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Recent results on solar activity at submillimeter wavelengths

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Abstract

Since the installation of the Solar Submillimeter Telescope (SST) in 1999 in the Complejo Astronómico El Leoncito (CASLEO, Argentina), the almost unexplored solar emissions at frequencies >100 GHz started to reveal new insights about thermal and non-thermal processes in active regions. SST operates at the frequencies of 212 and 405 GHz providing the unique opportunity to distinguish and investigate emission mechanisms. We present a review of the most relevant findings obtained. An statistical study made with observations of a selected sample of active regions shows that their flux density spectra increase with frequency. Rapid brightenings (pulses) are always observed both at 212 and 405 GHz in association to solar flares lasting for some tens to hundreds of milliseconds. They are well correlated between the two frequencies and have flux spectra either flat or increasing with frequency. The flux of submillimeter wave pulses remain within the same order of magnitude for different bursts, ranging typically 100–300 s.f.u. at 212 GHz and 500–1000 s.f.u. at 405 GHz. The time evolution of the pulse occurrence rate usually reproduces the time profile of the X-rays/γ-rays emission, and the bulk emission at submillimeter waves, when the latter is observable. There are examples of good correlation between individual pulses at submillimeter waves and hard X-rays/γ-rays. Submillimeter pulses are not restricted to flare events, but appear to be a general phenomenon that occurs over active regions as well. The starting time of the rapid submillimeter wave pulses is coincident or precedes the projected launch time of the coronal mass ejections. SST observations of the November 4, 2003 large flare revealed a new and yet unknown spectral component with intensities increasing towards even higher frequencies, appearing along with, but separated from the well-known microwave component.

Keywords: Submillimeter-waves; Sun: ratio-radiation; Sun: flares

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1. Introduction

The interest in submillimeter observations of solar phenomena is not new. First reports were only qualitative (see e.g. Coates, 1958; Gaitskell and Gear, 1966, and references therein). The first submillimeter fluxes ever reported (at 384 GHz) are those of Fedoseev et al. (1967) for the quiet Sun temperature. Clark and Park (1968) reported rapid (<1 min) temperature enhancements <100 K at 250 GHz in solar active regions. The first attempt to measure an impulsive submillimeter burst was made by Hudson (1975) who reported only an upper limit. After these works, submillimeter observations were restricted to the quiescent Sun. Nevertheless, some observations of the Sun activity at frequencies lower than 100 GHz indicated the importance of going further towards shorter wavelengths. Noticeably, Shimabukuro (1972) and Croom (1973) have shown a rising microwave spectrum up to 90 GHz (the maximum frequency of their instruments) that suggested intense submillimeter emission. For a review with more examples see e.g. Kaufmann (1996). With the advent of the Solar

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Submillimeter Telescope (SST, Kaufmann et al., 2001a), the only submillimeter solar dedicated instrument, the almost closed window started to be explored routinely, bringing new insights about the process of energy release in the solar atmosphere as well as new views of the quiescent Sun. In this short article we will review SST results since its installation in April 1999, and the new questions these findings have raised.

2. The Solar Submillimeter Telescope

A description of the SST and initial results were published in Kaufmann et al. (2001a). The SST is a radome enclosed single dish cassegrain antenna of 1.5 m diameter with a high precision altazimuth mount. It has a focal array of four custom made uncooled receivers at 212 GHz and two at 405 GHz. Three out of the four 212 GHz receivers overlap at 50% level of their HPBW (4 arc min) allowing the determination of the position of the centroid emission and the correction of the main lobe attenuation to get the absolute flux density (Giménez de Castro et al., 1999; Costa et al., 1995). Weather conditions at the site of El Leoncito allow observations during more than 300 days per year with characteristic zenith opacities of about 0.25 and 0.95 at 212 and 405 GHz, respectively (Melo et al., 2005).

3. The quiescent Sun

Raster scans maps of the Sun at radio frequencies above 1 GHz obtained since the early 1960s have shown the existence of regions of enhanced brightness temperature on the solar disk. These regions of higher temperature were found to be associated with Hα active regions, Sun spots, plages, and regions of strong magnetic fields (Kundu, 1970, 1971; Hachenberg et al., 1978; Bastian et al., 1993). A statistical study of solar maps at 212 and 405 GHz obtained by the SST was performed during 23 days of low atmospheric opacity. The brightest regions on the maps were chosen for this study. Their observed brightness temperature excess varies from 3–20% above quiet Sun levels (i.e., few hundred K) at both wavelengths. The brightness temperature were converted to flux density, S_ν, using the Rayleigh–Jeans approximation for a homogeneous source, and assuming sizes for the emitting areas measured from the maps. The flux density spectra of these sources were compared with the flux density at 17 and 34 GHz obtained by the Nobeyama Radioheliograph on the same days and show a different component increasing toward submillimeter wavelengths, yielding flux density spectral index with an average value of 2.0 (Fig. 1). This distinct component might be an indication of another denser thermal optically thick source (Silva et al., 2005).

