



Statistical Study of DH Type II Bursts and Associated CMEs During Solar Cycle 24

Tulsi Thapa^{1,2} and Yihua Yan^{1,2,3}

¹ State Key Laboratory of Solar Activity and Space Weather, National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China; tulsithapa@nssc.ac.cn

² School of Astronomy and Space Sciences, University of Chinese Academy of Sciences, CAS, Beijing 100190, China

³ National Astronomical Observatories, Chinese Academy of Sciences, CAS, Beijing 100190, China

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Abstract

Decameter-hectometric (DH) Type II bursts, arising from coronal mass ejection (CME)-driven shock waves, are crucial for understanding solar-terrestrial interactions and space weather forecasting. This study provides a comprehensive statistical analysis of CMEs associated with DH type II solar radio bursts during Solar Cycle 24 (2009–2019), utilizing data from the Wind/WAVES, Solar TERrestrial RELations Observatory/SWAVES, and Solar and Heliospheric Observatory/LASCO catalogs. Analyzing 180 events, we report key spectral and kinematic properties, including a mean CME speed of $(1058 \pm 531) \text{ km s}^{-1}$ and a mean width of (288.39 ± 99.3) , with 62% classified as halo CMEs. About 12% of the total CMEs are accelerated, 58% of them are decelerated, and 30% of them are constant. Similarly, CMEs having a speed $\leq 800 \text{ km s}^{-1}$ are constant, and those with speed $\geq 800 \text{ km s}^{-1}$ are decelerated. DH type II bursts displayed a mean starting frequency of $(12,169.72 \pm 4939) \text{ kHz}$, ending frequency of $(2152.69 \pm 3022.07) \text{ kHz}$, bandwidth of $(10,017 \pm 5353) \text{ kHz}$, and an average duration of $(345.62 \pm 453) \text{ minutes}$. A power-law relationship was established between the drift rate (df/dt) and burst duration (D), characterized by $df/dt = 2749.07 \cdot D^{-0.88}$, highlighting the inverse dependence of drift rate on burst longevity. This suggests a dynamic interplay between shock parameters and the ambient solar corona. The findings underscore the persistent and robust spectral coverage of CME-driven shocks, offering new insights into their evolution and impact on the heliospheric environment.

Key words: Sun: coronal mass ejections (CMEs) – Sun: magnetic fields – Sun: particle emission – Sun: radio radiation

1. Introduction

Type II solar radio bursts are characterized by a narrow band of intense radiation that drifts toward lower frequencies with time. It has long been accepted that magnetohydrodynamic (MHD) shock waves are the primary driver of type II radio bursts (Ramesh et al. 2012; Vasanth & Umaphathy 2014; Zucca et al. 2018; Jebaraj et al. 2021). These MHD shock waves can be produced in the solar corona by solar flares, coronal mass ejections (CMEs), and fast plasma flows in the areas where magnetic field lines are reconnecting (termination or quasi-stationary shock waves). The plasma emission process, first proposed by Ginzburg & Zhelezniakov (1958), is the most widely recognized explanation for the production of type II bursts. The fundamental assumption is that the radio bursts are produced in a multi-step process that begins with an electron beam, or a sub-population of electrons that are significantly faster than their surrounding electrons. The beam is believed to have been created by particles that were somehow powered by an interplanetary shock or CME (Cane & Stone 1984; Cane et al. 1987). Once the electron beam has formed, it becomes unstable to wave–particle

interactions through the common “bump-on-tail” instability, which can produce Langmuir waves with frequencies close to the plasma frequency in the local region. A portion of the energy contained in the Langmuir waves can be transformed into radio waves at the corresponding local plasma frequency, or its harmonic, through a combination of three-wave decay, ion scattering, and coalescence.

The onset frequency of type II bursts reflects the heliocentric distance where the underlying shock forms, linking CME kinetic energy with the heliocentric space reached by the shock (Patel et al. 2021). Type II bursts are classified based on wavelength into metric (m), decameter-hectometric (DH), and kilometric (km) bands. While DH and km bursts are widely accepted as being driven by CME shocks (Sheeley et al. 1997), the origins of metric bursts remain debated, with flares also proposed as potential drivers. Large-amplitude MHD waves, generated by flares or CMEs, form shocks when their speed exceeds the localized Alfvén speed. These shocks, particularly those driven by CMEs, are agreed to be the primary source of type II bursts observed in the interplanetary medium and outer corona

(Aguilar-Rodriguez et al. 2005; Gopalswamy et al. 2005; Gopalswamy 2006; Krupar et al. 2019; Chernov & Fomichev 2021; Patel et al. 2021, 2022; Ramesh et al. 2022; Thapa & Yan 2024). Recent studies have also suggested flares and other eruptive activity as possible contributors to shock-driven type II bursts (e.g., Nindos et al. 2011; Alissandrakis et al. 2021; Morosan et al. 2023).

The properties of CMEs associated with DH type II bursts have been extensively explored and documented (Gopalswamy 2000; Gopalswamy & Thompson 2000; Gopalswamy et al. 2003, 2010; Prakash et al. 2012; Vasanth & Umapathy 2013; Mäkelä et al. 2015; Sharma & Mittal 2017; Kalaivani et al. 2021), and the distinctions between radio-loud and radio-quiet CMEs have also been examined (Gopalswamy et al. 2010). In conjunction with white-light observations of CMEs by the Solar and Heliospheric Observatory (SOHO), a significant number of DH type II bursts observed by the Wind satellite were examined by Gopalswamy (2006). Radio observations of these bursts have been significantly advanced by the Radio and Plasma Waves Experiment (WAVES) onboard Wind, which records emissions in the 20–1040 kHz (low-frequency) and 1.075–13.825 MHz (high-frequency) bands (Bougeret et al. 1995). The comprehensive database developed by Gopalswamy et al. (2019) integrates data from Wind/WAVES and later Solar TERrestrial Relations Observatory (STEREO) missions, enabling detailed analysis of DH type II bursts and associated CMEs. This database has been instrumental in identifying the characteristics of solar eruptions and related radio emissions (Gopalswamy 2000; Gopalswamy & Thompson 2000; Gopalswamy et al. 2003, 2010). For instance, DH type II-associated CMEs had an average speed of 1115 km s^{-1} , an angular width of 139° , and a 42.5% prevalence of halo events (Gopalswamy et al. 2005). They discovered that compared to CMEs linked solely with coronal type II bursts, CMEs associated with interplanetary type II bursts are often more energetic and accompanied by more energetic flares. Faster CMEs are more likely to be connected with interplanetary type II bursts, according to Gopalswamy et al. (2010), who used SOHO and Wind measurements to make this observation. In general, it has been demonstrated that CMEs connected to DH type II bursts are faster and wider. Moreover, Vasanth & Umapathy (2013) discovered that the speed, width, and shock speed of CMEs in DH type II burst-associated events were higher in limb events than in disk events, indicating that projection effects may influence the results.

Several studies have examined the relationship between CME kinematics and type II burst characteristics. Prakash et al. (2011) studied 212 DH II bursts associated with CMEs, further classifying DH type II bursts based on CME acceleration profiles, finding that accelerating and decelerating CMEs possess more kinetic energy than those with constant speeds. Additionally, the general CMEs have been observed to exhibit lower speeds and widths compared to type II-

associated CMEs. Gopalswamy et al. (2015) noted that DH type II bursts are more accurate predictors of space weather than halo CMEs and found that Solar Cycle 24's (SC 24's) average CME speed (968 km s^{-1}) exceeded that of SC 23 (838 km s^{-1}). Further, they discovered that DH type II bursts were linked to all solar energetic particle (SEP) events. Recently, Patel et al. (2021) presented the characteristics of DH type II bursts for SCs 23 and 24 by classifying the events according to their end frequencies. They suggest that cycle 23 exhibits a significant dominance of DH type II bursts, which extend below 50 kHz and contain an affluent population of powerful CMEs traveling beyond 0.5 au. They also suggest that the duration of type II bursts and the initial speed or energetics of CMEs are partially correlated and that the survivability of the shock associated with CMEs is influenced by several variables/parameters linked to CMEs, flares, and the condition of the coronal and interplanetary medium.

Despite these advances, the spectral and statistical properties of DH type II bursts during SC 24 remain underexplored, especially compared to SC 23. Previous studies often limited their analyses by reducing frequencies for cross-cycle comparisons or based on the spectral properties and frequency bandwidth of DH type II bursts (Aguilar-Rodriguez et al. 2005; Gopalswamy et al. 2005), acceleration (Prakash et al. 2011), CME detection rate (Michalek et al. 2019), end frequency of DH type II bursts (Patel et al. 2021), and CME kinematics (Pappa Kalaivani et al. 2022). This study aims to bridge these gaps by conducting a comprehensive statistical investigation of all DH type II bursts and their associated CMEs during SC 24, focusing on spectral properties, kinematics, and their broader implications for space weather forecasting. This work is a complete reference for the DH type II bursts in SC 24 for the solar radio community.

This manuscript is organized as follows: Section 2 describes the data sources and methodology. Section 3 presents the results, emphasizing the association between DH II bursts and CMEs, while Section 4 concludes the study with key findings and implications for space weather forecasting.

