FAR INFRARED AND SUBMILLIMETER CONTINUUM OBSERVATIONS OF SOLAR FLARES: JUSTIFICATIONS AND PROSPECTS FOR GROUND-BASED EXPERIMENTS

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Abstract. Solar flare observations in the sub-mm spectral bands are essentially non-existent. There is evidence that some solar bursts exhibit a spectral component rising in intensity towards wavelengths shorter than 3 mm, displaying fast sub-second pulses at different repetition rates. On the other hand, the spectral features of white light flares are also unknown in the infra-red range of frequencies. In both wavelength ranges the physics of the emission processes may involve particles accelerated to high energies. The diagnostics of solar flare continuum emission in the IR and sub-mm spectral regions will provide crucial tests on various flare models and bring some clues on the initial primary energy release mechanisms. We propose the construction and operation of a ground-based telescope, operating at two sub-millimeter wavelengths (at about 210 GHz and 405 GHz), with high time resolution (one millisecond), capable of determining the spatial position of burst emission centroids with high definition (a few arcseconds) using the multiple beam technique. Final installation and operation at a high-altitude site in the Argentinian Andes mountains are planned in a joint cooperation with Argentina's Instituto de Astronomia y Fisica del Espacio, IAFE (M. Rovira and associates) and Complejo Astronomico El Leoncito, CASLEO, San Juan (H. Levato and associates); and Switzerland's University of Bern, Institute of Applied Physics, IAP, Bern (A. Magun and associates).

Key words: infrared: stars – Sun: flares – Sun: radio radiation

1. Introduction

Recent discoveries indicate that it is essential to complete the diagnostic of flare emission in the sub-millimetric and infrared range of wavelengths. However such measurements have never been made with instruments sensitive enough and capable of detecting rapid variations. Previous suggestions are reviewed showing that this knowledge has a crucial importance for the understanding of the primary processes of particle acceleration in plasma instabilities. We propose a project to diagnose solar flares at two sub-mm wavelengths located in atmospheric windows, with a time resolution of 1 millisecond and spatial definition, for burst emission sites, of a few arcseconds. Two frequencies are being considered: 210 GHz (using three receivers for a multibeam imaging capability), and a single receiver at 405 GHz to extend the spectral information. The system configuration at 210 GHz is similar to that used successfully at 48 GHz by the Itapetinga/Bern group (Georges *et al.*, 1989; Herrmann, 1990; Costa *et al.*, 1991), but at a much higher frequency and with an antenna scaled down to a smaller physical size. One single reflector, about 1.5 m in diameter, will concentrate solar radiation into the 210 GHz three feed-horn arrangement and the 405 GHz receiver. The proposed instrument can be built with a modest budget. Initially we plan two years of continuous operations at a site of exceptional quality in Argentinas's Andes Cordillera, known as El Leoncito, part of CASLEO (Complejo Astronomico El Leoncito), near San Juan, Argentina.

D. M. Rabin et al. (eds.), Infrared Solar Physics, 93–101.

2. The Flare Electromagnetic Spectrum

Figure 1 shows a simplified description of what is known about the electromagnetic continuum emission of a solar flare (after Kaufmann, 1988). Spectral curves I, II, III, IV and V are quite well known from observations and are explained by a number of existing models.

The band including sub-millimetric and infrared wavelengths is poorly known and essentially unexplored for flare emission. Spectral curves A, B and C are model computations. Spectral curve III shows the quiet Sun blackbody emission. Curve IV shows the optical-continuum of the white-light flares (WLF), which appears in some bursts. It is difficult to measure this, since its intensity is four orders of magnitude smaller than the quiet Sun emission. The nature of the WLF emission is still controversial; it can be found in both large and small flares (Cliver *et al.*, 1983; Henoux and Aboudarham, 1991). Irrespective of the physical mechanism which produces WLF, it seems to imply the acceleration of very energetic particles (Najita and Orrall, 1970).

