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THE POST–CORONAL MASS EJECTION SOLAR ATMOSPHERE AND RADIO NOISE STORM ACTIVITY

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ABSTRACT

We carried out a statistical study of solar radio noise storms whose onset was in the aftermath of coronal mass ejections (CMEs) that occurred during 1997–2004, the first half of present solar cycle 23. The work is an attempt to understand the post-CME corona through observations of noise storms since the latter are considered to be closely related to structural changes there. The radio events were taken as the starting point for our study, and details about start time and location were available for 340 of them. We imposed the following conditions to verify the association between the above two phenomena: (1) the noise storm must have occurred ≤24 hr from the onset of a CME and (2) the central position angle of the CME must be located inside an angular span of $\pm 45°$ with respect to the noise storm. We found that 196/340 noise storms were associated with CMEs. More interestingly, the time interval between CME liftoff and noise storm onset in all the above cases was ≤13 hr. We suggest that this represents the upper bound of the timescale over which coronal magnetic field reorganization had taken place in the aftermath of the aforementioned 196 noise storm associated CMEs. We also found that for a particular CME, the above temporal cutoff depends on its kinetic energy. Overall, it varies inversely with the logarithm of CME kinetic energy.

Subject headings: solar-terrestrial relations — Sun: activity — Sun: corona — Sun: magnetic fields — Sun: radio radiation

1. INTRODUCTION

Noise storms are the most frequently observed solar activity at meter wavelengths. They consist of occasional short-lived (0.1–1 s) narrowband radio enhancements (type I or noise storm bursts), superposed on often observed continuous, slowly varying, long-lasting (hours–days) broadband background emission called type I or more usually as noise storm continuum (Kai et al.1985 and references therein). The early phase of noise storms is generally associated with a global brightening in soft X-rays. But the latter are not due to flare occurring anywhere on the Sun (Habbal et al. 1989; Raulin & Klein 1994). In a recent statistical study, Benz et al. (2005) found only a weak correlation (<5%) between meter wavelength noise storms and X-ray flares. Similar correlative studies with Hα flares in the past also indicate that the two phenomena are not necessarily related (le Squeren 1963; Elgarøy 1977; Böhme 1993). On the other hand, Kerdraon et al. (1983) reported that noise storms are systematically preceded, both spatially and temporally, by brightenings in the white-light coronagraph images. No conspicuous structural changes were observed once the noise storm was established. The authors postulated that addition of new material to the corona in the aftermath of a CME leads to reorganization of the local coronal magnetic field, a necessary precondition for the onset of noise storm (Benz & Wentzel 1981; Spicer et al. 1981). Similar radio observations in the post-CME period were recently reported by Willson (2005) also through high angular resolution observations with the Very Large Array (VLA). Using the same kind of radio data, Habbal et al. (1996) had earlier shown that a type I radio noise storm is limited to the site of a CME despite the existence of a number of active regions on the disk. Again there are reports of CME-induced changes in the observational characteristics of a preexisting noise storm (Kahler et al. 1994; Chertok et al. 2001). Overall, there seems to be a close relationship between the CMEs and noise storm activity in the solar atmosphere. The post-CME corona has received relatively little attention so far. So a study of newborn noise storms during such period is expected to be useful in understanding the activity there.