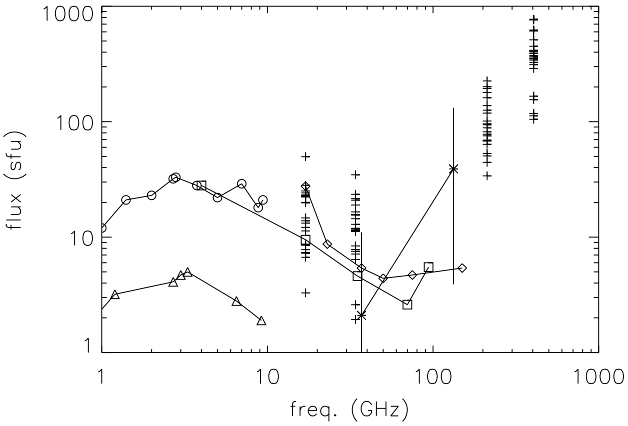

Fig. 1. Comparison of submm active region flux density spectra with previously published data. The diamonds represent Efanov et al. (1972) data, the asterisk Efanov et al. (1969) observations, while Tsuchiya and Takahashi (1968) observations are indicated by squares. Eclipse data are represented by triangles, from Castelli and Clemens (1966), and by circles (Kaufmann, 1968). The crosses represent the 23 submm and mm observations discussed in the text (Silva et al., 2005).

4. The active Sun

During impulsive events, the SST has observed two kinds of emission: sub-second pulses (or just pulses) and bulk emission. The top panel of Fig. 2 shows the

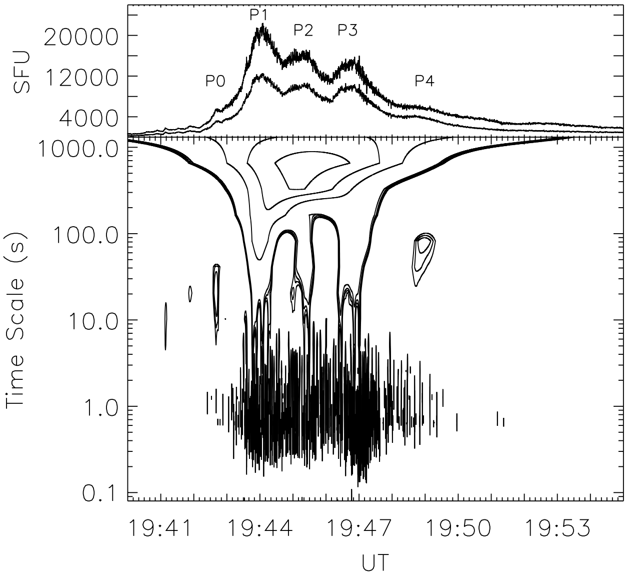

Fig. 2. (Top) time profile of the November 4, 2003 event at 405 GHz (above) and 212 GHz (below). P0$\cdots$P4 label individual peaks. (Bottom) Isocontours of the positive coefficients of the wavelet decomposition of the density flux at 212 GHz. The wavelet transform (e.g. Torrence and Compo, 1998) decomposes the signal in frequency without losing the time information. We have used the multi-resolution wavelet transform as it was defined by Bendjoya et al. (1993). Normally, instead of frequency it is used the time scale (or scale for brief) where frequency $\propto$ scale^{-1}. The representation adopted in this figure visually separate the different scales. Contour levels are 54, 81, 108, 163, 1084, 1626 and 2168 sfu. 99% Confidence level is 54 sfu.

time profile of the November 4, 2003 event at 405 and 212 GHz and the bottom panel the isocontours of the positive coefficients of the wavelet decomposition (Bendjoya et al., 1993) of the 212 GHz signal. In the last figure the bulk emission is represented by the long time scales contours, while the pulses are represented by the vertical narrow lines with time scales as short as 0.1 s. We have ruled out that these pulses have an origin other than Solar: tracking and atmospheric scintillation are discussed in Kaufmann et al. (2001b) and Raulin et al. (2003) analyze the system noise signal.

