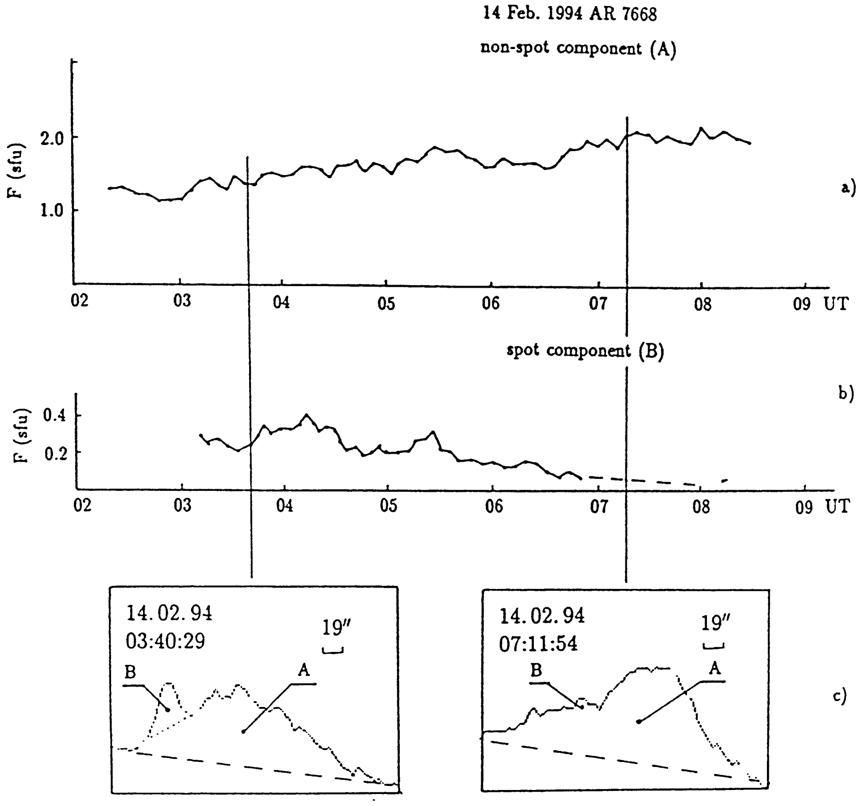

Fig. 4. The same as Fig. 2, but for 14 February 1994, AR 7668.

The following peculiarities of the flux variation are apparent:

- The flux decrease for both the sunspot and non-spot components occurs smoothly. Sharp flux variations like those of the rising phase of the S-component development are missing. Instead, smooth oscillations or enhancements of the flux curve occur with characteristic timescales of about 1–2 hours and amplitudes of about 0.1–0.2 sfu, independently of the background flux level. The reality of the existence of solar microwave flux variations down to 0.05 sfu was proved also by Benz & Fürst (1987).
- During the decay phase of the S-component sources three stages can be distinguished: The *first* (beginning) stage of the decay is connected with a decrease of the related sunspot area. During this stage a decrease of both, the spot and non-spot components (sources B and A in Fig. 2, respectively) can be stated. The *second* stage is characterized by a further decrease of the flux of the spot component down to ≤ 0.05–0.1 sfu, where the flux level falls down into the noise level (cf. Fig. 4). However, it is interesting to note that during this stage in 5 of 6 investigated active regions an increase of the flux, size, and brightness temperature of the non-spot component has been observed (source A in Fig. 4). In the *third* stage the flux of the spot component is ≤ 0.05–0.1 sfu (cf. Fig. 5) while the flux of the non-spot component remains at a higher burst-like fluctuating level.
- The degree of polarization of the sunspot component changes only insignificantly during the whole decay phase of a sunspot. On the average, the degree of polarization varies within the limit of about 25–35 %. However, during the observational period on 24 August 1994 (AR 7770) from 03 UT till 08 UT the degree of polarization exceptionally decreased from 30 % to 15 %.
- The brightness temperature T_b of the sunspot component during the decay of sunspots is different for different active regions. For instance, in the case of AR 7890 (16–18 July 1995) the averaged brightness temperature remained constant at a level of $T_b \approx 2 \times 10^6$ K, while in AR 7668 during the decrease of the sunspot area (11–13 February 1994) the brightness temperature decreased from 2×10^6 to 0.8×10^6 K.

