INVESTIGATIONS ON THE CHARACTERISTICS OF SOLAR FLARES AND CMEs ASSOCIATED WITH DH TYPE II RADIO BURSTS

W. Hannah Blessy[1], A. Mujiber Rahman*[2], S. Prasanna Subramanian[3], S.S.R. Inbanathan[*1,4]
[1] PG & Research Department of Physics, The American College, Madurai India
[2] HKRH College, Uttamapalayam, Theni, India
[3] Radio Astronomy Centre, NCRA-TIFR, Ooty, India
[4] Department of Applied Sciences, The American College, Madurai India
[*] Corresponding Author: mujib73@gmail.com, ssrinbanathan@gmail.com

ABSTRACT

This work reports some of the statistical characteristics of coronal mass ejections (CMEs), solar flares and solar energetic particle (SEP) events associated with decametric-hectometric (DH) (1–14 MHz) type II radio bursts, during the period 1997–2017. Most of the CMEs are wide and fast with nearly 57% of them being halo CMEs. It is found that 10 – 20˚ latitudinal belt and similar longitudes of the sun are the most preferred locations for CME-flares accompanied by DH type II bursts. Here, M-class flares are the most predominant with an occurrence rate of 50% associated with DH type II bursts. Nearly half of the DH type II radio bursts spread down below to 1MHz. Their frequency of occurrence follows the solar cycle maxima and minima. The probable source locations of flares and CMEs responsible for such bursts, energetic high speed CMEs and the extension of lower ending frequencies are found to be indicative of solar energetic particle events affecting space weather.

Keywords: Coronal Mass Ejections, DH Type II Bursts, Solar Flares, CME Speed, Flare Class, Drift Rate
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INTRODUCTION

The observations of Radio and Plasma Wave (WAVES) on the spacecraft Wind has been providingdata on the low-frequency radio emission of the Sun in the 1-14 MHz frequency band since its launch in 1994 [J.-L. Bougeret et al., 1995].This band of frequencies matches the decameter-hectometric (DH) wavelength range(~2-10 $R_⊙$) and tries to link the break between yesteryears' metre band accessible to radio telescopes on ground and the kilometre band employed by radio toolsspaceborne [N. Gopalswamy et al., 2001].The observations of DH radio bursts have provided new evidences on CMEs near the Sun and also on nonthermal radio bursts [N. Gopalswamy, M. L. Kaiser et al., 2000].

Coronal Mass Ejections (CMEs) emit a greatvolume of plasma with an intrinsic magnetic field from the Sun, generally by the mechanism of magnetic reconnection at the dynamic regions and also by quiet filament eruptions [Gosain, S. et al., 2009]. A distinct case of CMEs are the halo CMEs which are influencing the space weather phenomena near Earth [Webb, D.F. et al. 2000, Zhang, J. et al. 2003 and N. Gopalswamy et al., 2004]. That these halo CMEs are able to induce interplanetary type-II radio emissions is well documented by Lakshmi and Umapathy, 2012 [Lakshmi, M. Anna et al., 2012]. They have reported data on longitudinal CMEs alongwithwith DH type-II bursts during the 23rdsolar cycle and the change in properties with location of the source and even predict the incidence of halo CMEs.

The gradual change in thedrift rate of type-II radio bursts is often hailed as the radio marker of a collisionlessmagneto-hydrodynamic (MHD) shock wave created in the solar corona[Uchida et al., 1960].

Shanmugaraju et al., 2003 present that though type-II radio bursts arenoted in the metre-, decameter-hectometre (DH) and kilometre-wavelengths, only the DH type-II bursts are better connected with CMEs. CMEs driving fast interplanetary (IP) shocks (speed > 500 km/s) are essential for generating type II emissions [Cane H.V. et al., 1987]. Reiner et al. (1998), observe that even shocks driven by relatively slower CMEs (speed≤500 km/s) can also generate type II emissions in IP regions. Shanmugaraju et al. (2009)have stated that speed of CMEs depends on the latlong positions.

Another noteworthy associated phenomenon is the solar flare, a prominent explosion of energy from the lower corona detected as a rapidheightening in intensity acrossthevarious regions of the electromagnetic spectrum[Youssef and Mawad (2013)]. There have been earlier reports on CMEs and flares relatedto type-II radio bursts by Youssef and Mawad (2013) and Youssef (2013)as they aresignificant tools for learning the features of solar corona.Important characteristics of the DH type-II bursts associated CMEs for the period 1997–2005,especially the limb events, is done by Kalaivani et al. (2010).Sharma et al. (2015) have studied the radio-rich CMEs during 1997–2013 and predicted the possibility of arrival of shock at the Earth through CMEs associated with type-II burstsnear the centre of the sun's disk.

It is well-known that kilometric type II radio bursts and DH type II bursts are due to shocks by CMEs. Gopalswamy et al. [2000, 2001 and 2019] reported DH type II bursts associated with CMEs that were faster and wider on the average. Since metric type II bursts are not indicative enough of IP events [Gopalswamy et al. 1998, 2001], DH type radio II bursts aid as representations for energetic and geoeffective CMEs.

