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Journal of Atmospheric and Solar-Terrestrial Physics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.com/locate/jastp

Radio emission observed in decimetric waves associated with the onset of CMEs

J.R. Cecatto*, A.C. Soares, F.C.R. Fernandes, F.R.H. Madsen, M.C. Andrade, H.S. Sawant

Astrophysics Division, INPE, Av. Astronautas, 1758, PO Box 515, CEP: 12227-010, São José dos Campos, Brazil

Received 6 September 2004; received in revised form 22 December 2004; accepted 4 March 2005

Abstract

Since the first observations by Skylab and SMM satellites coronal mass ejections (CME) have been more and more investigated. However, until now their origin and trigger mechanism remain an open question no matter if they are associated to flares or not. Recent observations over a broad spectrum suggest that flare energy is released in regions from where the decimetric emission is coming. Then, investigations of decimetric radio emission observed in association with CME phenomena may give clues to solve the previously mentioned questions. Using the Brazilian solar spectroscope (BSS), observations of solar bursts dynamic spectra with high time (100, 50, 20 ms) and frequency (50–100 channels) resolutions have been carried out daily (~11–19 UT) within the range of 1000–2500 MHz. A sample of 274 CMEs were recorded by the large angle spectroscopic coronagraph (LASCO) instrument, on board the solar and heliospheric observatory (SOHO) satellite, within 11–19 UT, during the period of 1999–2002. From those, 42 CMEs are associated to BSS data and selected for analysis. It is interesting to note that in about half of the cases only one type of burst radio emission was recorded while in the remaining cases either two or more types were observed. There is a dominance of either continuum and/or pulsations. Here, we describe the association of burst radio emission with the starting time of CME phenomena.

Keywords: Radio emission; CME; Decimetric waves; Solar bursts

1. Introduction

CMEs are big plasma clouds, as magnetic bubbles that become unstable and buoyant, leaving the Sun and propagating out into the interplanetary space. These phenomena are observed in white light and were first imaged with space-borne coronagraphs in the early 1970s (Tousey, 1973; Gosling et al., 1974). Until now there are many unknown aspects and a controversy in those investigations concerning the relationship between CMEs and solar flares. While some authors show that <40% of CME phenomena are associated to flares (Munro et al., 1979; Webb and Hundhaunsen, 1987; St. Cyr and Webb, 1991), others concentrate on investigating the aspects of a significant relationship CMEs-flares (Verneta, 1997; Svestka, 1995; Sheeley et al., 1983; Kahler, 1994).

This work searches for the association of radio burst emission, using 4 years (1999–2002) of spectroscopic data from the BSS instrument (Sawant et al., 2001; Fernandes, 1997), within the 1000–2500 MHz frequency

*Corresponding author. Fax: +55 12 3945 6811/6090.
E-mail address: jrc@das.inpe.br (J.R. Cecatto).

1364-6826/$ - see front matter
doi:10.1016/j.jastp.2005.03.006

range, with the CMEs recorded by LASCO C2 and C3 coronagraphs. This association may give us a clue regarding CMEs origin and trigger mechanism from near the solar surface.

2. Instrumentation, observations and analysis

BSS is a digital spectroscope that operates routinely from 11 to 19 UT, at the National Institute for Space Research (INPE), at São José dos Campos, Brazil, in the decimetric wavelength range (1000–2500 MHz) with high time (100, 50, 20 ms) and frequency (3 MHz) resolutions, in conjunction with a polar mounted 9 m diameter parabolic antenna. This instrument allows us to select a suitable observing frequency range, frequency and time resolutions. The data can be digitized and recorded in upto 100 frequency channels. Time accuracy is ~3 ms and minimum detectable flux is ~3 sfu, for different combinations of observational parameters (Sawant et al., 2001; Fernandes, 1997).

LASCO is a three-coronagraph package, which has been jointly developed for the SOHO satellite. LASCO comprised three coronagraphs, C1, C2 and C3, which together imaged the solar corona from 1.1 to $30R_s$ (C1: 1.1–$3R_s$, C2: 2–$6R_s$ and C3: 3.7–$30R_s$). C2 and C3 coronagraphs are externally occulted instruments (Brueckner et al., 1995).