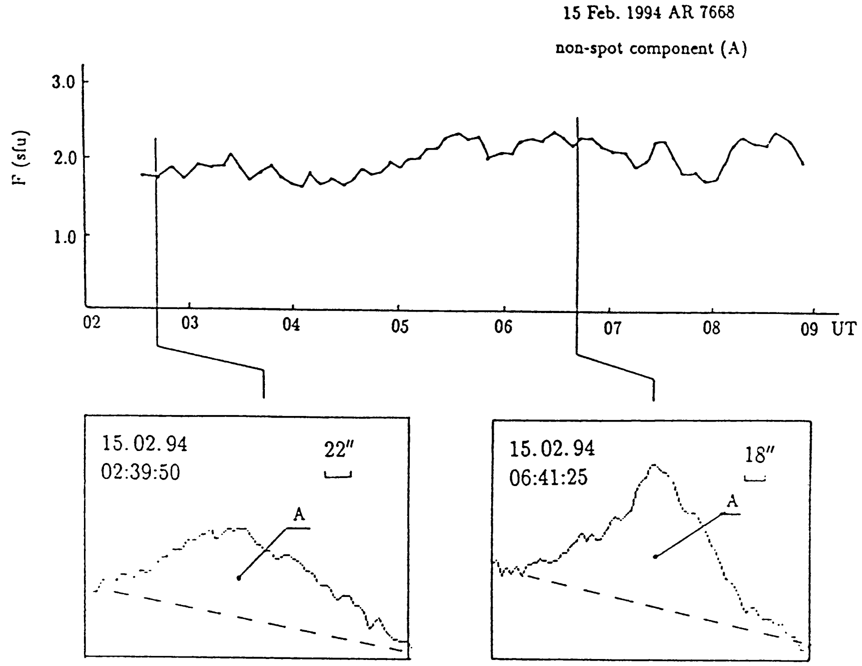

Fig. 5. The same as Fig. 2, but for 15 February 1994, AR 7668.

Sometimes the declining phase of the development of an active region is interrupted by the occurrence of new magnetic flux. Then, a repeated development of the radiation of the S-component can be noted with timescales characteristic for the rising phase of the S-component evolution (10–15 min), as it is seen, e. g., in the case of AR 7890 on 18 July 1995 (Fig. 6).

3. Discussion

3.1. Comparison between the rising and declining stages of solar active regions

As shown in Section 2.2, interesting features of the decay phase of the S-component above sunspots comprise flux enhancements or slow (gradual) oscillatory variations of the Stokes vectors I and V of about 1–2 hours duration and amplitudes up to about 0.1–0.2 sfu superimposed on the steadily decreasing flux level. In contrast to this behaviour, the flux increase in the rising phase occurs more step-like (cf. Fig. 1) accompanied by an increase of emerging magnetic flux of the order $(2\text{–}3) \times 10^{12}$ Wb (Nefedev et al. 1992). Moreover, these authors show examples for impulsive (burst-like) flux variations on shorter timescales at the birth of active regions.

According to the knowledge from S-component emission models one possibility to interpret the step-like flux increase would be by the rise of gyroharmonic levels ($s = 2$ or 3) into the hot corona as a consequence of emerging magnetic flux. Then a step-like flux time profile should be obtained if a rectangular box-like shape of the transition region with lower height above a sunspot is assumed. However, this can hardly explain more than two successive steps and a constant radius of the umbra during the rising phase of magnetic flux seems to be also not a very realistic assumption

