Coronal Mass Ejections and Type II Radio Bursts

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Abstract The simultaneous availability of white light data on CMEs from the Solar and Heliospheric Observatory (SOHO) and radio data on shock waves from the Radio and Plasma Wave experiment on board the Wind spacecraft over the past decade have helped in making rapid progress in understanding the CME-driven shocks. I review some recent developments in the type II - CME relationship, focusing on the properties of CMEs as shock drivers and those of the medium supporting shock propagation. I also discuss the solar cycle variation of the type II bursts in comparison with other eruptive phenomena such as CMEs, flares, large solar energetic particle events, and shocks detected in situ. The hierarchical relationship found between the CME kinetic energy and wavelength range of type II radio bursts, non-existence of CMEless type II bursts, and the explanation of type II burst properties in terms of shock propagation with a realistic profile of the fast mode speed suggest that the underlying shocks are driven by CMEs, irrespective of the wavelength domain. Such a unified approach provides an elegant understanding of the entire type II phenomenon (coronal and interplanetary). The blast wave scenario remains an alternative hypothesis for type II bursts only over a small spatial domain (within one solar radius above the solar surface) that is not accessible to in situ observation. Therefore the existence of blast waves cannot be directly confirmed. CMEs, on the other hand, can be remote sensed from this domain.

1. INTRODUCTION

Since their initial discovery by Payne-Scott et al. (1947) and subsequent classification by Wild and McCready (1950), the type II solar radio bursts in the corona have been studied for more than half a century (Kundu 1965; Zheleznyakov, 1969; Nelson and Melrose, 1985; Aurass, 1997; Cane, 2000; Gopalswamy, 2000; Reiner, 2000). The type II bursts are thought to be produced by electrons accelerated at MHD shock fronts by complex plasma processes (e.g., Uchida, 1960). In the interplanetary (IP) medium, these bursts were first detected by Malitson et al (1973) using data from the IMP 6 mission. The IP shocks first detected by space missions were soon linked to coronal shocks inferred from metric type II bursts (Pinter, 1973). Voyager (Boischot et al., 1980) and ISEE-3 (Cane et al., 1982) spacecraft also observed IP type II bursts. Payne-Scott et al. (1947) clearly alluded to the relationship of the radio source to mass ejections. Soon after the discovery of white-light coronal mass ejections (CMEs) by the OSO-7 satellite, Stewart et al. (1974 a,b) suggested that the metric type II bursts were due to CME-driven shocks. Despite the counter example reported by Kosugi et al. (1976) in which the CME and type II burst were temporally far apart to have a causal relationship, other observations pointed to a close CME-shock relationship: the above–average speed of CMEs associated with type II bursts [Gosling et al., 1976; Robinson, 1985] and the near one-to-one correspondence between limb type II bursts and CMEs [Munro et al. 1979]. The arguments against a close CME-type II relationship include: 1. The large number of CME-less metric type II bursts (Sheeley et al. 1984; and Kahler et al. 1984) require a non-CME shock source (flare blast waves). 2. The projected heights of the type II sources were smaller than the corresponding CME leading edges, an observation thought to be inconsistent with the CME source (Wagner and MacQueen 1983; Gary et al. 1984; Cane 1984; Robinson and Stewart 1985; Gopalswamy and Kundu 1992). 3. The disparity in speeds and directions of propagation of the CMEs and the associated shocks (Gergely, 1984) does not seem to support CME-driven mechanism.

The above controversy is mostly centered on metric type II bursts, which occur over a height range of ~1 Rs (solar radius) above the solar surface. IP type II bursts at frequencies below 2 MHz (occurring at heliocentric distances ≥10 Rs) were clearly CME-associated. Observations were seldom made in the 2-20 MHz range, which contributed to the independent treatment of metric and IP type II bursts. When the WAVES experiment (Bougeret et al., 1995) on board Wind began observing type II bursts in the 1-14 MHz frequency range (see, e.g., Kaiser et al., 1997; Reiner et al., 1998a; Gopalswamy et al., 2000b) the situation changed. The wavelength range corresponding to 1-14 MHz is decameter-hectometric or DH, for short. Simultaneous availability of coronagraph data from the Solar and Heliospheric Observatory (SOHO) mission, whose field of view (2-32 Rs) overlapped with the coronal/IP domain containing the 1-14 MHz plasma levels, enabled studies on the connection between CMEs and type II bursts. The DH type II bursts were also closely linked to CMEs that are faster and wider on the average (Gopalswamy et al., 2001b). Wind/WAVES also has frequency coverage below 1 MHz down to 20 kHz, which, when combined with ground based observations, made it possible to study type II bursts over the entire Sun-Earth distance.

Studying a set of metric type II bursts without IP counterparts and another set of IP shocks detected in situ without metric type II bursts over the same time interval, Gopalswamy et al. (1998) concluded that the shocks inferred from metric type II bursts and the IP shocks were of different origin. The implication was that the metric type II bursts were of flare origin and the IP shocks were of CME origin. None of the metric type II bursts studied by Gopalswamy et al. (1998) had counterparts in the WAVES spectral domain (below 14 MHz). When type II bursts started appearing at DH wavelengths, it was found that some type II bursts continued beyond the outer corona into the IP medium (see Fig. 7 of Gopalswamy, 2000). However, the discordance between the drift rates of metric and IP type II bursts continued to be present supporting the requirement for blast waves and CME-driven shocks present the same eruptive event (Cane, 2000; Reiner et al. 2001). In the meanwhile, the existence of CMEless type II bursts was brought into question. The CMEless type II bursts may be an artifact stemming from the nature of the CME visibility function, which favored limb CMEs (Cliver et al. 1999). Gopalswamy et al. (2001a) found that the CMEless type II bursts were indeed associated with EUV eruptions originating from close to the disk center (see also Classen and Aurass, 2002). Another development was the use of a realistic profile of the characteristic speed in the corona (Krogulec et al., 1994) for interpreting type II burst spectra (Mann et al., 1999; Gopalswamy et al., 2001a), which can account for the drift rate discrepancy in terms of CME-driven shocks. Finally, the close relationship between CME kinetic energy and the wavelength range of type II bursts provides a unified view of the type II bursts as a CME-related phenomenon.