2. Observations and Data Analysis

For this study, we analyzed 180 DH type II radio bursts from SC 24 (2009 January–2019 December), using data sets from the Wind/WAVES Type-II Burst Catalog and the SOHO/LASCO CME Catalog. The Wind/WAVES catalog,⁴ maintained by the Coordinated Data Analysis Workshop (CDAW) Data Center at NASA and the Catholic University of America, compiles observations from the Radio and Plasma Wave Experiment (WAVES) onboard the Wind spacecraft (Bougeret et al. 1995) and the SWAVE instrument onboard the STEREO (Bougeret et al. 2008). These instruments provide continuous measurements of solar radio emissions in the 14 MHz–20 kHz frequency range,

⁴ https://cdaw.gsfc.nasa.gov/CME_list/radio/waves_type2.html

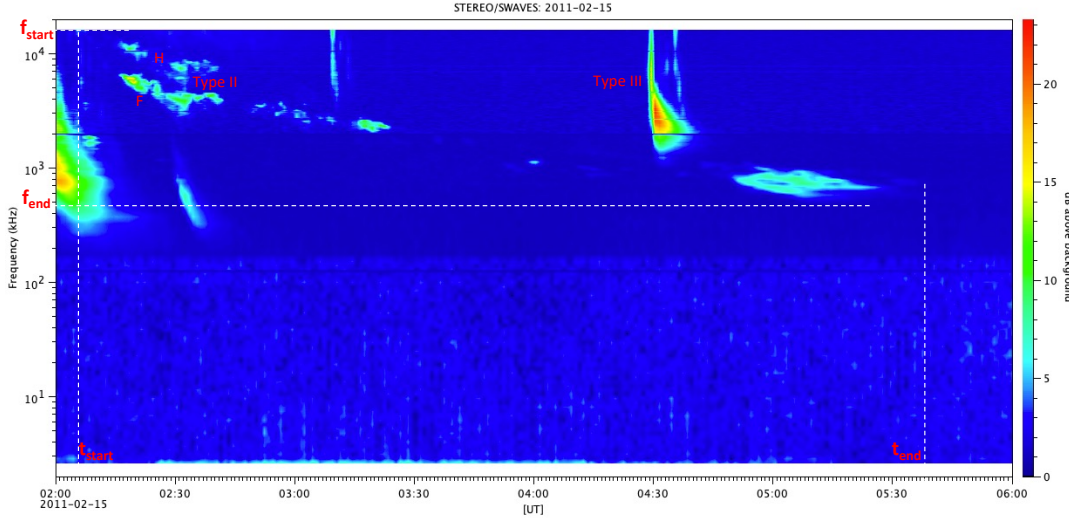


Figure 1. Dynamic spectrum recorded by STEREO/SWAVES on 2011 February 15, displaying a long-duration DH type II radio burst. The white dotted lines mark the starting and ending frequencies and times of the burst. This figure demonstrates the general methodology for determining these parameters from the radio dynamic spectrum. Note that DH type II bursts have weak signals at the starting time and are mixed with type IV bursts.

with SWAVE extending coverage up to 16 MHz to complement Wind/WAVES observations (Gopalswamy et al. 2008, 2010; Patel et al. 2022). The catalog also identifies CMEs linked to DH type II radio bursts, offering a comprehensive database for studying their characteristics. Further, to investigate CME characteristics, we used the SOHO/LASCO catalog, which records white-light observations of the solar corona spanning 2–30 solar radii (R_s). This catalog includes all manually identified CMEs observed by LASCO since 1996. LASCO’s three telescopes (C1, C2, and C3) initially provided coverage, but only data from C2 and C3 have been used since C1 was discontinued in 1998 to ensure uniformity (Gopalswamy et al. 2019).

From these data sets, we derived key parameters including start and end times, start and end frequencies, and drift rates of DH type II bursts (see Figure 1) and source locations, speeds, and accelerations of their associated CMEs. Calculations for CME dynamics, such as linear speed, were conducted within LASCO’s field of view (FOV), which serves as an average speed estimate. The behavior of CMEs—whether accelerating, decelerating, or moving at constant speed—was classified based on the sign and magnitude of their residual acceleration. An acceleration estimate requires a minimum of three height–time measurements, but the accuracy improves with more measurements. Thus, the accelerations are labeled with ** indicating that they are unreliable whenever based on only three measurements, whereas the missing data points are indicated by * in Table A1 (Appendix). No specific criteria were applied for selecting events; the data set represents all DH type II bursts during SC 24. Table 1 summarizes the statistical values (mean, median, and standard deviation) of the analyzed parameters. The inconsistency in the number of events used for statistical analyses, such as Pearson

Table 1

The Properties of DH type II Bursts and the Associated CMEs with their Mean, Median, and Standard Deviation (σ) of all the DH Type II Bursts of SC 24

Property	Mean	Median	S. D. (σ)
CME linear speed (km s^{-1})	1058.06	958	530.74
CME speed at $20 R_s$ (km s^{-1})	1049.99	966.5	532.58
CME height (R_s)	3.22	3	0.74
CME width (deg)	288.39	360	99.3
CME residual acceleration (m/s^{-2})	−17.46	−9.6	43.45
DH II starting frequency (kHz)	12169.72	14000	4939.15
DH II ending frequency (kHz)	2152.69	500	3022.07
DH II drift rate (kHz s^{-1})	3.19	1.06	5.24
DH II frequency bandwidth (kHz)	10017.03	15100	5353.08
DH II duration (minutes)	345.62	136.5	453
CME-DH II starting time lag (minutes)	12.36	2.5	55.63

correlations, stems from inherent measurement errors associated with space-based observatories. Despite these limitations, the data set offers robust insights into the spectral and kinematic properties of DH type II bursts and their associated CMEs.

3. Results and Discussion

3.1. Properties of DH Type II Bursts

3.1.1. Starting and Ending Frequency of DH Type II Bursts

The frequency of type II bursts decreases over time as the electron density in the solar atmosphere decreases with increasing heliocentric distance. As a result, the local plasma frequency, which determines the emission frequency, lowers. High-frequency radio emissions leave the solar corona faster than low-frequency emissions, resulting in a dynamic spectrum that shifts from high to low frequencies over time. Figure 2(a) and (b)

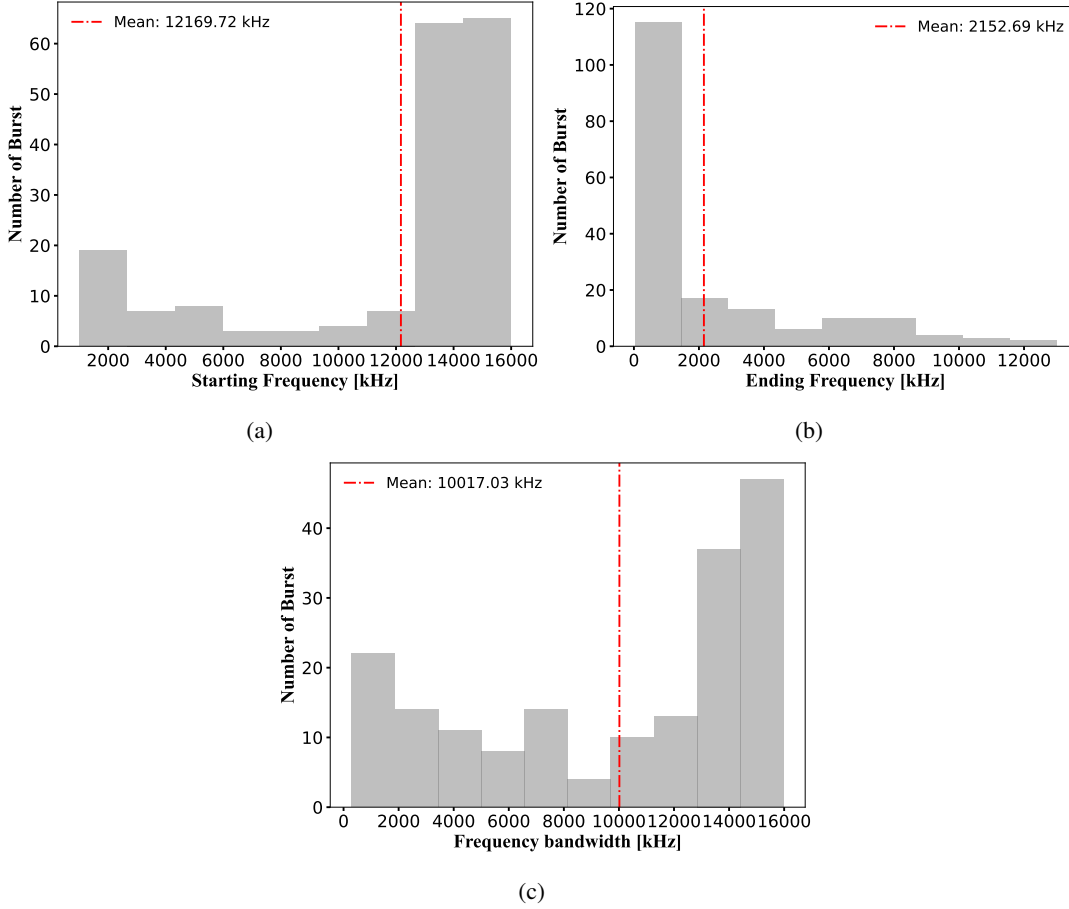


Figure 2. Distribution showing the DH II starting frequency in panel (a), ending frequency in panel (b), and frequency bandwidth in panel (c). The red dash–dotted line in each panel indicates their corresponding mean values.

presents histograms of the starting and ending frequencies of DH type II events, respectively. Most events (about 71%) have starting frequencies between 13,000 and 16,000 kHz, with 36% peaking at 16,000 kHz—the upper limit of Wind/WAVES after complementing observations from SWAVES. The mean starting frequency is $(12,169.72 \pm 4939.15)$ kHz. In contrast, the mean ending frequency is significantly lower, at (2152.69 ± 3022.07) kHz, with 64% (115 out of 180 events) below 1000 kHz. This trend suggests that CME-driven shocks in SC 24 are relatively robust, propagating into regions of comparatively low coronal density.