The extreme-ultraviolet imaging telescope (EIT) operating on board SOHO satellite provides wide-field images of the corona and transition region on the solar disc and upto $1.5R_s$ above the solar limb. Its normal incidence multilayer-coated optics selects spectral emission lines from Fe IX (171 Å), Fe XII (195 Å), Fe XV (284 Å), and He II (304 Å) to provide sensitive temperature diagnostics in the range from 6×10^4 to 3×10^6 K. The telescope has a 45 × 45 arcmin field of view and 2.6 arcsec pixels which provide approximately 5 arcsec spatial resolution (Delaboudinière et al., 1995).

During the period of 1999–2002, BSS operating daily (11–19 UT) in decimetric wavelengths carried out high time and frequency resolution observations of solar bursts, using either 100 or 50 frequency channels. Those observations were also done simultaneously by the LASCO experiment on board SOHO. A total of 274 CME phenomena were recorded by LASCO. A significant portion (~16%) of that amount were recorded with an estimated start time within ± 5 min of either start or end times of solar bursts recorded by BSS and selected for analysis. We want to remark also that the minimum time interval between two consecutive EIT, as well as LASCO images, is 12 min. All the LASCO–BSS associated phenomena originated from relatively low ($\leqslant 70^\circ$) heliographic coordinates as noted in Hα by NOAA instruments. However, EIT images were useful in some cases to determine the CME–BSS data association. Table 1 shows characteristics of the solar bursts recorded by BSS and associated to CME phenomena, as well as to flares.

Taking the example observed by LASCO C2 coronagraph at about 17–18 UT on April 05, 2001, Fig. 1 shows an image sequence with a CME time evolution. The white semicircle represents the Sun limb, while the larger black disk indicates the lower limit for C2 field of view. It is clear from the sequence of images that a CME starts before 17:26 UT. A sequence of 4 EIT (195 Å) images exhibiting the EUV emission from the solar disk during approximately the same time interval is shown in Fig. 2. Looking at the frames in the figure, it is clear that active region NOAA9415 located at S24 E50, near the centre, showed a noticeable increase in brightness around 17:00 UT remaining bright for more than 1 h until at least 18:24 UT. The dynamic spectrum recorded in decimetric wavelength range (1700–2000 MHz) by BSS can be seen in Fig. 3. A broad band (>300 MHz) continuum emission starting around 16:57 UT can be seen in the figure drifting from 1700 MHz to higher frequencies. These figures show one example. However, as we show in what follows the data strongly suggests an association CME (LASCO)–radio (BSS) phenomena.

We know that the decimetric activity originates in the high chromosphere-low corona, 10^3–10^4 km above solar surface, depending on the assumption of a specific density model. However, the fields of view seen by LASCO cover from ~1.0–$6.0R_s$ and 2.7–$30R_s$ (R_s is solar radius) above the solar surface for C2 and C3, respectively. This means that the field of view starts at distances of about $0.7–2.0\times10^6$ km from the solar surface. In terms of the travel time from the solar surface, C2 detects a CME after $\geqslant$6 min of its departure from the solar surface, taking into account the fastest CME observed with $v\approx2000$ km/s.

For C3, this means a minimum time of around 20 min. Therefore, in a first approximation we can investigate the association of CME (LASCO) within ±5 min from the start and end times of radio bursts recorded by BSS. To estimate the starting time of all CMEs in the sample from near the solar surface, we assume:

1. CME average velocity as measured by C2; for one case, as measured by C3.
2. Taking the coronagraphs field of view, we know the height above the solar surface.
3. Then, we estimate the time elapsed from the departure of the CME from near the solar surface and, as a consequence, its estimated starting time.
4. A comparison of the CME estimated starting time with the start and end times of BSS bursts taking into account for a ± 5 min interval allows us to check for the association.