This chapter provides a global view of the type II radio bursts and their physical connection to CME-driven shocks, irrespective of the wavelength domain of occurrence. One of the results highlighted in this paper is that the type II phenomenon can be explained by CME-driven shocks without resorting to the blast waves, thought to originate from the sites of associated flares. After a brief introduction to CMEs (section 2) and type II bursts (section 3), their interconnection is discussed and shown that the CME kinetic energy organizes the wavelength range of type II bursts (section 4). The solar cycle variation of type II bursts, CMEs, flares and solar energetic particles are presented in sections 5 and 6. A unified approach to the type II phenomenon, as dictated by the CME kinetic energy and the radial profile of the characteristic speed in the corona and IP medium, is presented in section 7. Finally the flare-type II relationship is discussed in the context of the unified approach (section 8) before providing the concluding remarks (section 9).

2. CORONAL MASS EJECTIONS

CMEs are large-scale magnetized plasma structures erupting from closed field regions such as active regions, filament regions, active region complexes and trans-equatorial interconnecting regions on the Sun (Tousey, 1973). Pre-eruption evolution of the closed field regions involving flux emergence, shearing motion or flux cancellation is thought to store free energy in magnetic fields. Release of this free energy often results in CMEs. Within the coronagraphic field of view, CMEs have speeds ranging from a few km/s to more than 2500 km/s (see e.g., Gopalswamy, 2004b and references therein), with an average value of ~450 km/s, which is slightly higher than the slow solar wind speed. The apparent angular width of CMEs ranges from a few degrees to more than 120 degrees, with an average value of ~47 deg (counting only CMEs with width less than 120 deg). The width of CMEs occurring close to the limb is likely to be the true width, whereas the width of CMEs occurring close to the disk center are severely affected by projection effects (Gopalswamy et al., 2000b: Burkepile et al., 2004). The total mass ejected ranges from a few times 10^{13} g to more than 10^{16} g with an average value of ~6.7×10^{14} g (Vourlidas et al., 2002; Gopalswamy, 2004b). Accordingly, the kinetic energy of CMEs with angular width <120^o ranges from ~10^{27} erg to ~10^{32} erg, with an average value of 5×10^{29} erg (see e.g. Hundhausen, 1997; Vourlidas et al. 2002). Some very fast and wide CMEs can have kinetic energies exceeding 10^{33} erg, generally originating from large active regions [Gopalswamy et al., 2005a].

CMEs occurring close to the disk center often appear to surround the occulting disk of the coronagraph and are known as halo CMEs (Howard et al. 1982). Only ~3% of CMEs are observed as halo CMEs, which are faster (~1000 km/s) on the average (Gopalswamy, 2004b). When front-sided, these CMEs can directly impact Earth causing geomagnetic storms, provided the magnetic field contained in the CMEs have a southward component. Such CMEs are known to be geoeffective. If the speed of the CMEs exceeds the local Alfven speed in the corona and interplanetary (IP) medium they can drive shocks, which can accelerate electrons and ions, generally known as solar energetic particles (SEPs). Such CMEs are sometimes referred to be SEPeffective. Accelerated electrons are inferred from the radio emission they produce, while the ions are detected after they propagate to particle detectors suitably located. The type II radio emission produced by CME-driven shocks is the primary subject matter of this chapter.

3. TYPE II RADIO BURSTS

Type II bursts are nonthermal radio emission originating from fast mode MHD shocks. The current paradigm for the generation of type II bursts is as follows: The shocks accelerate nonthermal electrons, which in turn produce radio emission at the fundamental and harmonic of the local plasma frequency via well-known plasma processes. In the dynamic spectra (intensity of radio emission displayed in the frequency-time plane) type II bursts appear as slanted features with the slope related to the speed of the shock and the density scale height in the medium. The spectral feature typically contains fundamental-harmonic components because radio emission occurs at the plasma frequency (fp) and its harmonic (2fp). Occasionally, emission is observed at the third harmonic (3fp) (Zlotnik et al. 1998). The components can be further split into upper and lower bands, thought to be caused by the density structure in the shock (see e.g., Nelson and Melrose, 1985; Vrsnak et al. 2001). Type II bursts occur at frequencies below ~150 MHz, although occasionally they are observed at higher frequencies (Vrsnak et al., 1995; Klein et al., 1999).

The high-frequency end of type II bursts corresponds to the radio emission close to the Sun, while the low frequency end corresponds to a location far away from the Sun where the radio intensity drops below the background. Type II bursts have been observed up to Earth orbit and beyond to a few AU.

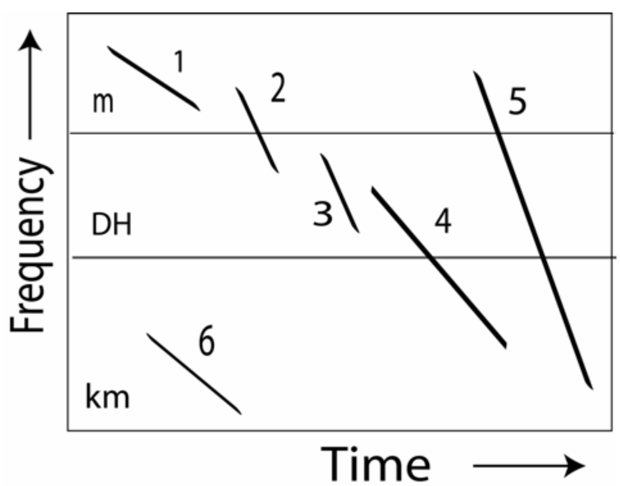

Figure 1. Schematic dynamic spectrum showing the commonly observed varieties of type II bursts confined to various wavelength ranges: metric (m), decameter-hectometric (DH), and kilometric (km). m type II bursts are generally observed by

ground based radio telescopes; DH and km bursts need to be observed from space because of the ionospheric cutoff between DH and m domains.

3.1. Type II Burst Varieties

The appearance of type II bursts in various wavelength domains is shown in Fig. 1: 1) bursts confined to the metric (m) domain; 2) bursts starting in the m domain but continuing into the DH domain; 3) bursts confined to the DH domain; 4) bursts starting in the DH domain and continuing into the kilometric (km) domain; 5) bursts having counterparts in all the wavelength domains, m-to-km; 6) bursts confined to the km domain. In the schematic picture, we have not shown the details of harmonic structure or band-splitting, which may or may not be present in all the events. In (6), the components in various spectral domains may and may not have direct continuity. The m variety (1) occurs typically above the ionospheric cutoff at ~20 MHz, observed from ground based radio telescopes. Radio emission from the Sun at longer decametric and km wavelengths cannot penetrate the terrestrial ionosphere, so spaceborne instruments observe varieties 2-6. Coronal densities similar to the ionospheric densities occur at a heliocentric distance of ~3 Rs, which is also considered to be the location of the source surface of the solar magnetic field. The ambient medium beyond the source surface is considered to be the IP space. Thus, the bursts at frequencies above the ionospheric cutoff are known as coronal (or m) type IIs, while the ones occurring at frequencies below the cutoff are known as the IP (or DH, km) type II bursts (Gopalswamy, 2004c). Occasionally, one can observe population 2 (m-to-DH) bursts using ground based instruments at geographical locations where the ionospheric cutoff is well below the nominal 20 MHz (Erickson 1997). One has to combine ground and space based observations to see the continuation from the m-domain to DH and km domains.