2. DATA AND METHODOLOGY

Observations of type I radio bursts covering almost the entire 24 hr period in a day are regularly reported by various observatories located at different longitudes around the globe. These are mainly spectral observations without any information about the event location in the solar atmosphere. The primary input required for the present work is noise storms with known position and start time. But imaging radio telescope arrays for dedicated solar observations in the meter wavelength range are sparse. Daily observations were available only for the interval 08 : 30–15 : 30 UT, during 1997–2004. Obviously, we had to begin with the radio noise storms and then look for associated events at other wavelengths. Information about the former was taken from the Solar-Geophysical Data prompt reports,[2] where events observed with the Nancay radioheliograph (NRH; Kerdraon & Delouis 1997) are published. Here again, although a large number of noise storms were reported, we considered only the 340 events whose start times were known. The CME data were taken from the list[3] generated using observations with the Large Angle and Spectroscopic Coronagraph (LASCO; Brueckner et al. 1995) on board the *Solar and Heliospheric Observatory* (*SOHO*). We adopted the following criteria to identify the liftoff time of a CME in the present case: (1) if the radial distance of the noise storm location (from the center of the solar disk) was $\leq 0.5\ R_\odot$ ($1\ R_\odot = 6.96 \times 10^5$ km = radius of the Sun), then the liftoff time obtained through the first-order fit (with y-intercept = 0) to the height-time measurements of the CME was used; (2) if not, the corresponding time given by the first-order fit with y-intercept = $1\ R_\odot$ was considered; (3) if the acceleration/deceleration of the CME exceeds ± 25 m s^{-2}, then we used the liftoff time estimated using the second-order fit.

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[2] See http://sgd.ngdc.noaa.gov/sgd/jsp/solarindex.jsp.
[3] See http://cdaw.gsfc.nasa.gov/CME_list.

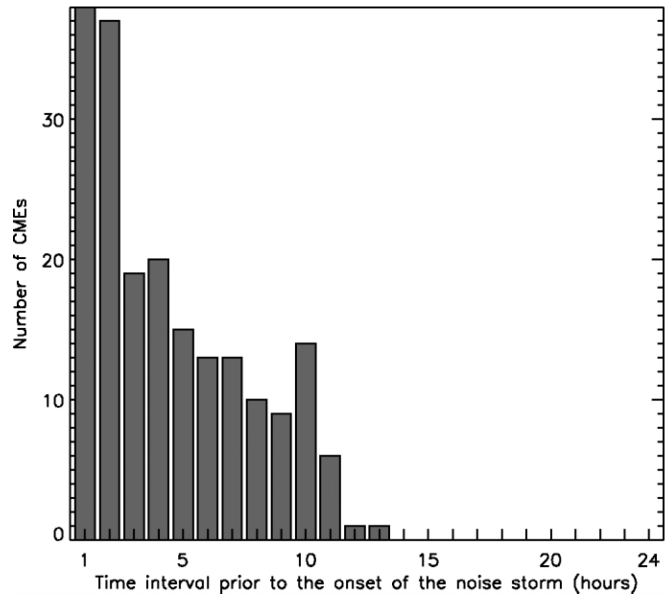

FIG. 1.—Number of CMEs whose liftoff time preceded the onset of noise storms within a time interval of ≤24 hr during the period 1997–2004. The central position angle of each CME was located within an angular span of ±45° from the position angle of the associated noise storm.

Note that only the heliographic position (in units of $R_\odot$) of noise storms are usually reported in the Solar-Geophysical Data. But for comparison with the CME location, we must know its corresponding position angle. The latter was obtained in the following manner: Consider a cartesian coordinate system with three mutually perpendicular axes x, y, and z and origin at the center of the Sun. Let x be along the Sun-Earth line; y and z represent the longitudinal and latitudinal direction on the Sun. Then the position angle is

$$\text{P.A.} = \begin{cases} 0^\circ + \tan^{-1}(y/z), & \text{if } y \text{ is} < 0 \text{ and } z \text{ is } \geq 0, \\ 90^\circ + \tan^{-1}(z/y), & \text{if } y \text{ is} < 0 \text{ and } z \text{ is } < 0, \\ 180^\circ + \tan^{-1}(y/z), & \text{if } y \text{ is} \geq 0 \text{ and } z \text{ is } < 0, \\ 270^\circ + \tan^{-1}(z/y), & \text{if } y \text{ is} \geq 0 \text{ and } z \text{ is } \geq 0. \end{cases}$$