Table 1
Decimetric bursts and flare activity associated to CME phenomena

Date	BSS			LASCO					H-alpha				
	Begin (UT)	End (UT)	Type	Coron.	Time (UT)	Velocity (km/s)	Estimated start time (UT)	LOC.	AR (NOAA)	Begin	Max	End	Imp.
05/08/99	1423	1426	Weak CNT	C2	14:50:05	641	14:31:54	N23W75	8526	1425	1429	1511	1F
06/24/99	1644	1717	Fine structure + pulsations	C3	17:55:52	621	17:05:08	No flare					
08/17/99	1243	1834	Noise + fine structure	C2	13:31:51	776	13:16:49	N26E35	8668	B1247	U1250	1405	SF
08/20/99	1827	1837	CNT	C2	18:50:07	631	18:31:38	S23E66	8674	1828	1828	1835	SF
09/13/99	170026	170030	Drift dots	C2	17:31:07	444	17:04:50	N15E06	8693	B1638	1644	1759	1N
04/27/00	120737	121312	Type III small group (< 10)	C2	12:30:05	764	12:14:47	No flare					
05/22/00	1324	1341	CNT	C2	14:06:06	419	13:38:16	No flare					
06/06/00	1501	1717	Inv.U + CNT + IIIib–nb	C2	15:30:05	929	15:17:31	N20E18	9026	1206	1521	1843	3B
			PreEF + CNT + dots + zebra + fiber	C2	15:54:05	1119	15:43:39	N20E18	9026	1206	1521	1843	3B
06/27/00	1256	1320	Fiber + noise storm	C2	13:31:56	311	12:54:25	S17E48	9062	1249	1254	1342	2N
07/06/00	1226	1237	Weak CNT + pulsations	C2	12:50:05	472	12:25:22	N18E25	9070	1222	1223	1226	SF
07/11/00	1313	1324	Oscillations	C2	13:27:23	1078	13:16:34	N18E27	9077	B1320	U1323	1837	2N
09/16/00	1323	1334	Patch	C2	13:50:05	1056	13:39:02	N14W10	9165	1326	1326	1328	SF
09/22/00	153415	153453	Dots	C2	16:06:05	445	15:39:52	No flare					
09/26/00	1823	1830	Weak CNT	C2	18:50:05	565	18:29:26	No flare					
11/24/00	1453	1520	CNT + TIIInb + pulsations	C2	15:30:05	1245	15:20:43	N22W07	9236	1501	1516	1557	2B
04/05/01	1653	1721	CNT	C2	17:06:05	1390	16:57:41	S24E50	9415	1633	1701	1849	2N
04/09/01	1520	1605	CNT + puls + TIIIRS + spikes	C2	15:54:02	1192	15:44:15	S21W04	9415	1524	1534	1703	2B
04/11/01	172345	172354	EF nb	C2	17:30:05	1145	17:19:53	S21W27	9415	1725	1726	1728	SF
04/25/01	1355	1356	Stria pq	C2	14:06:06	856	13:52:28	N18W09	9433	1344	1345	1420	2N
06/01/01	152425	152426	Weak int. variations	C2	15:54:07	449	15:29:08	No flare					
06/04/01	1512	1514	Weak int. variations	C2	15:30:05	632	15:11:37	S19E52	9488	1511	1517	1528	SF
06/13/01	1135	1142	CNT + weak int. variations	C2	11:54:05	1109	11:43:34	S29E66	9502	1135	1139	1218	1N
06/13/01	1135	1142	CNT + weak int. variations	C2	12:06:31	571	11:46:05	S29E66	9502	1135	1139	1218	1N
06/13/01	162944	162951	Weak FS nb	C2	17:30:05	196	16:30:34	S27E65	9502	1621	1628	1702	SF
08/27/01	165410	165411	Weak int. variations	C2	17:26:05	408	16:57:29	S20E11	9591	1653	1653	1659	SF
08/28/01	1600	1602	Weak FS Latfreq	C2	16:27:07	478	16:02:42	N13E68	9601	1601	1609	1614	SF
	160227	160356	Weak FS	C2	16:27:07	478	16:02:42	N13E68	9601	1601	1609	1614	SF
08/29/01	182230	182647	CNT rise + puls. rise–fall periodic	C2	19:04:23	317	18:27:35	N18E58	9600	1824	U1839	1929	1F
08/31/01	1529	1532	CNT + oscillations	C2	16:11:33	310	15:33:55	N13E29	9601	1529	1531	1552	SF
09/03/01	1822	1825	Weak CNT	C2	18:35:07	1352	18:26:29			1821	1841	1910	
09/05/01	115058	115059	Patch ISO tail	C2	12:31:27	282	11:50:05	No flare					
09/28/01	1402	1408	Weak int. variations	C2	14:54:05	249	14:07:14	S17W47	9628	1357	1359	1408	SF
10/19/01	1622	1706	Puls + CNT + fiber + hand-like	C2	16:50:05	901	16:37:08	N15W29	9661	1614	1636	1849	2B
10/22/01	1450	1509	Weak int. variations	C2	15:06:05	1336	14:57:21	S21E18	9672	B1425	1512	1602	2N
10/22/01	1747	1803	Puls./oscillations + nb EF	C2	18:26:06	618	18:07:13	S18E16	9672	1744	1758	1911	2B
10/25/01	1506	1531	Weak CNT slow var + weak lace-like	C2	15:26:05	1092	15:15:24	N09E26	9678	1456	1456	1519	SF
04/04/02	153534	153535	EF ISO	C2	15:54:05	790	15:39:19			1524	1532	1538	
04/13/02	1207	1233	Intermittent rise–fall	C2	12:50:06	599	12:30:37	S03E57	9907	1212	1213	1222	SF
07/19/02	1616	1620	CNT BxFr	C2	16:30:05	2047	16:24:23	No flare					
07/24/02	1543	1551	Weak interm. Puls. Nb	C2	16:06:08	528	15:44:02	S13E49	0039	1514	1545	1659	1F
			Weak interm. Puls. Nb	C2	16:06:08	414	15:37:57	S13E49	0039	1514	1545	1659	1F
10/31/02	1651	1652	CNT	C2	17:06:05	1061	16:55:05			1647	1652	1655	