3.2. Type II Drift Rates

One of the recent findings is the universal relationship between the drift rate of type II bursts and the frequency of emission (Vrsnak et al. 2001; Aguilar-Rodriguez et al. 2005): on a log-log scale, the measured drift rate (df/dt) has an excellent correlation with the emission frequency (f) with a correlation coefficient of >0.9. Fig. 2 shows plots of df/dt versus f for two sets of events: (1) type II bursts observed by Wind/WAVES and ISEE-3 (Lengyel-Frey and Stone, 1989) in various spectral domains, and (2) a set of m-to-km events from Gopalswamy et al. (2005b) for which measurement of drift rate was possible in the DH and km domains. The two sets were combined with metric type II data from Mann et al. (1996). Ideally one should have used the metric type II burst data in the same epoch as the DH and km type II bursts. Nevertheless, the trend is very clear that at higher frequencies the bursts have larger drift rates and the relation holds over six orders of magnitude in drift rate and three orders of magnitude in frequency. Thus one gets a power law relationship: $df/dt \sim f^{\alpha}$ where $\alpha \sim 2$. Taken alone, the km type II bursts show a slightly steeper slope. In fact, Aguilar-Rodriguez et al. (2005) found an increase in the power law index from $\alpha \sim 1.4$ in the m domain to $\alpha \sim 2.3$ in the km domain. This variation is most likely due to changing shock speed. The close relationship between df/dt and f can be understood from the fact that the shock travels with a speed V emitting at successively lower frequencies determined by the local plasma density (n), which decreases with heliocentric distance (r) as r^{-2}: $|df/dt| = V(df/dr)=V(f/2n)(dn/dr)= Vf^2$. Here it is assumed that the emission occurs at the fundamental plasma frequency ($f \sim n^{1/2}$). This simple relationship is remarkably similar to the observed one, provided V is approximately constant and the range of speeds is not too wide. This is not a bad assumption in individual domains, but we do know that CMEs and shocks decrease in speed between the Sun and 1 AU (Gopalswamy et al. 2000a) because of the drag force of the ambient medium acting on the CMEs (Gopalswamy et al. 2001b;Vrsnak, 2001). Also V can increase or decrease in individual domains. For example, close to the Sun (m domain) most CMEs are likely to be accelerating, while decelerating in the IP medium. For purely km type IIs, the

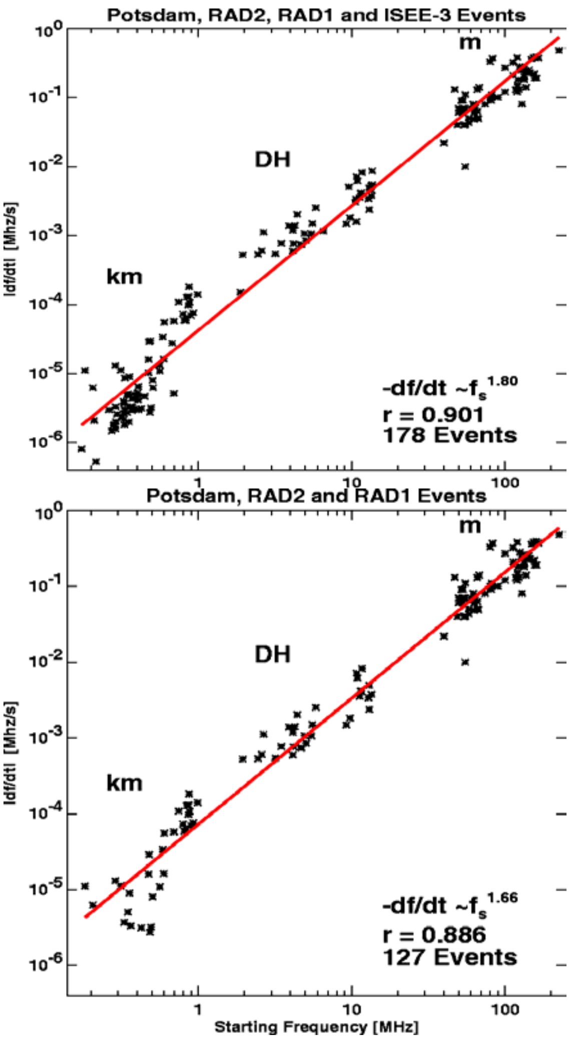

Figure 2. The drift rate and emission frequency of type II bursts. (top) m, DH, and km measurements are combined from various sources (ground based, WAVES, and ISEE-3). The data points in the km and DH domains may or may not correspond to the same burst. (bottom) WAVES type IIs with measurements in both in DH and km domains combined with m type IIs. The top and bottom plots use the same metric data from Mann et al. (1996).

CMEs may be accelerating far into the IP medium (Gopalswamy 2004a). In order to fully understand the df/dt – f relationship, one also needs to consider the variation of the solar wind speed. Additional considerations include the deviation from the r^{-2} dependence for density in the inner corona (m domain). One of the important implications of this universal relationship is that the m type II bursts behave very similar to the DH and km type II bursts.