In the UV and soft X-ray bands there are many measurements, and the emission consists of a superposition of several mechanisms, producing the continuum and discrete emission lines. The current models attribute the hard X-ray emission (curve V) to the bremsstrahlung of mildly relativistic electrons initially accelerated. For photon energies larger than about 400 keV, the gamma radiation appears in the continuum as well as in discrete lines that result from nuclear reactions; this has been fully confirmed by the gamma ray spectrometer on the SMM satellite in the 21st solar cycle. The production of these high energy photons requires extremely energetic particles: protons with tens to hundreds of MeV or some GeV, or electrons from MeV to hundreds of MeV. The only known mechanisms to reach such high energies are based on second-step accelerations (like Fermi acceleration). It has been shown, however, that gamma ray continuum and line emission can appear in the first few seconds of the initial phase of a flare, for which there is no proposed explanation so far (Forrest and Chupp, 1983; Rieger, 1991; Henoux and Aboudarham, 1991). Recent results from the BATSE experiment on board the GRO satellite, which has a sensitivity more than one order of magnitude better than the SMM HXRBS detector, have indicated the presence of well-defined hard X-ray pulses of 100 ms in duration (Machado *et al.*, 1992. Such fast time scales for hard X-rays cannot be easily explained by electron bremsstrahlung and may require a review of the concepts of the particle beam production in the very first phase of solar flares.

It is quite surprising that no solar flare measurements have yet been made in the sub-mm and IR bands. Until a few years ago, the acceleration of electrons up to ultrarelativistic energies was not conceivable in the first phase of a burst. They could appear as a result of acceleration in a second step, such as the first solar gamma-ray space observations suggested. According to Najita and Orrall (1970), Ohki and Hudson (1975), and others, the early appearance of these particles in great number would produce IR and sub-mm emission by bremsstrahlung and thermal interactions (curves A and B in Fig. 1, for the optically thin and thick cases, respectively). Therefore flare measurements in the sub-mm and IR bands never had a justified priority.