3. RESULTS AND DISCUSSIONS

CMEs are believed to be large-scale eruptions of closed magnetic fields that occur on dynamical timescales of tens of minutes to hours. In view of the close association between radio noise storms and magnetic field changes in the solar corona (Brueckner 1983; Stewart et al. 1986; Willson et al. 1998; Bentley et al. 2000), we verified the number of CMEs that preceded the 340 noise storms in the present case, over a period of ≤24 hr. In doing this, we selected only those CME events with central position angle located inside an angular span of ±45° with respect to the noise storm. We introduced the latter condition because (1) the average width of CMEs observed during the period under study was in the range 47°–61° (Yashiro et al. 2004); (2) CMEs are generally accompanied by a reconfiguration of the magnetic field over extensive regions of the solar atmosphere which in many cases exceeds the CME size (Fainshtein et al. 1998; Chertok et al. 2001); (3) activity occurring in association with magnetic field changes in the solar atmosphere can be noticed even at an angular distance of ∼30° away (Bruzek 1952; Kahler & Hundhausen 1992; Feynman & Martin 1995; Wang & Sheeley 1999); (4)

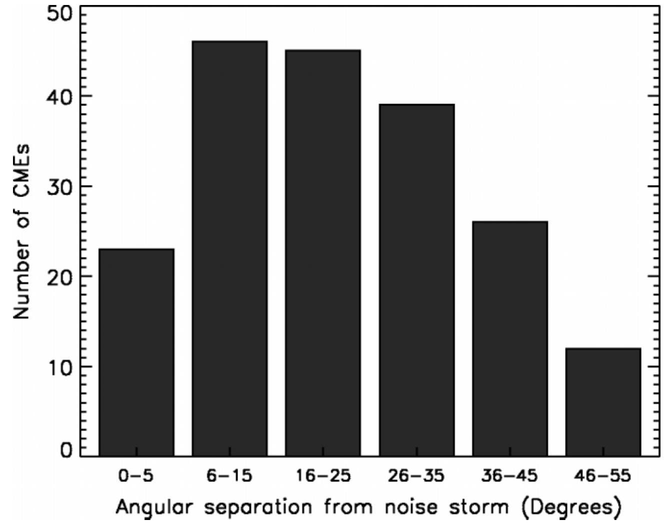

FIG. 2.—Position difference between noise storms and CMEs (leading edge) in Fig. 1.

the location of a radio noise storm can be close to the footpoint of a CME (Lantos et al. 1981; Willson 2005).

Figure 1 shows the result of our work. Of 340 noise storms considered, 196 events satisfied the criteria that we had set. More interestingly, the time interval between CME liftoff and noise storm onset in all the associated cases was ≤13 hr. We also found that the mean angular separation between the noise storm position angle and CME leading edge was ≈25° (Fig. 2). The sky-plane speed of the above CMEs was in the range 100–800 km s^{-1}, with peak around 350 km s^{-1} (Fig. 3). Their width distribution indicate that a vast majority of them have angular extent <120° (Fig. 4). We suggest that the above temporal bound in statistics at 13 hr is probably the upper limit of the timescale over which coronal plasma-magnetic field restructuring had occurred in the aftermath of the 196 noise storm associated CMEs in our study. An absence of CME association for a majority of the remaining 144 noise storms could be due to (1) weak/faint CMEs that are difficult to detect (Robbrecht & Berghmans 2004), (2) our condition regarding the location of noise storm with respect to CME, and (3) gaps in the LASCO data set. Some of them could also be due to (4) surges, as proposed by Garczynska et al. (1982), (5) coronal changes that result from emergence of new magnetic flux at the photospheric level (Brueckner 1983; Stewart et al. 1986), and (6) displacement of photospheric parasitic polarities (moving magnetic features) without significant flux emergence (Bentley et al. 2000).