During the November 4, 2003 burst the pulses start and end with the bulk emission. Makhmutov et al. (2003) have shown that during the December 13, 2001 flare no bulk emission were observed by SST, only pulses. The time evolution of the pulse repetition rate may mimic the time profile of the γ-rays as it was shown by Kaufmann et al. (2002) for the event of April 6, 2001 and by Raulin et al. (2003) for the event of August 25, 2001. Pulse amplitudes increase with the bulk amplitude (when both are observed simultaneously) and pulse positions are scattered over an area of a few tens arcsec (Raulin et al., 2003). Finally, good temporal coincidence between isolated submillimeter pulses and hard X-rays/γ-rays fine structures were found when both data sets were available (Kaufmann et al., 2002).

One of the most intriguing findings of the SST is the temporal association between the launch time of coronal mass ejections (CMEs) and the onset of the sub-second pulses occurrence (Kaufmann et al., 2003). In six events analyzed all have an associated CME. The extrapolation of the apparent CME position to the solar surface shows that they occurred nearly coincident in time with the onset of submillimeter pulses for all six events. In one case no flaring activity was observed, but the SST observed pulses starting nearly simultaneously with the launch time of the CME.

Pulses were also reported over non-flaring active centers. Their spectra have and index equal or greater than 0, reinforcing the interest in observing at higher frequencies where the flux should be greater (Pacini et al., 2002).

The first detection of the bulk submillimeter emission occurred during the event of March 22, 2000 (Trottet et al., 2002). It was a small enhancement followed by a more intense post burst increase. Good time correlation between 212 GHz bulk emission and γ-rays was found for the burst of April 6, 2001 (Kaufmann et al., 2002). During the microwave peak time of the same event, the flux densities at 212 and 15 GHz are roughly the same. This is a puzzling problem that might be explained either by a composition of multiple spectra, a free-free absorption (Ramaty and Petrosian, 1972), a new and yet unknown spectral component, or a classical synchrotron spectrum peaking between 15 and 212 GHz.

A definitive evidence of a new spectral component was observed during the big event of November 4, 2003 occurred in Active Region 0486. NOAA Preliminary Report and Forecast 1471 yielded an estimate for the 1–8 Å X-rays peak flux of X28 but from ionospheric observations Thomson et al. (2004) derived a new value of X45. SST observed the flare during good atmospheric conditions: zenith opacities were measured 20 min before the flare and yielded 0.23 and 1.0 at 212 and 405 GHz, respectively. We applied the before mentioned multibeam technique to obtain the flux density from the three antenna temperatures. Source derived positions, projected positions and HPBW of the SST beams are shown in Fig. 3 over an EUV 195 Å image taken with the EIT on board SoHO. This event appeared in close time correspondence at microwave and millimeter waves. Fig. 2 (top) shows that the flux density at 405 GHz is always greater than at 212 GHz. Fig. 4 shows an inversion in the spectrum above 212 GHz during the peaks labeled P1 and P4. Although the 44 GHz observations during P1 were completely saturated, during P4 was helpful to confirm the difference in the spectral components. The spectra of the intense sub-second pulses on this event also have a positive index (Kaufmann et al., 2004).

The origin of this spectral component is not known and suggests a maximum somewhere in the THz range. The observed features at submillimeter waves bring severe constraints for the interpretation using existing models for the impulsive phase of flares. The flare submillimeter source remained stable in space, within 15 arcsec, for the time interval containing the three major

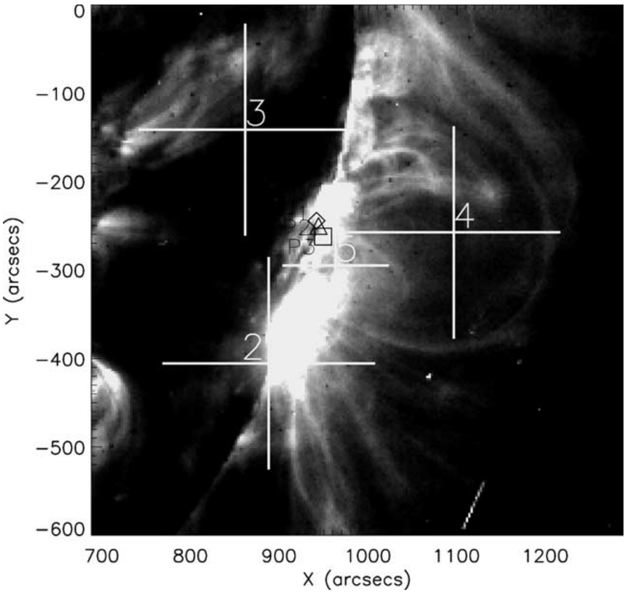

Fig. 3. Position of the submillimeter-wave telescope half-power beams, projected on a 195 Å ultraviolet image taken by the EIT on the SoHO at 19:36:13.4 UT just before the 2003 November 4 large flare. The symbols represent positions occupied by the source of submillimeter-wave radiation for the three major peaks of the impulsive phase (the time structures for P1 [diamond], P2 [triangle], and P3 [square] are shown in Fig. 2).