The bandwidth of type II emissions is determined by the electron density of the medium through which the shock propagates, making the observed spectral profiles sensitive to variations in density within the shock region. Figure 2(c) illustrates the distribution of bandwidths of DH type II bursts, defined as the difference between starting and ending frequencies. The mean bandwidth is $(10,017.03 \pm 5353.08)$ kHz, indicating wide spectral coverage. This wide bandwidth highlights the capability of DH type II bursts during SC 24 to span a broad

spectrum observable by both space-based and ground-based instruments.

3.1.2. Duration and Drift Rate of DH Type II Bursts

The duration of DH type II bursts (D) was analyzed, with the distribution presented in Figure 3(a). The average duration is (345.62 ± 453) minutes, with 51% of events (92 out of 180) lasting less than 180 minutes.

The drift rates of DH type II bursts, calculated as $(df/dt) = (f_{\text{start}} - f_{\text{end}})/D$, exhibit a broad distribution (Figure 3(b)) with the average of (3.19 ± 5.24) kHz s^{−1}. Notably, 67% of events (121 out of 180) exhibited drift rates below this mean, indicating that most bursts have relatively narrow spectra (and/or longer duration). The large uncertainty (± 5.24 kHz s^{−1}) implies heterogeneous shock conditions, with drift rates more sensitive to local coronal structures than bulk CME motion. This skewness suggests that the majority of shocks propagate through moderate coronal density gradients (Mann et al. 1999), while the high-drift-rate tail likely arises from strong shocks in steep gradients (Vršnak et al. 2002; Vlahos et al. 2019).

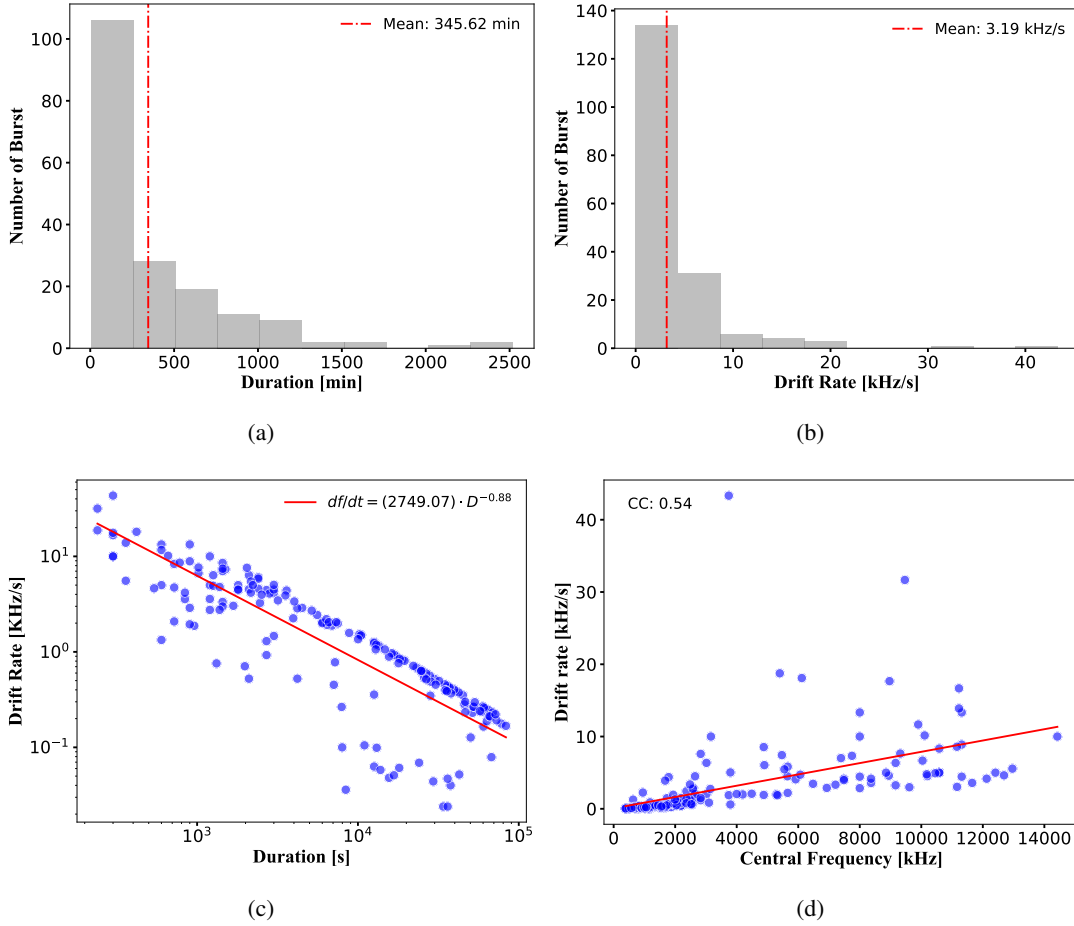


Figure 3. Distribution showing the duration in panel (a) and drift rate of DH type II burst in panel (b). The red dash-dotted line in each panel indicates their mean values. A scatterplot of the drift rate and the duration of the DH type II burst is illustrated in panel (c). The red line represents the power law of the form $df/dt = aD^b$ with their best-fitting values shown in the legend. Panel (d) illustrates the drift rate as a function of central frequency, along with the best-fit linear regression line (red solid) and corresponding Pearson correlation coefficient in the legend.

Figure 3(c) presents the relationship between the drift rate (df/dt) of DH type II radio bursts and their duration (D), demonstrating a power-law dependence of the form $df/dt = aD^b$, with $a = 2749.07$ and $b = -0.88$ as the best-fitted coefficients. This is consistent with the expected inverse dependence according to the definition; however, the variability in frequency bandwidth across events introduces scatter, and the idealized mathematical relation does not fully manifest in our sample. Moreover, deviation from an idealized D^{-1} trend implies that df is not constant but modulated by shock-plasma interactions (Kouloumvakos et al. 2019). The power-law dependence shown in the picture highlights the underlying relationship between shock-driven radio emission characteristics and frequency drift rate. It suggests that the drift rate decreases in proportion to the duration of DH type II bursts, a tendency supported by physical processes in the interplanetary medium and solar corona. This finding is consistent with a previous study by Cane & Erickson (2005) and Reiner (2001), who found correlations between drift

rate and shock parameters such as velocity and density gradients within key atmospheric layers.

Additionally, the dependence of drift rates on frequency was also analyzed, revealing a moderate positive correlation ($CC = 0.54$) between drift rates and central frequencies, calculated as the geometric mean of the starting and ending frequencies (Figure 3(d)).

3.2. Properties of Associated CMEs

3.2.1. Speeds of CMEs

The distribution of CME speeds associated with DH type II bursts during SC 24 is shown in Figure 4. CME speed is measured as the linear speed (hereafter speed of CMEs referred to as linear speed), obtained by applying a first-order polynomial fit to height-time measurements, representing the average speed within the LASCO FOV. The histogram reveals a mean CME speed of $(1058.06 \pm 530.74) \text{ km s}^{-1}$, indicating that these events are generally fast (Gopalswamy & Mäkelä 2019). Notably, 34

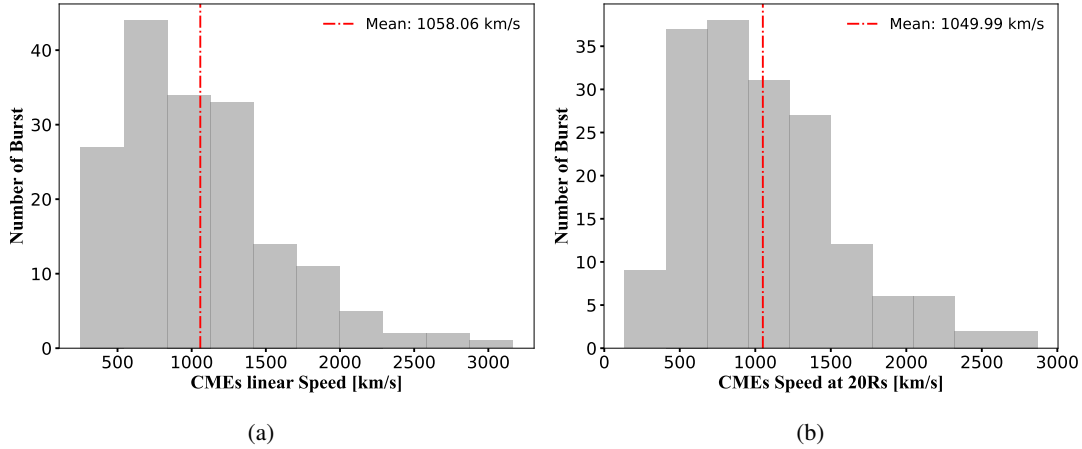


Figure 4. Distribution showing the number of DH type II bursts associated with CMEs, illustrating their linear speed in panel (a) and their speed at $20 R_s$ in panel (b). The red dash–dotted line indicates the mean value for each distribution.

CMEs exceeded speeds of 1500 km s^{-1} , with the highest recorded at 3163 km s^{-1} on 2017 September 10. CME speed is further characterized at a height of 20 solar radii (R_s) using a quadratic speed derived from a second-order polynomial fit to the height–time measurements. This metric allows for standardized event comparisons, accounting for variations in the time required to reach a final size. The average speed at $20 R_s$ is $(1049.99 \pm 532.58) \text{ km s}^{-1}$, closely aligning with the linear speed. To gain further understanding, we further divide the speed distribution into three groups: (i) Approximately 39% of CMEs have speeds below 800 km s^{-1} , (ii) Around 45% fall within the range of $800\text{--}1500 \text{ km s}^{-1}$, and (iii) Nearly 16% exceed 1500 km s^{-1} . Thus, it can be affirmed that SC 24 is accompanied by fast CMEs, a feature integral to understanding their role in driving DH type II radio bursts.

