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Solar microwave bursts in milliseconds - Observations from Mexico City

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RESUMEN

Los picos de radio en escala de milisegundos asociados con emisión coherente no térmica constituyen una área en rápido desarrollo de la radioastronomía solar. Estos fenómenos se relacionan muy cercanamente con la aceleración de partículas y la liberación de energía en las ráfagas. En este artículo describimos los diferentes aspectos de estos fenómenos y hacemos mención de los otros tipos de emisiones solares que están asociadas a ellos. También delineamos el marco teórico del proceso de emisión de estos picos y los esfuerzos que se han hecho en la ciudad de México para observar estallidos solares en microondas a una longitud de onda de 4 cm con un tiempo de resolución de milisegundos.

PALABRAS CLAVE: radioastronomía solar, estallidos de radio, ráfagas, picos de milisegundos.

ABSTRACT

Millisecond scale radio spikes associated with nonthermal coherent emission are closely related to particle acceleration and energy release in flares. In this paper we describe the various characteristics of these phenomena as well as their relation to other solar emissions. We also outline a theoretical framework of the spike emission process and some efforts made in Mexico City to observe solar microwave bursts at 4 cm wavelength with a time resolution of milliseconds.

KEY WORDS: solar radioastronomy, radio bursts, flares, millisecond spikes.

INTRODUCTION

The study of millisecond radio spikes is a rapidly growing field of solar radioastronomy. Their role and diagnostic capabilities for flare theory or their emission mechanism are still unclear. However, considerable progress in our understanding of this phenomena has been achieved over the last few years. Spikes today are generally agreed to be a non-thermal, coherent emission closely connected with particle acceleration and energy release in flares. A review of this field was presented by Benz (1986). Similar phenomena have been found in nearby stars by Lang (1986). Millisecond spikes of the solar radio emission have been known for more than two decades, but recently there is a surge of interest among theoreticians because of some extraordinary characteristics such as their high brightness temperature (up to 10^{15} K), their association with hard X-ray bursts, and their possibly intimate relation to electron acceleration.

It seems that presently only two species of spikes can safely be distinguished: spikes in noise storms at metric frequencies, which seem to be identical with type I bursts except for their shorter duration, and "real" spikes, which extend to much higher frequencies and are associated with flares. This paper deals with the second kind. Whether or not these spikes need to be divided according to frequencies (such as decimetric vs. microwaves) or associated metric activity (type III vs. type IV) is something that needs further investigation.

THE SPIKE PHENOMENA

TIME PROFILE

The duration of spikes is several orders of magnitude shorter than any other type of radio emission. Their discovery took place when appropriate instruments (with short enough time resolution) became available. Early observations are shown in figure 1. Many authors have reported contradictory values for the duration of single spikes, although limited instrumental resolution may explain some of the discrepancies. There seems also to be a trend to shorter duration at higher frequencies (Dröge (1967), Tarnstrom and Philip (1972b)).

Considering only measurements with sufficient resolution, the typical durations of single spikes around 250 MHz are 50 - 100 ms (Dröge, 1967; Benz *et al.*, 1982). However, Barrow *et al.* (1984), measuring spikes with 0.3 ms resolution noted some structure down to 5 ms. The typical duration of a spike decreases to 10 - 50 ms at 460 MHz and to 3 - 7 ms at 1420 MHz (Dröge, 1967). The duration seems to be below 10 ms for frequencies around 3000 MHz (Zhao and Yin, 1982; Stäli and Magun, 1986).

Tarnstrom and Philip (1972b) noted that the duration of spikes is comparable to the electron-ion collision time,