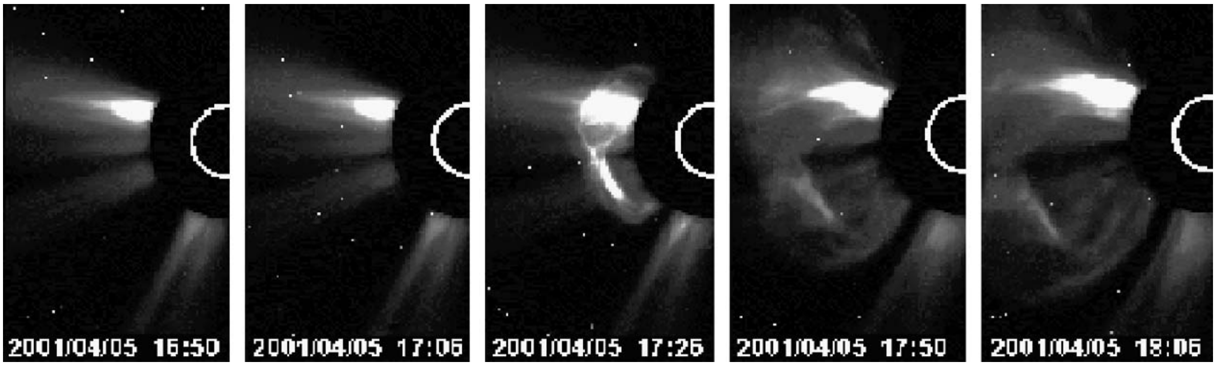

Fig. 1. Sequence of 5 images from C2 (LASCO) coronagraph showing a CME start and evolution. A CME can clearly be seen around 17:26 UT as a bright magnetic arch.

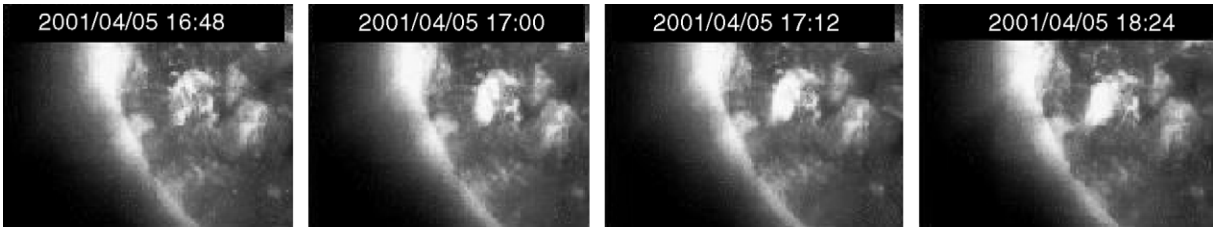

Fig. 2. Sequence of EIT (195 Å) images showing an event observed on the Sun disk (NOAA 9415, S24 E50) recorded between 17:00 and 18:24 UT on April 05, 2001.