3.2.2. Widths of CMEs

CME widths are a critical factor in determining their impact on space weather events (Kahler et al. 1984). The apparent width of CMEs significantly influences their kinetic energy estimates, with broader and faster CMEs showing strong associations with DH type II bursts (Gopalswamy et al. 2003; Prakash et al. 2012). To explore this relationship, we analyzed the widths of CMEs during SC 24. Determining the actual width of halo CMEs presents challenges, particularly due to projection effects in 2D images, which obscure the true dimensions, especially for disk events (longitudes within $\pm 60^\circ$). As shown in Figure 5(a), CME widths during SC 24 ranged from 26° to 360° , with a mean value of (288.39 ± 99.30) . Full halo CMEs accounted for approximately 62% of the events, reinforcing observations by Michalek et al. (2019), who reported that SC 24 CMEs were generally broader than those in SC 23. Additionally, the correlation between CME width and speed was evaluated using Pearson correlation coefficients. Figure 5(b) depicts a positive and moderate correlation coefficient ($CC = 0.51$). This finding aligns with

prior studies of DH-associated CMEs, which reported similar correlations ($CC = 0.44$; Gopalswamy 2000; Gopalswamy et al. 2001a). Notably, limb CMEs, which are less affected by projection effects, showed a stronger correlation ($CC = 0.56$; Gopalswamy et al. 2001a), further highlighting the influence of geometry on width measurements. These results underscore the role of broad and fast CMEs in driving space weather phenomena and their significant association with DH type II radio bursts.

To better understand how CME geometry affects our results, we excluded full halo CMEs, events significantly influenced by our observational perspective. We focused on the characteristics of other limb and partial halo events. As illustrated in Figure 5(c), the CME widths in this reduced sample range from 26° to 292° , with a mean width of 172.29° . This mean is notably narrower than the overall sample mean of 288.39° , underscoring the impact of excluding halo events on the distribution (Michalek et al. 2006, 2015). The effect of this exclusion is further reflected in the speed–width relationship. Figure 5(d) shows a positive correlation between CME width and linear speed, as evidenced by a Pearson correlation coefficient of $CC = 0.37$. Although this correlation is weaker than that observed for CMEs in the complete data set ($CC = 0.51$), it remains consistent with the general trend that faster CMEs tend to be wider (Yashiro et al. 2004; Gopalswamy et al. 2010). This reduction in correlation likely indicates a diminished dynamic range in CME widths after removing the most extreme halo events. These refined subset analyses better emphasize the influence of projection effects on estimating CME properties. By omitting full halo events, the observed distributions more accurately reflect the actual physical widths, particularly for CMEs directed toward the Sun’s edge. Even within this smaller subset, the persistent positive speed–width relationship confirms the fundamental link between CME dynamics and geometry. This reinforces the established view that broad and fast CMEs are more likely to drive shocks capable of

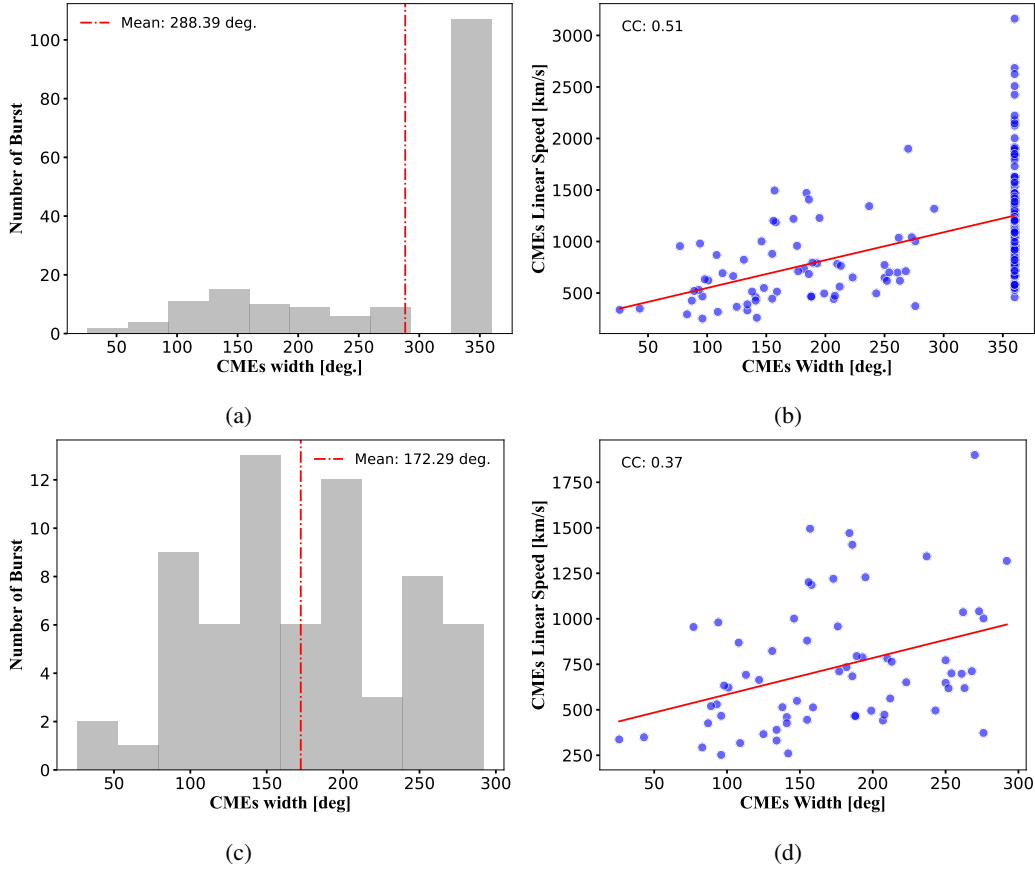


Figure 5. Distribution showing the number of DH type II bursts associated with CMEs during SC 24, illustrating their width in panel (a). Panel (b) shows the correlation between CME speed and width. Panels (c) and (d) display the corresponding width distribution and speed–width correlation after excluding full halo CMEs. The red dash–dotted line indicates the mean value for each distribution in panels (a) and (c), whereas the red solid line represents the best-fit linear regression in panels (b) and (d), with the corresponding Pearson correlation coefficient (CC) given in the legend.

producing DH type II radio bursts (Cane et al. 1987; Cane & Erickson 2005).

3.2.3. Acceleration of CMEs

The number of height–time sampling points influences the estimation of CME velocity and acceleration, with limited sampling contributing to uncertainties (Michalek et al. 2019). LASCO coronagraph images, restricted to detecting apparent speeds and widths, exacerbate these uncertainties. Within the LASCO FOV, gravitational and propelling forces significantly diminish, leaving deceleration due to drag as the dominant force. Consequently, the CME catalog reports “residual acceleration” reflecting these dynamics (Gopalswamy et al. 2019).

Figure 6(a) illustrates the distribution of accelerations for CMEs associated with DH type II radio bursts during SC 24. The observed acceleration values range from -240 to 165.9 m s^{-2} , with a mean of $(-17.46 \pm 43.45) \text{ m s}^{-2}$. Based on the classification by Pappa Kalaivani et al. (2022), we found: 12% of CMEs are accelerating ($a > 7.5 \text{ m s}^{-2}$), 58% are decelerating ($a < -7.5 \text{ m s}^{-2}$), and 30% exhibit constant speeds (-7.5 m s^{-2}

$> a < 7.5 \text{ m s}^{-2}$). When categorized by CME width, the following trends emerge: Halo CMEs are predominantly decelerated, with a mean acceleration of $(-22.83 \pm 50.07) \text{ m s}^{-2}$, narrow CMEs ($< 120^\circ$) are nearly constant, averaging $(-5.01 \pm 15.17) \text{ m s}^{-2}$ and moderately wide CMEs ($120^\circ < \text{CMEs width} < 360^\circ$) are slightly decelerated, with a mean of $(-7.8 \pm 25.24) \text{ m s}^{-2}$. These findings align with earlier work by Prakash et al. (2014), though some discrepancies exist due to differing classification schemes. The relationship between CME acceleration and speed also reveals notable behavior. CMEs are (i) Constant for speeds $< 800 \text{ km s}^{-1}$ (with a mean of $-5.78 \pm 9.09 \text{ m s}^{-2}$), (ii) Slightly decelerated for speeds between 800 and 1500 km s^{-1} (mean: $-14.20 \pm 23.68 \text{ m s}^{-2}$), and (iii) More decelerated for speeds $> 1500 \text{ km s}^{-1}$ (mean: $-45.73 \pm 82.64 \text{ m s}^{-2}$). Figure 6(b) shows a scatterplot of CME acceleration versus speed, revealing a weak negative correlation ($\text{CC} = -0.39$). These results indicate that the wide and fast CMEs typical of SC 24 experience greater deceleration. Pappa Kalaivani et al. (2022) further attributed SC 24’s reduced heliospheric pressure to enabling greater expansion and deceleration of CMEs, resulting in peak speeds at lower altitudes compared to SC 23. This

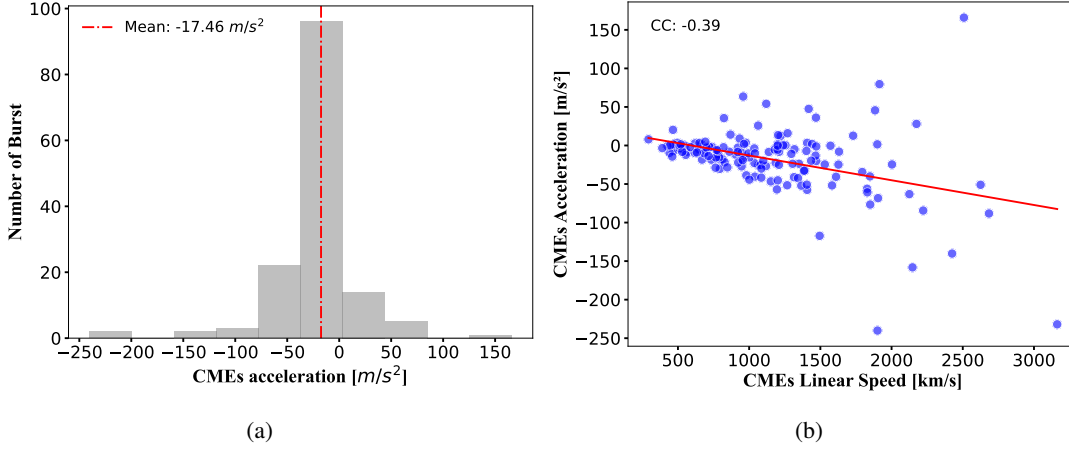


Figure 6. Distribution showing the acceleration (residual acceleration) of the associated CMEs under consideration in panel (a). The red dash–dotted line indicates the corresponding mean value. Correlation plots for the CME acceleration and speed are shown in panel (b). Here, the red solid line is the best-fit linear regression line with the Pearson correlation coefficient (CC) value given in the legend.