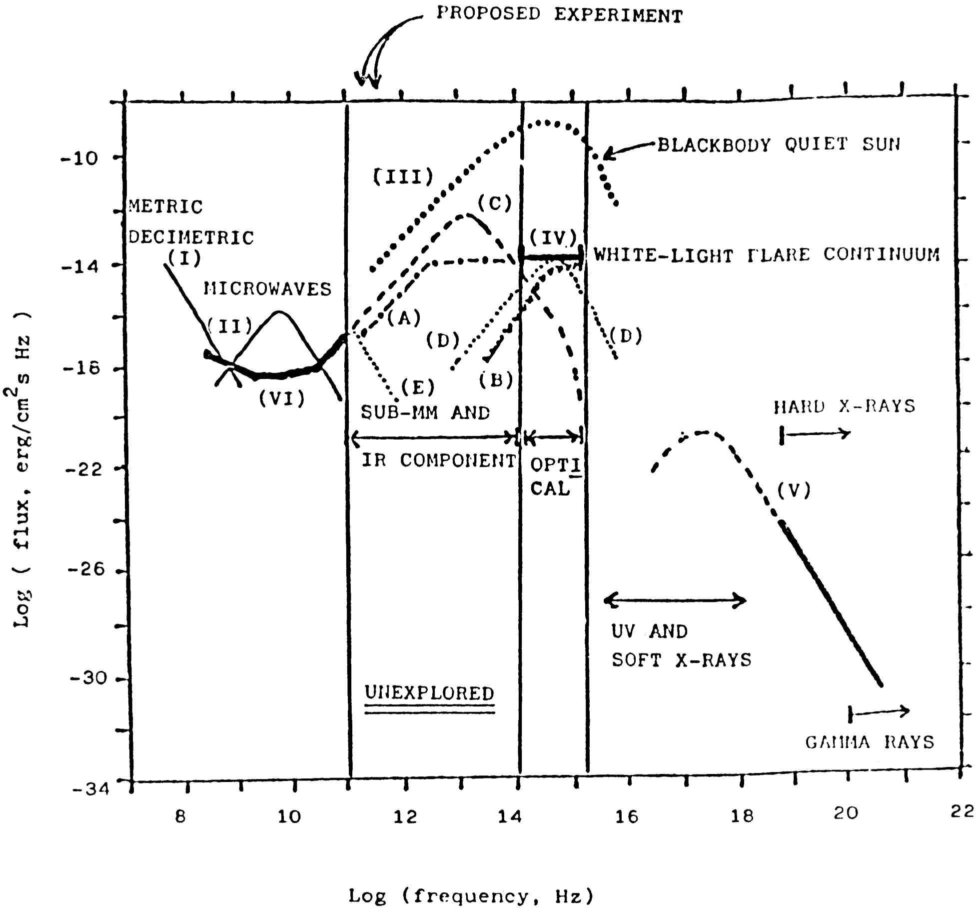

Fig. 1. The electromagnetic spectrum of solar-burst continuum emissions (discussed in the text). The flare spectrum in the frequency band covering the sub-mm and IR is essentially unknown. Curves I - VI refer to observations. All others refer to models: A, B Ohki and Hudson, 1975; C Kaufmann *et al.*, 1986; D Stein and Ney, 1963; Shklovsky, 1964; and E de Jager *et al.*, 1987.

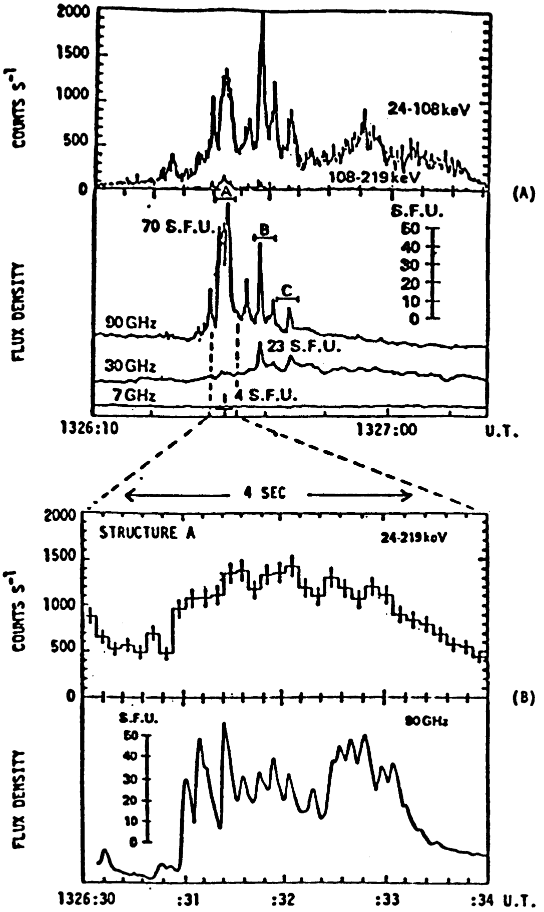

Fig. 2. The extraordinary solar burst of 21 May 1984 which exhibited various time structures, with 90 GHz emission, coincident with hard X-ray emission, much more intense than at 30 GHz and lower microwave frequencies. Each structure consisted of multiple fast pulses, with rise times smaller than 30 milliseconds (see expansion at bottom (B)). This result is hard to explain with current models (Kaufmann *et al.*, 1986).

Recent observations, however, have entirely changed our perspective. Curve VI in Figure 1 shows the spectrum of an extraordinary solar flare that occurred on May 21, 1984. This event shows the flux intensity increasing with frequency at least up to about 100 GHz (Kaufmann *et al.*, 1985; Correia and Kaufmann, 1987) (Fig. 2). It consists of very rapid pulses (30 ms) with start times coincident with the hard X-ray emission. This spectral component needs to be better defined in the sub-mm and IR bands (frequencies larger than 100 GHz). If this emission component is part of a thermal spectrum (curve A or B in Fig. 1), the time scales are too short by many orders of magnitude, so that this mechanism is not acceptable.