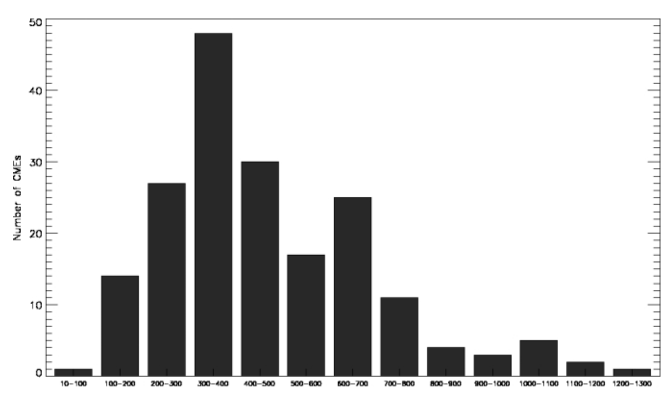

FIG. 3.—Speed distribution of CMEs in Fig. 1.

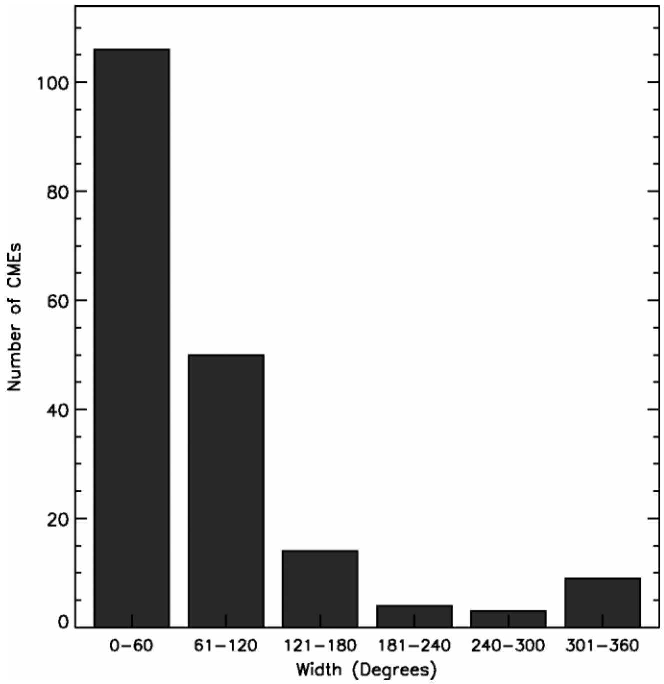

FIG. 4.—Same as Fig. 3, but for the width distribution of CMEs in Fig. 1.

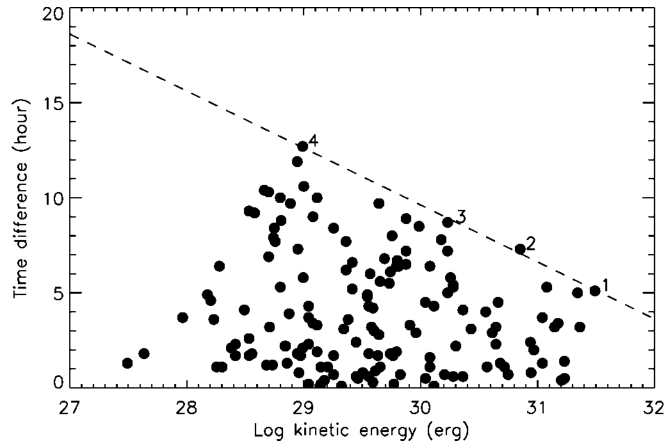

FIG. 5.—Variation of the CME-noise storm onset time difference with kinetic energy of the CME. The straight line (obtained using points numbered 1, 2, 3, and 4) indicates the cutoff in the above time interval for different values of CME kinetic energy.