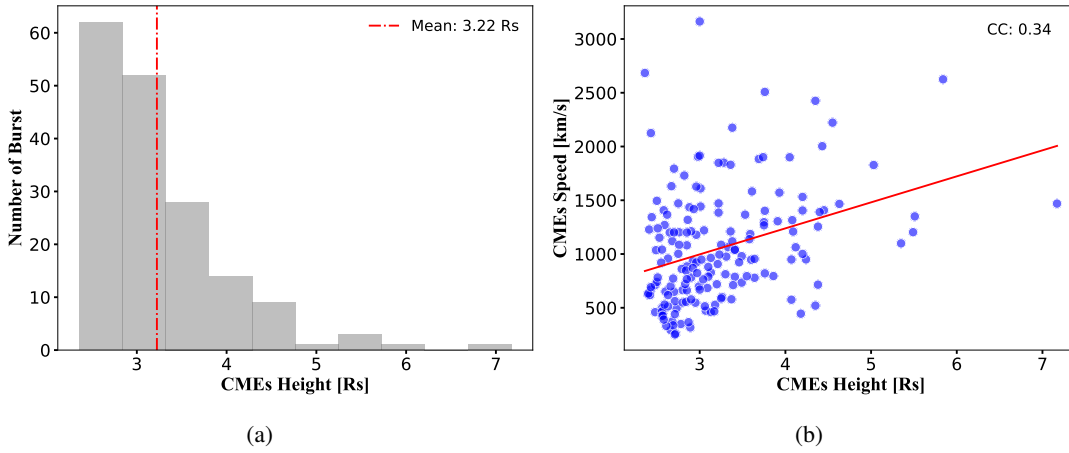


Figure 7. Distribution illustrating the height of associated CMEs during SC 24 in panel (a). The red dash–dotted line indicates the corresponding mean value. The correlation plot of the height of CMEs as first appeared in LASCO/C2 and speed is shown in panel (b). The red solid line is the best-fit linear regression line with the Pearson correlation coefficient (CC) value given in the legend.

phenomenon aligns with the observation that DH type II radio emissions in SC 24 originate at higher starting frequencies (see Section 3.1.1).

3.2.4. Height of CMEs

From the height–time measurements provided in the SOHO/LASCO CME Catalog, we derived the heights of CMEs at their starting times, corresponding to their first appearances in LASCO/C2. The height distribution, shown in Figure 7(a), indicates values ranging from $2.36 R_s$ to $19.73 R_s$, with a mean height of $(3.22 \pm 0.74) R_s$. An outlier, recorded on 2014 December 19, reached a height of $19.73 R_s$ and was excluded from the mean calculation. The correlation between CME speed and height is weak, with a correlation coefficient of $CC = 0.34$ as shown in Figure 7(b). This result suggests limited direct dependence between these parameters during the initial

appearance of CMEs. Errors in determining CME heights are unavoidable due to the reliance on single-position angle measurements in 2D images, which inherently limit accuracy.

3.3. Correlation Between DH Type II Bursts and Associated CMEs

We examined the temporal relationship between DH type II bursts and their associated CMEs by analyzing the time lags between their respective onsets. Specifically, we compared the CME start times, defined by their first appearance in the LASCO/C2 or C3 coronagraphs, with the start times of the DH type II radio bursts. The start times of the DH type II bursts were taken from the first clear detection in the dynamic spectrum (Wind/WAVES or STEREO/SWAVES). Figure 8(a) illustrates the distribution of these time delays. The calculated mean delay is (12.36 ± 55.63) minutes, suggesting that DH type II bursts

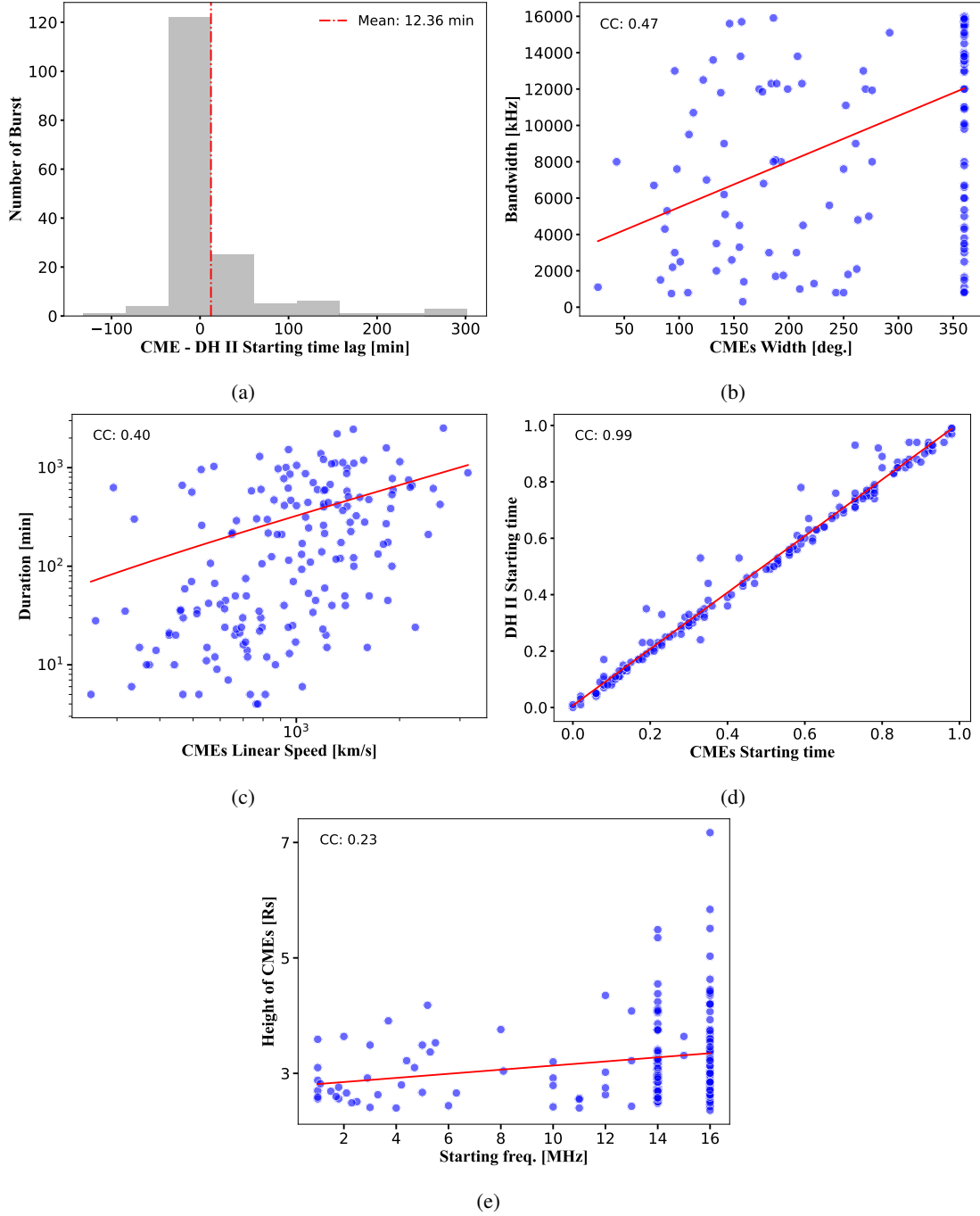


Figure 8. In panel (a), the distribution of the time lag between the CME starting time and the duration of DH II bursts is illustrated. The red dash–dotted line indicates the mean value of this time lag. In panel (b), the DH type II bandwidth is plotted against the associated CME width; in panel (c), the duration of DH II bursts is plotted against the speed of CMEs; in panel (d), the starting time of DH type II bursts is analyzed against the CME starting time; and finally in panel (e), the starting height of CMEs is plotted as a function of starting frequency of DH type II bursts. Each panel features a solid red line representing the best-fit linear regression line and the corresponding Pearson correlation coefficient (CC) value provided in the legend.

generally occur shortly after CME onset. However, five events with unusually long delays, where DH type II bursts followed CMEs by nearly a day, were excluded from the statistical calculation to avoid skewing the mean. Such extended delays could result from the CME becoming super-Alfvénic only at

greater heliocentric distances, possibly due to either a low initial CME speed or a high background Alfvén speed (Gopalswamy et al. 2001b). Alternatively, the delayed appearance of CMEs in LASCO images may be attributed to their slow propagation beneath the occulting disk, leading to a discrepancy between the

true onset and the observed first detection (Gopalswamy et al. 2003; Prakash et al. 2017). These results reinforce the close temporal association between CME initiation and DH type II radio emission, supporting the role of CME-driven shocks as the dominant source mechanism for these bursts.

