JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. A7, 1280, doi:10.1029/2002JA009729, 2003

Launch of solar coronal mass ejections and submillimeter pulse bursts

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Received 8 October 2002; revised 28 February 2003; accepted 29 April 2003; published 9 July 2003.

[1] The rapid solar spikes (100–500 ms) recently discovered at submillimeter waves bring new possibilities to investigate energetic processes near the solar surface that might have an important role in the launch and propelling of ionized mass away from the Sun. We present a study on the association between the launch time of coronal mass ejections (CMEs) observed by the LASCO instruments on the SOHO spacecraft and the onset of the new kind of rapid solar spikes (100–500 ms) observed at submillimetric waves (212 and 405 GHz) by the new Solar Submm-wave Telescope (SST). We investigated six submm-wave events, all found associated to CMEs. Seven related CME were identified. Five of them were associated with flares with large GOES class soft X-rays, presenting distinct time histories and associations at other energy ranges, and two of them were related to flares behind the solar limb, with simultaneous related activity observed in the visible solar disk. Ultraviolet images from EIT on SOHO show some kind of small or large-scale magnetic activity or brightening for all events. The extrapolation of apparent CME positions to the solar surface show that they occurred nearly coincident in time with the onset of submm-wave pulses for all six events. These results suggest that pulse bursts might be representative of an important early signature of CMEs, especially for events beginning near the center of the solar disk, sometimes identified as "halo" CMEs. They lead to several challenging questions relative to the physical nature of the pulses and its association to the launch and acceleration of coronal mass ejections. Although these evidences may favor multiple rapid energy releases at the origin near the solar surface, they require further research in order to better understand both diagnostics and model descriptions. *INDEX TERMS:* 2722 Magnetospheric Physics: Forecasting; 2118 Interplanetary Physics: Energetic particles, solar; 7513 Solar Physics, Astrophysics, and Astronomy: Coronal mass ejections; 6954 Radio Science: Radio astronomy; *KEYWORDS:* solar submm-wave bursts, solar radio astronomy, CME launch, CME precursors, pulse bursts

Citation: Kaufmann, P., C. G. Giménez de Castro, V. S. Makhmutov, J.-P. Raulin, R. Schwenn, H. Levato, and M. Rovira, Launch of solar coronal mass ejections and submillimeter pulse bursts, *J. Geophys. Res.*, *108*(A7), 1280, doi:10.1029/2002JA009729, 2003.

1. Introduction

[2] The solar-most energetic transient phenomena are coronal mass ejections (CMEs), which are observed by coronagraphs as white light emission due to Thompson scattering of photospheric radiation by plasma propelled into the interplanetary medium. These sporadic ejections of material can be detected at many wavelengths across the electromagnetic spectrum (radio, H-α, UV, X-rays) and in situ by particle detectors in spacecrafts [see *St. Cyr et al.*, 2000, and references therein]. CMEs were described in greater details with the use of coronagraphs on board of spacecrafts, beginning with Skylab [*Gosling et al.*, 1974; *Kahler*, 1977], the NRL coronagraph on the P78-1 satellite [*Howard et al.*, 1985; *Michels et al.*, 1980], the C/P experiment on the Solar Maximum Mission [*MacQueen et al.*, 1980], and since 1995 by the Large Angle Spectroscopic Coronagraph (LASCO) on board the Solar Heliospheric Observatory (SOHO) mission [*Brueckner et al.*, 1995; *Schwenn et al.*, 1997; *St. Cyr et al.*, 2000]. The comparison of earlier coronal mass ejection descriptions to the more sensitive SOHO LASCO results has shown that their basic properties are basically the same and that there is no significant population of fainter CMEs [*St. Cyr et al.*, 2000].

[3] As for CMEs studied at other wavelengths, limb flares observed by the HXT experiment on Yohkoh satellite have indicated that a large fraction of events exhibit X-ray emission from ejected plasmoids [*Ohyama and Shibata*,

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2000; *Kundu et al.*, 2001]. The expansion of CMEs from the solar corona into the interplanetary medium is followed by their radio emissions, from microwaves to metric and decametric wavelengths [*Gergely et al.*, 1984; *Gary et al.*, 1984; *Pick et al.*, 1998; *Klein et al.*, 1999; *Gopalswamy and Thompson*, 2000; *Klein and Mouradian*, 2002]. The probability of correlation between CMEs and microwave (1.4–15.4 GHz) bursts seems to increase with radio flux densities, becoming of the order of 70% for fluxes greater than 500 sfu (1 sfu = 10^{-22} $w^{-1}m^{-2}Hz^{1}$) [*Dougherty et al.*, 2002].

[4] The CMEs carry masses equal or larger that 10^{14} g, at radial velocities in the range of 200–2000 km/s, corresponding to energies $\geq 10^{31}$ erg, comparable or larger than the total energy of large solar flares (see recent reviews by *Webb* [2000], *St. Cyr et al.* [2000], and references therein). There are MHD approaches to explain the physical causes originating CMEs, which were applicable to the observation of specific events, assuming destabilization of large scale coronal streamers or to plasma flows produced by filaments disruptions [*Wu et al.*, 2000]. However, other indications show that such disruptions might not be a general cause for all CMEs [*Simnett*, 2000]. Many CMEs are not associated with flares and although the CME's rate of occurrence approximately follows the solar cycle, there is no clear association between their occurrence and sunspot number [*Howard et al.*, 1985; *Webb*, 2000; *St. Cyr et al.*, 2000].

[5] It is recognized that the CMEs have the most serious impact in the interplanetary medium and especially in space weather conditions in the vicinity of the Earth [see *Schwenn*, 1983, *St. Cyr et al.*, 2000, and references therein]. An association has been found of nearly 83% between "halo" mass ejections from central regions of the solar disk and strong geomagnetic storms [*St. Cyr et al.*, 2000]. CMEs which strike our planet may produce auroral particle precipitations, disturbances in telecommunications, degradation and damages in instruments in orbiting satellites, failures in spacecraft guiding devices, and enhanced doses endangering biological life in space, including human beings [*Lanzerotti et al.*, 1999, 2001]. The relationships between solar activity and the strongest energetic manifestation of the CMEs with the Earth outer and inner environment are far from being well understood. However its importance has justified the implementation of large coordinated international research efforts, such as the International Solar Cycle Studies (ISCS program, 1998–2002), the International Living with a Star (ILWS) program initiated by NASA, and the Climate, Weather and the Sun Earth System (CAWSES program, 2004–2008), organized by the Scientific Committee of Solar-Terrestrial Physics (SCOSTEP).

2. Early Signatures of CMEs

[6] The prediction of early phases or signatures preceding the launch of CMEs is one of the major goals of current research. Progress in understanding the physical processes involved require the diagnostics of CMEs observed by coronagraphs together with other evidences of solar activity, of quiescent conditions, and of flare related phenomena as well as theoretical studies to explain how these huge masses of plasma are formed, ejected, and propelled away from the Sun.

[7] There were indications that the launch times are closely related to weak soft X-ray enhancements, which often precede larger flares, and also larger X-rays bursts [*Harrison*, 1986]. However, as said before, there are also indications of CMEs without any obvious flare connection [*Webb*, 2000]. CMEs may occur even during solar minimum phase, once every other day [*Yashiro et al.*, 2002]. On the other hand, it is often difficult to associate CMEs to other solar phenomena, on the surface, or in the corona because of its own complexity. Some events present complex spatial features, which may or may not be due to the same ejection. There are indications of CMEs apparently triggered by others at remote locations in the solar disk, similarly to the so-called sympathetic flares [*Biesecker and Thompson*, 2000], sometimes without any indication of some kind of solar activity in the region where the CME might have been launched. One interesting possibility is the suggestion of remote triggering of CMEs by Moreton-like waves on the solar surface [*Webb*, 2000, *St. Cyr et al.*, 2000, and references therein].

[8] Mass ejections launched from lower heliographic longitudes near the Earth-Sun line, often named as "halo" CMEs [*Howard et al.*, 1985], are more difficult to describe because the apparent coronagraph position does not indicate whether the material is being propelled toward the Earth or away from it, if launched from the back side of the Sun. The CME related features observed on the solar disk show little contrast in the visible. However, some typical precursor signatures have been suggested at X-rays, with the formation of an S-shaped sigmoid configuration of the emitting active region prior to a CME event [*Rust and Kumar*, 1996; *Sterling*, 2000]. There are indications that CMEs' launch sites are often related to UV activity in the solar disk such as brightenings and magnetic arch dynamics, detected by the Extreme Ultraviolet Imaging Telescope (EIT) on SOHO [*Delaboudinière et al.*, 1995; *Dere et al.*, 1997]. X-ray (YOHKOH) and UV EIT (SOHO) images of the solar disk sometime indicate emission "dimming" in certain regions, in close context with CME events [*Hudson and Webb*, 1997; *Gopalswamy and Thompson*, 2000].

[9] Recent results obtained on solar activity at submillimeter wavelengths have shown the occurrence of rapid subsecond pulses during flares, with a rate of occurrence approximately proportional to the bulk of flare intensity emissions at higher energy ranges (X- and gamma-rays) [*Kaufmann et al.*, 2001a, 2002]. This newly discovered solar submm-wave spikes might have a nature similar to the subsecond pulsations found in the optical range in flares [*Wang et al.*, 2000; *Trottet et al.*, 2000] and in quiescent active regions [*Williams et al.*, 2001]. The physical origin of these spikes raises a number of constraints for both thermal and nonthermal interpretations [*Raulin et al.*, 2003]. They may have connection with microflares, waves, or quakes, with possible important role in the heating of the solar corona [*Sturrock and Uchida*, 1981; *Lin et al.*, 1984; *Sturrock et al.*, 1984; *Zharkova and Kosovichev*, 2000].

[10] The submm-wave rapid spikes might be representative of multiple small-scale plasma instabilities in active regions triggered by large-scale magnetic instabilities in active regions with growing complexity [*Sturrock*, 1986,

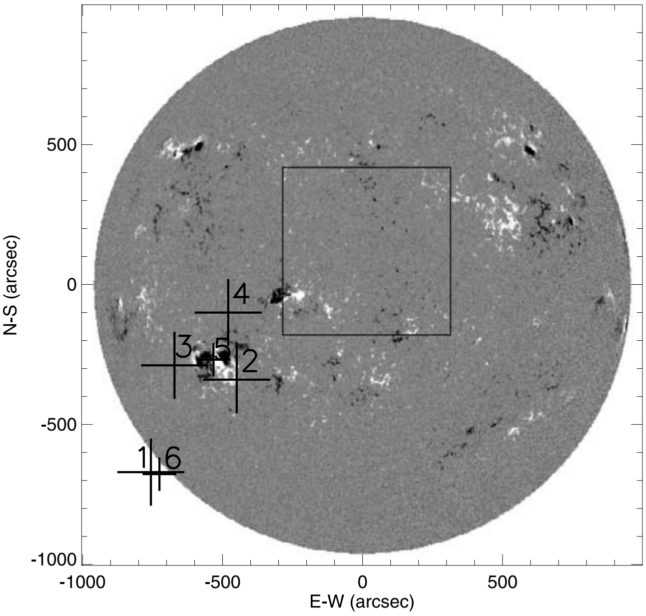

Figure 1. Example of the SST beams projected on the solar disk for 6 April 2001. Three 212 GHz beams, 2, 3, and 4, are partially overlapping each other, allowing burst position determinations. One 405 GHz beam, 5, is at the center of the cluster. The other 212 (1) and 405 GHz (2) beams are coincident and displaced by about 7 arcminutes from the cluster (in this day the second 405 GHz channel 6 was not operational).

and references therein]. The combination of large and small-scale instabilities might play an important role in the launch and acceleration of large masses of ionized gas as observed in the solar corona and interplanetary space.