The evolution of a CME in the solar atmosphere is considered to depend on its kinematics. To verify the above, we plotted the CME-noise storm onset time difference against kinetic energy of the associated CMEs (see Fig. 5). It appears that the upper limit/cutoff (~13 hr) in the time interval varies with CME kinetic energy. To quantify this, we generated a straight line using maximum values of the aforementioned time difference (for different values of CME kinetic energy) and with the following conditions: (1) all data points in the distribution should lie below the line and (2) it should pass through as many maxima points as possible. The dotted line in Figure 5 is the best fit and is given by $t_{\rm diff} = -2.99 \log {\rm KE}_{\rm CME} + 99.5$, where KE is the kinetic energy. One can infer that the CME-noise storm onset time difference varies inversely with the logarithm of the CME kinetic energy. The scatter in the time interval (for a particular value of CME kinetic energy) below the cutoff could be due to differences in either the angular extent or speed of the corresponding set of CMEs. On extrapolation, we found that the aforementioned cutoff is ≈4 and 19 hr for CMEs with kinetic energy $\sim 10^{32}$ and 10^{27} ergs, respectively. The above limiting values are consistent with the results of Hansen et al. (1974); Hiei et al. (1993) on timescales of coronal activity in the aftermath of a CME. The authors had reported white-light observations of coronal helmet streamer reformation that occurred over a period of ~ 5 and 18 hr, respectively, at the CME location. This indicates that structural changes in the post-CME corona and subsequent noise storm activity are related to energetics of the associated CME. Similar (albeit radio) observations of post-CME coronal activity at 34.5 MHz were published by Ramesh & Sastry (2000). A CME of kinetic energy $\sim 10^{29}$ ergs resulted in transient coronal material depletion that lasted for <24 hr. The exact lifetime of the radio event was not known due to nonavailability of continuous radio data. The above empirical relation derived in the present case indicates that the coronal magnetic field restructuring in the aftermath of the above CME must have occurred within ≈13 hr.

We would like to add here that observations of Hα/*Geostationary Operational Environmental Satellite* X-ray flares were reported in the above 13 hr time interval between the CME liftoff and noise storm onset, in the present case. But noise storms are evidence of successive and continued electron acceleration. The flares usually lead to transient acceleration resulting in other forms of nonthermal radio bursts (Dulk 1985). So we rule out flare–noise storm scenario in the present case. The existing observational results mentioned in § 1 also indicate the same. Again, the flares themselves may be due to magnetic field changes in the aftermath of a CME (Harrison et al. 1990; Kahler 1992; Gosling 1993; Hundhausen 1993; Fainshtein et al. 1998).

4. CONCLUSIONS

We performed a statistical study of solar radio noise storms whose onset was in the aftermath of CMEs reported during the period 1997–2004. Details about start time and location were available for 340 radio events during the above period. To verify the association between the above two phenomena, we had imposed conditions that the noise storm must have occurred ≤24 hr from the onset of a CME. And the CME central position angle must be located inside an angular span of $\pm 45°$ with respect to the noise storm. Our main results are (1) 196/340 noise storms considered were associated with a CME; (2) the mean separation between the position angle of noise storm and CME leading edge was ≈25°; (3) the sky-plane speed of CMEs was in the range 100–800 km s^{-1}, with peak around 350 km s^{-1}; (4) the angular extent of a vast majority of the CMEs was <120°; (5) depending on the kinetic energy of the preceding CME, each one of the 196 radio events occurred within a specific time interval from the CME onset. Overall, the onset of all the noise storms was ≤13 hr from the CME liftoff time; (6) the above cutoff for a particular CME depends on its kinetic energy and varies inversely with the logarithm of the latter. The corresponding numbers are ≈4 and 19 hr for CMEs with kinetic energy $\sim 10^{32}$ and 10^{27} ergs, respectively.

Finally, we would like to note that there could be changes in the coronal magnetic field configuration in the absence of CMEs also. Some of these lead to the onset of radio noise storms as pointed out in the previous section. But the present study relates mainly to the post-CME corona and the noise storms that occur there.

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