Vasanth and Umapathy[2014] have studiedtype II radio bursts of longer wavelength associated with CMEs and flares during the 23rd solar cycle. They have reported that energetic CMEs are formed during the decay phase of the solar cycle produce intense geomagnetic storms at earth.Thus, by observing the width and speed of CMEs and ending frequencies of solar flares associated with DH type II bursts, we can recognizeaspects that drivespread far into the IP medium [N. Gopalswamy et al., 2001, M. J. Reiner et al. 1998].

Temporary enhancements of the intensities of high energy protons, electrons and ions which occur in the interplanetary medium, known as Solar energetic particles (SEPs),are proven to succeed phenomena like flares and coronal mass ejections. Particle acceleration has been explained by small scale processes during flares and also shock waves driven by CMEs (Klecker et al., 2006). One of the many approaches to studythe relationship between SEPs and the undermining solar activity is statistical in nature. Various studies have found out that SEP events are associated both with flares(Garcia, 2004) and/or radio bursts (Kahler, 1982a, 1982b), and with fast and wideCMEs (Kahler, 1992; Reames, 1999). A more extended study of SEP events during the 23rd solar cycle by Cane, Richardson, and von Rosenvinge (2010) has also confirmed this.

The presentwork is considered to be an extension ofsuch earlier works.The qualitative results of this study are expected to be similar to those obtained earlier with a few differences in the numerical estimates.The study aims to investigate the establishment of connection of the flares, CMEs andSEPs with DH type-II radio bursts byanalyzingthe characteristics of these phenomena in terms of variation and distribution from the period 1997–2017, which spans solar cycles 23 and 24.

DATA SELECTION

The following criteria governs this dataset:

(i) Radio bursts of DH type-II and solar-flares-associated CMEs and SEPs only are taken into account.

(ii) The SEPs, CMEs and associated flares are assumed to originate from the same location.

Wind/WAVES type II catalogue (http:// cdaw.gsfc.nasa.gov/CME list/radio/waves type2.html) has provided the data for the specified period (1997–2017). This list also provides information on 'DH type II radio bursts' accompanied solar flares and CMEs (including halo-CMEs). Based on theabove-mentioned criteria,497CME events were selected for further analysis. Since the CMEs reported in this study produce DH type II bursts, they are considered to be radio-loud. SEP data was taken from the major SEP event catalogue given in https://cdaw.gsfc.nasa.gov/CME_list/sepe/. And out of the 152 SEPs listed, only 129 are taken into account due to their association with radio bursts, CMEs and flares. Those with incomplete data on all of these solar activities were not taken into account.

The results of the statistical characteristics of solar energetic particles (SEPs), solar flares and coronal mass ejections (CMEs) associated with radio bursts of decametric-hectometric (DH) type II are presentedbelow.

DISCUSSION

In this study, 497 CMEs have been identified, out of which 286 are halo CMEs. The average width of CMEs of DH type II for this time period is found to be 274 deg. The speed of the CMEs including that of halo CMEs varies from 191 to 3387 km/s averaging on 1164 km/s. Also, about 53 are slow CMEs (<500 km/s) while 443 are fast (>500 km/s) CMEs.And 129 SEP events are probed for their association with various parameters like flare location, CME speed and angular width and starting and ending frequencies of type II radio emissions.

ASSOCIATED CME,FLARE AND SEP CHARACTERISTICS

Analysingradio bursts of type II for their intricate physical connection to SEP events is one of the study's predominant reasons. This is due to the fact that theshock which accelerates electrons, also producesradio bursts of type II, protons and heavy ions that constitute an SEPevent. Significantcorrelations between the number of SEP events and bursts of type II from the western hemisphere and CMEs with a southward magnetic field component have been proved to be geoeffective by Gopalswamy et.al. [2008]. This statistical study also finds that 81 % of associated SEPs are from the western hemisphere. Researches by N. Gopalswamy, A. Lara et.al. [2000] have shown that CMEs which reach Earth originated close to the disk centre with an average latitude of 17 deg and a longitude of 28 deg, with which our results also agree.

The distribution of solar flares corresponding to heliographic latitude (Figure1A) finds that there is an equal distribution of flares-triggered-CMEs accompanied by the radio bursts of DH type II originating from the northern and southern hemispheres. Also, the latitudinal belt of 10–20˚around the centre of the disk is found to be more predominant during the period of study (Figure 1B).