$$\tau = \frac{0.18\,T^{3/2}}{n_i \ln \Lambda} \tag{1}$$

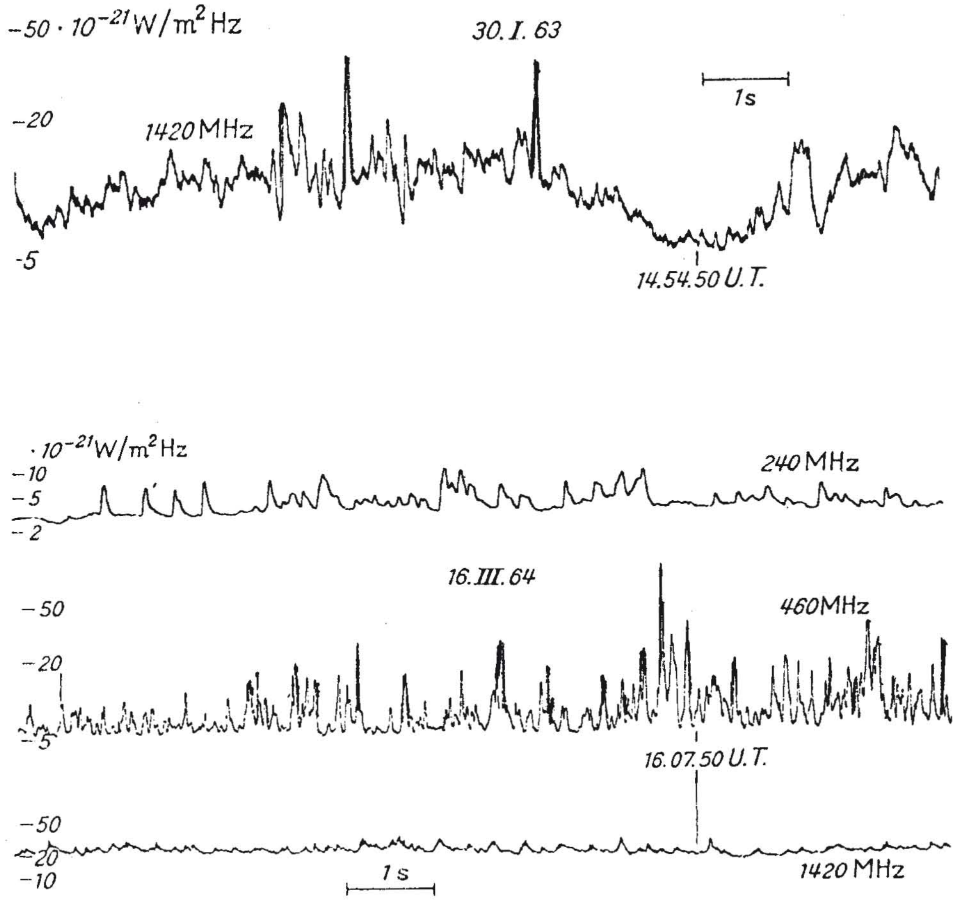

Fig. 1. Full disk radio observations (total flux vs. time) of a solar flare at different frequencies. Top: spikes superimposed on major type IV event in microwaves. Bottom: spikes at 460 MHz associated with metric type III bursts at 240 MHz (from Benz 1986).

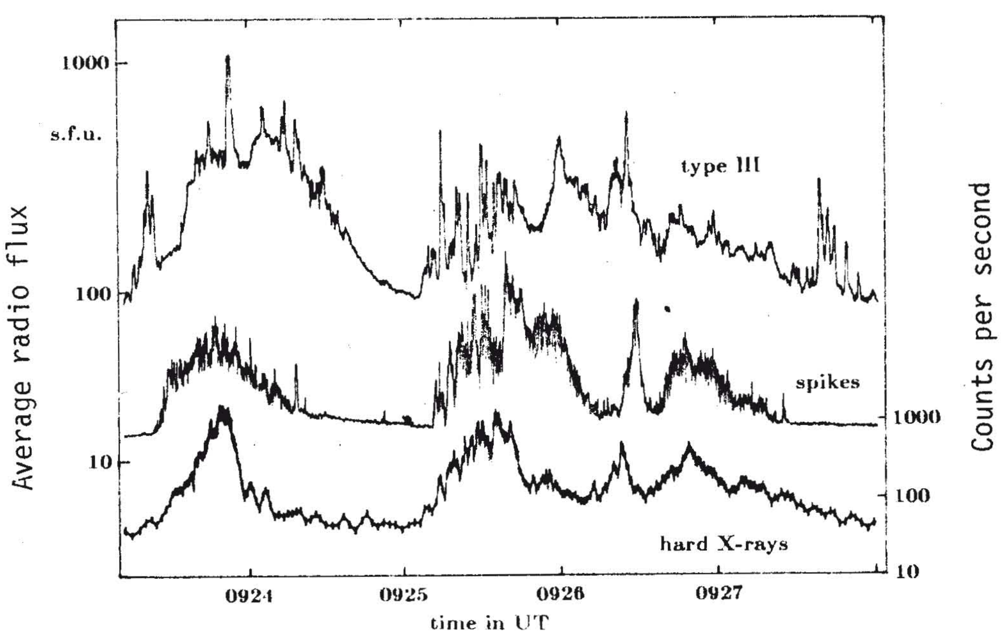

Fig. 2. Correlation of frequency-averaged spike flux in the frequency band 580-640 MHz (middle) with type III emission in the 250-310 MHz band (top) and HXR (bottom). The radio data have been recorded with the Zürich digital spectrometer (IKARUS), the HXR observations were made by HXRBS/SMM (from Benz, 1986).