To explore potential dependencies, we examined the relationship between the bandwidth of DH type II bursts and the widths of associated CMEs. Figure 8(b) displays a scatterplot showing a weak correlation ($CC = 0.47$), suggesting that while broader CMEs might contribute to wider frequency bandwidths, other factors likely influence this relationship. These results underscore the wide spectral range and robust shock dynamics associated with DH type II bursts in SC 24, contributing to a deeper understanding of their role in solar and space weather studies. To investigate the relationship between burst duration and CME kinematics, we conducted correlation analyses. The scatterplot in Figure 8(c) shows a moderate positive correlation between burst duration and CME speed ($CC = 0.40$), consistent with findings by Patel et al. (2021).

The DH type II bursts closely follow the onset time of CMEs with a brief delay. To further investigate this phenomenon, we conduct a cross-correlation analysis to determine the relationship between the timing of CMEs and the starting times of DH type II bursts. It can be noted here that to enable the statistical correlation analysis between DH type II bursts and CME starting times, all clock times were converted into fractional day values (e.g., 00:00 UT = 0.0, 24:00 UT = 1.0), allowing proper numerical analysis and visualization. A significant linear correlation ($CC = 0.99$) was observed between the two time series, as shown in Figure 8(d), reinforcing the idea that DH type II bursts are primarily driven by CME-driven shocks (Patel et al. 2021). The minimal delay observed further supports the scenario in which the shock forms early in the CME's outward propagation.

In addition, we explored the link between DH type II bursts and solar flares, particularly X-class events. Of the 180 DH type II bursts examined, 23 were found to be temporally associated with X-class flares (among 47 flares identified during SC 24). This suggests that stronger and longer-duration flares may contribute to conditions conducive to type II shock generation. This trend is consistent with earlier findings by Prakash et al. (2014), emphasizing the role of impulsive magnetic energy release through reconnection in flare-driven shocks.

Using correlation analysis, we also investigated the expected physical link between the starting frequency of DH type II bursts and the heights of their associated CMEs at the inferred time of shock formation. The starting frequency of a type II burst is theoretically connected to the local plasma frequency, which scales with the square root of the ambient electron density ($f_{pe} \propto \sqrt{n_e}$). Since coronal density falls with altitude, one would expect an inverse link between the emission frequency and the shock generation height (Gopalswamy et al. 2001c). However, as

shown in Figure 8(e), our analysis reveals only a weak correlation ($CC = 0.23$) between these two variables. Several physical and observational factors may contribute to this weak correlation: (i) inhomogeneities in coronal density that affect the plasma frequency at a given height (Mann et al. 1999), (ii) projection effects that underestimate the true radial distance (Gopalswamy et al. 2001a; Reiner et al. 2003), as CME heights are typically measured from plane-of-sky coronagraph observation, (iii) variability in the location and timing of shock formation, including cases where the emission arises from CME flanks rather than the nose (Cane & Richardson 2003; Cane & Erickson 2005; Magdalenic et al. 2014; Zucca et al. 2018) and (iv) measurement uncertainties in determining the exact start time of bursts and the corresponding CME front position. These observational and physical complexities likely obscure the idealized frequency–height relation, highlighting the need to account for coronal variability and 3D CME geometry in such analyses.

4. Summary and Conclusions

CMEs are large expulsions of plasma and magnetic fields from the solar corona, which can significantly impact the solar system. Among these, more energetic CMEs are associated with type II radio bursts, which are characterized by their ability to generate radio emissions across a broad range of frequencies (Gopalswamy & Thompson 2000; Gopalswamy et al. 2001a, 2001b). These bursts originate as a result of shock waves produced by the CME as it travels through the solar atmosphere and into the heliosphere. High-energy CMEs are capable of producing type II bursts that are detected at various solar radii, indicating their extensive reach. This phenomenon implies that the CME-driven shocks are not only persistent but also capable of sustaining strong radio emissions. The ability to observe these emissions across different spectral domains, ranging from meters to kilometers, supports the notion that the energy and intensity of the CME's propagation can produce lasting effects on the surrounding space environment (Zucca et al. 2018; Alissandrakis et al. 2021). In this study, we have investigated the characteristics of CMEs associated with DH type II radio bursts using the consistent and extensive high-quality data available on radio bursts (Wind/WAVES and STEREO) and CMEs (SOHO/LASCO). The statistical and spectral properties of DH type II bursts during SC 24 offer profound insights into the solar phenomena driving these emissions. Our analysis revealed key characteristics of CMEs associated with DH type II bursts, emphasizing their speeds, widths, accelerations, and temporal relationships with the radio bursts. Below, we discuss the significant findings and their broader implications:

1. *Association between DH type II bursts and CMEs.* The observed high correlation ($CC = 0.99$) between the starting times of DH type II bursts and CMEs underscores the critical role of CME-driven shocks in generating these bursts. This finding corroborates earlier studies, affirming the dominant role of CMEs over other drivers, such as flares,

particularly in the DH regime. However, there is a time delay of about 12.36 minutes between the onset of CMEs and the DH type II bursts. These findings support the idea that CME-driven shocks are the primary source mechanism for these bursts and demonstrate the strong temporal correlation between CME initiation and DH type II radio emission. A comparison between CME samples including and excluding halo events reveals the significant influence of projection effects. When halo CMEs are excluded, the mean CME width decreases from 288.39° to 172.29° , and the speed–width correlation weakens from $CC = 0.51$ to $CC = 0.37$. Despite this, the positive trend persists, indicating that broader and faster CMEs remain key drivers of DH type II bursts even in less projection-biased samples.

2. *CME dynamics.* Our results highlight that faster and broader CMEs are strongly associated with DH type II bursts, consistent with SC 24’s reduced heliospheric pressure. The mean CME speed ($1058.06 \pm 530.74 \text{ km s}^{-1}$) suggests enhanced shock-driving capabilities. Notably, the deceleration of halo CMEs (with a mean acceleration of $-22.83 \pm 50.07 \text{ m s}^{-2}$) and for speeds $> 1500 \text{ km s}^{-1}$ (mean: $-45.73 \pm 82.64 \text{ m s}^{-2}$) aligns with drag-dominated dynamics observed in previous cycles, where aerodynamic drag slows faster CMEs at greater heliocentric distances (Gopalswamy et al. 2005; Pappa Kalaivani et al. 2022).
3. *Frequency and bandwidth characteristics.* The starting frequencies of DH type II bursts in SC 24 (mean: $12169.72 \pm 4939.15 \text{ kHz}$) indicate shock onset at relatively low heliocentric distances. The broad frequency bandwidths (mean: $10017.13 \pm 5353.08 \text{ kHz}$) further support the persistence and strength of these shocks. These findings suggest that SC 24’s CMEs retained significant energy over extended distances, making them efficient drivers of type II bursts across the DH spectrum. Additionally, the mean cutoff frequency is much lower at (2152.69 ± 3022.07) kHz, with 64% (115 out of 180 occurrences) falling below 1000 kHz. This trend indicates that CME-induced shocks in SC 24 are notably resilient, extending into areas of relatively low coronal density.
4. *Temporal durations and drift rates.* The average duration of DH type II bursts (345.62 ± 453 minutes) reflects extended shock activity in SC 24. The moderate correlation ($CC = 0.54$) between drift rates and central frequencies suggests a consistent relationship between burst evolution and the underlying shock dynamics. This aligns with the broader understanding of how density gradients in the solar corona influence radio burst evolution. Further, the observed power-law $df/dt = 2749.07D^{-0.88}$ suggests that the duration of a radio burst plays a significant role in shaping its frequency evolution, with longer-duration bursts exhibiting

lower drift rates. These scaling relationships have significant ramifications. They not only help us better understand the dynamics of CMEs, but they also help us comprehend how these shocks affect the generation of type II radio bursts. Therefore, understanding how burst duration determines frequency evolution is crucial to developing theoretical models that explain solar and interplanetary phenomena. We ought to improve our understanding of the fundamental processes governing solar radio emissions and their observational properties by combining these results with well-established models in the years to come.

5. *Solar cycle comparisons.* Comparisons with SC 23 reveal intriguing differences in CME kinematics and burst properties, attributable to SC 24’s unique heliophysical conditions. The observed deceleration of high-speed CMEs and the higher starting frequencies of DH type II bursts in SC 24 highlight the cycle’s subdued activity and altered heliospheric environment.

This study significantly enhances our understanding of solar radio bursts and carries important implications for space weather forecasting. The robust correlations identified between CMEs and the parameters of DH type II bursts serve as predictive markers for forecasting SEP events and geomagnetic storms. Future research should prioritize the integration of multi-spacecraft observations and an in-depth investigation of SC 25 to build upon these findings. Moreover, exploring the potential influence of additional drivers, such as solar flares and eruptive prominences, will further refine our comprehension of type II burst phenomena. The capacity of high-energy CMEs to generate type II bursts across various solar radii emphasizes their extensive reach and powerful nature, underscoring their significant impact on both solar dynamics and the larger heliospheric environment. Furthermore, the persistent shock emissions observed across multiple wavelengths highlight the critical importance of studying these events for a holistic understanding of solar-terrestrial interactions.