[11] Here we investigate the association of CMEs to the onset of submm-wave pulses. Owing to the new nature of these measurements, the SST data analysis is time-consuming and only a few events were analyzed to the present date. Six submm-wave events were well analyzed, five of them presenting GOES soft X-ray high class emission level, and one might have been related to weak subflare activity unrelated to a weak soft X-ray excess. It turned out afterward that all events had associated CMEs detected by LASCO coronagraphs, with two ejections for the first and more complex submm-wave burst. We applied a linear (constant speed) extrapolation of the CMEs measured time height diagrams to the solar limb to define the CME launch time [*Yashiro et al.*, 2001]. The actual location on the solar disk might be off by a fraction of one solar radius, which is negligible compared with the other sources of uncertainties in space and time. Examples of CMEs' observed closer to the solar surface revealed an initial acceleration phase with slower speeds, which might imply in actual launch times earlier than those defined by the linear extrapolation by tens of minutes [*Zhang et al.*, 2001; *Klein and Mouradian*, 2002]. For the CMEs analyzed here we found in general good agreement for times of interception the solar surface using this method, compared with CMEs' projected position, by assuming a particular active region or flaring site location for the origin, as derived in the CME catalog from the Center for Solar Physics and Space Weather by the Catholic University of America/Naval Research Laboratory/NASA (CSPSW/NRL). There are two CMEs possibly associated to flares behind the solar limb, as will be discussed in sections 3.1 and 3.6. We show that, in general, the CMEs launch times show a clear association to the occurrence of submillimeter "pulse bursts."

3. Submm-Wave "Pulse Bursts" and Associated CMEs

[12] The solar submillimeter-wave telescope (SST) is operated at the Complejo Astronomico El Leoncito, Argentina Andes, at two frequencies: 212 GHz with four beams and at 405 GHz with two beams, all simultaneously, with time resolution of 1 ms. Its overall characteristics were described elsewhere [*Kaufmann et al.*, 2001b]. The SST beams projected into the solar disk are shown in Figure 1, for 6 April 2001 as an example. All six radiometers operate simultaneously. The beams are operating such that they continuously keep tracking a given position on the solar

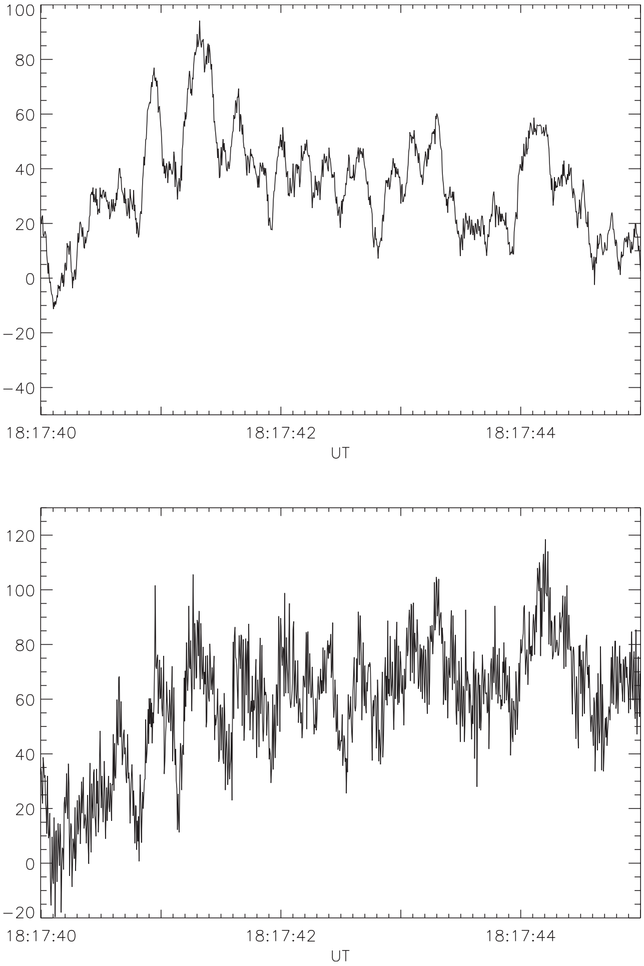

Figure 2. Example of subsecond pulses during the 22 March 2000 solar flare, observed at 212 GHz (above, for channel 2) and at 405 GHz (below, for channel 5), in a 5 s time interval, 15 ms time resolution, with intensities in units of antenna temperature.

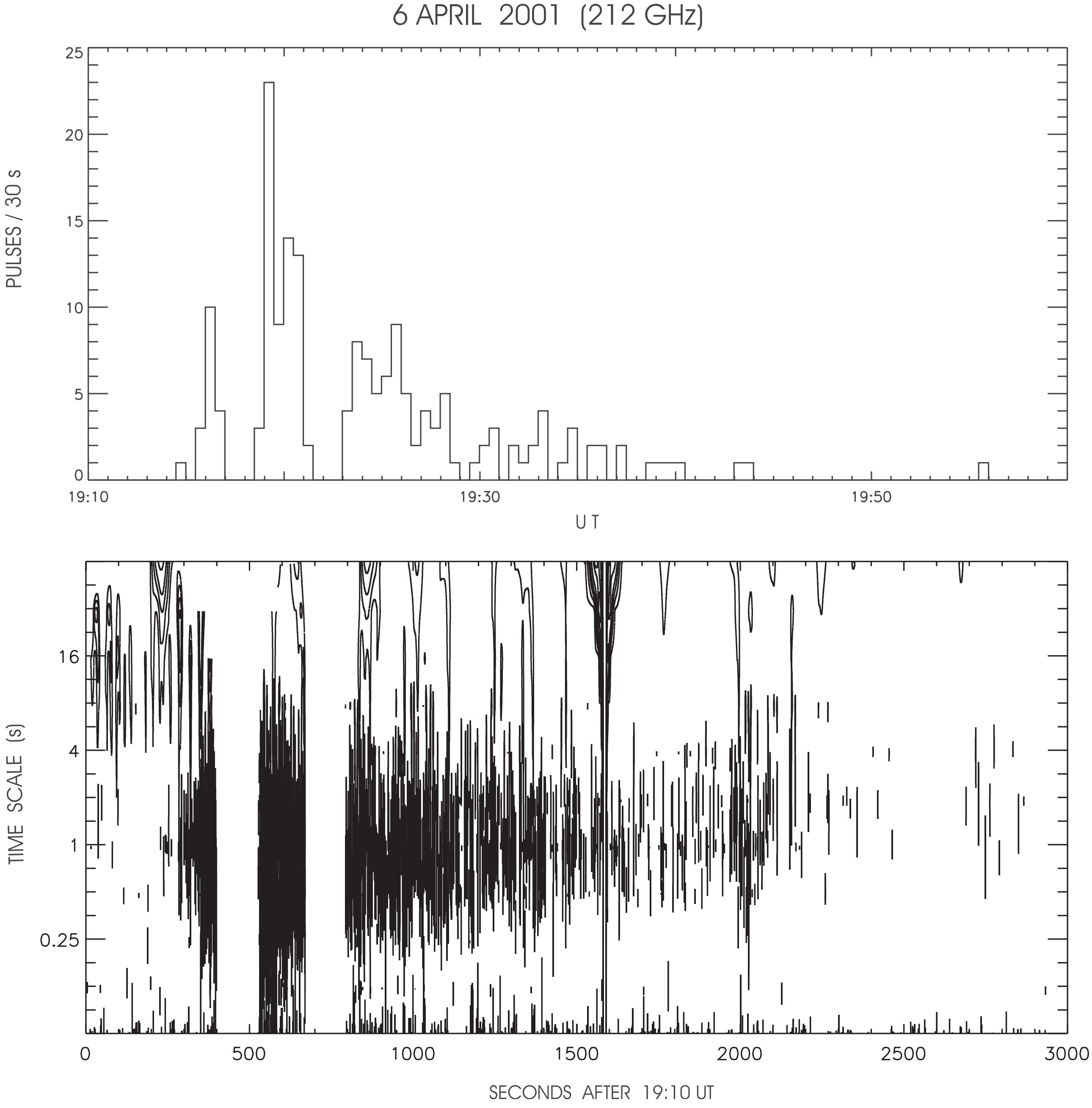

Figure 3. Comparison between occurrence rate of pulses, shown above, and the wavelet scalogram representation, shown below, for the pulse burst for the 6 April 2001 event observed at 212 GHz.

disk. SST observations are done keeping the antenna beam 5 (405 GHz) pointing to the selected active region. The adjacent beams 2, 3, and 4 (212 GHz) are partially overlapping each other and to beam 5. The beams 1 (212 GHz) and 6 (405 GHz) are coaligned and nearly 7′ displaced with respect to the cluster of the other four beams. The half power beamwidths are of 2′ at 405 GHz and 4′ at 212 GHz (except for the 22 March 2000 event when the beams were wider, about 7′ and 9′, respectively, because SST was not yet fully focused).

[13] One example of rapid pulses observed at submm-waves is shown in Figure 2, for the 22 March 2000 solar flare, which will be further discussed ahead. The pulses were counted using a peak finder algorithm [*Raulin et al.*, 1998]. For the present study the data analysis has been done using wavelets decomposition based on the algorithm developed by *Bendjoya et al.* [1993] that is an implementation of the multiresolution analysis done by *Mallat* [1989]. In Figure 3 we show a comparison of the two representations for a 212 GHz pulse burst (for the 6 April 2001 event). The occurrence rate of pulses with time is shown in the upper panel, and a wavelet scalogram is shown below. Although both representations provide similar basic information on the occurrence of pulses, the wavelet decomposition display is more complete, exhibiting simultaneously the variations with time of the time