where n_i is the ion number density, T is the absolute temperature of both ions and electrons (Zheleznyakov, 1970). With $\ln\Lambda \cong 11.2$ and for fundamental plasma emission

$$\tau \cong 4.0\left(\frac{1}{v}\right)^{2}\left(\frac{T}{2\times10^{6}}\right)^{3/2} \qquad (2)$$

where v is the observing frequency in GHz. Several authors found that the upper limit for the source size is smaller than $c\tau$ where c is the speed of light, but on the other hand, it seems unlikely that the smallest size decreases with frequency.

In a spike emission event, the basic units of the spike group are single spikes crowded together to form separate spike clusters. A spike cluster may consist of 10 - 100 single spikes. The duration of a spike cluster is often 10 - 100 ms, and a large spike cluster may exist for more than 1s. The time interval between clusters is 10 - 1000 ms. Jin Sheng-Zhen *et al.* (1990) showed that some of the spikes with very steep rising phase and decay phase were not yet resolved in 1 ms time resolution.

Every individual spike is composed of a series of fluctuations, each with a fast step rise phase and a rather slow decay phase. The rise time of a spike is about 0.1 - 0.3 ms, and the decay time is about 1 ms. The quasi-period of the fluctuation is about 0.5 ms. It seems that a single spike is composed of a group of "micro-spikes" with 0.1 ms fine structure (Jin Sheng-Zhen, 1990).

Some rapid quasi-periodic oscillations have been found in the millisecond spike emission. The quasi-periods of the oscillations are 0.1 - 10 s (Jin Sheng-Zhen, 1990). Such oscillations might be associated with the Alfvén or magnetoacustic waves. The wave fluctuation modulates the magnetic field, the plasma density and even the pitch angle of the particle beam in the magnetic loop. Therefore, the growth rates of the electron cyclotron maser instability can be influenced (Zhao *et al.*, 1989).

SPECTRUM

Early spectra revealed that spikes are very narrow-banded. Reported observations of the bandwidth vary between 0.5 and 15 MHz; the measured values depend on the peak flux. The first quantitative spectra of spikes have been published very recently. The half-power width at practically instantaneous time is typically 10 MHz, or 1.5%, at a center frequency of 600 MHz. This extremely narrow width is a powerful restriction on possible emission processes. It is clear today that spikes are most abundant in the decimetric range, i.e. from 300 to about 3000 MHz.

Various drift rates of the time of peak flux vs. frequency have been reported. Generally the drift rate is negative (i.e., from high to low frequency) and much higher than in type III bursts caused by electron beams (Benz *et al.*, 1982). Slowly drifting spikes, however, seem to occur in about 1% of the cases (Tarnstrom and Philip, 1972a). Barrow *et al.* (1984) reported drift rates of -50 MHz/s at 263 MHz. Elgaroy and Sven (1979) have published a case with -23 MHz/s at 525 MHz.

FLUX DENSITY

The flux density of the spike emission is higher than for radio bursts. The ratio of the spike intensity to the normal radio burst background intensity may be about 10 - 100 (Jin Sheng-Zhen *et al.*, 1990).

POLARIZATION

De Groot (1962), Chernov (1974, 1977) and Slottje (1978) reported "strong" circular polarization of spikes. More recent measurements (Slottje, 1980; Benz *et al.*, 1982; Stähl and Magun, 1986; Nonino *et al.*, 1986) agree that the polarization is generally higher than that for type III bursts, but it can vary from 0 to 100%. It is interesting to note that these observers measured spikes at different frequencies (from 0.2 to 3.2 GHz) and associated with different metric activity (type III and type IV). The polarization averaged over many events is between 25 and 30%. Surprisingly, the value does not vary between 0.238 GHz and 3.2 or even 5.2 GHz.