4. CME AND TYPE II BURST HIERARCHY

The likelihood of an interplanetary type II burst following a metric type II was found to be greatly increased if accompanied by strong, long-lasting H-alpha and soft X-ray flares (Robinson et al., 1984). Such flares are known to be indicative of energetic CMEs. CMEs associated with DH type II bursts were generally faster and wider than those associated with metric type II bursts (Gopalswamy et al., 2000b; Lara et al. 2003). Furthermore, m type IIs followed by IP events (shocks and/or IP CMEs) were always accompanied by halo or partial halo CMEs (Gopalswamy et al. 2001a), which are generally more energetic than other CMEs (Gopalswamy, 2004a). IP type II bursts below 1 MHz were known to be associated with energetic CMEs (Cane et al., 1987), but it is not clear whether they belong to variety 4, 5 or 6 in Fig. 1. The trend of more energetic CMEs resulting in longer wavelength type II bursts was revealed in a systematic study involving: i) m type IIs with no counterparts in the DH or km domains (same as variety 1 in Fig. 1), ii) DH type IIs, irrespective of the presence of counterparts in the metric and km domains (varieties 2-5), iii) m-to-km type IIs (variety 5), and iv) purely km type IIs (variety 6. The purely m type II bursts were chosen such that the associated source regions were within 30 deg. of either limb (hence referred to as m-limb events). When the CME properties of these populations were compiled and compared, a systematic relationship was found (Gopalswamy et al., 2005b): the CME speed, width, deceleration and the fraction of full halos (apparent width = 360 deg.) increased in the following order: m, DH, m-to-km (see Table 1). Since the width is proportional to the mass, faster and wider CMEs are more energetic. Thus, CMEs associated with m type IIs (population i) are the least energetic, while those associated with the m-to-km type IIs (population iii) are the most energetic. CMEs associated with DH type IIs (population ii) are of intermediate kinetic energy. Table 1 shows that the CMEs associated with purely km type IIs do not quite fit into this hierarchy: while the CME speed and width are similar those of m type II bursts, the acceleration is of opposite sign (positive). These CMEs accelerate gradually and attain shock-driving capability only far into the IP medium when the speed becomes high enough to be super-Alfvenic (Gopalswamy, 2004b). The fraction of halo CMEs is also much larger than that of the m type II bursts (17.2% vs. 3.8%). The purely km population also explains the presence of IP shocks without metric type II bursts, as found in Gopalswamy et al. (1998). Table 1 also shows that all the CME populations associated with type II bursts are more energetic than the general population.

Property	All	m	DH	mkm	km
Speed (km/s)	487	610	1115	1490	539
Width (deg)	45	96	139	171	80
Halos (%)	3.3	3.8	45.2	71.4	17.2
Acceleration (m/s^2)	-2	-3	-7	-11	+3

Table 1. CME-type II burst hierarchical relationship compiled from Gopalswamy (2005b). Column 1 includes all the CMEs observed by SOHO from 1996 to the end of 2004. Other columns list properties of CMEs associated with type II bursts in various wavelength domains.

The link between CME kinetic energy and the wavelength extent of type II bursts has an important practical implication: it is possible to isolate the small number of energetic CMEs that are geoeffective and SEP-effective based on the observation of m-to-km type II bursts.

4.1. CME Height and metric type II onset

The starting frequency of type II bursts indicates the distance from the eruption center at which the shock begins to accelerate electrons. The frequency of emission is proportional to the square-root of the electron density in the vicinity of the shock, so higher starting frequencies imply shock formation closer to the Sun. The starting frequency of type II bursts rarely exceeds ~150 MHz, although higher starting frequencies have been reported occasionally (Vrsnak et al. 1995). Considering a set of 80 purely m-limb type II bursts with known emission mode (fundamental or harmonic), the average starting frequency was found to be 101 MHz [Gopalswamy et al., 2005b]. The starting frequency of metric type II bursts with interplanetary counterparts was quite similar, if not higher (111 MHz). Robinson et al. [1984] who used a sample of only 16 metric type II bursts with IP counterparts and found that ~78% of them had starting frequencies < 45 MHz, compared to ~20% for all type II bursts. From this they concluded that MHD shocks which formed higher in the corona were more likely to produce IP type II bursts. We could not reproduce this result because the fraction of metric type II bursts with low starting frequencies (below 50 MHz) is rather small: ~33% for purely metric type IIs and ~17% for the m-to-km events. Their alternative suggestion that blast waves becoming shocks at large heights in the corona can escape into the IP medium is also not supported by the recent results.

Considering only limb events (to avoid projection effects) the CME leading edge was found to be at a heliocentric distance of ~2.2 Rs at the onset of purely metric type II bursts and virtually the same distance (2.3 Rs) for the m-to-km events (Gopalswamy et al. 2005b). The similarity in CME leading edge heights (which always refer to the Sun center unless otherwise stated) of the m-to-km and purely metric populations reflects the similarity in starting frequencies of the two populations. In other words, type II bursts form roughly at the same heights irrespective of whether or not an IP type II burst follows. Robinson et al. (1984) had estimated that the shocks responsible for metric type II bursts form in the height range of 1.6 – 2 Rs, which is not too different from (but slightly less than) the heights of CME leading edges obtained by Gopalswamy et al. (2005b). This remarkable similarity between the type II burst heights and the leading edges of CMEs associated with type II bursts indicate that the type II bursts are physically related to CMEs. The slightly smaller heights of type II bursts indicate that they may be originating from the flanks of the CME-driven shocks. A more important point is that a CME present in the corona at the time of metric type II burst as a possible shock driver.

5. SOLAR CYCLE VARIATION

Solar-cycle variation of m and DH type II burst rates binned by Carrington Rotations (CRs) is shown in Plate 1 for the period from 1996 to the end of 2004. The number of CMEs and flares per CR (divided by 10 and 20, respectively to fit the scale) are also given for comparison. Only C, M, and X-class GOES flares have been included. There is a clear increase in the number of type II bursts from the solar minimum to maximum like any other indicator of solar activity. In particular, the number of metric type II bursts tracks the CME rate. The number of DH type II bursts also has a minimum-to-maximum variation, but the dependence on CME rate is less pronounced. This is because the DH type II bursts are associated with more energetic CMEs. Plate 1 also demonstrates that the type II bursts are a relatively rare phenomenon. Only 850 of the 9000+ CMEs (<10%) detected by SOHO between 1996 and 2004 were associated with m type II bursts. The fraction of CMEs associated with DH (2.5%) and m-to-km (0.8%) is much smaller. Cumulative distribution of CMEs as a function of speed (Gopalswamy, 2006) is consistent with these association rates because the number of CMEs fall rapidly at higher speeds needed for type II association (see also Table 1). On the other hand, the number of flares per CR (counting only C-, M-, and X-class flares) is higher by a factor of ~20 than the m type II burst rate.

Periods with large number of metric type II bursts with virtually no DH type II bursts have been reported (Gopalswamy et al. 2004b) when the mean CME speeds are lower. The overall number of m type II bursts is also typically 4 times that of DH type II bursts. For both m and DH type II bursts, the first requirement is the presence of a CME (Gopalswamy et al. 2005b). Then comes the speed, because the average speed of CMEs associated with DH type II bursts is almost twice the average speed of CMEs associated with m type II bursts. It was shown by Gopalswamy et al. (2003a) that the peaks in DH type II rate coincided with the peaks in the mean speed of CMEs.