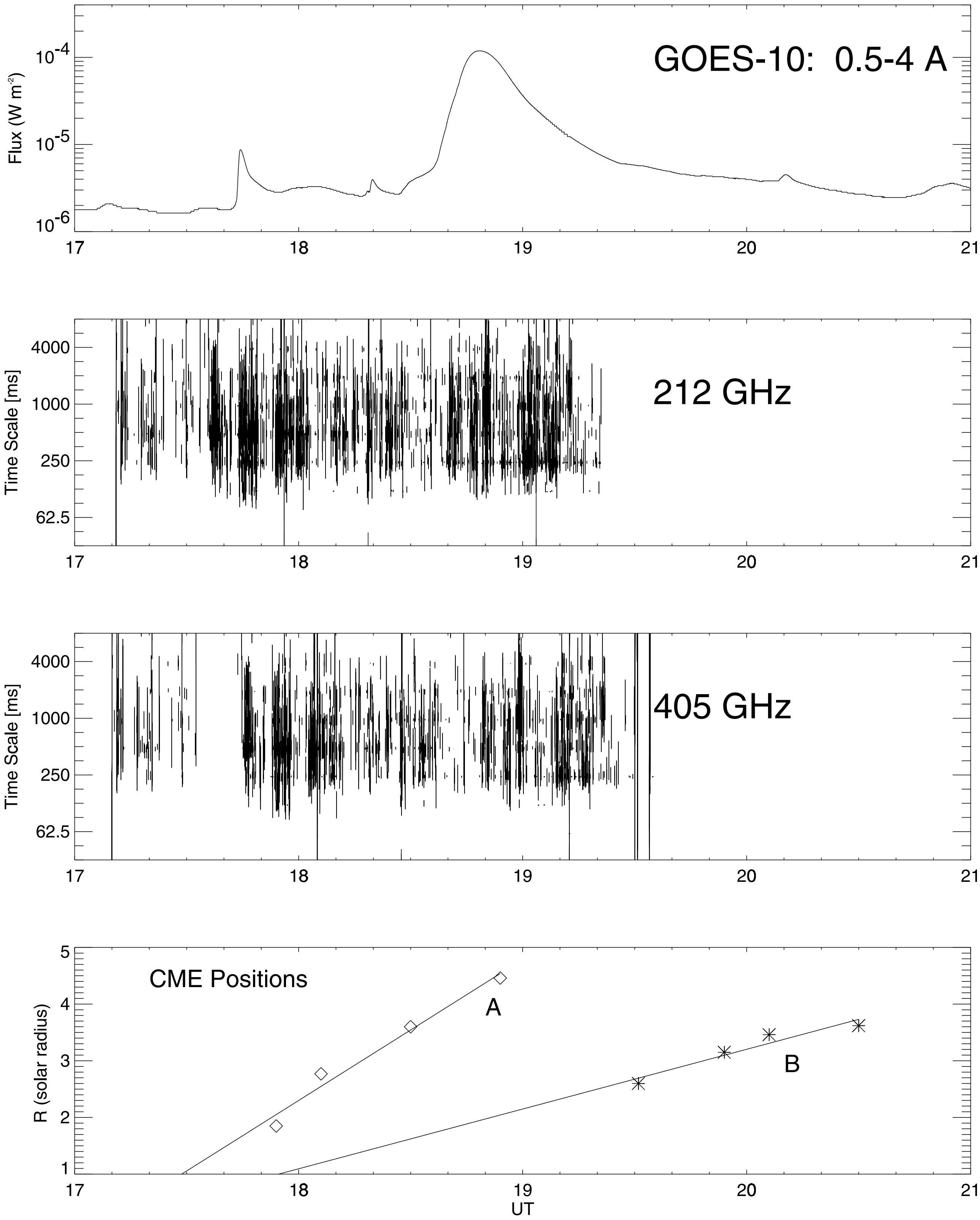

Figure 4. The 22 March 2000 flare with the GOES soft X-rays at the top and the 212 GHz and 405 GHz wavelet scalograms below. The CMEs apparent positions with time are shown at the bottom. The extrapolation of two CMEs positions to the surface of the Sun suggests a close association to the times related to the start of the major pulse bursts. The 212 GHz pulse bursts are presented in occurrence rates together with LASCO CME images in Figure 5.

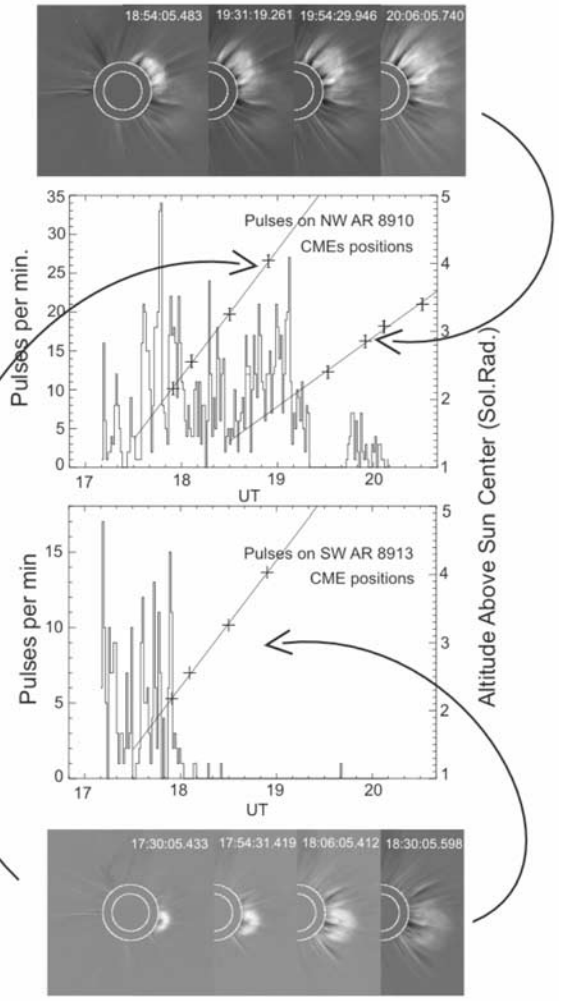

Figure 5. The C2 coronagraph LASCO images for the CMEs on 22 March 2000 are shown. The images for the first one are shown at the bottom. The extrapolation of the apparent positions to the solar surface correspond to the first concentration of 212 GHz submm-wave pulses, observed on the beam 4, on AR 8910, and on beam 1, on AR 8913, represented here in pulse occurrence rates. The second CME LASCO C2 images are at the top. The extrapolated apparent positions correspond to the onset of the submm-wave pulses connected to the large flare in AR 8910, which were observed only by the beam 4.

scales of the fast structures, their frequency or occurrence rate changes with time, and qualitatively, the emission intensity. In Figure 3 the scalogram indicates that as the pulse time scales become shorter than one second, their occurrence rate with time also increases. The two methods of pulse burst representation, by counting the occurrence rate and by wavelet decomposition, will be further compared in section 3.1. The wavelet analysis was done using SST data time integrated to 15–20 ms for all six events.

[14] The coronal mass ejections' images analyzed here were obtained from movies by the C2 and C3 coronagraphs of LASCO on SOHO [*Brueckner et al.*, 1995; *Schwenn et al.*, 1997]. For the same events we have analyzed 195 Å UV movies on the solar disk obtained by EIT on SOHO [*Delaboudinière et al.*, 1995] at the 195 Å band where the time resolution is usually better. To complement the events description, unless the data source is quoted specifically, we have referred to H-α flares, GOES X-rays, and microwave and metric radio data reported by NOAA Solar Geophysical Data Bulletins (SGD) [*NOAA*, 2000, 2001, 2002].

3.1. 22 March 2000 Burst

[15] This is the most complex event studied here and was the first one to exhibit submm-wave pulse bursts [*Kaufmann et al.*, 2001a]. It corresponded to a GOES X1.1 class flare that occurred in NOAA AR 8910, N14W57, at about 1830–1930 UT. One H-α subflare was observed in AR 8917 (N19W31) at about 1741 UT, and a major 2N H-α was observed in AR 8910 at 1835 UT. The maximum of the 212 GHz bulk emission of about 50 sfu was detected at about 1845 UT [*Trottet et al.*, 2002], considerably smaller than the fluxes in excess of the pulses associated to the event (of the order of 200 sfu at 212 GHz and of 500 sfu at 405 GHz) [*Kaufmann et al.*, 2001a]. Tracking of AR 8910 started at 1711 UT. There were several pulse bursts detected while tracking this active region in the days before and after 22 March. The most pronounced pulse bursts in 22 March are shown in the scalograms of Figure 4, showing time structures shorter than about 100 ms, to which two major CMEs were associated. There are several clusters of pulses observed, the first broad pulse burst event starting at about 1730 UT and another major broad pulse cluster starting at about 1835 UT, with an intermediate pulse cluster event at 1805–1825 UT. Some gross associations between the occurrences of pulse bursts to enhancements in GOES soft X-rays are suggested.

[16] The two successive CMEs observed by LASCO coronagraph C2 were in the SW and NW quadrants as seen in Figure 5, lower and upper panels, respectively. The extrapolation of the positions to the solar surface for the first SW CME suggests a launch time at about 1730 UT close to the onset of the first submm-wave pulse cluster, shown in Figure 4. For comparison the pulse bursts are also shown in Figure 5, as the pulse occurrence rates at 212 GHz, for beam 4, above, tracking AR 8910, and for beam 1, below, tracking AR 8913. The latter was located in the SW solar quadrant without any flare reported in the disk at that time.

[17] The second CME was ejected in the NW direction with launch time at about 1810 UT, coincident with the start of another cluster of submm-wave pulses, followed by another pulse enhancement at about 1835 UT. The onset of clusters of submm-wave pulses, or pulse-bursts, occur approximately with the GOES soft X-rays enhancements, at 1740, 1820, and 1835 UT, suggesting a possible association of the mass ejection somewhere in the lower solar atmosphere, with the origin possibly close to the surface.

[18] The EIT images in Figure 6 were taken at 1712 UT and at 1736 UT, where a sudden new arch formation in AR 8910 can be noticed. It occurred about simultaneously with a brightening at AR 8917 as well as with weaker, but clear, activity in AR 8913, which may have an association to the first submm-wave pulse burst cluster and CME launch. Moreover, by inspecting UV movies from TRACE and EIT centered on AR 8910 (S. L. Freeland, private com-

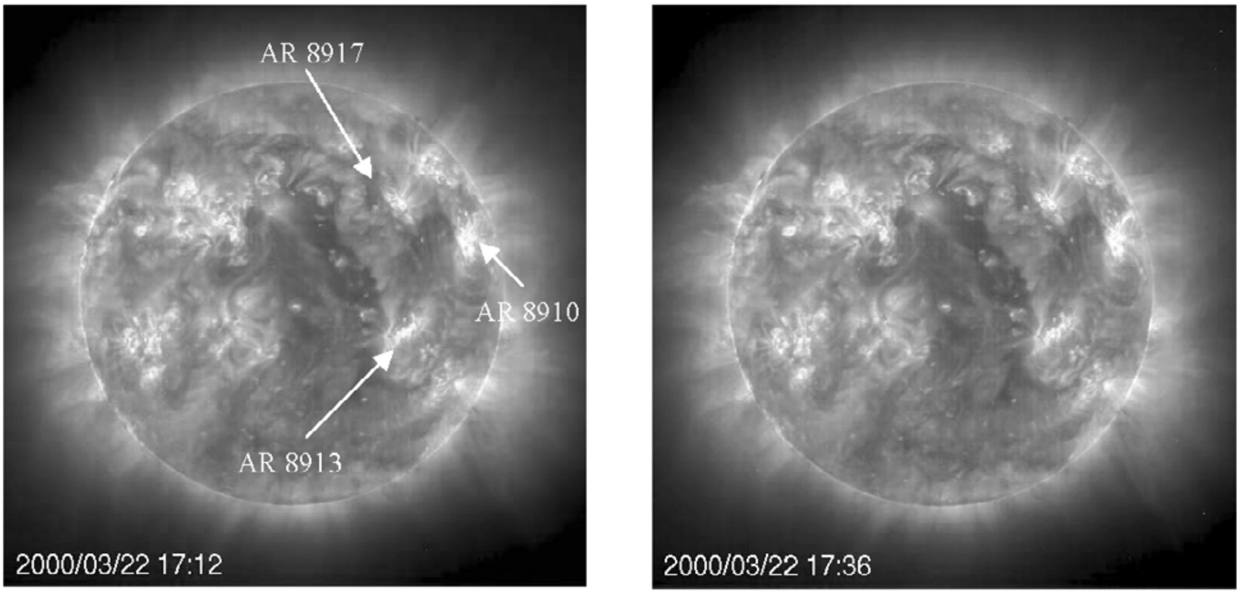

Figure 6. EIT 195 Å images for 22 March 2000, just before the first pulse burst, at left, showing the three active regions at 1712 UT, and at about the time the three regions exhibited magnetic changes and small brightening, at right, nearly coincident to the launch of first CME, and the first cluster of submm-wave pulses observed by beams 4 (on AR 8910) and 1 (on AR 8913). These might be representative of sympathetic activities in the visible disk coupled to the mass ejection that might have been associated to a flare behind the solar limb.

munication, 2000), we see that important activity occurs at about 1700 UT. TRACE has shown a major change in magnetic topology of AR 8910, with the appearance of a new large active loop system at sometime between 1715 and 1740 UT. The pulse rate occurrence measured by the distant beam 1, pointed to AR 8913, shown in Figure 5, third panel from the top, vanishes after about 1800 UT, giving further support that the SW CME launch was associated to activity at that region. H-α images taken at 1633, 1647, and 1801 UT from Holloman and Ramey observatories in SEC-NOAA web pages, show that a filament was partially blown up as the SW CME evolved, suggesting that its launch origin has a counterpart in the visible disk. The SW CME positions versus time reported by the NASA/NRL Catalog indicate the interception with the solar surface at about 1700 UT, suggesting the launch to be associated to a flare behind the limb. The difference in time compared to the present determinations (of about 30 min) might be too large in view of the timing and measuring inaccuracies that can be of the order of ±15 min. After careful checking of positions and timing for different CME features in LASCO movies, which are the same in both MPIAe and NRL/NASA catalogues, no explanation has been found for the discrepancy. Therefore the observational evidences suggest that the first SW CME was associated to a flare behind the solar limb, concurrent to large scale sympathetic events, at about the same time (between 1645 and 1730 UT), with magnetic changes and brightenings detected in the UV at three AR (8910, 8917, and 8913) on the disk.