Acknowledgments

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Appendix

Table A1
List of All 180 DH Type II Bursts ((a)–(f)) and Associated CMEs ((g)–(k)) Observed by Wind/WAVES During Solar Cycle 24

S. No.	Starting Date (a)	Starting Time (b)	Ending Date (c)	Ending Time (d)	Frequency (kHz) (e)	Drift Rate (kHz s ⁻¹)(f)	Start Time (g)	Width (deg) (h)	Speed (km s ⁻¹)(i)	Speed @20R _s (km s ⁻¹) (j)	Accel. (m s ⁻²) (k)
1	2010-08-01	9:20	2010-08-01	17:30	2000–700	0.044	*	*	*	*	*
2	2010-08-18	6:05	2010-08-18	7:45	13000–700	2.050	5:48	184	1471	1416	−20.2
3	2011-01-13	9:15	2011-01-13	10:05	16000–3500	4.167	9:36	122	664	675	2.2
4	2011-01-27	12:20	2011-01-27	12:35	16000–8000	8.889	12:36	43	349	264	**
5	2011-02-13	17:50	2011-02-13	18:00	16000–8000	13.333	18:36	276	373	793	**
6	2011-02-15	2:10	2011-02-15	5:40	16000–480	1.231	2:24	360	669	471	−18.3
7	2011-02-24	12:50	2011-02-24	15:10	1000–700	0.036	7:48	158	1186	1117	−22.4
8	2011-03-07	14:30	2011-03-07	15:00	16000–7000	5.000	14:48	261	698	632	−8.3
9	2011-03-07	20:00	2011-03-08	8:30	16000–200	0.351	20:00	360	2125	2034	−63.1
10	2011-05-09	21:00	2011-05-10	4:00	16000–900	0.599	20:57	292	1318	1306	−4.9
11	2011-05-29	21:10	2011-05-30	13:40	16000–90	0.268	21:24	186	1407	1416	3.4
12	2011-06-02	8:00	2011-06-02	8:25	15000–4000	7.333	8:12	360	976	996	3.6
13	2011-06-04	7:00	2011-06-04	13:45	16000–300	0.646	6:48	360	1407	1294	−57.6
14	2011-06-04	22:00	2011-06-05	1:30	16000–25	1.268	22:05	360	2425	2281	−140.2
15	2011-06-07	6:45	2011-06-07	18:00	16000–250	0.389	6:49	360	1255	1265	0.3
16	2011-06-21	3:07	2011-06-21	3:21	10000–7000	3.571	3:16	360	719	708	−1.3
17	2011-08-02	6:15	2011-08-02	7:30	16000–3000	2.889	6:36	268	712	596	**
18	2011-08-04	4:15	2011-08-05	17:00	13000–60	0.098	4:12	360	1315	1208	−41.1
19	2011-08-08	18:10	2011-08-08	20:10	6000–400	0.778	18:12	237	1343	1207	−42.3
20	2011-08-09	8:20	2011-08-09	8:35	16000–4000	13.333	8:12	360	1610	1506	−40.6
21	2011-09-06	2:00	2011-09-06	23:40	14000–200	0.177	2:24	360	782	1662	**
22	2011-09-06	22:30	2011-09-07	15:40	16000–150	0.256	23:05	360	575	582	**
23	2011-09-22	11:05	2011-09-22	24:00	14000–70	0.300	10:48	360	1905	1809	−68.3
24	2011-09-24	12:50	2011-09-24	22:45	16000–300	0.440	12:48	360	1915	2089	79.6
25	2011-09-25	5:30	2011-09-25	6:00	16000–8000	4.444	5:12	193	788	576	**
26	2011-10-21	13:15	2011-10-21	13:50	16000–6500	4.524	13:25	109	317	331	**
27	2011-11-09	13:30	2011-11-09	17:00	16000–400	1.238	13:36	360	907	869	−12.1
28	2011-11-26	7:15	2011-11-27	00:00	10000–50	0.165	7:12	360	933	975	9
29	2011-12-21	3:00	2011-12-21	8:15	16000–400	0.825	3:12	360	1064	977	−25.5
30	2011-12-25	18:45	2011-12-25	18:55	14000–7000	11.667	18:48	125	366	266	**
31	2012-01-02	15:00	2012-01-02	15:45	16000–4000	4.444	15:12	360	1138	1109	−8.4
32	2012-01-19	15:00	2012-01-20	2:45	16000–100	0.376	14:36	360	1120	1390	54.1
33	2012-01-23	4:00	2012-01-23	15:00	16000–40	0.403	4:00	360	2175	2216	28
34	2012-01-27	18:30	2012-01-28	4:45	16000–150	0.430	18:27	360	2508	2761	165.9
35	2012-03-05	4:00	2012-03-05	12:20	16000–400	0.520	4:00	360	1531	1476	−24.6
36	2012-03-07	1:00	2012-03-08	19:00	16000–30	0.106	0:24	360	2684	2594	−88.2
37	2012-03-09	4:10	2012-03-09	6:05	14000–1000	1.884	4:26	360	950	876	**
38	2012-03-10	17:55	2012-03-11	12:30	14000–30	0.209	18:00	360	1296	1261	−10.9
39	2012-03-13	17:35	2012-03-13	00:00	16000–200	0.684	17:36	360	1884	1987	45.6
40	2012-03-18	0:20	2012-03-18	1:20	16000–200	4.389	0:24	360	1210	1194	−8.2
41	2012-03-24	0:40	2012-03-24	10:40	16000–300	0.436	0:24	360	1152	1020	−46.6
42	2012-03-26	23:15	2012-03-26	23:55	16000–1500	6.042	23:12	360	1390	1318	−32.3
43	2012-03-27	21:45	2012-03-27	22:30	4000–1500	0.926	22:00	101	622	623	**
44	2012-04-09	12:20	2012-04-09	13:00	16000–5000	4.583	12:36	360	921	909	−2.8
45	2012-04-15	2:30	2012-04-15	2:50	16000–4000	10.000	2:24	173	1220	1269	12.3
46	2012-05-17	1:40	2012-05-17	6:20	16000–300	0.935	1:48	360	1582	1473	−51.8
47	2012-07-04	17:00	2012-07-04	17:20	14000–8000	5.000	17:24	360	662	0	**

Table A1
(Continued)

S. No.	Starting Date (a)	Starting Time (b)	Ending Date (c)	Ending Time (d)	Frequency (kHz) (e)	Drift Rate (kHz s ⁻¹)(f)	Start Time (g)	Width (deg) (h)	Speed (km s ⁻¹)(i)	Speed @ 20R _s (km s ⁻¹) (j)	Accel. (m s ⁻²) (k)
48	2012-07-05	22:40	2012-07-05	23:50	3000–800	0.524	22:00	94	980	855	−38.7
49	2012-07-06	23:10	2012-07-07	3:40	16000–300	0.969	23:24	360	1828	1730	−56.1
50	2012-07-08	16:35	2012-07-08	22:00	16000–300	0.805	16:54	157	1495	1442	−117.2
51	2012-07-12	16:45	2012-07-13	9:00	14000–250	0.235	16:48	360	885	2265	**
52	2012-07-17	14:40	2012-07-18	5:00	12000–150	0.230	13:48	176	958	1319	63.5
53	2012-07-19	5:30	2012-07-19	6:20	5000–600	1.467	5:24	360	1631	1616	−8
54	2012-07-23	2:30	2012-07-23	21:40	16000–20	0.232	2:36	360	2003	1972	−24.6
55	2012-08-31	20:00	2012-08-31	23:45	16000–400	1.156	20:00	360	1442	1446	2
56	2012-09-27	23:55	2012-09-28	10:15	16000–250	0.423	00:12	360	947	817	−27.1
57	2012-10-22	1:50	2012-10-22	11:15	1000–200	0.024	(09/28)	243	496	528	3.5
							(10/21)				
58	2013-01-16	22:00	2013-01-17	1:30	1000–200	0.063	19:00	250	648	616	−4.9
59	2013-03-15	7:00	2013-03-15	21:30	14000–100	0.266	7:12	360	1063	1161	25.8
60	2013-04-11	7:10	2013-04-11	15:00	10000–200	0.348	7:24	360	861	819	−8.1
61	2013-04-18	18:00	2013-04-18	19:10	16000–4000	2.857	18:24	199	495	470	−2.9
62	2013-04-21	20:25	2013-04-21	22:12	14000–1700	1.916	20:36	212	562	470	−8.3
63	2013-05-13	2:20	2013-05-13	3:00	16000–2000	5.833	2:00	360	1270	1325	15.9
64	2013-05-13	16:15	2013-05-13	19:10	16000–300	1.495	16:07	360	1850	1723	−76.6
65	2013-05-14	1:16	2013-05-14	8:20	16000–240	0.619	1:25	360	2625	2548	−51
66	2013-05-15	1:49	2013-05-15	7:57	16000–230	0.714	1:48	360	1366	1196	−52.1
67	2013-05-22	13:10	2013-05-24	6:00	16000–150	0.108	13:25	360	1466	1438	−13.2
68	2013-06-21	3:35	2013-06-21	5:15	14000–2000	2.000	3:12	270	1900	1903	1.5
69	2013-06-28	1:53	2013-06-28	3:26	14000–400	2.437	2:00	360	1037	976	−22.8
70	2013-07-04	20:57	2013-07-04	21:27	11000–2900	4.500	20:12	188	468	391	−7.1
71	2013-08-06	2:01	2013-08-06	2:11	14000–11000	5.000	2:12	207	441	286	−9.6
72	2013-08-17	20:25	2013-08-18	3:05	1800–150	0.069	19:12	360	1202	1208	1.7
73	2013-08-30	2:34	2013-08-31	4:00	14000–50	0.152	2:48	360	949	884	−17.1
74	2013-09-06	22:29	2013-09-06	22:34	5000–2000	10.000	20:48	182	734	619	−18.4
75	2013-09-29	21:53	2013-09-30	21:00	14000–60	0.168	22:12	360	1179	1164	−5.3
76	2013-10-02	20:46	2013-10-02	21:10	10000–5200	3.333	20:36	263	619	636	2.7
77	2013-10-05	7:00	2013-10-05	14:46	16000–200	0.565	7:09	360	964	970	1.9
78	2013-10-11	7:23	2013-10-11	11:43	14000–100	0.891	7:24	360	1200	1182	−5.5
79	2013-10-13	18:47	2013-10-14	5:15	2100–600	0.040	14:12	83	293	448	8
80	2013-10-22	21:33	2013-10-22	22:08	14000–650	6.357	21:48	360	459	282	**
81	2013-10-25	15:08	2013-10-25	22:32	16000–200	0.593	15:12	360	1081	1015	−25.2
82	2013-10-26	3:01	2013-10-26	4:00	14000–200	3.898	3:12	208	473	497	1.3
83	2013-10-26	9:34	2013-10-26	10:10	14000–5000	4.167	9:48	141	460	135	−14.4
84	2013-10-27	18:12	2013-10-27	18:36	14000–1700	8.542	18:12	189	795	744	−18
85	2013-10-28	4:41	2013-10-28	11:51	14000–200	0.535	4:48	156	1201	1116	−45.2
86	2013-10-28	15:24	2013-10-28	15:29	14000–9000	16.667	15:36	360	812	674	−17.7
87	2013-11-04	5:10	2013-11-04	8:00	16000–450	1.525	5:12	360	1040	878	−40.4
88	2013-11-07	10:26	2013-11-07	20:04	16000–100	0.458	10:36	360	1405	1273	−50.8
89	2013-11-19	10:39	2013-11-19	20:20	14000–100	0.399	10:36	360	740	730	−2
90	2013-11-29	22:18	2013-11-30	9:20	1800–100	0.043	17:24	188	465	719	20.3
91	2013-12-05	12:45	2013-12-05	13:00	4200–1600	2.889	10:24	148	549	547	−0.1
92	2013-12-05	20:48	2013-12-05	21:35	14000–2500	4.078	*	*	*	*	*

