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A NEW SOLAR BURST SPECTRAL COMPONENT EMITTING ONLY IN THE TERAHERTZ RANGE

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ABSTRACT

Solar flare energy manifestations were believed to be the result of the same kind of particle acceleration. It is generally accepted that a population of relativistic electrons accelerated during the impulsive phase of solar flares produces microwaves by synchrotron losses in the solar magnetic field and X-rays by collisions in denser regions of the solar atmosphere. We report the discovery of a new intense solar flare spectral radiation component, peaking somewhere in the shorter submillimeter to far-infrared range, identified during the 2003 November 4 large flare. The new solar submillimeter telescope, designed to extend the frequency range to above 100 GHz, detected this new component with increasing fluxes between 212 and 405 GHz. It appears along with, but is separated from, the well-known gyrosynchrotron emission component seen at microwave frequencies. The novel emission component had three major peaks with time, originated in a compact source whose position remained remarkably steady within 15″. Intense subsecond pulses are superposed with excess fluxes also increasing with frequency and amplitude increasing with the pulse repetition rate. The origin of the terahertz emission component during the flare impulsive phase is not known. It might be representative of emission due to electrons with energies considerably larger than the energies assumed to explain emission at microwaves. This component can attain considerably larger intensities in the far-infrared, with a spectrum extending to the white-light emission observed for that flare.

Subject headings: plasmas — radiation mechanisms: nonthermal — submillimeter — Sun: flares —
Sun: infrared — Sun: radio radiation

1. INTRODUCTION

Energy production processes in solar flares are investigated from their emission spectra at various wavelength ranges. The basic physical mechanisms in the impulsive phase emissions are usually attributed to a population of relativistic electrons producing microwaves by synchrotron losses in the magnetic field with a spectral maximum lying typically in the range of 10–30 GHz, depending primarily on the energy of the accelerated electrons (for the restricted range of magnetic field values found in the solar active regions) and producing X-rays by collisions in denser regions of the solar atmosphere (Kundu 1980; Tandberg-Hanssen & Emslie 1988, p. 148). There are rare microwave spectral examples peaking at higher frequencies, up to 94 GHz, the upper limit for solar observations made in the past (Croom 1973; Kaufmann et al. 1985; Ramaty et al. 1994; Chertok et al. 1995).

Solar flare emission at frequencies above 100 GHz ($1 \text{ GHz} = 10^9$ Hz) is poorly known. Few early models suggested impulsive phase emission at those frequencies due to synchrotron emission by ultrarelativistic electrons ($E >$ 10 MeV). They were assumed to account for white-light emissions (Stein & Ney 1963) to explain solar flare X-rays (Shklovsky 1964; Brown 1976) or the free-free thermal continuum in the gradual phase (Ohki & Hudson 1975). These suggestions, however, were never verified, leading to the general belief that no other flare emission component could be found in the range between short radio wavelengths and the visible.

To extend frequency range of flare observations to above 100 GHz, a solar submillimeter telescope (SST; Kaufmann et al. 2001) has been designed and built at the El Leoncito Observatory located at 2550 m altitude in the Argentina Andes. The SST has a 1.5 m reflector with four 212 GHz and two 405 GHz radiometers operating simultaneously with 5 ms time resolution. The main-beam cluster consists of three 212 GHz beams (about 4′ half-power beamwidth) partially overlapping each other and one 405 GHz beam (about 2′) in the center of the three, as shown projected into the solar limb in Figure 1. This disposition allows the centroid position determination of burst structures by comparing their outputs (Giménez de Castro et al. 1999). Two other beams are nearly 8′ away from the central cluster, pointing to the solar disk, and do not need to be considered here. The first results obtained with the new instrument revealed rapid subsecond pulses for all events analyzed, for which the burst bulk emissions levels were part of the well-known microwave spectrum, exhibiting spectral intensities reducing for higher frequencies, sometimes lower than the sensitivity limits (Kaufmann 2002; Raulin et al. 2003). The submillimeter-wavelength pulses' occurrence rates and amplitudes were found to follow approximately the time profiles of fluxes of bulk emission—when the latter were observed above the sensitivity limit—and at hard X-ray and gamma-ray energy ranges (Kaufmann 2002; Raulin et al. 2003).

2. THE 2003 NOVEMBER 4 FLARE TERAHERTZ RADIATION COMPONENT

The 2003 November 4 solar large flare produced a *GOES* X-ray X.28 class burst (NOAA SEC 2003),[6] the largest ever

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[6] See the NOAA Space Environment Center Web site, http://www.sec.noaa.gov.