POSITION

The center to limb variation of the rate of occurrence of spikes has been investigated by statistics on associated Hα flare positions. No longitudinal effect has been noted by Benz *et al.* (1982) at 0.3 GHz and Stähl and Magun (1986) at 3.2 GHz. It may thus be concluded that propagation effects do not play a major role in the spike process. Only one direct measurement of the position of a spike event has been reported (Heyvaerts *et al.*, 1978). The sources were found separated from the associated type III burst by about 1 arc min. Therefore, it seems that both the emission mechanism and the source environment of the two radiations are different.

PHENOMENA ASSOCIATED WITH SPIKES

The timing of spike emission in relation to the flare process is an important indicator for the interpretation of spikes. In the following we describe other solar phenomena frequently associated with millisecond spikes.

OTHER RADIO EMISSIONS

Spikes most frequently appear at times of type III bursts, the radio signature of electron beams in the corona. Even with a film recording spectrograph spikes are observed near the starting frequency of type III bursts in 10% of all cases (Benz *et al.*, 1982). They occur generally at higher frequency (and thus from a higher density source) than the associated type III bursts. An example of type III-spike associations is given in figure 2; it shows a relatively close correlation of the time variations. It seems very likely that spikes are caused by energetic electrons on their acceleration process.

Karlicky (1984) has analyzed spikes in big outbursts (usually type III and IV). He finds that spikes are not always related to type III bursts. Some appear shortly before the start of a type II or another manifestation of mass ejection. Spikes generally occurred before pulsations, which have been proposed to be caused by energetic particles trapped in magnetic loops. These observations suggest that spike emission requires neither streaming nor trapped particles.

Stähl and Magun (1986), Slottje (1978) and others, find the spike activity to generally occur in the rise and maximum phase of the impulsive microwave (synchrothron) emission. An example of the phasing of spikes in relation to the impulsive microwave emission is given in figure 3.

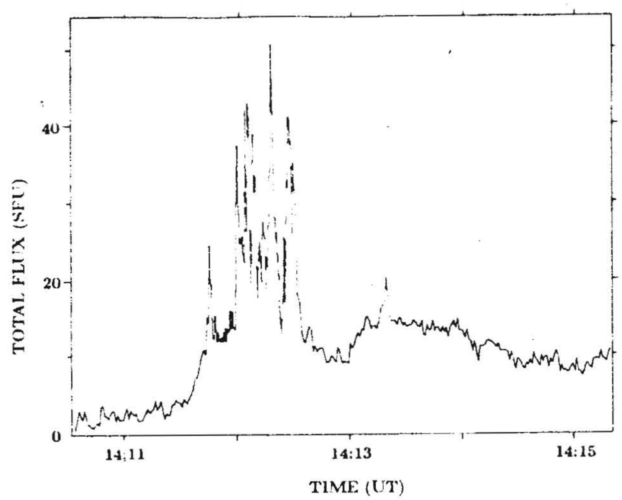

Fig. 3. Observations of spikes at 5.2 GHz by the Institute of Applied Physics in Bern on 10 February, 1982. The spikes are superposed on the smoother, impulsive synchrothron emission (from Benz, 1986).

X-RAY EMISSION

Hard X-ray (HXR) emission originates from bremsstrahlung and provides reliable information on the energy of fast electrons. The correlation of HXR and spikes can be very close; however, it is not as good and reliable as, e.g., between HXR and microwave emissions. The occurrence of spikes seems to require additional conditions on the source or on the exciter. Benz and Kane (1986) have observed that HXR emission associated with spikes tends to be more impulsive and shorter in duration than any of the average HXR bursts. All major spike events are accompanied by enhanced HXR. The occasionally close association of spikes with impulsive HXR emission suggests that spikes are intimately related to the energization of fast electrons. The understanding of spikes may thus yield information on the primary energy release in flares.

Soft X-ray observations of the 31 August 1980 flares by Strong *et al.* (1984) yield preflare densities with plasma frequencies in the range of the spikes observed later during the flare (Benz, 1985). It is generally believed that spike emission occurs at a frequency which is within a factor of two of the local plasma frequency. The observations thus indicate that spikes occur near the flare site before the density increase by evaporation of chromospheric material. The range of the spikes in frequency limits the density in the primary energy release region to about 10^9 - 10^{11} cm^{-3}.