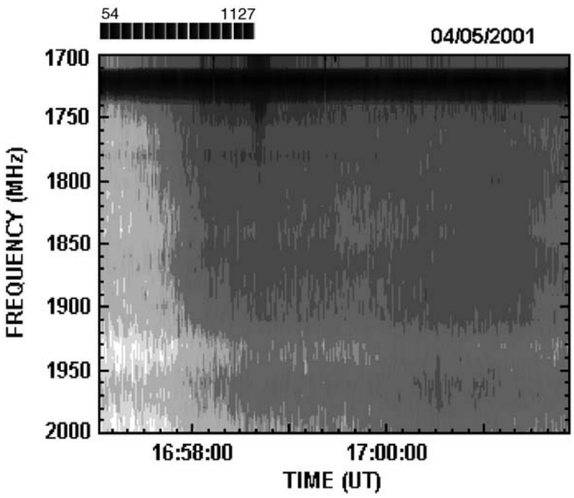

Fig. 3. Dynamic spectrum (1700–2000 MHz) recorded for the radio burst observed starting around 16:57 UT on April 05, 2001. A darker region indicates a stronger broad band continuum emission observed at the beginning of this radio burst.

Taking April 05, 2001 CME phenomenon as an example:

1. Average velocity and initial time as measured by C2 are 1390 km/s and 17:06:05 UT, respectively.
2. Time taken by the CME from the surface until it is recorded by C2 is: $\Delta t = 700{,}000\,\text{km}/1390\,\text{km/s} = 1577\,\text{s} = 8\,\text{min},\ 24\,\text{s}$.
3. Subtracting this time from the initial time measured by C2 we obtain the CME estimated starting time from near the solar surface as 16:57:41 UT. The decimetric activity showed by a broad band continuum in Fig. 3 starts around 16:57 UT. Therefore, it is associated to a CME recorded by LASCO.

3. Discussions and conclusion

A look through the sample of all 274 CME, observed between 11 and 19 UT, on the basis of an association with flare activity shows that approximately 20% of CMEs are flare related. From those, about two thirds (~13%) are also associated to decimetric (1000–2500 MHz) radio burst emission, while an additional 3% is just associated to decimetric emission. Then, most BSS bursts associated to CME phenomena are also flare associated.

It has to be pointed out that the limited frequency range (1000–2500 MHz) used in the observations does not mean radiation is absent beyond these lower, as well as higher frequency limits. Particularly, emission could be observed beyond the lower limit, which tells us that, the agent exciting it is propagating towards the higher corona. The emission could jointly be observed beyond the higher limit. Both are important contributions to improve and/or increase the statistics in favour of the CME-decimetric radio burst emission association.

In addition that small fraction of CMEs flare related, and not associated to decimetric emission, can be due to the following reason. A limited frequency range prevented us from observing decimetric emission at lower and/or higher frequencies associated either to CME phenomena or to flares. Also, the limited sensitivity ($\geqslant 3$ sfu) of BSS instrument imposes a minimum threshold on the intensity level allowed for the observations. Yet, a small (although existing) fraction of flares may not contribute to radio emission within the frequency range of observations. Finally, the presence of coronal density inhomogeneities in the path of radiation to the observer produces a selective absorption in frequency. These four factors together, and even some more, could explain the portion of observed CME flare associated which is not associated with decimetric radio burst emission within the frequency range mentioned above.