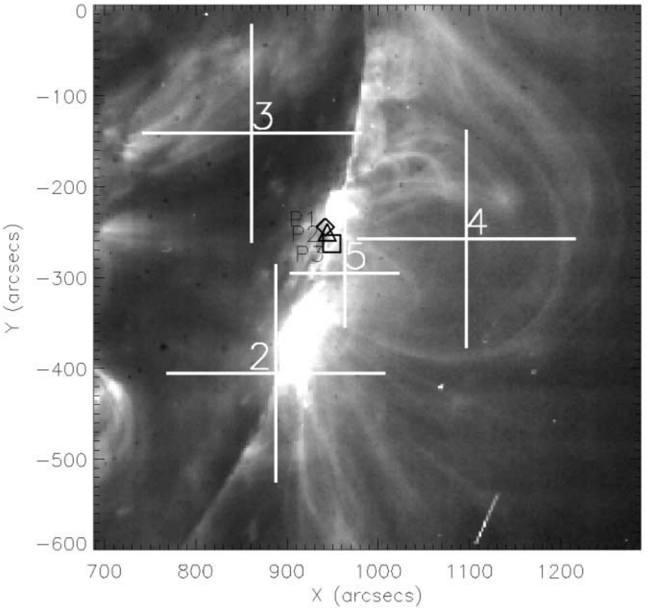

FIG. 1.—Position of the submillimeter-wave telescope half-power beams, of about 4′ at 212 GHz and 2′ at 405 GHz, projected on a 195 Å ultraviolet image taken by the EUV Imaging Telescope on the *Solar and Heliospheric Observatory* (Delaboudiniere et al. 1995) at 19:36:13.4 UT just before the 2003 November 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).

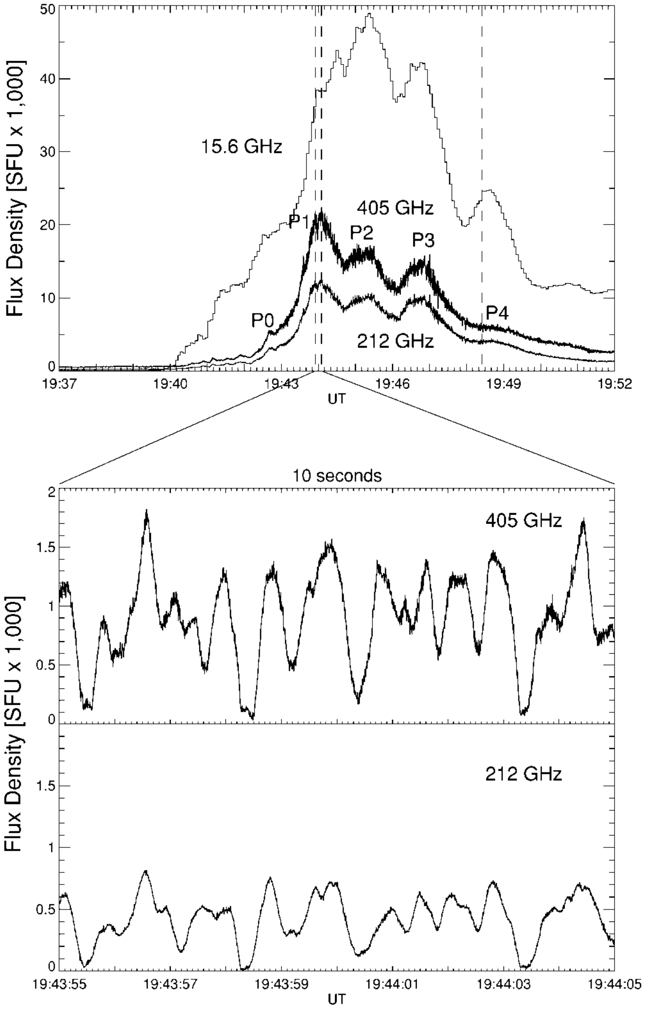

FIG. 2.—Time profiles of the burst at 405, 212, and 15.6 GHz (*top*) in units of thousands of solar flux units. The submillimeter data have 40 ms time resolution while OVSA data have 4 s time resolution. An example of the intense subsecond pulses is shown over a 10 s period during the first peak P1 at the bottom, with 5 ms time resolution. The independent channel output data for this period are shown in Fig. 3. The time indicator at structure P4 corresponds to a measurement available at 44 GHz, shown in Fig. 4.