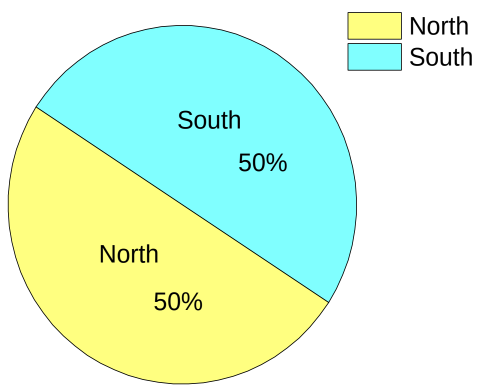

Figure 1A Latitudinal distribution

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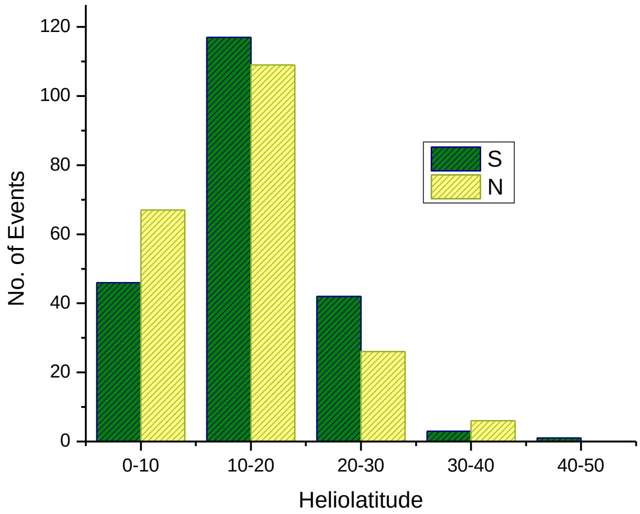

Figure 1B Latitudinal distribution of solar flares associated with CMEs accompanied by type II radio bursts

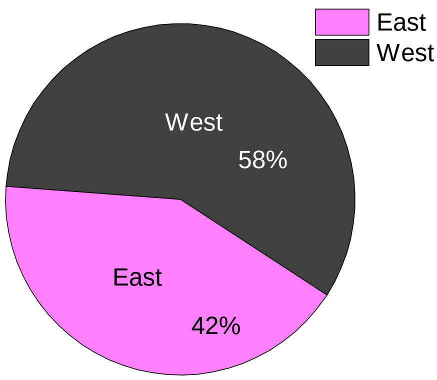

Figure 1C Longitudinal distribution of CMEs

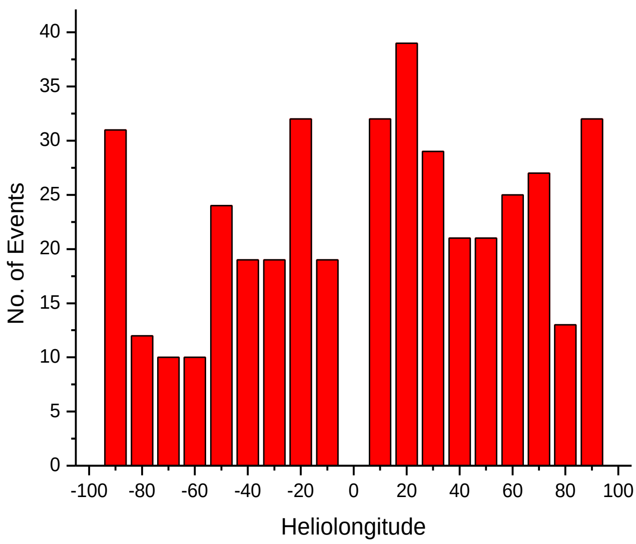

Figure 1D Longitudinal distribution of solar flares associated with CMEs accompanied by type II radio bursts

Looking at Figures 1C and 1D, it is clear that a larger number of CMEs arise from solar flares located in the western hemisphere, than those in the eastern hemisphere, although there is an equal probability of occurrence in both the hemispheres. A majority of CMEs tend to lie around E20˚ and W20˚ regions. There is a strong bias for the western CMEs to be associated with SEP events because western sources are well-connected to Earth, which is a significant factor for applications relating to space weather. This is in agreement with N. Gopalswamy, S. Yashiro et. al. [2008] in their study on CMEs, type II bursts and SEP events, wherein they have found that CMEs with DH type II bursts occur throughout all longitudes, except for those producing SEP events which are predominantly in the western hemisphere because of the magnetic connectivity between the Earth and the source region of SEP.

The annual average and median speeds of CMEs for the period 1997-2017 are tabulated in Table 1.

Year	Number of Events (DH Type II CMEs)	Average CME Width	Median CME Width	Standard Deviation of CME Width	Average CME Speed	Median CME Speed	Standard Deviation of CME Speed
		deg	deg		km/s	km/s	
1997	11	203	155	128	565	441	401
1998	23	245	268	113	1096	1099	522
1999	19	255	303	114	1071	1006	559
2000	52	269	360	127	1060	1062	472
2001	54	264	360	117	1228	1183	553
2002	53	266	360	119	1200	1099	531
2003	32	293	360	103	1489	1406	537
2004	29	278	360	107	1245	1180	559
2005	37	331	360	85	1605	1679	613
2006	9	291	360	112	1130	911	487
2007	3	210	164	133	1107	995	226
2008	3	197	197	120	809	809	416
2010	2	272	272	125	1171	1171	424
2011	28	287	360	100	1075	955	557
2012	27	315	360	89	1360	1220	550
2013	38	283	360	98	953	957	485
2014	42	295	360	99	925	786	473
2015	23	291	360	98	1001	995	364
2016	4	187	145	118	800	539	629
2017	8	292	360	127	1474	1402	833

Table 1 The annual average and median speeds of all types of CMEs during the period 1997-2017