[19] The arches in AR 8910 kept developing until the major brightening at 1836–1848 UT, followed by huge outward coronal arch expansion, in connection to the second major submm-wave pulse burst and the NW CME. A moderate intensity microwave burst was reported at 1836–1902 UT, with maximum intensity nearly flat in spectrum at 8.8–15.4 GHz, with 1100 sfu. Metric burst reported were one Type IV (1849–2030 UT) and a Type II (1849–1900 UT). The start times for these events indicate a connection to the second submm-wave pulse burst and CME.

3.2. 6 April 2001 Event

[20] This event corresponded to a GOES class X5.6 flare related to activity in NOAA AR 9415, located at S21E31, observed by SST at 212 GHz only, because the atmospheric propagation was highly attenuated at 405 GHz in that day. Good time association was found between submm-wave pulse rate occurrence and gamma rays [*Kaufmann et al.*, 2002]. The 212 GHz bulk peak emission was of about 5800 sfu, with pulses intensities in excess of the order of 200 sfu. Figure 7, top, shows LASCO images of the CME for 2001 April event. In Figure 8, top, we show burst bulk emission normalized time profiles, at soft X-rays (GOES) and at 212 GHz, the wavelet scalogram for the 212 GHz data (middle), and in the bottom the CME apparent positions with time as derived from data of both coronagraphs. A single pulse burst shows time scales reducing from seconds to less than 100 ms, repeating at higher rates as the time scales reduces, near the maximum of bulk emissions at 212 GHz and at soft X-rays. The pulse event begins at about the same time the launch of the CME, suggesting a close association between the start of the two phenomena in time and space.

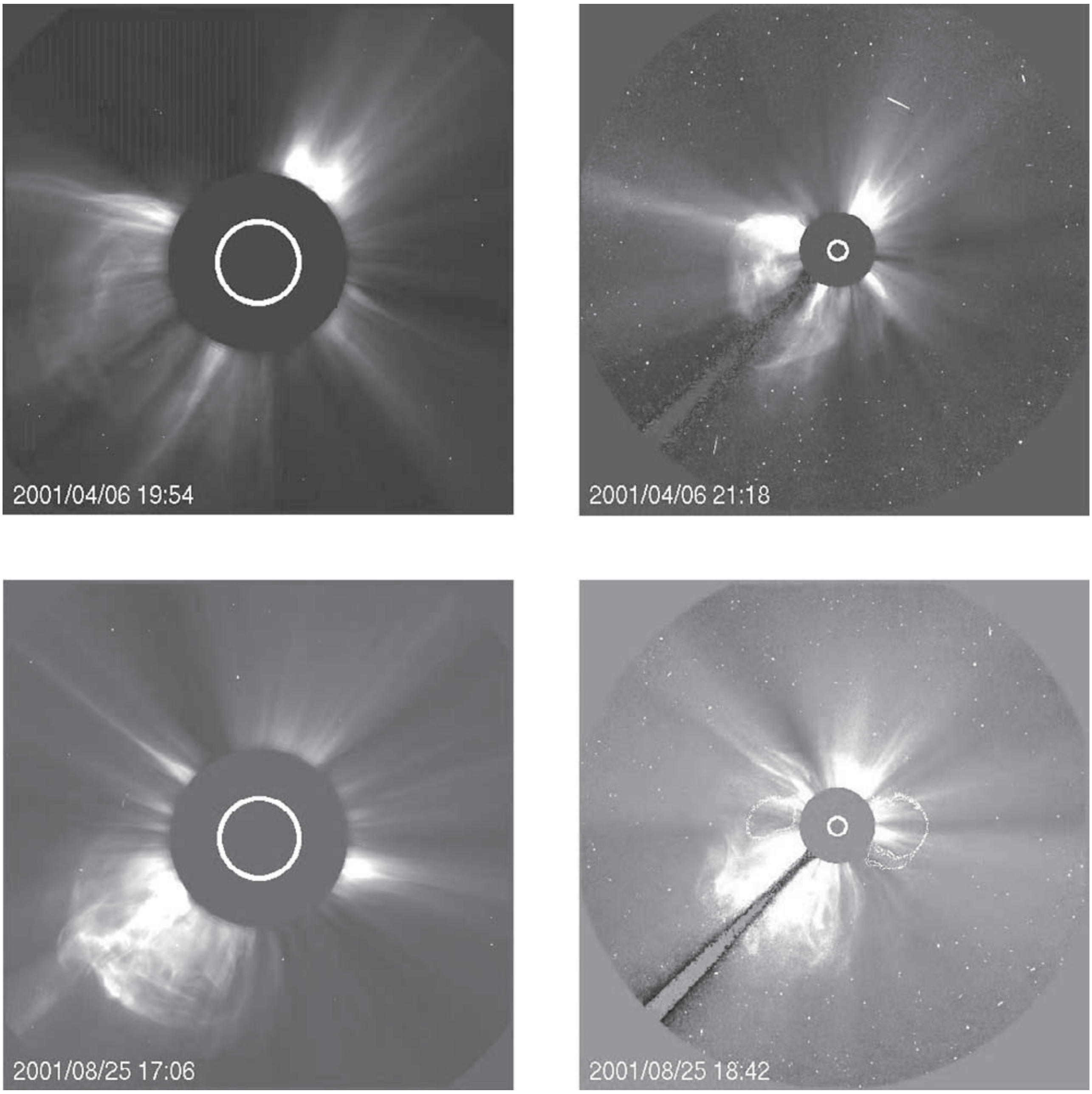

Figure 7. LASCO coronagraphs C2 (left) and C3 (right) CME images for the events of 6 April 2001 (top) and 25 August 2001 (bottom).

[21] There was one UV brightening in AR 9415 somewhere between 1848 and 1924 UT, shown in the Figure 9 195 Å image, top picture at left. It was followed by several dynamic arch interactions with neighboring ARs until 2300 UT.

[22] A strong microwave burst was reported (1914–1950 UT), with flux increasing with frequency, attaining 6700 sfu at 15.4 GHz, with a peak somewhere between 15.4 and 212 GHz. Metric Type V was observed (1915–1931 UT), but no Type II.

3.3. 25 August 2001 Event

[23] The very large GOES class X5.3 event occurred in NOAA AR 9591, at S17E34, corresponding to a 3B H-α flare. The results on the association of the submm-wave emissions and X- and gamma rays for this event are being published elsewhere [*Raulin et al.*, 2003]. An important CME has been imaged by LASCO coronagraphs C2 and C3 as shown in Figure 7, bottom. The normalized burst time profiles for the bulk emissions at 405 GHz and at soft X-rays are shown in Figure 10 (top), the scalograms below, and CME apparent positions with time at the bottom. The shortest time scales become considerably smaller than 50 ms at the maximum of the event, which has saturated the 212 GHz radiometers. Despite the high atmospheric attenuation at 405 GHz at that day, the pulse burst was well defined at the peak of the event. The extrapolation of the CME positions to the solar surface

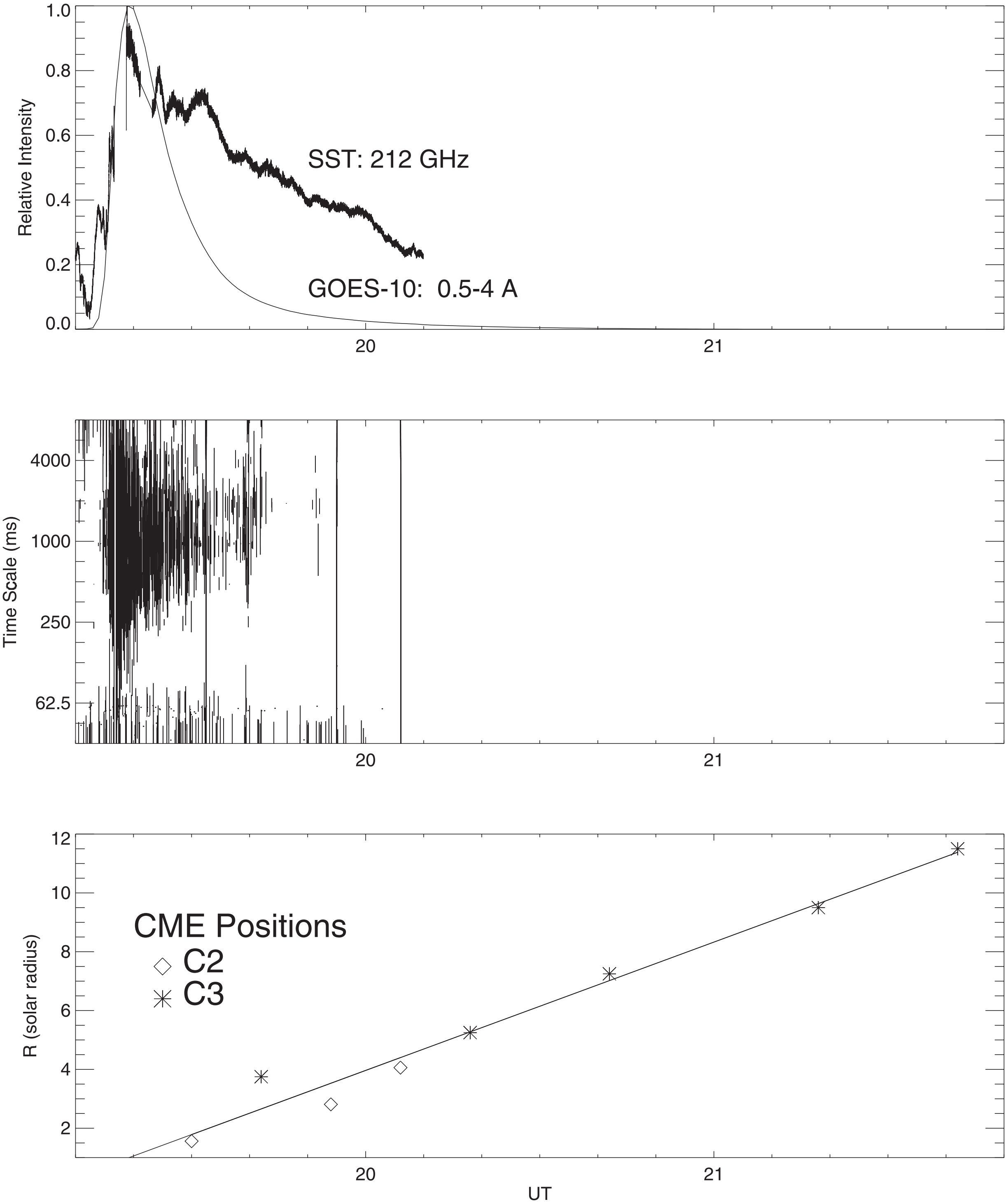

Figure 8. The 6 April 2001 solar event: the GOES soft X-rays and submm-wave bulk emission normalized time profiles (top), the 212 GHz scalogram showing the pulse burst event (middle), and the CME apparent positions vs. time as derived from LASCO coronagraphs C2 and C3 for feature A displayed in Figure 7, top.

indicates a good association with the onset of submm-wave pulse burst.