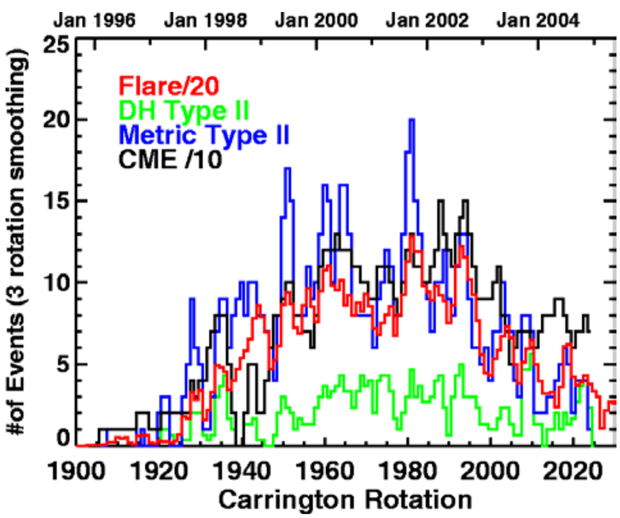

Plate 1. Solar cycle variation of m and DH type II bursts compared with the CME and flare rates (counting flares at and above C-class). All quantities are averaged over Carrington rotation (CR) periods. The plots have been made by smoothing over 3 rotations. The CME and flare rates are divided by 10 and 20, respectively to fit the scale. The UT scale is given at the top.

Figure 3 shows the correlation between m and DH type II bursts with the CME occurrence rate and mean speed. As we noted before, the number of m type II bursts has the best correlation with the CME rate (r=0.67). The type II occurrence rate is also reasonably correlated with the CME mean speed (r=0.50). Note that there are no type II bursts when the CME mean speed is less than 200 km/s (see

Figs.3a,b), which is close to the characteristic speed of the inner corona. If the type II bursts are not closely connected to CMEs, one would not obtain such a speed relationship.

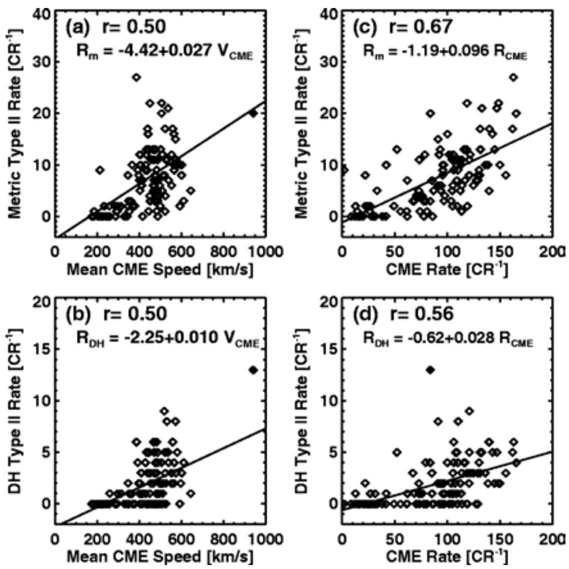

Figure 3. Correlation between the occurrence rates of m (R_m) and DH (R_{DH}) type II bursts with CME mean speed (V_{CME}, left) and CME occurrence rate (R_{CME}, right). All numbers are averaged over Carrington rotations (CRs). The correlation coefficients and the equations of the regression lines are noted on the plots.

6. TYPE II BURSTS AND SOLAR ENERGETIC PARTICLES

The close connection between metric type II bursts and solar energetic particles was recognized as early as 1971 by Dodson and Hedemen, who noted that “a type II burst was the only unusual aspect of a flare apparently associated with a proton enhancement” [quoted by Svestka and Fritzova-Svestkova, (1974)]. Kahler et al. (1978) found that “a mass-ejection event is a necessary condition for the occurrence of a prompt proton event”, suggesting a physical link between CME-driven shocks and particle acceleration. The starting time of a metric type II burst marks the time when a shock is present nearest to the Sun (≤2.2 Rs). At the time of SEP release near the Sun, the CME is at a height of ~2.7 Rs (Kahler 1994; Kahler et al. 2003). For SEP events with ground level enhancements (GLEs), the corresponding CME height is somewhat larger (4.5 Rs, Gopalswamy et al. 2005d). The DH type II bursts originate in the same height range as the estimated release heights of SEPs, and it is not surprising that there is a 100% association between SEP events and DH type II bursts (Gopalswamy, 2003; Cliver et al., 2004b). Type II bursts at frequencies below 2 MHz were also found to be associated with large SEP events (Cane and Stone, 1984). Combining all these, one can

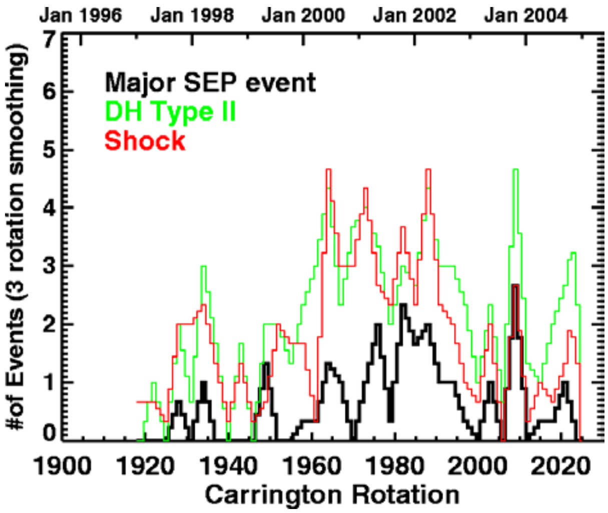

Plate 2. The occurrence rates of IP shocks, DH type II bursts and major SEP events. The major SEP events are defined as those which produce a 10-pfu proton event at Earth in the >10 MeV channel. Note that all the three events are closely related.

conclude that the same shock accelerates electrons to produce type II bursts, and ions detected in situ. The relative variation of IP shocks, large SEP events, and IP type II bursts is illustrated in Plate 2. The shocks were detected in situ by spacecraft in the solar wind. The large SEP events (events with proton intensity >10 pfu in the >10 MeV channel) were recorded by the GOES satellite. The occurrence rates of these events (binned over Carrington Rotations) are close to each other. The small differences can be attributed to the differing observability functions. For example, the SEP events are generally smaller in number because they are observed only when the SEP source is well-connected to the observer. The DH type II bursts are slightly larger in number because even backside eruptions can produce them, whereas the shocks from these eruptions may not arrive at Earth. The rate is also similar for fast and wide CMEs from the front-side western hemisphere of the Sun (Gopalswamy et al., 2003b). This is also expected because the shocks DH type II bursts, and SEPs are associated with fast and wide CMEs. One of the important practical implications is that the DH type II bursts (promptly detected compared to SEPs and in situ shocks) can clearly isolate the small number of SEP-effective CMEs. As we noted above, it may not be possible to tell whether the associated shock will propagate far into the IP medium from the observation of metric type II burst alone. If the metric type II burst is associated with a fast and wide CME, then it is likely that a DH type II and an SEP event (if the CME is western) will follow.