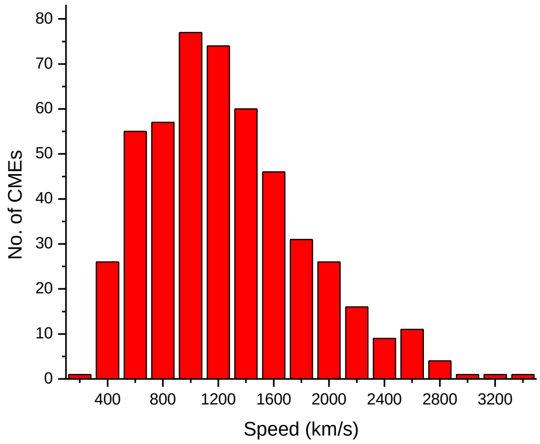

Figure 2A Distribution of CMEs with respect to their speeds

Figure 2Arepresents the distribution of associated CMEs with their speed (km/s), which seems Gaussian. It is found that the average velocity is 1164 km/s (Table 1).This number correlates well with the one (1100 km/s) projected for bursts of DH type II associated with intermediate speed CMEs by Gopalswamy [2006].This average is approximately thrice the average of (487 km/s) nearly 3000 CMEs observed by LASCO between 1996 and 2000 as observed by St. Cyr, O.C., et al. [2000].

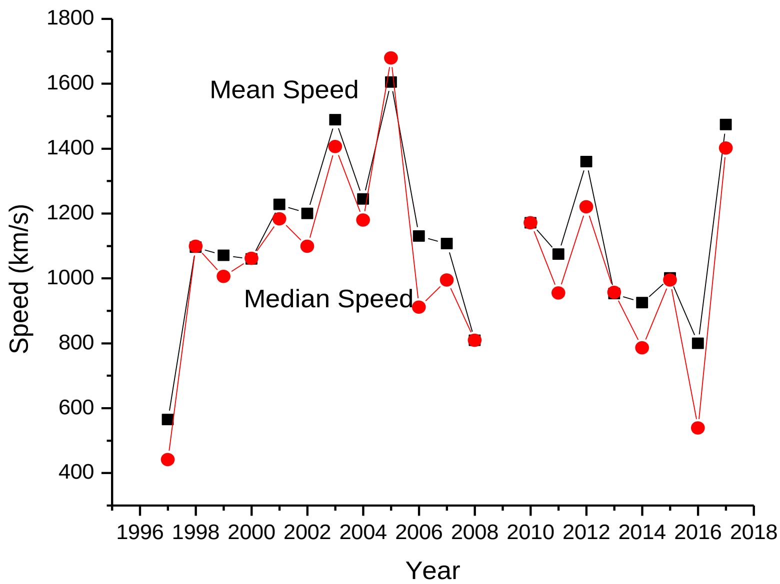

Figure 2B Annual Average and Median CME Speeds from 1997 - 2017

The graph of the annual average (mean) and median speeds is shown in Figure 2B with a break in 2009. CME speeds are found to track the solar activity as documented earlier by Gopalswamy et al. [2004].

CME width (W) is an important criterion since it is interrelated to its mass (M)as apparent from the equation, $\log(M) = (12.6) + (1.3)\log W$given by Gopalswamyet al., (2005).

Table 1 shows that most of the entries are halo CMEs. Figure 3A reveals that the widths of associated CMEs are relatively high, proportional to increased kineticenergy. This classification ofbursts of type II by CME kineticenergy substantiates the postulate that type II phenomenacan be explained by shocks driven by CMEs. The initialkinetic energy infersthe distance through which a CME can drive shocks into the IP medium, while the energetic CMEs emit radio bursts at several distances from theSun (therefore at various wavelengths).

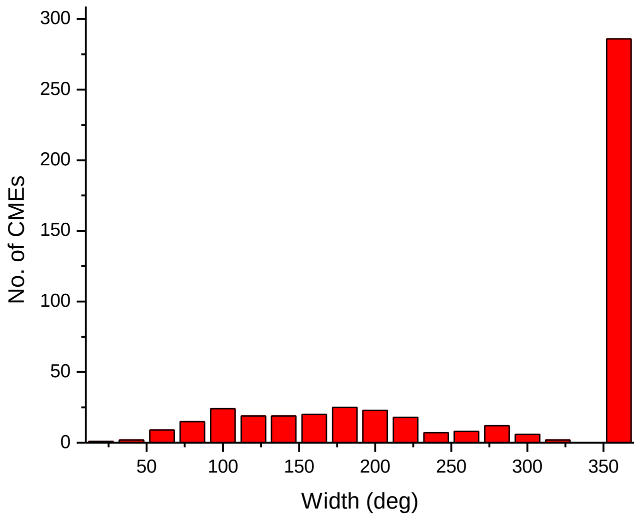

Figure 3A Distribution of CMEs with their Widths

The width of a CME beingdirectly related to its mass, wider and faster CMEs are more energetic. In fact, earlier reports [Gopalswamy, N., E. AguilarRodriguez et al., 2005] detail that CMEs with radio bursts of DH type II have kinetic energy corresponding to the spatialdomain around 2 R⊙ to 200 R⊙. Webb et. al. [2012] observe that it has been documented [Gopalswamy, N., Akiyama, S. et al., 2010] that halo CMEs seem faster and more energetic than non-halo CMEs. Our results reveal a correlation of R = 0.5 for the variation of widthwith the speed of CMEs related tobursts of DH type II.