ACTIVE REGIONS

Jin Sheng-Zhen *et al.* (1990) observed, with reference to sunspot groups, that 84.8% of the spike emission events occurred in active regions with sunspot groups types D, E and F. This led to the conclusion that a strong and complex magnetic field is an important requirement for the occurrence of spike emission (Zhao, Jin and Fu, 1985; Jin, Zhao and Fu, 1986; Fu *et al.*, 1987).

THEORY OF SPIKES

Recent observations at decimeter and microwave frequencies have shown that millisecond spikes are associated with the impulsive phase of primary energy release in flares. They often correlate with HXR and type III radio emission, both manifestations of 10-100 KeV electrons. Occasional absence of correlation has been interpreted in terms of unfavorable source conditions (Benz and Kane, 1986): type III emission requires electrons streaming on quasi-open field lines, HXR have a high threshold for detection, and the conditions for spikes are unknown. It is generally agreed today that spikes are signatures of energetic electrons.

SOURCE SIZE AND BRIGHTNESS TEMPERATURE

Estimates of the source size of spikes yield small values and thus lead to enormous brightness temperatures of spike radiation. Upper limits based on duration may not be very meaningful, since the duration seems to depend on frequency and decreases approximately with the mean collision time. Estimates using the bandwidth seem to be more reliable. Assume that the emission frequency depends on a characteristic frequency (such as the local plasma frequency or gyrofrequency). The source dimension l of a spike is determined by the scale length λ of the characteristic frequency and the bandwidth $\Delta\omega$ of the spike:

$$l \cong \lambda \frac{\Delta \omega}{\omega} \qquad (3)$$

If the natural width of the emission frequency cannot be neglected, this equation only gives an upper limit on the source size. Quantitative measurements of all variables in this equation yield $l < 200$ km (Benz, 1985). This is an order of magnitude smaller than the "speed of light dimension" derived from the duration of spikes at 600 MHz, but comparable to that upper limit at 3 GHz. With a diameter of 200 km and for a circular source, the brightness temperature of spikes is up to 10^{15} K. Only a coherent emission process can reach such an intensity.

EMISSION PROCESS

Early ideas on the emission mechanism included plasma emission and electron cyclotron emission and were based on analogies to other impulsive radio emissions (Malville *et al.*, 1967; Tarnstrom and Philip, 1972b). A plasma wave model was first presented by Zheleznyakov and Zaitsev (1975). They proposed emission at the harmonics of Langmuir waves generated by unstabilized electron beams. As soon as the "gentle-beam" instability stabilizes, the beam emits ordinary type III radiation. Chernov (1978) developed the model further and realized that such beams would have to be small in size (500 km) and nearly monoenergetic. Although plasma emission is still used today in modelling spike emissions, its predicted similarity to type III emission contradicts the observations. Spikes have a much smaller intrinsic bandwidth, higher polarization and, most of all, a 4 orders of magnitude higher brightness temperature. Spikes probably have a different emission mechanism.

Langmuir waves may still be the cause of spikes. Their transformation into radio emission, however, would have to be an extraordinary process. A further possibility has been studied by Vlahos *et al.* (1983) who considered the coherent wave-wave coupling of two antiparallel upper-hybrid waves. The random initial phase and finite coherence length produce a spiky radio emission. This emission process, however, still needs to be shown to agree with the wealth of observations summarized in the previous sections.

Cyclotron emission is today the favored process for spike radiation. Cyclotron waves grow exponentially in loss-cone velocity distribution of electrons. Such a distribution may be the result of trapping (or just one reflexion) of energetic particles in magnetic mirrors. Of particular interest is the cyclotron maser instability, in which electrons with velocity υ are in resonance with the transverse electromagnetic waves (ω, k) if:

$$\omega - s\Omega_e - k_{\parallel} v_{\parallel} = 0 \qquad (4)$$

where the index $\parallel$ is the component parallel to the magnetic field, s is the harmonic number of the wave, and Ω_e the relativistic electron gyrofrequency. Equation (4) describes the equality of wave and particle gyrofrequency in the Doppler-shifted frame of the electron. The term "maser" was given to this instability since it generally occurs for electron distribution depleted of particles with low perpendicular velocity constituting a reversed population. The instability directly converts particle energy into radiation and is able to produce very high brightness temperatures. For this reason it was proposed as the emission process of spikes by Holman *et al.* (1980). This process was first proposed by Wu and Lee (1979) as the source of Earth's auroral kilometric radiation (AKR). This process explains the general characteristics of the spikes. These characteristics include the high intensity of spike bursts (as well as of AKR), their high intensities and narrow bandwidths, and the characteristic emission frequencies.