[24] The EIT images have shown a sudden large scale change in magnetic field arcades somewhere between 1600 and 1625 UT, together with the submm-wave pulse burst onset and just before the UV flare brightening (1625–1636 UT). The peak 195 Å flare image is shown in Figure 9, top figure at right. It was one of the largest radio events for the present solar cycle, for which all basic kinds of coronal emissions were reported by SGD. The microwave burst (1914–1950 UT) exhibited fluxes increasing with frequency, attaining 41000 sfu at 15.4 GHz, with a spectral

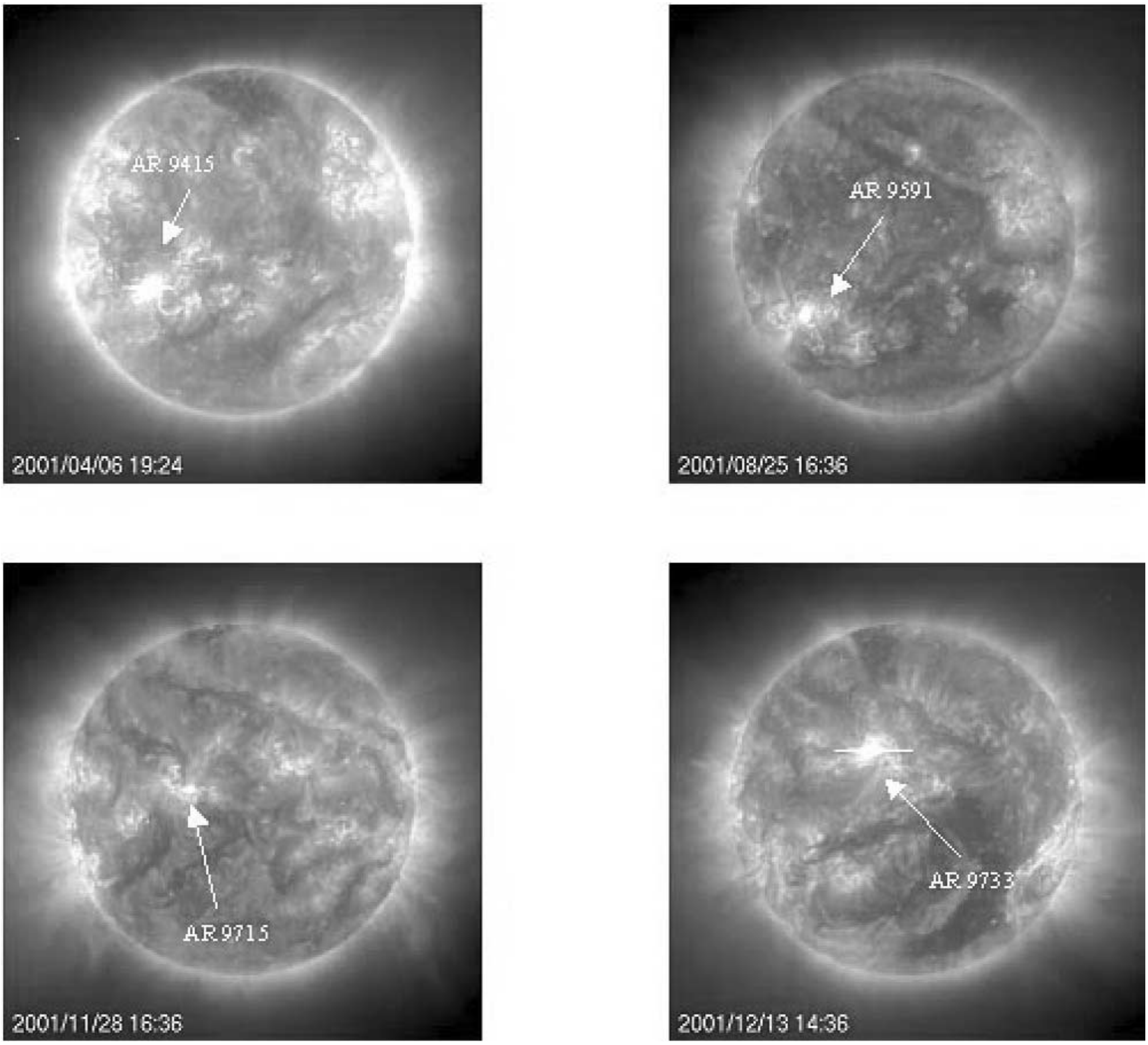

Figure 9. UV main flares obtained by EIT 195 Å for the events of 6 April, 25 August, 28 November, and 13 December 2001.

peak somewhere between 15.4 and 212 GHz. Type IIIs (1626–1651 UT and 1639–1705 UT) together with Type IV (1639–1705 UT) and a shock wave Type II (1632–1643 UT) were observed. The start times of these coronal radio emissions seem to be close to the onset of the submm-wave pulse burst.

3.4. 28 November 2001 Event

[25] This GOES class M6.9 was associated to a 1B H-α flare located at NOAA AR 9715, N04E16, producing a "halo" class CME, shown in Figure 11 in LASCO C2 and C3 coronagraph images. A short impulsive event (about 50 s) was observed at 212 GHz, presenting weak bulk emission (about 80 sfu) while the 405 GHz emission was totally attenuated by atmospheric propagation. The properties of this event are being reported separately (C. G. Giménez de Castro et al., manuscript in preparation, 2003).

[26] In Figure 12 we show the GOES soft X-rays at the top, the 212 GHz scalogram below, and the C2 LASCO coronagraph apparent positions versus time at the bottom. A short pulse burst (less than 1 min) was well defined at about 1634 UT, with time scales shorter than 200 ms, nearly at the same launch time of the CME. There were no pulse bursts associated to the three other soft X-rays bursts observed by GOES.

[27] The EIT images exhibited a small brightening in AR 9715 sometime between 1536 and 1548 UT, followed by some kind of ejecta-like faint brightening at 1612–1624 UT, which occurred simultaneously to a loop network excitation at the remote SW AR 9714 (S10W26), followed by the main UV brightening in AR 9714 at 1624–1636 UT, shown in Figure 9, bottom left panel, to which the short submm-wave pulse burst might have been associated.

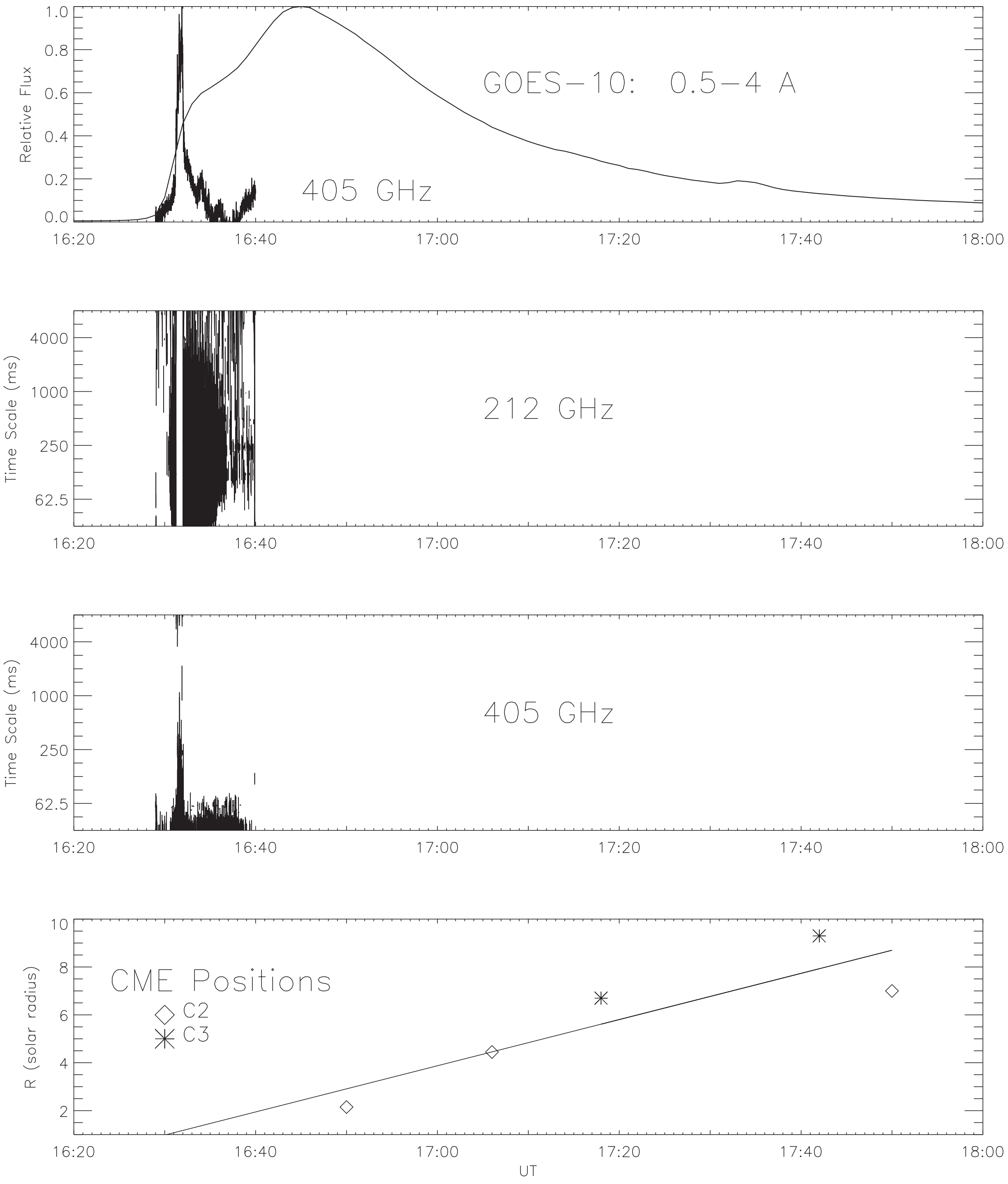

Figure 10. The normalized time profiles for bulk emissions at 405 GHz and GOES soft X-rays for the 25 August 2001 large solar flare are shown at the top. Scalograms below show the association of an important pulse burst, with time structures shorter than 50 ms and high occurrence rates with time. The bottom plot of CME positions, derived from C2 and C3 LASCO coronagraphs (see Figure 7, bottom), suggest a start time near the solar surface associated to the onset of submm-wave pulses.