6.1. CME Interaction and SEPs

Interaction between CMEs near the Sun was first identified from a long wavelength radio enhancement in the Wind/WAVES dynamic spectra (Gopalswamy et al., 2001c) in association with two colliding CMEs within the field of view of SOHO/LASCO. Some active regions are copious producers of CMEs, so the corona above such regions is expected to be highly inhomogeneous due to preceding CMEs and their aftermath. When a shock passes through density (n) and/or magnetic field (B) inhomogeneities, the upstream Alfven speed (Va) will be modified according to dVa/Va = dB/B - (1/2) dn/n. If dn/n > 2dB/B, then dVa/Va <0, which means an increase in the upstream density (above the quiet values) can lower Va and hence increase the Mach number of the shock. Stronger shocks accelerate more electrons resulting in enhanced radio emission. Other situations may arise depending on the signs of dB/B and dn/n and their relative magnitudes (Lugaz et al., 2005). In the same way interacting CMEs affect the type II radio emission, the SEP events may also be affected (Gopalswamy et al., 2002, 2004a). If a CME-driven shock propagates through a medium with density and magnetic field fluctuations, the shock strength will be modified. If the shock propagates through a preceding CME, trapping of particles in the closed loops of preceding CMEs can repeatedly return the particles back to the shock, thus enhancing the efficiency of acceleration (Gopalswamy et al., 2004; Kallenrode and Cliver 2001). A systematic survey of the source regions of large SEP events of cycle 23 has revealed that the SEP intensity is high when a CME-driven shock propagates into a preceding CME or its aftermath originating from the same solar source (Gopalswamy et al. 2004a, 2005c). According to theoretical calculations, existence of preceding CMEs can greatly enhance the turbulence upstream of the shock, resulting in shorter acceleration times and higher SEP intensities (Li and Zank, 2005).

7. A UNIFIED APPROACH TO TYPE II BURSTS

Flare blast waves and CME-driven shocks have been considered as two possible sources of metric type II bursts, while the DH and longer wavelength bursts are due to CME-driven shocks. The primary observational support for the blast wave scenario are: (i) CMEless type II bursts and (ii) the discrepancy between the metric and IP type II bursts. In this section, we present evidence showing that these two may not hold anymore, further supporting the unified approach to the type II bursts in terms of CMEs.

7.1 CMEless Type II bursts

The existence of CMEless metric type II bursts (Sheeley et al., 1984; Kahler et al. 1984) became questionable when the solar sources of such type II bursts were examined (Cliver et al., 1999; Gopalswamy et al., 2001a): most of the CMEless type II bursts originated from close to the disk center. Coronagraphs, by their very nature, are ill-positioned to detecting CMEs occurring close to the disk center (Cliver et al. 1999), although such eruptions can be clearly seen in coronal images obtained in EUV and soft X-rays (Gopalswamy et al. 2001a). This is especially true for purely metric type II bursts because they are associated with CMEs of just above average kinetic energy and weaker flares (see Section 8). The CME visibility function is such that about half of the CMEs associated with C-class flares occurring close to the disk center may not be detected by LASCO, whereas most of them will be detected if the associated flares occurred near the limb (Yashiro et al., 2005). Furthermore, considering only type II bursts occurring close to the solar limb, there is nearly a 100% association with CMEs (Gopalswamy and Hammar, under preparation. Thus, the CMEless type II bursts clearly is an artifact of the visibility function of CMEs.

In a recent paper, Classen and Aurass (2002) suggested that the metric type II bursts belong to three different classes originating from: 1. flare blast waves, 2. nose of CME-driven shocks, and 3. flanks of CME-driven shocks. However, the majority of m type II bursts interpreted with the blast wave scenario originated from close to the disk center. In fact, when we reexamined the 19 class 1 metric type II bursts (kindly provided by T. Classen), we found that all of them were associated with EUV eruptions with many having spatial extent much larger than that of the active region. Such a signature is indicative of CMEs, which might have been missed by LASCO because of the occulting disk. Some of them might have been missed because of multiple CMEs from the same region. One of the criteria used by Classen and Aurass (2002) to designate a type II event as blast wave case is that the temporal separation between the type II burst and the associated CME must exceed 1 hr. Longer delay is expected for the disk-center CMEs because they have to expand significantly before appearing above the occulting disk. Thus the existence of CMEless type II bursts, which was considered to be the strongest support for blast waves, is in serious doubt. This issue can be settled once and for all by studying CMEs and type II bursts associated with a set of C-class flares detected by the two spacecraft of the STEREO mission. From an entirely different point of view, Mancuso and Raymond (2004) suggest that most of the type II bursts are consistent with a CME-driven shock scenario with the radio emission originating from the nose or flanks of the shock. They obtained the coronal density profile using synoptic UVCS observations in the corona (1.5-3.5 Rs) before the occurrence of 29 metric type II bursts and showed that the computed type II burst locations were consistent with CME-driven shocks.

7.2 Relation between metric and IP type II bursts

The discrepancy between the drift rates (or shock speeds) of metric type II bursts and IP type II bursts (see, e.g. Cane, 2000; Reiner et al. 2001) has been thought to argue against the same shock causing the metric and IP type II bursts; it favors a blast wave for the metric type II burst and a CME-driven shock for the IP type II burst with both disturbances originating from the same eruption. The drift rate problem can be traced to the over-simplified radial variation of the characteristic speed. In fact, it will be shown that a realistic profile of the characteristic speed naturally explains the drift rate discrepancy and all the observed features of the type II bursts phenomenon.

In the mid 1980s, when the debate regarding the source of coronal type II bursts was underway, it was thought that the Alfven speed had a discontinuous jump from tens of km/s in the chromosphere to ~500 km/s in the corona (the thick solid curve in Fig. 4, adapted from Bougeret, 1985). The classical definition of "fast CMEs" (400-500 km/s), stems from this characteristic speed (Gosling et al., 1976, Bougeret, 1985; Cliver et al., 1999). The thick solid curve in Fig. 4 implies that only disturbances propagating with speeds exceeding ~500 km/s can drive shocks in the corona. But some metric type II bursts do occur in association with CMEs slower than 500 km/s (see, e.g., Kundu et al., 1989; Gopalswamy et al., 2001a). If the shocks are blast waves the CMEs are just accompanying events with no role in shock driving. The other possibility is that the local Alfven speed is not the constant value, but can be low enough for the slow CMEs to drive shocks. Recent studies indicate that this to be the case. A low and variable Alfven speed in the inner corona is evident even with simple models of the density and magnetic field in the quiet corona (see, e.g., Krogulec et al., 1994). As shown in Fig. 4 (thin solid curve marked QS), the fast mode speed starts from a low value (~200 km/s) near the coronal base, reaches a peak in the outer corona, and then slowly declines in the IP medium. The fast mode speed is similar to the constant value used in Bougeret (1985) only around the peak.