detected, presenting unique new features at submillimeter wavelengths reported here. The event occurred in the highly complex NOAA Active Region 0486 located at S19°, W83°. The SST beams were tracking this source at the solar limb, as shown in Figure 1. Observations were obtained on clear weather and good atmospheric transmission conditions. The zenith attenuations, measured 20 minutes before the burst, were of 0.23 and 1.0 nepers, at 212 and 405 GHz, respectively. With the Sun at 40° elevation, correction factors of 1.43 and 4.74 at 212 and 405 GHz, respectively, were applied on the antenna temperatures with estimated uncertainties of the corrected values of about $\pm 2.5\%$ and $\pm 5\%$ at the two respective frequencies. Other uncertainties need to be added to convert the antenna temperatures, corrected for atmospheric transmission, into solar flux units ($1 \text{ sfu} = 10^{-22}$ W m^{-2} Hz^{-1}): the approximations for the beam shapes used for the source position determination and the innaccuracies in antenna aperture efficiencies determined from planet observations, resulting in final uncertainties of about $\pm 5\%$ and $\pm 10\%$ at 212 and 405 GHz, respectively.

In Figure 2 we show at the top the time profiles of the burst bulk emissions at 212 and 405 GHz, in solar flux units. For comparison, the time profile of emission at 15.6 GHz, due to the well-known gyrosynchrotron mechanism, is also shown with data from the Owens Valley Solar Array (OVSA; Hurford, Read, & Zirin 1984). At the bottom is a 10 s period during peak P1, at 5 ms time resolution, showing the superposed rapid pulses with the main bulk emission subtracted. The independent radiometer outputs at 212 GHz (channels 2, 3, and 4) and 405 GHz (channel 5) are shown in Figure 3 in corrected antenna temperatures, above the bulk level. The effect of system noise increase due to burst antenna temperature enhancement was negligible compared to the fast time features analyzed. For 5 ms data in peak P1 shown in Figure 3, for example, the system noise increase due to the burst emission corresponded to corrected antenna temperature fluctuations of 4–6 K, rms, for 212 GHz channels 2–4 and of 10 K, rms, for 405 GHz channel 5, or to the equivalent of about 50 and 80 sfu at 212 and 405 GHz, respectively, shown in Figure 2 (*bottom*). These values correspond to the noise seen in the profiles of both Figure 2 (*bottom*) and Figure 3, and therefore all pulses are of solar origin.

A remarkable new burst spectral component was found, exhibiting fluxes considerably larger at 405 GHz in comparison to 212 GHz, indicating a spectral peak lying somewhere in the terahertz region, as shown in Figure 4. The terahertz range is a designation commonly given to the broadband 0.1–100 THz ($1 \text{ THz} = 10^{12}$ Hz). This new bulk emission component is well distinguished from the microwave radio component, whose spectrum from 1.2 to 18 GHz as seen in OVSA data peaks somewhere greater than 18 GHz for structures P1, P2, and P3 and less than 18 GHz for other structures. The flux spectral reduction for shorter microwaves is confirmed at 44 GHz for time structure P4, detected after saturation by the Itapetinga 13.7 m radio telescope in Brazil (Kaufmann et al. 1982). The spectral index from 212 to 405 GHz for the bulk emission peak