Melrose and Dulk (1982a) have worked out the details of the growth and energetics of the maser emission. The effects of the ambient plasma have been included by Sharma *et al.* (1982). Growth and escape of the various modes and harmonics have been discussed for coronal conditions by Sharma and Vlahos (1984) and for auroral kilometric radiation by Melrose *et al.* (1984). It seems that the maser mechanism operates only in strong magnetic fields ($\omega_p/\Omega_e < 0.9$) and mainly emits on the fundamental (s = 1). Then it may be a strong radio source and it may even considerably heat the ambient medium and thus redistribute the flare energy (Melrose and Dulk, 1984) or accelerate particles (Sprangle and Vlahos, 1983).

A considerable effort has been made to theoretically understand the maser instability and interpret the high brightness temperature. Little has been done to explain other features of spikes. Previous research on spike burst fine structure focused on explaining the short duration of the bursts (Li, 1987; Winglee, Dulk and Pritchett, 1988). Only a few authors examined the causes of frequency drift (Achwanden, 1990; Güdel and Benz (1990)), though not incorporating the influence of a second harmonic absorbing layer on the fine structure.

Previous work on the influence of the second harmonic absorbing layer on the propagation of maser radiation through the corona has indicated that the radiation is heavily absorbed in this layer, with calculations showing that the linear opacity of the layer is much larger than unity in nearly all circumstances (Melrose and Dulk, 1982b, 1984; McKean, Winglee and Dulk, 1989). Linear theory predicts that essentially no radiation can escape the second harmonic layer. However, McKean, Winglee and Dulk (1989) used particle simulations to show that a few percent of radiation incident on the second harmonic layer can escape through nonlinear absorption and reemission.

McKean, Winglee and Dulk (1990) investigate the source of the fine structure by using particle simulators to model the emission of maser radiation and its propagation through the solar corona. The fundamental emission and the second harmonic absorption layers are included. In this model, the formation of fine structures is dependent on the existence of small scale magnetic field inhomogeneities in the fundamental emission and in the second harmonic absorbing layers. These inhomogeneities are attributed to flare current systems associated with the impulsive phase.

In conclusion, the emission mechanism is still unclear. Cyclotron masering looks attractive, but other possibilities are still open and should be investigated.

SPIKES AND THE FLARE PROCESS

Since spikes appear during the primary energy release in flares, it is most interesting to view them in the general context of flares. The close agreement of the source density of spikes with the preflare density of flare loops, as derived from soft X-rays, suggests that spikes are emitted from a source close to the primary acceleration region. Unless some novel coherent radiation mechanism is at work, the exciter of spikes must be fragmented into 10,000 or more single elements. This is usually assumed for maser models. Then the simplest assumption is that the flare energy, or at least the part taken up by fast electrons, is released in ten thousands of elements (microflares). This scenario should be confirmed by observations. These flare elements may be the result of a global MHD instability of the flare region.

OBSERVATIONAL EFFORTS IN MEXICO CITY

The solar radio interferometer of small base at the Institute of Geophysics (UNAM) in Mexico City, for observing at a central wavelength of $\lambda = 4$ cm, is under modification in order to be able to detect coherent radiation from solar flares with a time resolution of the order of milliseconds. Among the changes in the device, there is an automatic trigger in the acquisition system in order to record data with two different sampling frequencies, that is, two different intervals of time between one signal sample and the next. It will record at 1000 Hz when it does not detect an event, but will switch to 0.5 Hz in the case of an event. With this sampling frequency we will be able to detect variations in milliseconds, which is the basis for the detection of spikes.

The data storage and the control of the signal processing were handled by an Apple computer. The system had to be changed for the new requirements. An interphase card between the radiointerferometer and a new PC were developed. The computer programing is done, but some problems with the electronic equipment remain, which the technical team in charge of the radiointerferometer is currently working on. We expect that before the end of this year the radiointerferometer will be working in order to be able to detect the millisecond spike emission from the Sun.

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