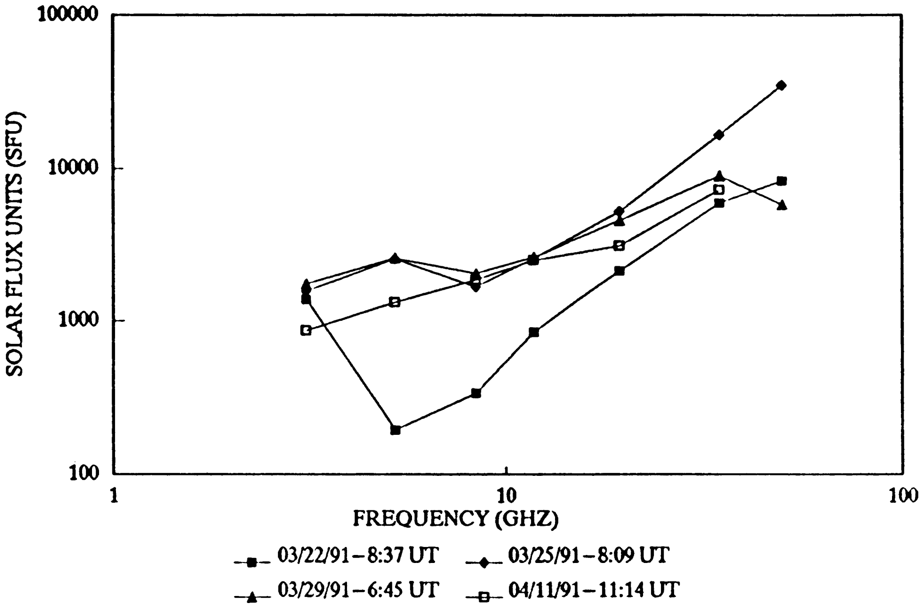

Fig. 3. More recent examples of solar bursts showing spectra with intensity increasing for frequencies larger than 19 GHz (Correia *et al.*, 1992).

In fact, spectra similar to curve VI (Fig. 1) or with fluxes rising with frequency towards 100 GHz have been found for other solar bursts in the past (Hachenberg and Wallis, 1961; Croom, 1970; Cogdell, 1970 ; Shimabukuro, 1970, 1972; Akabane *et al.*, 1973; Zirin and Tanaka, 1973). The data, however, were obtained with poor sensitivity and time resolution. Recently Correia *et al.* (1992) have shown that such events are not so rare. Analyzing spectra of 115 events with fluxes larger than 100 sfu at 35 and 50 GHz, obtained by the Bern Observatory (Magun *et al.*, 1991), they found that more than 25 percent of the bursts had rising intensities for frequencies above 35 GHz (Fig. 3), and that 50 percent displayed nearly flat spectra in that range of frequencies. The later may belong to a class of events found by Hachenberg and Wallis (1961), interpreted by Ramaty and Petrosian (1972) as due to free-free absorption of gyrosynchrotron emission from non-thermal electrons.