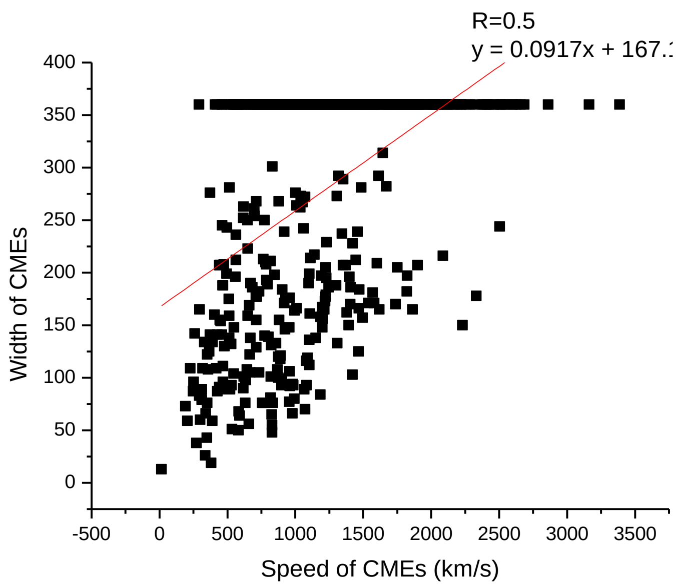

Figure 3B Variation of Width of DH Type II CMEs with their Speeds

Our results (Figure 3B)also indicate that most wide CMEs (width > 120˚) are connected with fast CMEs (with speed > 500 km/s) (a staggering 86% of the total CMEs). Therefore, increased CME velocities would most probably lead to enhanced radiationlevels and constitute a factor of prominent radiation risk as suggested by Athanasios et.al. [2016]. This study also finds that around 97 % of the associated SEP events follow wide (CME width >120 deg) and fast (CME speed > 500 km/s) CMEs.

B. Vrsnak [2008 and references therein] reports that afascinatingfeature of CMEs is their relation to solar flares. Though the association rate is not high, there is a clear connection between these two phenomena, particularlyamongst fast CMEs and major flares.

According to Sheeley Jr et al. (1999), thereare two dynamical classesof CMEs– the first class comprises the gradual CMEs, which are slower, accelerating in the fields of view (FOV) of the coronagraphs, andare favourablylinked with prominence eruptions; the other class being the impulsive CMEs, faster, and which decelerate and most probably associated with solar flares.Many researchers like Gosling et al. (1976) have documented records of CME coronagraphs which prove theinclination for fast CMEs to be associatedwith solar flares.

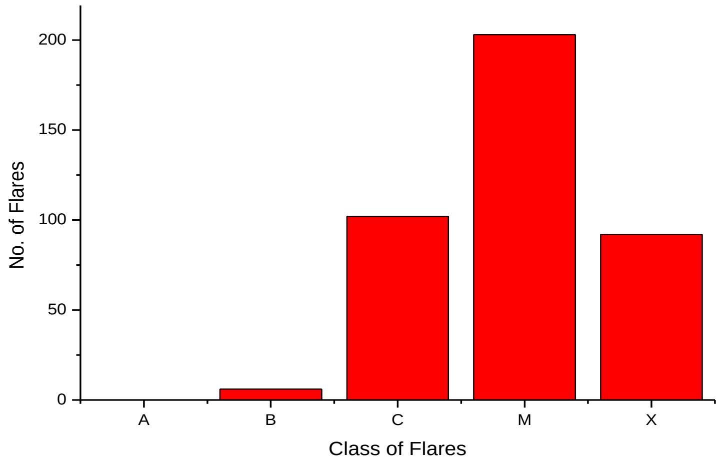

Figure 4A Distribution of Flare Class from 1997-2017

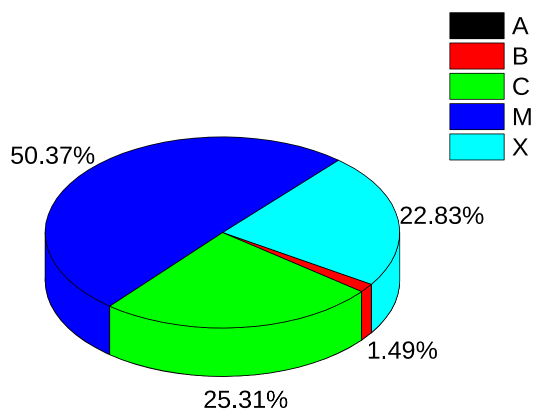

Figure 4B Percentage of Flare Class for the period of study

For bursts of DH type II, the flaresize has been reported to be intermediate with the M and X class flares constituting a majority (73%), with about one-fourth of the flares to be ofC-class [Gopalswamy, N., E. Aguilar-Rodriguez et al., 2005]. The results here too (Figures 4A, 4B) correlate well with the earlier studies, with M-class flares being the most predominant with an occurrence of 50%. Yet, X-class flares with an occurrence of about 23%, are associated with CMEs (mostly halo CMEs) having the maximum mean speed of 1565 km/s and maximum average width of 332 deg. This outcome is in agreement with Gosling et.al (1976) and Moon et.al (2002) who predicted the association of stronger flares with fast CMEs.