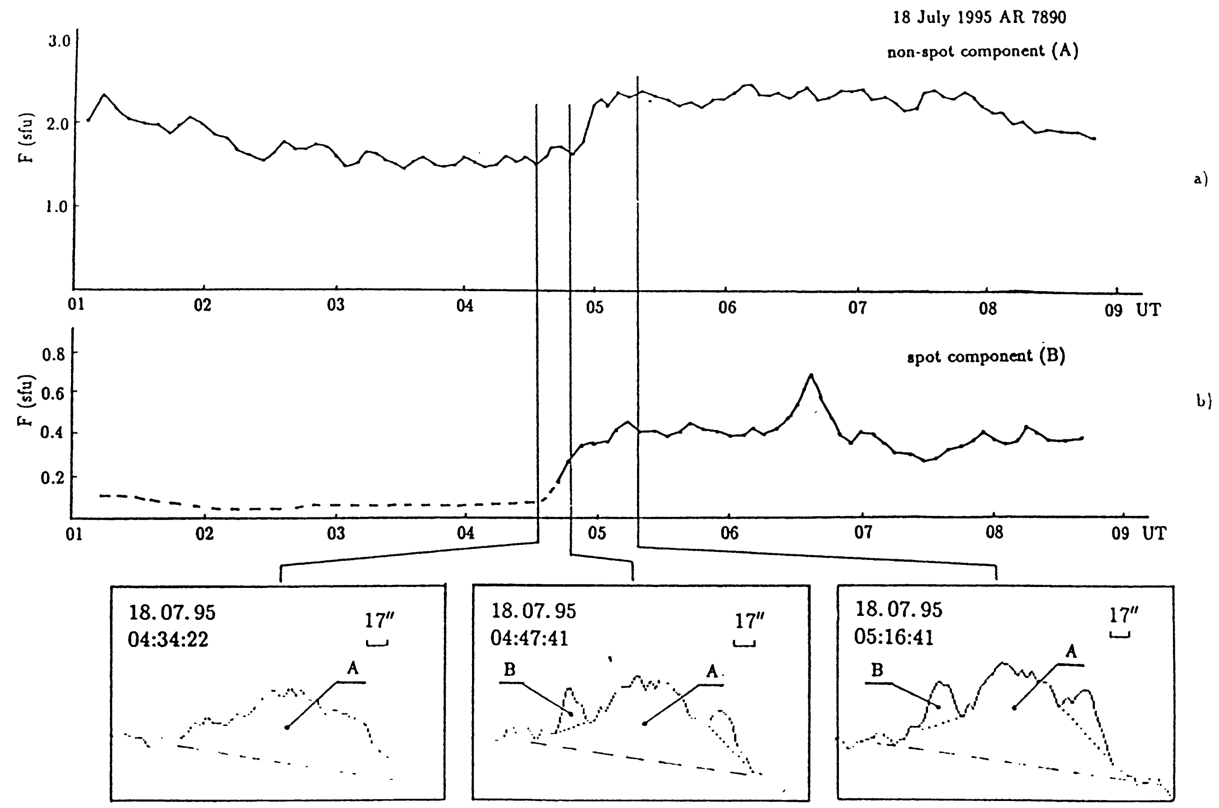

Fig. 6. The same as Fig. 2, but for 18 July 1995 (AR 7890) as an example of a repeated activation of the sources of the spot component (B) and non-spot component (A).

Another interpretation of a step-like flux increase appears posssible by the assumption of impulsive burst-like processes superimposed on a steadily increasing flux level: The flux enhancement may tentatively be interpreted as signature of processes in a current sheet which is driven by newly emerging magnetic flux at the contact surface to the preexisting flux. It is well known that a number of current-driven instabilities can be excited by such sheets. Such instabilities, which include the tearing and coalescence instabilities as well as kinetic current-driven instabilities, have been discussed as drivers of flare-energy release (Heyvaerts et al. 1977; Kliem 1995). If they occur on a smaller scale, comprising only parts of a current sheet, the more gentle enhancements of the radiative output occur, such as the observed step-like enhancements of the microwave flux during the rise of an active region, seen in Fig. 1 as a rise of the S-component. The various possible instabilities release energy in different forms, however, all involve plasma heating. Episodes of plasma heating will increase the microwave flux, since the radiation is optically thick at the observing frequency of 5.8 GHz. On the other hand, during the decay phase of active regions and their S-component emission, the magnetic flux is dispersed so that other magnitudes and space/timescales of energy release and related variations of microwave emission must be anticipated for this evolutional stage.