It has generally been believed that the time scales for the energy conversion processes in flares are of the order of tens to hundreds of seconds, which is now recognized as entirely incorrect. Early radio observations at decimetric wavelengths had, in fact, already suggested the presence of very fast time structures in solar bursts (Butz *et al.*, 1976; Droge, 1977; Slottje, 1978). In the last (21st) solar cycle, millisecond time structures, multiple and discrete, were observed in solar bursts in microwaves and mm-waves (Kaufmann *et al.*, 1975; 1980; 1984). They were also suggested as being present in hard X-rays (Kiplinger *et al.*, 1983), and concurrently in hard X-rays and microwaves (Takakura *et al.*, 1983). Models intending to explain the energy conversion in flares as a result of multiple, rapid and discrete micro-bursts, eventually quasi-quantized in energy, have been suggested (Kaufmann *et al.*, 1978; Loran *et al.*, 1985; Sturrock *et al.*, 1985; de Jager *et al.*, 1987). These ideas are now being confirmed by more recent observations obtained at decimetric and microwave wavelengths, being associated with the "fragmentation" of energy release in solar flares (Alaart *et al.*, 1991; Qijin *et al.*, 1991; Benz, 1991). A striking confirmation of the concept is being obtained by the initial results from high-sensitivity hard X-ray solar flare observations from the GRO satellite (Machado *et al.*, 1992). It is likely, however, that solar flare continuum emission at hard X-ray, mm, sub-mm, and IR wavelengths does not have a direct physical connection to the emission observed at decimetric and centimetric wavelengths.

Almost three decades ago, white-light continuum emission in flares was suggested to be part of a synchrotron radiation spectrum (Stein and Ney, 1963) produced by ultrarelativistic electrons, with a spectral maximum in the IR and visible. Shklovsky (1964) suggested that, associated with the ultrarelativistic electrons, a large number of IR photons would necessarily be produced. These early models have not survived, however the reasons for their rejection must be revisited. The time scales, then believed to be hundreds of seconds, did not require the rapid acceleration of particles to such high energies. The early evidence of flare-associated hard X-rays, known from a few rocket measurements, raised the suggestion of inverse-Compton processes operating in those events (Shklovsky, 1964; Zheleznyakov, 1970). This concept was further explored by Korchak (1971) and Brown (1976), but it did not prosper, mostly because of the long time scales (10 to 1000 seconds) then believed to apply and for which the bremsstrahlung mechanism was sufficient to explain the observed X-rays (Acton, 1964). Another reason was the complete absence of flare diagnostics at sub-mm and IR wavelengths, a situation that still remains today.

The recent observations mentioned above impose severe boundary conditions on the interpretation of the explosive processes occurring in the first phase of bursts in solar plasmas. The presence of ultrarelativistic electrons in this phase is a possibility that again becomes likely. Other mechanisms for energy losses producing X-rays, like inverse-Compton scattering in very dense and compact sources of ultrarelativistic electrons, may again become a plausible possiblity (Kaufmann *et al.*, 1986; McClements and Brown, 1986). According to this concept, at least for certain flares, the primary process would involve multiple and discrete events with ultrarelativistic particles accelerated and slowed down in few tens of milliseconds (not measurable by most experiments). This would result immediately in beams of mildly relativistic electrons, whose behaviour is better described and interpreted. This area of research can be clarified with measurements in the sub-mm and IR bands.

3. High Altitude Ground-Based Submillimeter Solar Telescope (SST)

For a practical low cost investigation, we consider ground based solar observations from a high-altitude site, at frequencies in the sub-mm range, through the atmo-