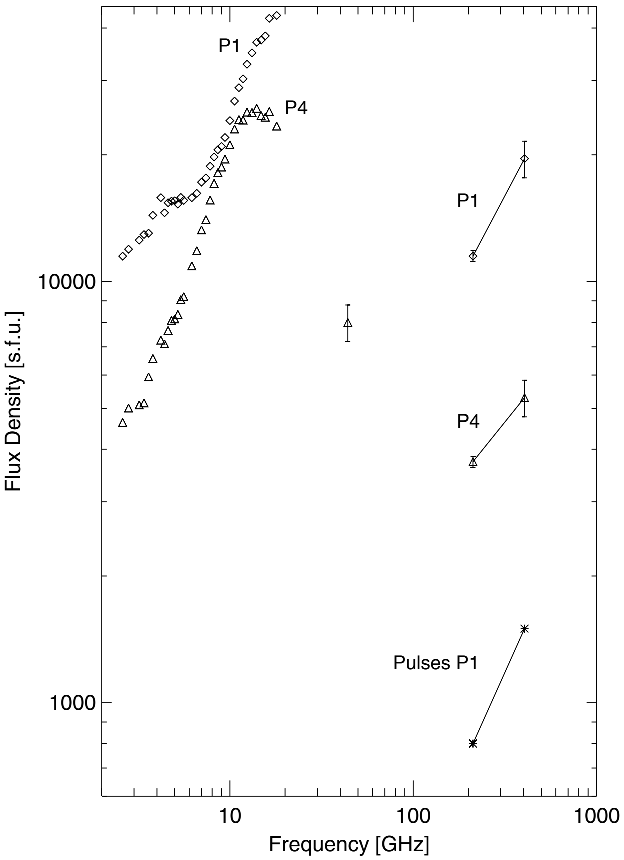

Fig. 4. Spectra of the burst exhibiting two distinct components. A sample mean spectrum for the sub-second pulse flux in excess of the bulk emission is shown for structure P1 (Kaufmann et al., 2004).

peaks, P1, P2 and P3 (see Fig. 3). The observed flux densities at 212 and 405 GHz are 3–4 orders of magnitude larger than those predicted by the thermal interpretation used to explain white-light flare emissions (Ohki and Hudson, 1975). Furthermore the submillimeter fluxes are close to the same order of magnitude of the estimated White Light Flares fluxes. The thermal interpretation becomes further complicated by the presence of rapid sub-second pulses, exhibiting occurrence rates and amplitudes well correlated to the bulk emission time evolution, as well as by the good time correspondence found between the bulk emission time profile and the higher energy γ-rays channels detected by the SONG experiment on board of CORONAS-F satellite (Myagkova, 2004).

The newly discovered THz emission component might therefore be a likely response to some highly energetic non-thermal physical process at the flare origin to be further investigated. A THz spectral component, peaking somewhere close to 10 THz, has been predicted to account for the sub-second time structures observed at millimeter wavelengths, producing hard X-rays by inverse Compton action on dense synchrotron electrons, with energies of the order of tens of MeV (Kaufmann et al., 1986). One possible mechanism to explain this new component is the synchrotron emission from ultra-relativistic positrons. The interaction between high energetic protons and α-particles with ambient nuclei produce pions which rapidly decay to positrons with energies in the range from 10 to 100 MeV (Murphy et al., 1987). Recently Kozlovsky et al. (2004) have extended the analysis to include also ^{3}He reactions. The synchrotron emission of these positrons has a maximum around a few THz (Lingenfelter and Ramaty, 1967).

5. Summary and perspectives

Submillimeter observations made by the SST are showing new characteristics of the solar atmosphere and energy release process. Of particular interest are the rising spectra of the density flux over active regions, of the sub-second pulses and of the bulk emission during bursts, denoting the importance of observing at even higher frequencies with better sensitivity to build theoretical models. We are presently designing new instruments to reduce the gap between the submillimeter and the optical windows. An upgrade of the SST receivers will increase its sensitivity by a factor of 10. An infrared high cadence rate (30 s^{-1}) camera will be installed at the focus of a coelostat at the site of El Leoncito allowing simultaneous observations in the range 7–14 μm. Finally, the Hα Solar Telescope for Argentina, (HASTA, Bagalá et al., 1999) installed at a site near El Leoncito, is being upgraded to allow image acquisition at a cadence rate of 30 s^{-1}.

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