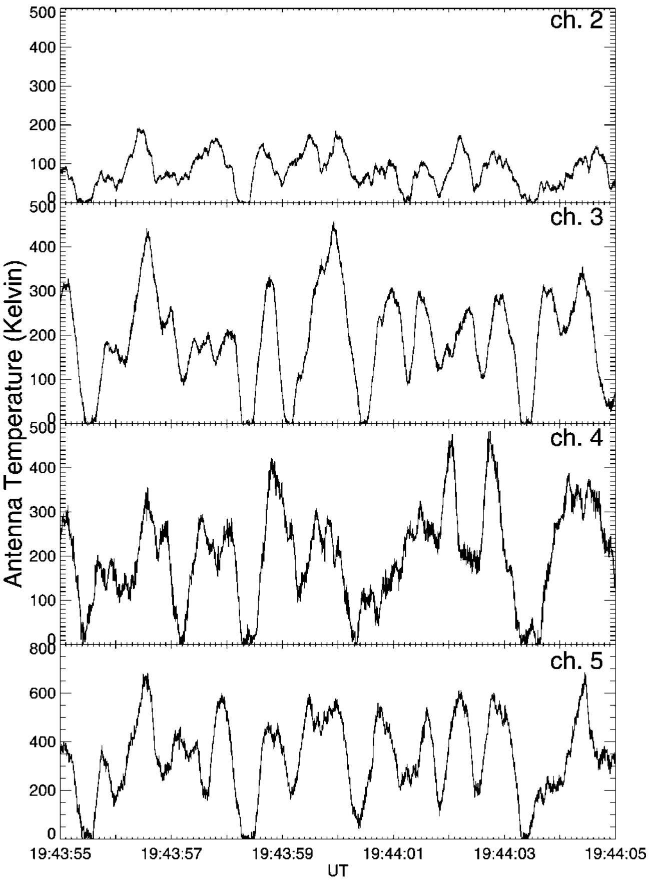

FIG. 3.—Independent outputs of the 212 GHz channels 2–4 and 405 GHz channel 5, for the time interval shown in Fig. 2 (*bottom*), in corrected antenna temperatures above the bulk emission values, 5 ms time resoluion.

P1 was 0.8. It becomes about 0.6 for the time structure P4. For the pulses' flux, sampled for peak P1 with the bulk emission removed, the spectral index is close to 1.0. These indices might become steeper if we assume that the observed submillimeter-wave emissions contain contributions from the tail of the microwave spectral component decreasing at higher frequencies. Figure 1 shows the positions for major peaks derived from the three 212 GHz outputs. The absolute uncertainty in the beam positions with respect to the solar disk is less than about 30″, and the uncertainty of relative position of the source with respect to the beams is of the order of 10″. It becomes rather suggestive that the submillimeter-wave bulk emission is near the solar surface, remaining remarkably stable within less than about 15″ during nearly 5 minutes of time, with a possible genuine displacement of peak P3 by about 15″.

The rapid subsecond pulses at 212 and 405 GHz, within the 10 s time sample shown in Figures 2 (*bottom*) and 3, present some of the properties found for other events reported recently (Kaufmann 2002; Raulin et al. 2003). A positive spectral index for their flux in excess of the bulk emission is shown in Figure 4. The spatial positions for the pulses, referring to their fluxes in excess to the bulk underlying level, were sampled for peaks P1, P2, and P3. Their positions are quite concentrated with respect to the bulk positions, scattered by less than about 12″ rms. The timescales of the individual pulses are typically 500–700 ms, longer than the 100–500 ms found before (Kaufmann 2002; Raulin et al. 2003). The rapid pulses might be directly counted in a digital oscilloscope, for example. This is not practical, of course, for large samples. A pulse count algorithm has been developed (Raulin et al. 1998) allowing the pulse identification, amplitude, and pulse rate determinations. It was used to find a characteristic property shown in Figure 5 consisting of a general association among the pulse occurrence rate, the pulse amplitude, and the bulk emission time profile: the larger the intensity, the higher both the pulse repetition rate and the pulse amplitude, shown here for 405 GHz data.

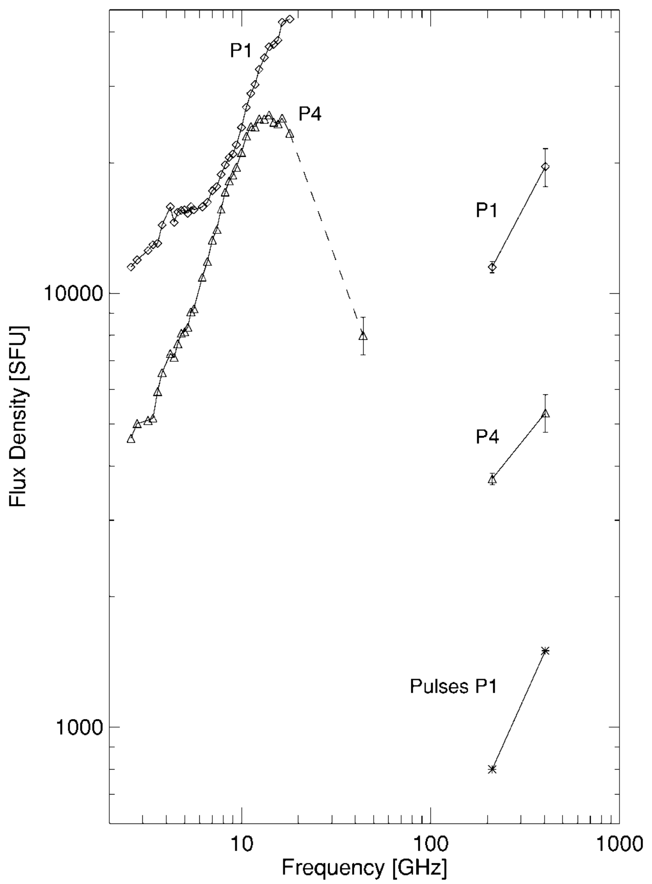

FIG. 4.—Spectra of the burst exhibiting two distinct components, the new radiation source found with rising intensities for higher frequencies into the terahertz range and the well-known gyrosynchrotron source at microwaves, with intensities decaying for higher frequencies. OVSA 1.2–18 GHz microwave data are shown for the major peak P1 and for the smaller peak P4 for which there were 44 GHz data obtained by Itapetinga. A sample mean spectrum for the pulse flux in excess of the bulk emission is shown for structure P1.