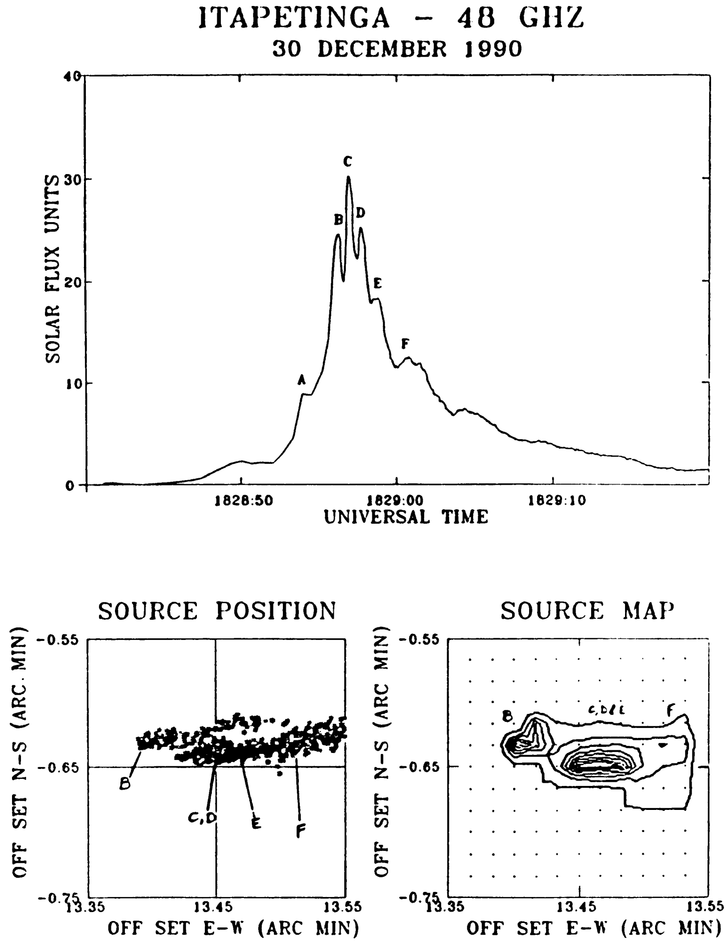

Fig. 4. December 30, 1990 solar burst observed at Itapetinga Radio Observatory at 48 GHz. In the boxes we show the emission center positions at different times marked in the event time profile. This is an example of a well localized event. The position variation stays inside an area smaller than 12 × 12 arcsec (Costa *et al.*, 1991).

spheric transmission windows centered at 210 GHz and 405 GHz. Inspecting the spectra shown in Figure 1, we see that data obtained at those two frequencies will allow unambiguous inferences relative to different models of production of the observed radiation.

We are considering a mountain site, located in the Argentinian Andes at 2500-m altitude, known as El Leoncito near the city of San Juan. It is part of the Complejo Astronomico El Leoncito (CASLEO), and already enjoys an excellent local infrastructure.

Theoretical estimates of atmospheric transmission have been made by the atmospheric physics group of the University of Bern, Switzerland (Kampfer, 1991), using typical meteorological, atmospheric, and precipitable-water-vapor data known for El Leoncito (Filloy and Arnal, 1991; Levato, 1991). The water-vapor content is generally smaller than 4 mm from March to December, being on average less than 2 mm, and very often there are minima of about 0.5 mm. The average increases to 5 mm from January to March. Furthermore, El Leoncito exhibits clear days 80% of the year. Kampfer (1991) estimated a central frequency at 405 GHz for the upper window, as well atmospheric transmissions for various conditions. For the extremes of atmospheric conditions the predicted zenith transmissions at 405 GHz range from 32% to 78%, which indicates that the El Leoncito site presents fairly good atmospheric conditions for extended periods during the year.

For the sub-mm telescope design there are compromises to be followed in order to obtain enough sensitivity (about 1 sfu), with high time resolution (milliseconds), with beamwidths large enough to cover a solar active center (arcminutes) and then allowing dynamic imaging, at least in one frequency. These specifications can be met using a 1.5-m Cassegrain reflector. The antenna effective aperture and telescope performance can be determined using major planets, with sufficient integration time to detect them.

Finally, based on the successful concept of dynamic imaging of bursts observed at 48 GHz, using the Itapetinga 13.7-m antenna (Herrmann, 1990; Costa *et al.*, 1991), we are considering the use of three beams at 210 GHz, overlapping by about (HPBW/2). As a solar burst evolves it is possible to describe the centroid of emission, and its displacements, with a few arcseconds accuracy, and time resolution of milliseconds with such a system.

Acknowledgements

CRAAE is jointly operated by the Universities of Sao Paulo, Campinas and Mackenzie, and the National Institute for Space Research. This program is being partially supported by Sao Paulo State Foundation for Research (FAPESP).

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