[28] A microwave burst was reported (1632–1644 UT) with maximum intensity of 2000 sfu at 15.4 GHz, spectral peak somewhere between 15.4–212 GHz. A metric Type III radio event (1627–1635 UT), together with Type IV (1636–1659 UT), and a shock wave Type II (1636–1646 UT) were reported. The start times were associated to the short submm-wave pulse burst (at about 1634 UT), to within a few minutes.

3.5. 13 December 2002 Event

[29] This event occurred at NOAA AR 9733, N16E09, producing a 3B H-α flare and GOES class X6.2 soft X-ray

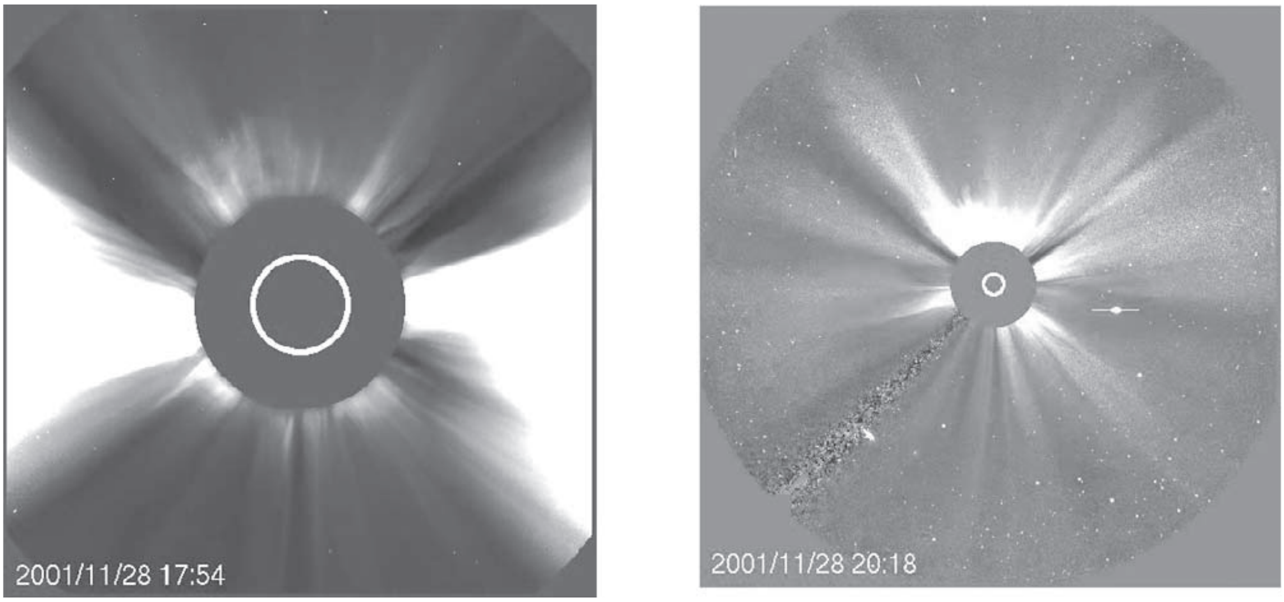

Figure 11. LASCO CME images for the 28 November 2001 event for coronagraphs C2 (left) and C3 (right).

burst. The "halo" CME observed is shown in Figure 13, for feature A from LASCO C2, and for feature B from LASCO C3. The time evolution of the apparent positions of the two CME features is shown in Figure 14, bottom. The two features have different apparent ejection velocities but the extrapolation of their positions to the solar surface nearly coincide at about 1420 UT, close to the onset of one important 212 GHz pulse burst, which may have started few tens of minutes earlier. The scalogram indicates time scales reducing from few seconds to less than 125 ms near the peak of the soft X-rays.

[30] The EIT images have shown smaller brightening (1412-24 UT) preceding the main UV flare (1424–1436 UT), shown in Figure 9, bottom right, accompanied by a suggestive large scale expanding feature at 1636–1700 UT. There was one impulsive microwave radio burst, 1423–1449 UT, maximum at 1426 UT. The spectral turnover frequency was at 8.8 GHz, with peak flux of 3100 sfu. The flux of the bulk emission component was beyond the detection sensitivity at 212 GHz at that day (i.e., less than about 50 sfu). Metric events were reported: Type III and V (1417–1422 UT), Type IV (1424–1454 UT), and a shock Type II (1423–1443 UT), i.e., with start times close to the onset of the submm-wave pulses.

3.6. 16 July 2002 Event

[31] One typical "halo" CME was observed by the LASCO C2 and C3 coronagraph, as shown in Figure 15. Other solar activity evidences in the solar disk were weak or inexistent, suggesting a CME association to a major flare behind the solar limb. Weak activity was observed on the disk at about the same time, associated to NOAA AR 0030: two subflares were reported at the approximate position N21W07, with start-maximum times at 1536–1539 UT and 1614–1615 UT, respectively. Another subflare was reported far from the region being tracked, near the solar limb, in AR 0027, N15W67, at 1622 UT. GOES level C2 X-ray enhancement was observed at approximately 1500–1730 UT, without any clear association to the subflares or to the submm-wave pulse burst.

[32] The SOHO EIT images do not show any UV strong brightening. However, a new magnetic arch formed in AR 0030 at about 1624–1636 UT, fading out at about 1925 UT, as seen in Figure 16. This magnetic activity might have had some association to the first H-α subflare reported and connection to the CME launch. Indeed, the Big Bear Solar Observatory H-α movie shows the disappearance of a small filament at about 1609 UT. The CME positions versus time for features A and B shown in Figure 15 suggest different apparent velocities. Their extrapolation to the solar surface suggest a common launch time, at about 1540 UT, when there was observed a submm-wave pulse burst, shown in Figure 17 scalograms. Other pulse bursts, with shorter time scales components only, were observed at about 1610, which might be tentatively associated to the following subflare in AR 0030 (at 1614 UT), and at 1635 UT which might have some connection to the next subflare reported at the remote AR 0027 (at 1622 UT). There was a suggestion of a weaker submm-wave pulse burst at about 1655 UT, without any associated phenomena detected in the solar disk. No other microwave or metric radio emissions were reported for this event.

4. Discussion

[33] The analysis of SST data is very laborious and time-consuming. Only few events were investigated so far. Therefore it is significant to find out that seven CMEs were associated to all six submm-wave events studied, showing a clear association between the onset of pulsations at submillimeter waves with coronal mass ejections at times which coincide approximately to the extrapolated CMEs apparent positions close to the solar surface. For two events a connection to flares behind the solar limb might be

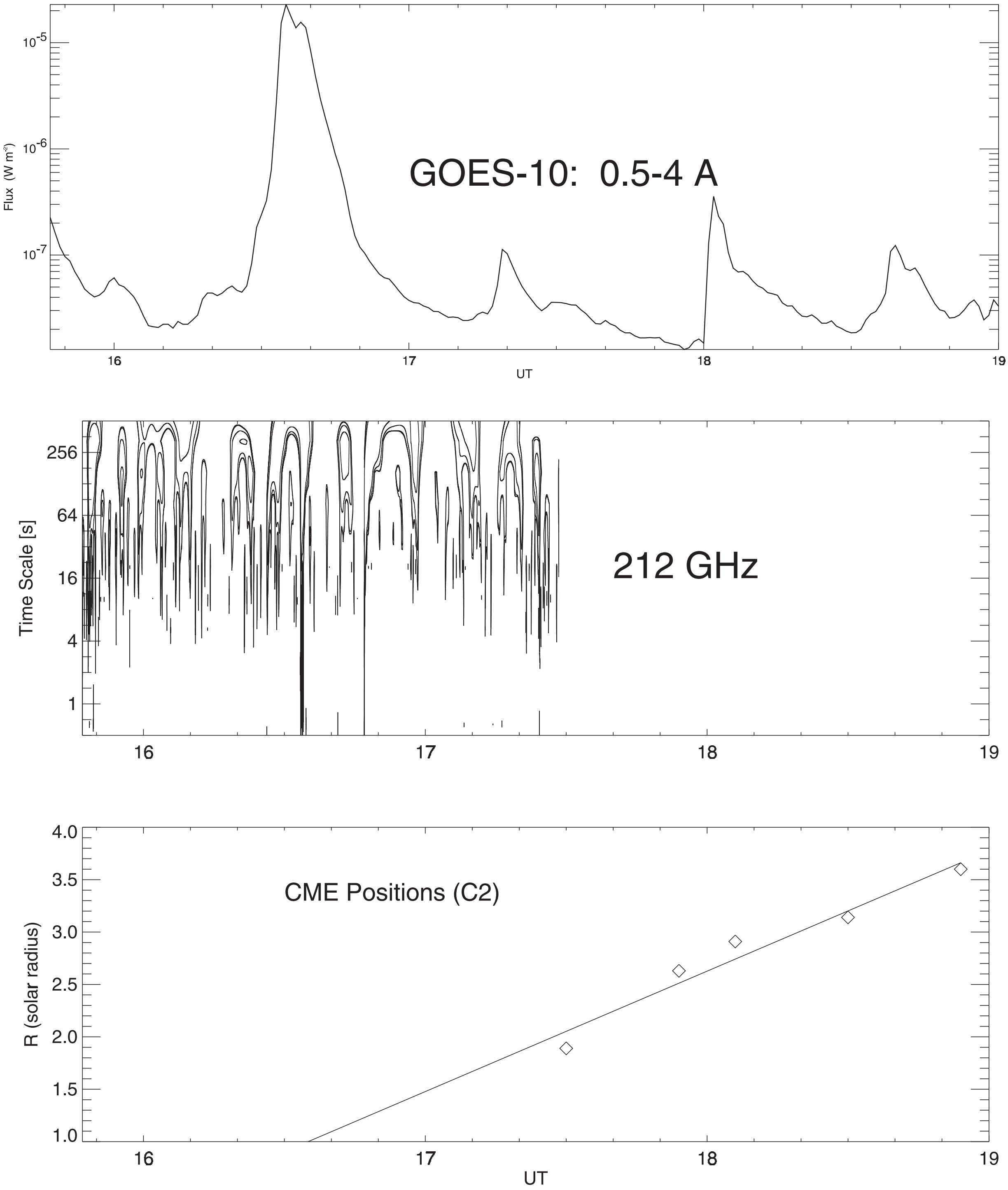

Figure 12. Time profiles for the 28 November 2001 event. GOES soft X-rays at the top, 212 GHz wavelet decomposition showing a short pulse burst (less than 1 min) at about 1633 UT and the CME C2 apparent positions versus time.

assumed, with suggested sympathetic activity at active regions on the solar disk. The accuracy in timing is of course restricted to the time interval between LASCO frames, tens of minutes, and on the sensitivity threshold set for the submm-waves wavelet analysis which depends primarily on the signal attenuation by atmospheric propagation. Nevertheless, the agreement between the occurrence of submm-wave pulse bursts and the CME launch time is extraordinarily good for all events, suggesting a close physical connection with the propelling mechanism of CMEs in time and in space.