This preliminary analysis of the association between radio burst emission observed by BSS at decimetric wavelengths (1000–2500 MHz) and CME phenomena recorded by C2–C3 (LASCO) experiment permitted us to conclude that:

1. An association between CME phenomena and decimetric wavelength burst emission exists for approximately 16% of the CMEs observed between 11 and 19 UT. It has to be mentioned that the limited frequency range of observations may explain this relatively low association rate between CME and decimetric burst emission. This association takes into account $\pm$ 5 min for the CMEs estimated starting time near the solar surface. It has to be noted that the CMEs were observed in association with radio burst emission coming from active regions located $\leqslant 70^\circ$ of the solar disk centre. Then, we are dealing with an opposite case that permits us a clear identification of a limb CME against the sky. This is due to the presence of brighter structures in LASCO images, which prevents identification of CMEs against the solar disk. Also, those brighter structures minimize the contrast in most of EIT images then masking the CME emission on the disk.
2. About half of the cases showed only one type of radio emission observed in association with the CME, while either two or more types are associated with the other cases.
3. Continuum and/or pulsations either combined or not are the dominant types of decimetric radio burst emission associated with CME phenomena. While the broad band continuum associated with CMEs indicates a possible type IV radio burst, the pulsations suggest a trapping plus precipitation of particles into a magnetic loop.

Association of a significant portion of CMEs with solar activity observed in the limited (1000–2500 MHz) frequency range indicates there are special conditions in the solar atmosphere, particularly in active regions and near the energy release sites where decimetric emission originates, that can cause, as well as follow, a fraction of CMEs. Additional high spectral and spatial resolution observations with a broad band in decimetric waves are important to make a more detailed investigation of the CME–radio bursts association possible. This is important to find a clue about the origin and trigger mechanism at least for that fraction of CMEs associated to solar activity observed at radio waves. A detailed qualitative analysis of this association is in course and will appear elsewhere.

Acknowledgements

We are grateful to the Brazilian Financial Agencies CNPq, FINEP, FAPESP for financial support. We would also like to thank the SOHO team for maintaining the database and processing of LASCO and EIT data. SOHO is operated by ESA, NASA scientists whose dedication has made data available to the solar community. Our acknowledgements to the SEC team that maintains "The Weekly" report and forecast of solar geophysical data. Thanks are also given to the referees for their helpful comments on the manuscript.

References

Brueckner, G.E., et al., 1995. The large angle spectroscopic coronograph (LASCO). Solar Physics 162, 357–402.

Delaboudinière, J.P., et al., 1995. EIT: extreme-ultraviolet imaging telescope for the SOHO mission. Solar Physics 162, 291–312.

Fernandes, F.C.R., 1997. Espectrógrafo digital decimétrico de banda larga e investigações de flares solares em ondas decimétricas e raios-X, Tese de Doutorado, INPE-6396-TDI/612, São José dos Campos.

Gosling, J.T., et al., 1974. Mass ejections from the Sun: a view from Skylab. Journal of Geophysical Research 79, 4581–4587.

Kahler, S.W., 1994. Injection profiles of solar energetic particles as functions of coronal mass ejection heights. Astrophysical Journal 428, 837–842.

Munro, R.H., Gosling, J.T., Hildner, E., MacQueen, R.M., Poland, A.I., Ross, C.L., 1979. The association of coronal mass ejections transients with other forms of solar activity. Solar Physics 61, 201–215.

Sawant, H.S., et al., 2001. Brazilian solar spectroscope. Solar Physics 200, 167–176.

Sheeley Jr., N.R., Howard, R.A., Koomen, M.J., Michels, D.J., 1983. Associations between coronal mass ejections and soft X-ray events. Astrophysical Journal 272, 349–354.

St. Cyr, O.C., Webb, D.F., 1991. Activity associated with coronal mass ejections at solar minimum: SMM observations from 1984–1986. Solar Physics 136, 379–394.

Svestka, Z., 1995. Private comunication.

Tousey, R., 1973. The solar corona. In: Rycroft, M.J., Kuncorn, S.K. (Eds.), Space Research XIII. Akademie-Verlag, Berlin, pp. 713–730.

Verneta, A.I., 1997. On the problem of the relationship between solar flares and coronal mass ejections. Solar Physics 170, 357–364.

Webb, D.F., Hundhaunsen, A.J., 1987. Activity associated with the solar origin of coronal mass ejections. Solar Physics 108, 383–401.