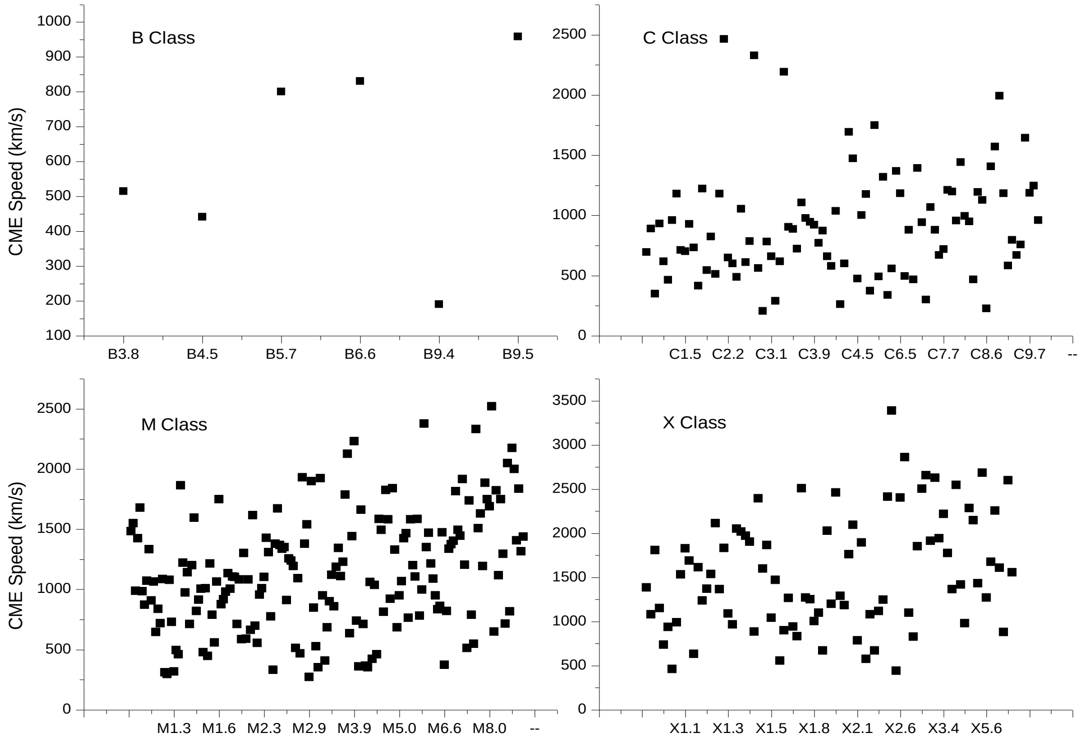

Figure 4C Distribution of CME Speed with Intensity of Flare Class for DH type II associated events during 1997-2017

The mean CME speed associated with bursts of DH type II (Figure 4C) tends to be larger for M-class (upper limit is 2500 km/s) and X-class flares (ranging from 500 – 3500 km/s) when compared to B- or C-Class flares. Robinson et al.[1984] found that the probability of an IP type II burst ensuinga metric type II was increased greatly if accompaniedby strong, persistent H-alpha and soft X-ray flares, indicativeof energetic CMEs. Our results here too confirm that around 90% of the associated SEPs are traced to high intensity X- and M-Class flares (X-class flares-40%, M-class flares-50%).

CHARACTERISTICS OF RADIO BURSTS OF DH TYPE-II

A close linking between CMEs and type II bursts as evident from the hierarchical relationship between energies of CMEs and the array of wavelength of type II bursts is observed by N. Gopalswamy [2011]. Also, the general drift rate spectrum echoes the evolution of CME consistent with the suggestion thatall bursts oftype II can be attributed to shocks driven by CMEs.

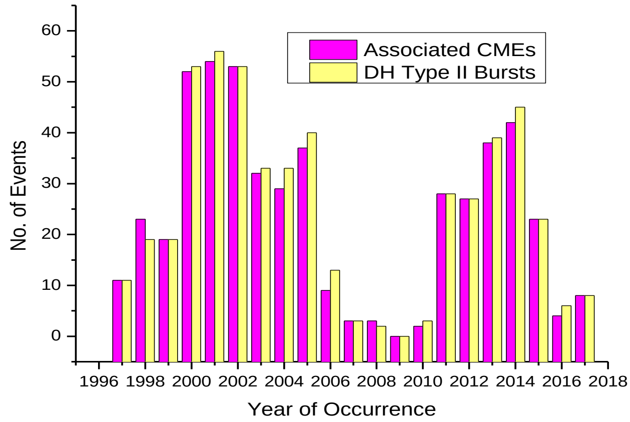

Figure 5Variation of DH type II bursts and associated CMEs from 1997 to the end of 2017

Figure 5clearly indicates theincrease in the quantity of DH type II bursts and associated CMEs from solar minimumto maximum similarto other pointers of solar activity. A noteworthy point is that, the dependence of number of DH type II burstson CME rate isless pronounced sincebursts of DH type II areassociated with energetic CMEs[Gopalswamy, N., E. AguilarRodriguez et al., 2005].