[34] On the observational standpoint, the onset of submm-wave rapid pulses does not seem to be necessarily well correlated to the soft X-rays time profiles or to the bulk

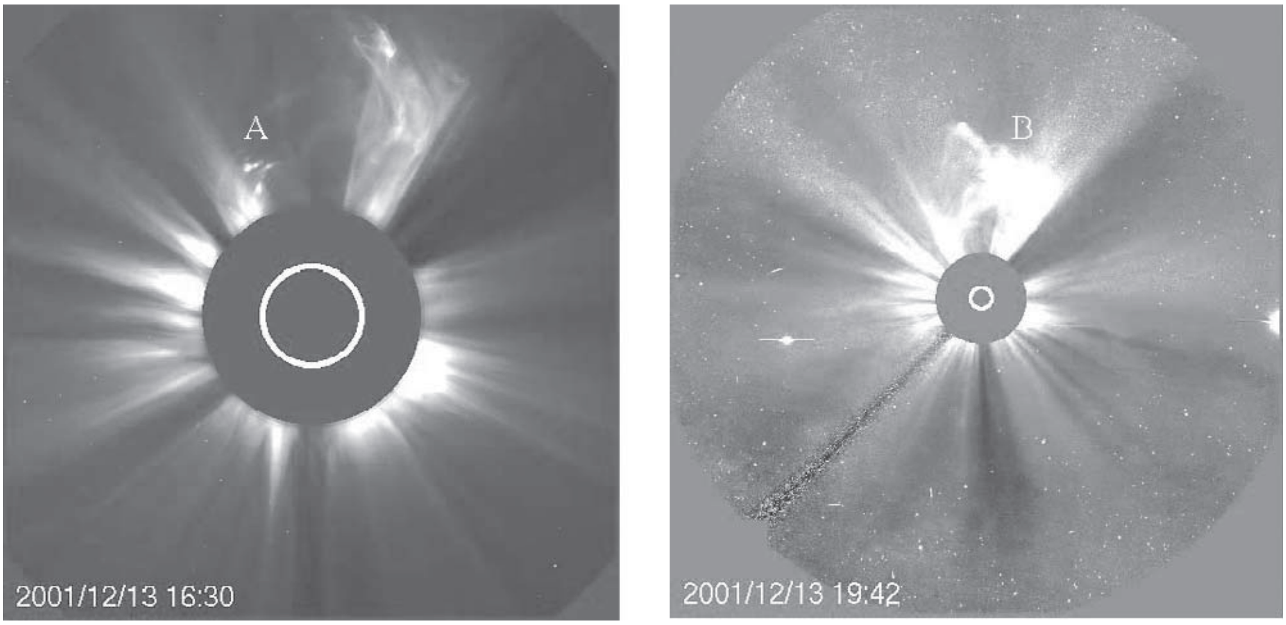

Figure 13. The LASCO coronagraphs C2 (left) and C3 (right) images for the "halo" CME of 13 December 2001, for which the submm-w pulse bursts are shown in Figure 14.

of submm-wave emission, when the latter is observed. There was a good time coincidence between the submm-wave pulse bursts and the impulsive bulk in radio emission only for the 6 April 2001 and 25 August 2001 events shown in Figures 8 and 10, respectively. However, for the 22 March 2000 event, Figure 4 shows at least five major pulse concentrations. The first submm-wave pulse onset starts with the small soft X-ray enhancement at about 1735 UT, followed by a burst at about 1745 UT. Three active centers have shown activity at about the same time period, with a possible sympathetic flare occurring behind the solar limb. The larger pulse burst started at about 1835 UT, corresponding to the main soft X-ray burst. The bulk emission time profile for the impulsive radio burst was defined only for the approximate time interval 1835–1855 UT, with a peak preceding by several minutes the soft X-ray maximum [*Kaufmann et al.*, 2001a, 2001b; *Trottet et al.*, 2002]. The pulse burst for the 25 August 2001 (Figure 10) is coincident with the impulsive bulk emission at submm-waves and with the first soft X-ray enhancement at about 1628 UT. In this case, however, there were no more pulses at the time for the maximum soft X-ray emission. For the 13 December event (Figure 13) there was a clear association between the onset of the pulse burst and the soft X-ray burst starting at about 1420 UT. Finally, the apparent positions with time for the "halo" CME of 16 July 2002 intercepts the solar surface in coincidence to a submm-wave pulse burst, together with a small subflare and apparently unrelated weak soft X-ray emission. For this event the CME connection to a flare behind the solar limb suggests some large-scale coupling with the weak activity measured on the solar visible disk.

[35] There was microwave bulk emission counterparts for all except one of the submm-wave pulse bursts. Negligible or no submm-wave bulk emissions were detectable for four of the six events, three of them being classified as Great Bursts at microwaves. The onset of the submm-wave pulse bursts appear to be well associated to the presence of accelerated energetic particles in the solar corona, as suggested by metric radio bursts Type III, V, and IV found for five out of six events and to Type II shocks for four out of six events. Although there were no common descriptions found, the EIT images have indicated the association of some kind of magnetic field activity and brightening for all submm-wave pulse bursts. Some large-scale magnetic coupling was suggested for some events. However, owing to the relatively small number of events analyzed so far, it is not possible to establish whether there are submm-wave pulse events without CMEs or CMEs without pulse events also occurring.

5. Concluding Remarks

[36] We have shown that despite the many differences in the time histories and in correlations between emissions for five solar flares in H-α, soft X-rays, and submm-waves, all have in common the launch of CMEs with origin in time associated to the onset of rapid submillimeter-wave pulses or "pulse bursts." EIT small and large scale brightening and/or magnetic structure dynamic changes at the onset of submm-wave pulse bursts were seen for all events, although there were no common patterns. The definition of the CME launch time used in this paper takes apparent positions as observed extrapolated to the solar limb to avoid any bias or systematic errors which may arise when assuming that the mass is ejected perpendicularly to a given AR location on the solar disk or behind it, which might not be true in many cases.

[37] The suggested association of pulse bursts at submm-waves to the launch time of CMEs may have great significance for improving the forecast of these large solar disturbances. Pulse bursts might become particularly useful

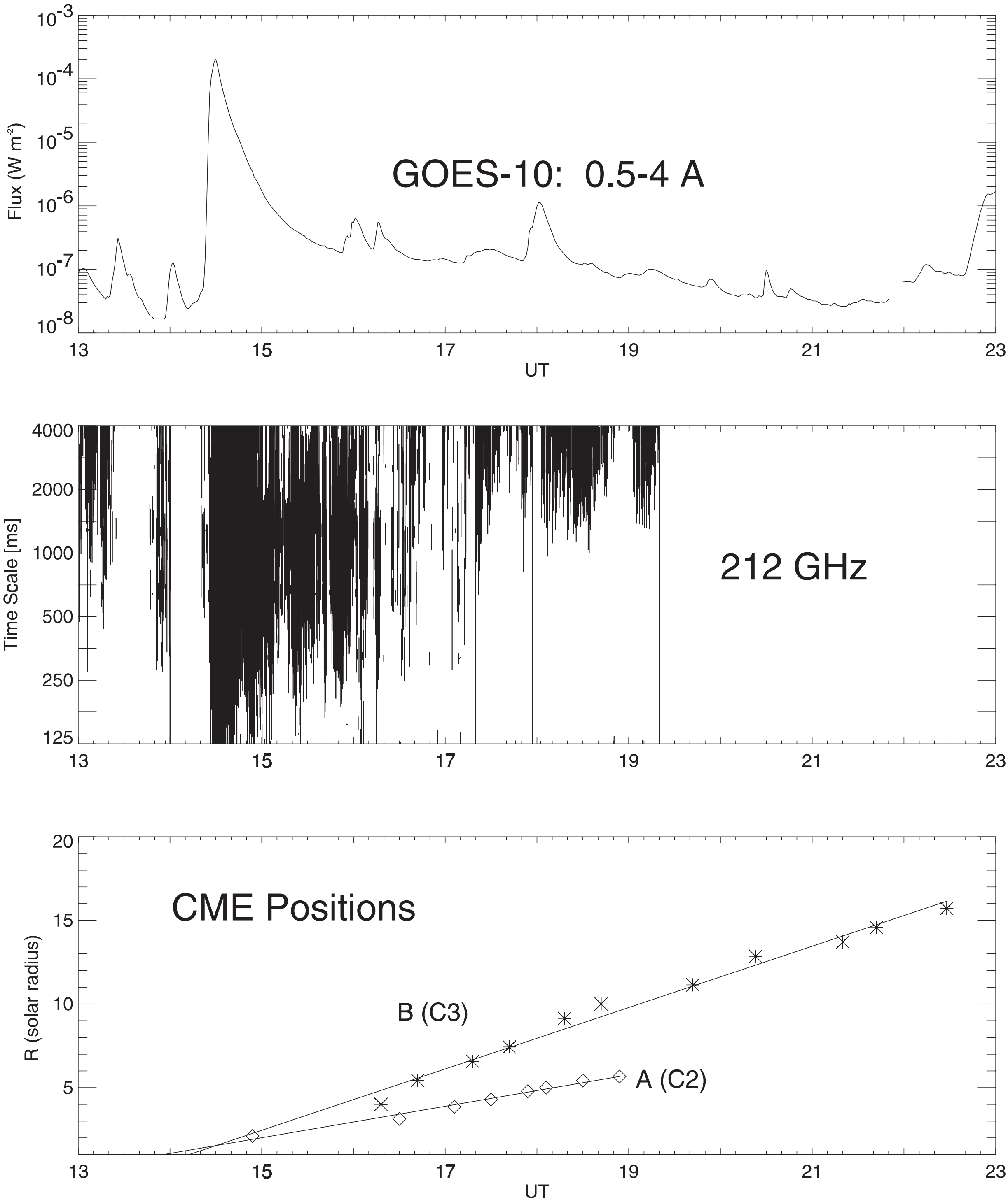

Figure 14. The GOES soft X-ray time profile (above) with the 212 GHz wavelet decomposition, below, for the 13 December 2001 solar event. Two different velocities are found for the CME apparent positions of features A and B, shown in Figure 13, both intercepting the solar surface at about the same time, close to onset of the submm-wave pulses.

indicators when events are produced near the center of the Sun, generating the "halo" CMEs, which often are difficult to identify unambiguously in coronagraph images. Pulse bursts are also suggested to be responses of regions activations in the visible solar disk as CMEs are launched in connection to flares behind the solar limb.