3.2. On the origin of time variations of S-component radiation

Considering the present SSRT observations and our knowledge from model calculations, we discuss possible reasons causing the flux variations of the S-component radiation, viz. (i) changes of the magnetic field distribution and, hence, changes of the positions of the gyroharmonic levels therein, (ii) changes of the temperature distribution of the thermal coronal background plasma, (iii) changes of the electron density of the background plasma, and (iv) the appearance of nonthermal electrons with various density and energy distributions. Furthermore it is in question whether the flux variations observed are periodic or aperiodic in nature: Although not principally excluded, the present observations cannot provide an unambiguous prove for periodic oscillations.

Magnetic fields [item (i)] reflect the overall evolution of active regions and influence immediately the S-component radiation, where the observed parameters (in particular I, V, and source sizes in dependence on time and observing frequency) can be used as a diagnostic mean of the magnetic field and other coronal plasma parameters. The decisive influence of the magnetic field on the S-component radiation becomes visible especially at the rising stage of solar active regions.

Temperature variations of the background plasma [item (ii)] concern, e. g., variations of the height of the chromosphere-corona transition region, evaporation of chromospheric plasma, and other forms of energy supply which are characteristic for microwave bursts (cf. next Section).

Variations of the electron density [item (iii)] should play a minor role in the case that gyromagnetic emission remains optically thick.

The sources of nonthermal particles [item (iv)] inside the S-component emitting volumes may be either due to in-situ energy release (e. g. via magnetic field reconnection) and/or particle and wave input from outside this region.

3.3. S-component subsources and relation to microwave burst radiation

Spatially resolved observations show that the microwave radiation from active regions forming the "S-component" may originate in different source regions with different characteristics. At first, one can distinguish the radiation originating in coronal regions above sunspots from the radiation originating in regions between or surrounding the sunspots, the so-called spot and non-spot components, respectively. Unlike the spot component, the nature of the non-spot radiation may be rather complex and can consist of several subsources, e. g., a plage component, a loop component, a more extended halo component, and so-called peculiar sources (cf., e. g., Gelfreikh 1990; Krüger et al. 1990). Unfortunately the resolution of such subsources requires high-resolution heliography which cannot be achieved by the scans used in the present paper. The peculiar component is expected to be generated by current sheets situated above neutral lines of the photospheric magnetic field and is capable to deliver nonthermal particles, and also the halo is known for high brightness temperatures. Hence, the question arises in which way S-component and microwave burst radiation are physically distinct and how they can be distinguished. An attempt to characterize both fundamental types of solar microwave emissions goes back to their definition: The "S-component" is originally defined by its long timescale behaviour derived from whole-Sun flux density measurements. Considering the presently detected small-timescale features in S-component sources, either a revised definition of S-component emission appears necessary or the flux variations here described must be considered as "burst-like".

Looking at all main phenomenological parameters, e.g., the amplitude of radiation fluxes, the energy parameters, and also at the emission process, a certain overlapping can be stated for both the S-component and burst emissions. If we follow the practical traditional way to distinguish bursts and S-component by their time scales then the short-term evolutional features detected by the SSRT are simply to be classified as "burst-like". Related to the timescale, the emission features may be more "impulsive" in the rising phase of the development of an active region, and more "gradual" in the declining stages. However, much more information is needed to study quantitatively the details of "small-scale S-component physics" and "burst physics".

4. Conclusions

The study of extended time series of the radiation of single S-component sources obtained by the SSRT at 5.2 cm wavelength led to the detection of smooth flux variations with timescales of about 1–2 hours and amplitudes of the order 0.1 sfu superimposed on a steadily decreasing flux level during the declining phase of the development of active regions. This behaviour is somewhat different from the flux variations during the rising phase which are characterized by shorter timescales and larger amplitudes. A general increase of the flux level during the rising phase of the evolution of S-component sources is certainly due to the penetration of emerging magnetic fields into the lower corona. The "S-component" originally has been defined by its long-timescale behaviour derived from whole-Sun flux density measurements. However, the small-timescale features detected here in S-component sources make it difficult to distinguish them from microwave bursts. Thus, it may be concluded that presently either a revised definition of "S-component emission" becomes necessary or the flux variations described here must be considered as "burst-like". For a systematic study of the details of the exciting physical processes and of the interrelation between spatial and temporal scales which are of high relevance to the fundamental question of the development of solar activity, observation of still higher space and time resolution are required.

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