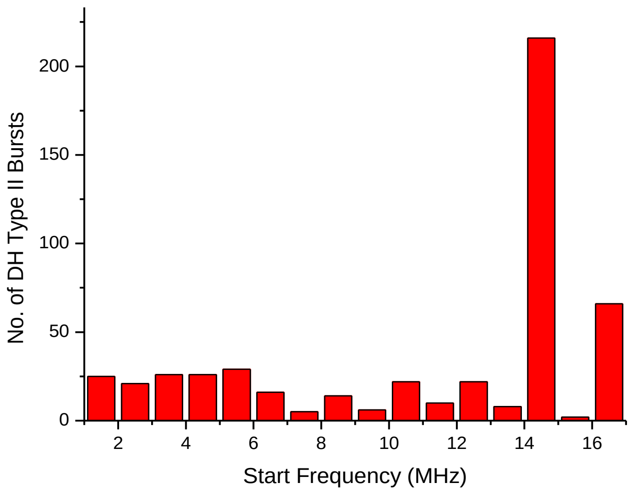

Figure 6Distribution of Start frequency of the DH-type II Bursts

The distribution of start frequencies of the DH-type II bursts for the period of study is shown in Figure 6. For most of the bursts, the start frequency varies between 1MHz and 14MHz. About 44% of the DH-type II bursts hover around at 14MHz, the higher cut-off frequency of theWAVES, indicating that there is a non-zero probability for some events to becontinuation of type II bursts in the metric domain. Since bursts of DH-type II are considered to be radiosignatures of CME-driven shocks [N. Gopalswamy et al., 2001], the starting frequency specifies the altitude around which radio emission from shocks becomediscernable [Gopalswamy, N., E. AguilarRodriguez et al., 2005].The starting frequency of bursts of type II is indicative of the remotenessof the centre of outburst from where the electrons are being accelerated by the shock. Also, since the emission frequency is proportional to the square root of the density of electrons around the region of shock, large values of starting frequencies infer formation of shock nearer the Sun. About 61% of the associated SEP events in this study have starting frequency to be around 14 MHz indicating a strong association between starting frequencies of DH-type II bursts and shocks.

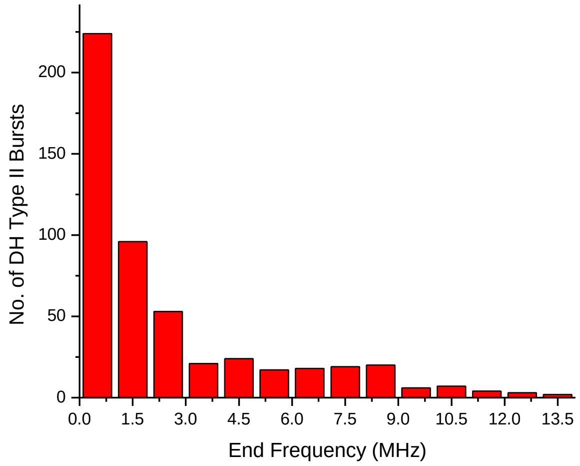

Figure 7Distribution of End frequency of the DH-type II Bursts

The variation of number of DH-type II bursts with their end frequenciesisdepictedin Figure 7. The end frequencyindicative of energies of CMEs, distributes itself from 1 MHz to 14 MHz. Nearly 56% of the DH type II bursts are in the range of 1 MHz. This implies that the shocks produced by wide and fast CMEs undergo reduction in speed between the Sun and a distance of 1 AU [Gopalswamy, N., A. Lara et al., 2000] as theytravel longer into the IP medium [N. Gopalswamy, R. Mewaldt et al., 2006] and spread to the kilometric range.IP type II bursts having ending frequencies lessthan 1 MHz are identified to be connected with energetic CMEs [Cane H.V. et al., 1987].

Gopalswamy et. al. [2019] have summarized that a type II burst below 14 MHz is anindisputableresult that a shock accelerating electrons and ions is CME-driven. Also, if a type II burst happensto be on the western hemisphere, which is actually the case in our study, there is a sure chance to observe an SEP event, with theoccurrence rate rapidly increasingwith the speed of the CME. Our study also finds out that 95% of the recorded SEPs have ending frequencies below 4 MHz, suggesting a strong correlation between the end frequencies of DH-type II radio bursts and SEPs.

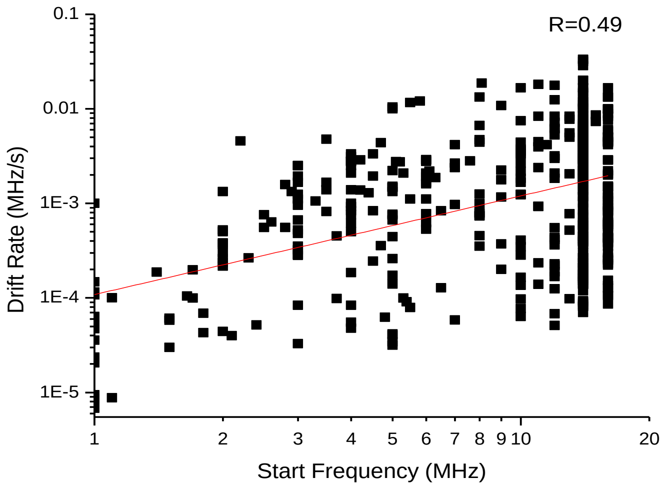

Figure 8Variation of Drift rate with Start frequency of DH-type II Bursts

The variation between the type II burst drift rate and the emission frequency on a log-log scale as presented in Figure 8shows a fairly goodcorrelation (R=0.49). The trend is obvious that bursts of DH type II at higher start frequencies have larger drift rates [N. Gopalswamy, W. T. Thompson et al. 2009, AguilarRodriguez, E. et al. 2005, Vrsnak B. et al., 2001] and it holds for four orders of scale in drift rates and two orders of magnitudein frequency.