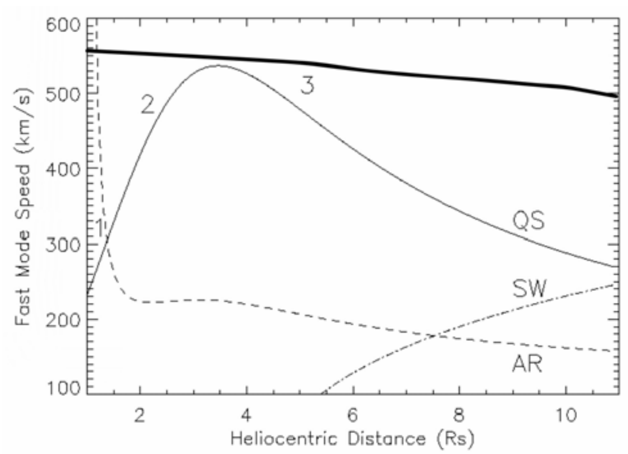

Figure 6. Fast mode speed in the quiet (QS, thin solid curve) and active region corona (AR, dashed line) compared with the solar wind speed (marked SW) adapted from Gopalswamy et al. (2001a). The thick solid curve is a sketch of the Alfven speed profile from Bougeret (1985). Region 1 corresponds to active region core where the fast-mode speed is high, so it is difficult to form shocks in this region. Metric type II bursts occur in region 2. IP type IIs occur in region 3. The Alfven speed is close to the fast mode speed since the sound speed is very small, so we use fast mode and Alfven speeds interchangeably.

Mann et al. (1999) used such a speed profile (QS in Fig. 4) to suggest that flare generated coronal shocks need to have speeds exceeding the peak value in order to penetrate into the IP space. Most of the type II bursts occur in the vicinity of active regions, so using the quiet Sun fast mode speed is not quite appropriate especially close to the active region. To remedy this, Gopalswamy et al. (2001a) introduced the active region component of the fast mode speed (the curve marked AR in Fig. 4), which drops from a few thousand km/s at the active region core to ~200 km/s at 2 Rs (see also Mann et al., 2003). The resultant fast mode speed has a minimum in the inner corona (region 1 in Fig. 4), rises to a peak in the outer corona (region 2), and then slowly declines in the IP space (region 3). It was noted in Fig. 3 that type II bursts occur only when the CME mean speed is greater than 200 km/s, which is the minimum speed in Fig. 4 that has to be exceeded for shock formation. Furthermore, when coronal shocks are driven by CMEs, the initial speed need not exceed the peak fast mode speed in order to penetrate into the IP space, since slower and accelerating CMEs are routinely observed beyond the height of the fast mode peak. CMEs typically accelerate in region 1, so they are likely to have higher speed in region 3 than in regions 1 and 2. This is an important factor that contributes to the speed discrepancy for shocks derived from type II bursts in regions 2 and 3. Another factor is the location of the radio source with respect to the radial direction. If the metric type II emission occurs at the flanks of the shock (where quasiperpendicularity is satisfied, see Holman and Pesses, 1983), then the drift rate is determined by the scale height along the locus of the quasiperpendicular region, rather than along the density gradient. If the IP type II burst, on the other hand occurs at the nose of the shock, then one would also expect different drift rates for the metric and IP type II bursts. Emission from the nose and flanks of the same shock might explain the occasional events with simultaneous bands of emission in the metric and IP domains (Raymond et al. 2000). A final possibility is that the flank and nose of the shock correspond to different sections of the fast mode profile in Fig. 4. The flank is likely to a lower fast mode speed region compared to the nose.

The modified fast mode speed profile (AR+QS) in Fig. 4 can account for various observed features of type II bursts from the corona and IP medium if the shock driver is a CME. 1. The high fast mode speed in the active region core does not allow shock formation there, thus providing a natural explanation for the relatively low starting frequency of type II bursts (~150 MHz). 2. At heliocentric distances < 2 Rs where metric type II bursts form, the fast mode speed is relatively low, so it is easy to drive shocks. This explains the higher abundance of metric type II bursts compared to the IP type II bursts (see Plate 1). 3. The average speed of CMEs associated with type II bursts confined to the metric domain is ~600 km/s (see Table 1). This is about the peak fast mode speed (see Fig. 4). These CMEs are super-Alfvenic only in region 2, and hence the corresponding type II bursts are confined to the metric domain. 4. Some of the energetic shocks can continue beyond the fast-mode peak, resulting in the m-to-DH and m-to-km type II bursts. CMEs associated with such type II bursts are of highest speed (>1200 km/s) and hence are capable of driving such shocks (see Table 1). 5. CMEs with intermediate speeds can drive shocks in the metric domain (where the fast mode speed is low), lose the shock in the outer corona (where the fast mode speed has its peak) and again drive a shock beyond the outer corona when the fast mode speed declines**.** A blast wave cannot do this because once it ceases to be a shock it is lost for ever since there is no driver behind it. 6. Accelerating, low-speed CMEs may produce shocks in the DH and/or km domains even though they do not drive shocks in the metric domain (Reiner et al. 1998; Gopalswamy, 2004a). This again suggests that the initial speed of disturbances need not exceed the fast mode peak for shocks forming in the IP space. 7. Since the constraint on the speed of the shock driver is different in the inner and outer corona (dictated by the fast mode profile), drift rates derived from the type II radio bursts are expected to be different even for the same driver. 8. The fast mode speed profile in Fig. 4 is based on simple density and magnetic field profiles. In reality, it may vary in the peak value and the location of the peak depending on the prevailing physical parameters in the corona. This allows for the possibility that a 250 km/s CME could be a fast CME, while a >1000 km/s CME could be a slow CME depending on the local fast mode speed. This way, the large number of fast and wide CMEs without type II bursts can be explained as a consequence of the high characteristic speed (Sheeley et al., 1984; Gopalswamy et al. 2001b). In summary, the possibilities resulting from the combination of CME and medium properties can result in all the known varieties of type II bursts shown in Fig. 1, thus providing a simple possibility of explaining type II bursts in all spectral domains using CME-driven shocks.