3. CONCLUDING REMARKS

The nature of the newly discovered flaring source producing the emission component peaking in the broad terahertz band is yet unknown. Large fluxes, increasing with frequency, as observed, might arise from cold (10^3–10^4 K) and dense ($>10^{13}$ cm^{-3}) plasma near the solar photosphere (Ohki & Hudson 1975). However, the short duration of the high bulk flux values of the new emission component combined with the subsecond pulse timescales brings severe constraints for interpretation. It is likely to be due to a process accelerating particles to energies considerably higher than those producing the well-known microwave spectrum. The overall proportionality between the flux of bulk emission and the rate of rapid pulses suggests that they might be the signatures of energetic injections. The two spectral components and the short timescales of pulses observed might favor the model of inverse Compton quenching on the synchrotron photons emitted by ultrarelativistic electrons (tens of

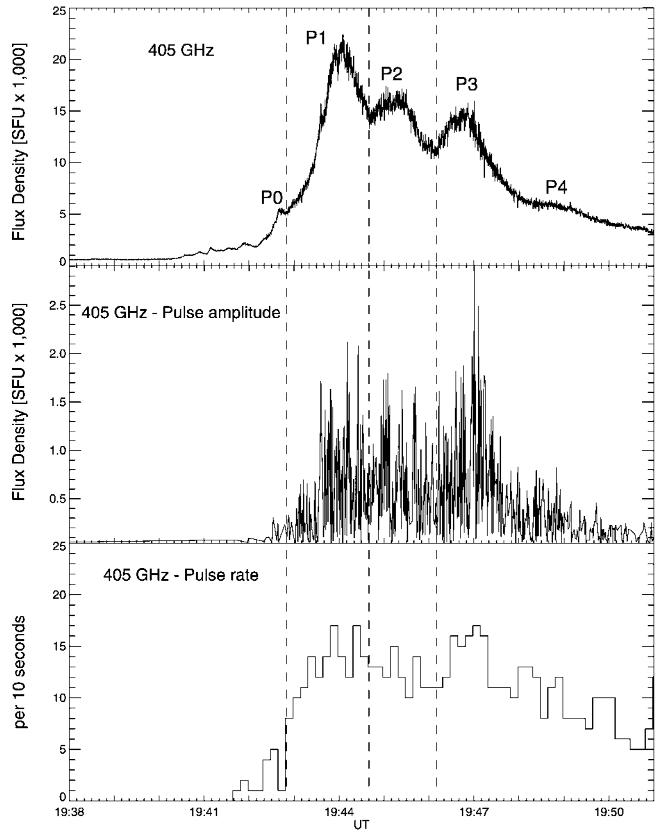

FIG. 5.—Marked property of the rapid pulses is represented by the overall correlation among the bulk emission time profile (*top*), the subsecond pulse amplitude (*middle*), and the pulse occurrence rate (*bottom*), shown here for the 405 GHz data (nearly identical results are obtained at 212 GHz).

MeV) with spectrum peaking somewhere in the 1–10 THz range (Kaufmann et al. 1986). A similar concept is used to interpret rapid bursts in compact extragalactic sources (Kellerman & Pauliny-Toth 1969; Dent et al. 1983), at different time and scale sizes but possibly similar physical conditions. If this is the case, the electron energies are predicted to rapidly decay into mildly relativistic energies, producing the well-known microwave spectrum and other flare-related effects. Further tests on this possibility will require comparative studies with the microwave component and with emissions at higher energies, in the visible, UV, and X-rays—the latter available for this event only from *GOES* detectors at lower energy ranges. From an observational standpoint there is a clear indication that 405 GHz is still too low a frequency to describe completely the new source of solar flare emission component. It would be of great interest to investigate whether the burst intensities may become substantially larger in the 1–100 THz range, which would require instrumentation operated outside the Earth's atmosphere. The terahertz emission component might be common to many solar events—detectable by systems operating in the far-infrared, requiring devices built using new techniques lying between electronics and photonics.

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