The end frequencies of DH type II bursts are an excellent gauge for the occurrence of a SEP event. The possibility of the bursts of DH type II continuing to lesser frequencies, around 4 MHz, might indicate SEP occurrence. The variation ofspeed of CMEs and end frequency of DH-type II bursts for the period of study is shownin Figure 9. One of the earliest indicators of CME-driven shocks are the type II bursts, originating from the front-side of the Sun which continue to survive in the IP space. When detectedby spacecraft in the solar wind, the faster radio -loud CMEs are found to decelerate, which is also the result of this study.

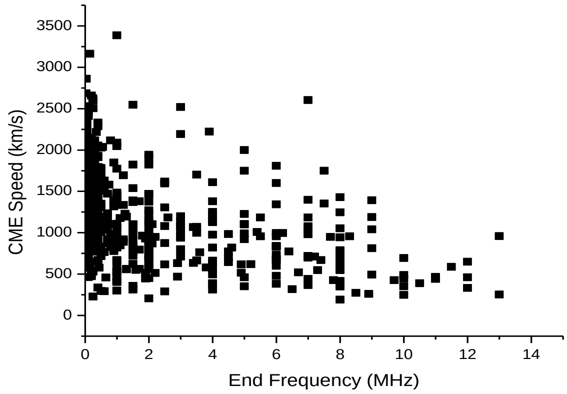

Figure 9Variation of CME Speed with End Frequency of DH-type II Bursts

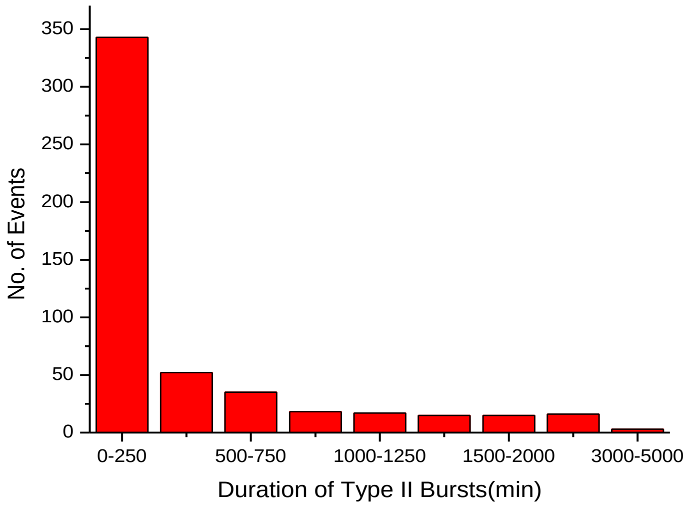

Figure 10 Distribution of duration of DH Type II Radio Bursts from 1997-2017

Figure 10 displays the spreading of duration of bursts of DH type II for the period of study. The DH type II bursts lie mostly in < 250 minute bin, which is directly related to the kinetic energy of the associated CMEs [Mohamed Nedal, 2019].

SUMMARY AND CONCLUSIONS

We investigated the properties of 497 DH typeII bursts and that of associated CMEs, flares and SEPs. The fact that all DH type II bursts are relatedto CMEs infer that CMEs drive strong IP shocks in the IP medium. Consequently, the sources of these bursts are mostly positioned in the belt of the active region. Location of source regions on the western hemisphere indicate that there is an undeniable probability for SEP events to be detected, which have been substantiated through this study. The CMEs arefast and wide on an average. The annual occurrenceof DH type II bursts roughly follows the solar cycle maxima and minima. For more than about a one-half of the studied events, the end frequency was at or below 1 MHz, signifying strong shocks.The mean CME speed for the associated DH type II bursts is observed to be larger for M-and X-class flares when compared to B- or C- class flares, indicative of energetic CMEs and thereby SEPs. There is an undeniable connection between fast CMEs and intense flares. To summarize, our study suggests that bursts of DH type II are indicative of wide and fast CMEs, which are a means to identify solar eruptions that are likely to reach 1AU. There is also an increased probability of CMEs in the west to induce a SEP event if the speed of the CME is high around >500 km/s. This study also finds that around 97 % of the associated SEP events follow wide and fast CMEs. The findings of this study confirm a strong correlation between the starting and ending frequencies of DH-type II radio bursts and SEPs.

Our results were found to be well-matched with the previous works (as discussed in the introduction) and the differences among the results may be due to different periods of study, correlating with varied levels of solar activity, dissimilarcriteria of selection or the many limitations on the data, yet, is expected tofurther our knowledge on radio bursts and their associationwith CMEs and flares.

Acknowledgment

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