The place of blast waves in the overall picture of type II phenomenon needs to be mentioned: the varieties 2-6 in Fig. 1 are due to CME-driven shocks, while a fraction of events under variety 1 may be due to flare blast waves (Vrsnak and Lulic, 2000). This would imply that the CME-driven shock mechanism works for the entire Sun-Earth distance and for a narrow region of ~1 Rs from the solar surface an additional mechanism (blast waves) may operate. Unfortunately, there is no simple way to detect such blast waves because they do not propagate far from the Sun for in situ detection. Theoretical studies indicate that blast waves may not survive to reach the IP medium due to the refraction of the waves towards solar surface (Vainio and Khan, 2004). Since all the metric type II bursts are associated with super-Alfvenic CMEs (see point 3 in the previous paragraph), the blast waves and CMEs need to coexist near the Sun, which complicates the blast wave propagation. Interpretation of Moreton waves (in H-alpha, EUV) as blast waves is also problematic because CMEs accompany Moreton waves. Papers seeking to identify Moreton waves with blast waves (e.g. Hudson et al. 2003) do not account for the accompanying CMEs, which are physically present in the spatial domain of the problem, and hence cannot be ignored.

8. FLARES AND TYPE II BURSTS

It must be pointed out that all metric type II bursts are associated with flares although only a small fraction of flares are associated with type II bursts (see Cliver et al., 1999; see also Plate 1). Unlike disk CMEs, there is no problem in detecting flares associated with type II bursts (except for the behind-the-limb flares). Flares also fit into the overall hierarchical relationship between CMEs and type II bursts discussed in section 4. Table 2 shows the X-ray flare sizes corresponding to the m-limb, DH, and m-to-km type II bursts (Gopalswamy et al. 2005b). Flares of size ≤B1.0 (GOES X-ray class) are listed as "other". The m-limb type II bursts are predominantly associated with C- and M-class flares (84%), while the vast majority of the m-to-km bursts are associated with M- and X-class flares (86%). For the DH type II bursts, the flare size is intermediate: the M and X class flares still constitute the majority (73%), but about a quarter of the flares are of C-class. Clearly the m-to-km type II bursts are associated with biggest flares while the m-limb type II bursts are associated with the smallest flares (see also Robinson et al., 1984). Association of the m-to-km type II bursts with the most energetic CMEs and largest flares reminds us of the "Big-flare Syndrome" (Kahler, 1982).

	X	M	C	other
m-to-km	42%	44%	8%	6%
DH	25%	48%	23%	4%
m-limb	3%	40%	44%	13%

Table 2. Fraction of soft X-ray flares associated with m-limb, DH, and m-to-km type II bursts. "other" denotes B-class and lower size flares.

There are ~20 times more flares and 10 times more CMEs than the number of metric type II bursts (see Plate 1) but only those flares accompanying CMEs are associated with type II bursts. Such a conclusion is consistent with the result obtained many years ago that metric type II bursts are associated only with eruptive flares (Munro et al., 1979). Eruptive flares are so called because of the accompanying mass motion in the form of H-alpha ejecta, which we now know form the core of CMEs. Non-eruptive (or compact flares) are neither associated with CMEs nor with type II bursts.

The close connection between flare size and type II wavelength may appear consistent with the blast-wave scenario for metric type II bursts. But the required presence of CMEs complicates such an interpretation. X-ray observations have shown that the flare site is typically located close to the Sun (~10^4 km above the surface, see Catalano and van Allen, 1973), while the CME leading edge is at a much larger height when the flare starts. In the CSHKP model of an eruptive event (see Anzer and Pneuman, 1982 for example), the flare site is considered to be the reconnection site far below the CME leading edge. If a blast wave starts from the flare site, it has to propagate through the moving medium (CME material), which is not favorable for shock formation. Therefore, the blast wave speed with reference to the CME speed has to exceed the local characteristic speed to drive a shock, whereas the CME has to simply exceed the coronal Alfven speed to drive a shock. It is interesting to note that even X-class flares are not associated with type II bursts if they are non-eruptive.

9. SUMMARY AND CONCLUSIONS

There is a hierarchical relationship between CME kinetic energy and the wavelength range over which type II bursts occur: purely metric type II burst are associated with CMEs of low average speed (~600 km/s) while the m-tokm type II bursts are associated with much faster CMEs (average speed ~1500 km/s) with the DH type II bursts associated with CMEs of intermediate speed (~1100 km/s). The widths are also progressively higher as one goes from metric to m-to-km bursts, which implies a progressive increase in kinetic energy. This organization of type II bursts by CME kinetic energy lends support to the idea that the whole type II phenomenon can be explained by CME-driven shocks. The initial kinetic energy essentially decides how far a CME can drive a shock into the IP medium. The most energetic CMEs obviously can drive shocks far into the IP medium, so the shock produces radio emission at various distances from the Sun (and hence at various wavelengths). As expected, such energetic CMEs are also highly associated with SEP events. The DH and km type II bursts correspond to the spatial domain from 2-200 Rs and are associated with CMEs. It seems reasonable to extend the applicability of CME-driven shocks by another solar radius or so to include the m type II bursts in the unified approach to the type II phenomena. This is further supported by the non-existence of CMEless type II bursts. The universal relationship found between the drift rates of type II bursts in various wavelength domains is also consistent with such an interpretation. The consistency between type II source heights from radioheliographic observations and CME leading edges at the time of type II bursts also calls for a close association between type II bursts and CMEs. The discordant drift rates (or derived shock speeds) in the corona and IP medium, an argument often used for two different shock sources, can be readily explained when a realistic radial profile of the fast mode speed is used. There is undeniable relationship between flares and type II bursts, but the flares need to be eruptive (accompanied by CMEs). The presence of CMEs in eruptive flares implies that flare blast waves, if present, have to propagate through moving plasmas (CMEs with an average speed of at least 600 km/s), and hence less conducive for shock formation. The strongest argument against the blast waves is that they have never been observed in the IP medium. Future in situ observations close to the Sun (such as from the Solar Orbiter and Solar Probe) may settle the issue of blast waves. The fact that the shock-driving ability of CMEs depends on their kinetic energy has an important practical utility: the type II bursts extending to the IP medium can isolate the small number of CMEs relevant for space weather.

Acknowledgments. Research supported by NASA/LWS and SR&T programs. I thank M. L. Kaiser for the Wind/WAVES type II catalog and G. Michalek, S. Yashiro, S. Petty for help with figures.

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