[38] The association of CMEs launch time to the clustering of rapid and successive pulses at submm-waves favor physical mechanisms based on rapid energy releases, possibly at common sites, closer or at the solar surface. A scenario for the CMEs phenomena has been recently suggested, assuming the superposition of multiple or frag-

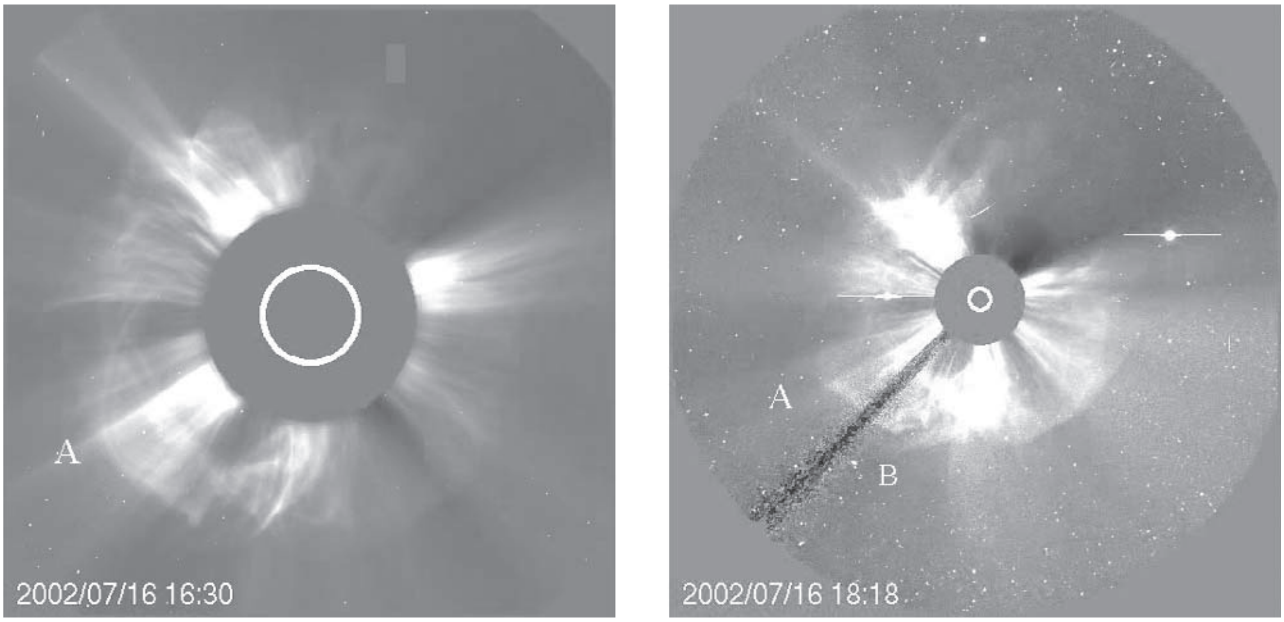

Figure 15. The LASCO images for the "halo" CME of 16 July 2002 for coronagraphs C2 (left) and C3 (right). CME edges A and B have shown different apparent velocities, with a common launch time (see Figure 17).

mented energy releases [*Biesecker and Thompson*, 2000], as indicated by a number of flare diagnostics and model descriptions [*Frost*, 1969; *van Beek et al.*, 1974, *Kaufmann et al.*, 1980; *Kaufmann*, 1985; *Lu and Hamilton*, 1991; *Zirker and Cleveland*, 1993; *MacKinnon et al.*, 1996]. As the magnetic complexity grows at an active region, conditions might be reached for a major large-scale instability to set in, inducing multiple and faster instabilities on smaller scale magnetic arcades or fluxules [*Sturrock and Uchida*, 1981; *Sturrock et al.*, 1984; *Sturrock*, 1986, and references therein]. The energy released by such elementary instabilities may produce nanoflares or, when clus-

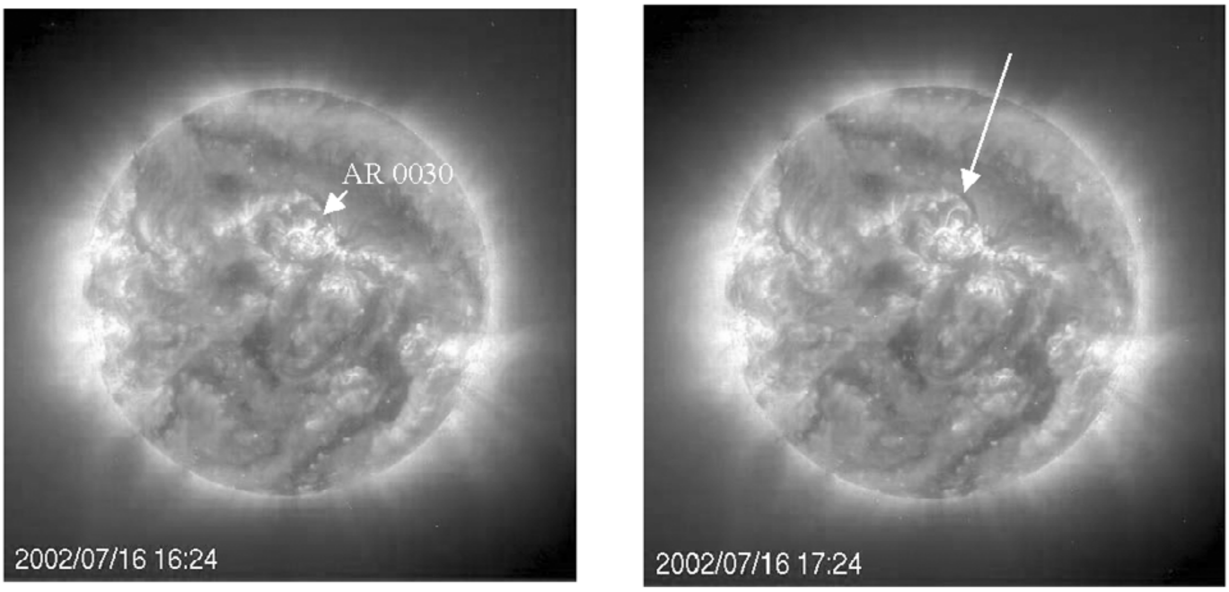

Figure 16. The EIT 195 Å solar images for 16 July 2002, just before the event (left) and at about the time there was the onset of the submm-wave pulse bursts (right) showing a new magnetic arch formation on AR 0030, at a time that correlates well with the CME launch time. These are likely sympathetic responses observed in the visible disk to the mass ejection associated to a flare behind the solar limb.

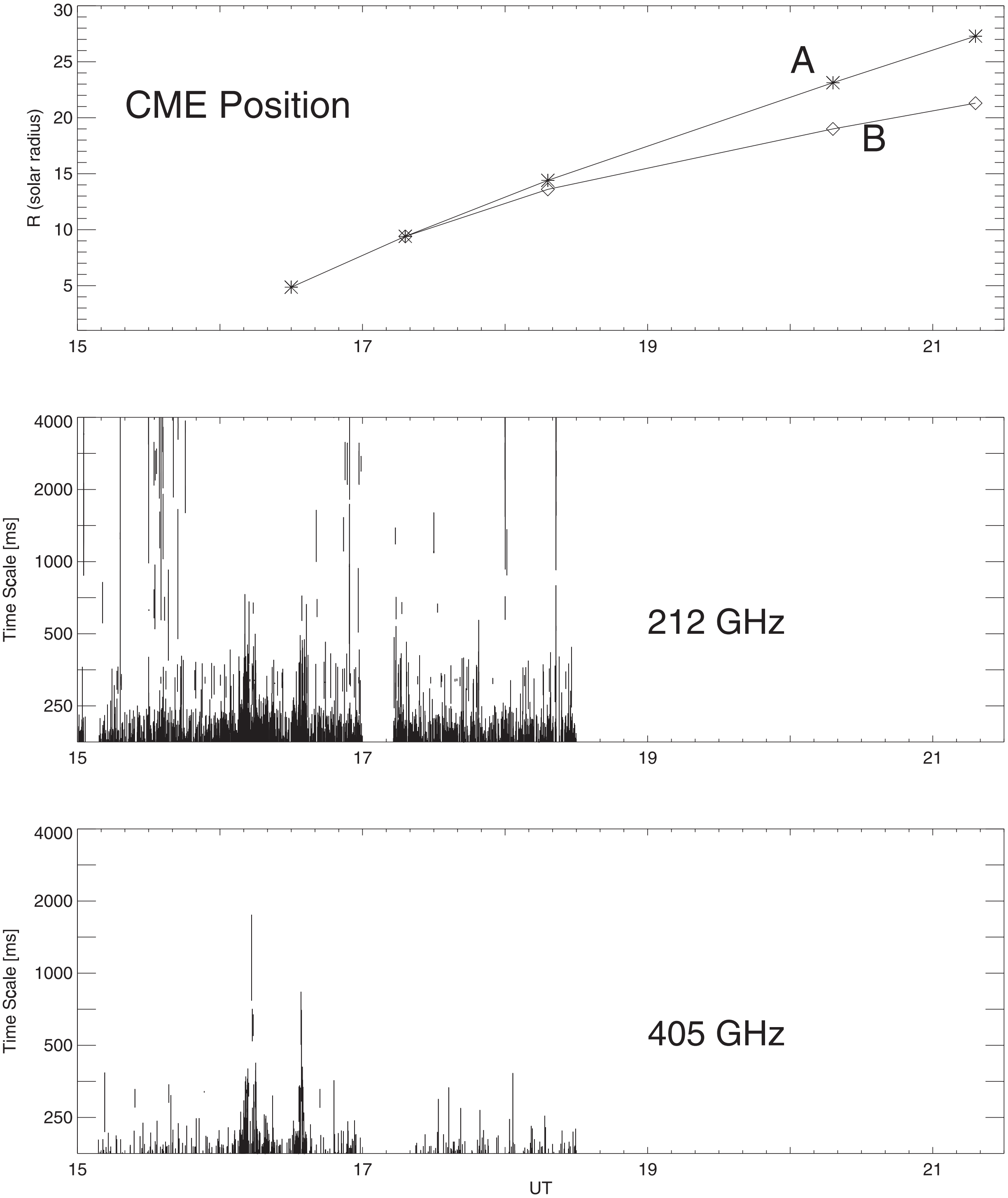

Figure 17. The apparent CME positions (top) with time indicate a launch time nearly coincident to the group of submm-wave pulses, shown in the wavelet decompositions below, for 212 and 405 GHz.

tered in larger number in short time, to brighter flares. Models based on larger spatial scale structures describe CMEs arising from the disruption of certain coronal streamer configurations by flux-rope instabilities at photospheric levels [*Wu et al.*, 2000], which might be reconciled with similar scenarios with multiple and complex magnetic structures.

[39] The origin and the physical nature of the submillimeter pulses is far from being well understood. They may be of the same nature of the subsecond time structures known at cm-mm wavelengths [*Kaufmann et al.*, 1980; *Raulin et al.*, 1998] and to subsecond pulsations observed in the optical range [*Wang et al.*, 2000; *Trottet et al.*, 2000]. However, there are major differences to be considered. For

example the occurrence rate of submm-wave pulses are not necessarily well related to the time profile of the bulk of the impulsive emission. The correlation seems to be better with emissions at higher energies.

[40] The present results raise challenging questions to be clarified for a better understanding of the association of CME launches to the occurrence of pulse bursts at submm-waves and support theoretical models on the mechanisms producing them. Diagnostics efforts are suggested addressing to the following: (1) are there solar flares without submm-wave rapid time structures, (2) are there pulse bursts without other measurable flaring signatures in the solar disk, (3) are there CMEs without submm-wave pulse bursts associated, (4) are submm-w pulses always connected to CMEs without any obvious flare connection, (5) what are the relationships between magnetic field precursors and the onset of submm-wave pulse bursts, (6) can large scale disturbances, such as Moreton waves, trigger the onset of submm-wave pulse bursts and the launch of CMEs at sites remote from the main flare, (7) are there differences in pulse bursts characteristics which can be found with more detailed studies on scalograms, and (8) are there relationships between CMEs physical features in space and times with submm-wave pulses detailed characteristics in time and spectral frequency?

[41] **Acknowledgments.** We are grateful for the CASLEO engineering and technical staff in SST operational support and for the help in data analysis given by Arline M. Melo and Alessandra A. Pacini. SOHO LASCO and EIT operations and data analysis are being supported by NASA, USA and MPAe, Germany. This research was partially supported by Brazil agencies FAPESP, contract 99/06126-7, and CNPq, grant 304822/89-2, and Argentina agency CONICET. VSM acknowledges the Visiting Professor support given by Brazil agency CNPq, grant 300607/01-6(NV).

[42] Lou-Chuang Lee thanks Kenneth P. Dere and S. T. Wu for their assistance in evaluating this paper.

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