Table A1
(Continued)

S. No.	Starting Date (a)	Starting Time (b)	Ending Date (c)	Ending Time (d)	Frequency (kHz) (e)	Drift Rate (kHz s ⁻¹)(f)	Start Time (g)	Width (deg) (h)	Speed (km s ⁻¹)(i)	Speed @ 20R _s (km s ⁻¹) (j)	Accel. (m s ⁻²) (k)
93	2013-12-07	7:43	2013-12-07	8:36	14000–3000	3.459	7:36	360	1085	854	−41.7
94	2013-12-12	3:55	2013-12-12	21:30	12000–70	0.188	3:36	276	1002	943	−15.3
95	2013-12-20	8:23	2013-12-20	13:24	1500–400	0.061	4:36	26	337	470	**
96	2013-12-28	17:31	2013-12-28	18:05	16000–500	7.598	17:36	360	1118	967	−26.7
97	2014-01-04	17:41	2014-01-04	18:47	9000–100	2.247	*	*	*	*	*
98	2014-01-04	19:03	2014-01-05	9:00	6500–100	0.127	*	*	*	*	*
99	2014-01-06	7:57	2014-01-06	22:30	14000–80	0.266	8:00	360	1402	1385	−7.1
100	2014-01-07	18:33	2014-01-08	21:00	14000–60	0.146	18:24	360	1830	1714	−60.8
101	2014-01-20	22:24	2014-01-20	22:36	14000–8000	8.333	22:00	360	721	707	−2.1
102	2014-02-18	2:16	2014-02-18	2:51	2000–900	0.524	1:36	360	779	712	−11.3
103	2014-02-20	8:05	2014-02-20	8:29	12000–7700	2.986	8:00	360	948	907	−9.5
104	2014-02-25	0:56	2014-02-25	11:28	14000–100	0.367	1:25	360	2147	2069	−158.1
105	2014-03-04	18:24	2014-03-04	20:10	16000–2000	2.201	18:48	360	794	692	−30.3
106	2014-03-05	13:33	2014-03-05	17:10	16000–500	1.190	13:48	360	828	716	−21.8
107	2014-03-25	7:52	2014-03-25	11:30	1700–400	0.099	5:36	223	651	680	3.4
108	2014-03-29	0:12	2014-03-29	0:48	14000–2200	5.463	23:48 (03/28)	138	514	476	−4
109	2014-03-29	17:59	2014-03-30	9:58	14000–200	0.240	18:12	360	528	505	−4.1
110	2014-04-02	13:42	2014-04-03	8:10	14000–60	0.210	13:36	360	1471	1468	−1.2
111	2014-04-02	18:49	2014-04-03	6:40	2400–200	0.052	*	*	*	*	*
112	2014-04-04	14:02	2014-04-04	14:07	14000–11000	43.333	14:12	96	467	482	1.3
113	2014-04-18	13:05	2014-04-18	22:50	14000–150	0.397	13:25	360	1203	1245	13.5
114	2014-05-07	16:24	2014-05-07	23:18	16000–200	0.636	16:24	360	923	842	−22.1
115	2014-05-08	3:21	2014-05-08	5:26	16000–1100	1.987	3:24	360	847	732	−28.4
116	2014-05-09	2:40	2014-05-09	4:30	14000–500	2.045	2:48	360	1099	1043	−19.8
117	2014-05-10	4:32	2014-05-10	8:37	16000–400	1.061	4:36	360	1086	934	−29.9
118	2014-06-10	12:58	2014-06-10	15:00	16000–1000	2.049	13:30	360	1469	1540	36.1
119	2014-06-12	22:14	2014-06-12	22:35	14000–6000	6.349	22:12	186	684	566	−10
120	2014-07-30	7:44	2014-07-30	8:00	6300–4500	1.875	7:00	254	700	684	−2.6
121	2014-08-01	18:58	2014-08-02	5:00	1000–150	0.024	18:36	360	789	704	−15.2
122	2014-08-22	10:37	2014-08-22	11:18	14000–6000	3.252	11:12	360	600	440	**
123	2014-08-25	15:20	2014-08-25	16:02	14000–4000	3.968	15:36	360	555	453	−12.2
124	2014-08-25	20:43	2014-08-25	21:00	14000–7200	6.667	20:48	177	711	692	**
125	2014-08-28	17:05	2014-08-28	22:08	16000–600	0.847	17:24	360	766	660	−15.5
126	2014-09-01	11:12	2014-09-01	20:05	16000–150	0.496	11:12	360	1901	1216	−240.1
127	2014-09-09	0:05	2014-09-09	13:00	11000–100	0.234	0:06	360	920	877	−8.4
128	2014-09-10	17:45	2014-09-11	12:00	14000–100	0.212	18:00	360	1267	1119	−51.6
129	2014-09-20	5:10	2014-09-20	5:30	14000–9700	3.583	5:24	87	426	714	**
130	2014-09-22	6:13	2014-09-22	6:50	16000–4900	5.000	6:12	252	618	497	−9.6
131	2014-09-23	23:41	2014-09-23	23:47	14000–12000	5.556	23:36	134	331	700	**
132	2014-09-24	20:54	2014-09-24	23:48	16000–500	1.485	21:30	360	1350	1210	−23.7
133	2014-10-02	21:23	2014-10-02	21:56	3300–1900	0.707	19:12	159	513	506	−0.5
134	2014-10-10	18:11	2014-10-10	18:33	2500–1500	0.758	16:12	210	782	745	−6.7
135	2014-10-21	12:33	2014-10-21	13:01	14000–8900	3.036	12:48	142	260	0	**
136	2014-11-08	16:57	2014-11-08	17:18	14000–7800	4.921	16:36	141	426	412	−0.8
137	2014-12-13	14:27	2014-12-13	14:51	14000–3900	7.014	14:24	360	2222	2111	−84.4
138	2014-12-17	4:09	2014-12-17	4:19	2900–2100	1.333	2:00	108	869	931	14.1
139	2014-12-17	5:00	2014-12-17	5:09	14000–11500	4.630	5:00	360	587	571	−2.1

Table A1
(Continued)

S. No.	Starting Date (a)	Starting Time (b)	Ending Date (c)	Ending Time (d)	Frequency (kHz) (e)	Drift Rate (kHz s ⁻¹)(f)	Start Time (g)	Width (deg) (h)	Speed (km s ⁻¹)(i)	Speed @20R _s (km s ⁻¹) (j)	Accel. (m s ⁻²) (k)
140	2014-12-18	22:31	2014-12-18	22:54	5100–1300	2.754	01:04 (19/12)	360	1195	1331	−57
141	2014-12-21	12:05	2014-12-21	12:28	14000–7400	4.783	12:12	360	669	498	**
142	2015-03-03	2:33	2015-03-03	2:37	8100–3600	18.750	1:48	213	764	681	−28.8
143	2015-03-06	8:00	2015-03-06	11:30	4700–200	0.357	7:12	155	880	1241	**
144	2015-03-10	0:10	2015-03-10	0:27	14000–6200	7.647	0:00	360	995	966	−10.2
145	2015-03-11	10:30	2015-03-11	14:50	1000–250	0.048	8:24	93	530	429	−8.3
146	2015-03-24	9:00	2015-03-24	11:47	14000–400	1.357	8:24	360	1794	1727	−34.4
147	2015-04-26	3:21	2015-04-26	3:33	8000–4600	4.722	3:24	360	820	809	−2.3
148	2015-05-05	22:24	2015-05-05	23:14	14000–500	4.500	22:24	360	715	685	−13.6
149	2015-05-12	3:00	2015-05-12	3:04	14000–6400	31.667	2:48	250	772	740	−5.9
150	2015-06-09	20:23	2015-06-09	22:35	2300–200	0.265	20:12	262	1036	1022	−3.8
151	2015-06-14	5:26	2015-06-14	5:41	3000–1250	1.944	4:12	195	1228	1355	**
152	2015-06-18	17:42	2015-06-18	19:40	3700–500	0.452	17:24	360	1305	1219	−23.7
153	2015-06-21	2:33	2015-06-21	21:20	5500–150	0.079	2:36	360	1366	1434	**
154	2015-06-22	18:20	2015-06-22	21:55	14000–300	1.062	18:36	360	1209	1147	−25.1
155	2015-06-25	8:35	2015-06-25	16:30	14000–150	0.486	8:36	360	1627	1594	−24.8
156	2015-07-01	16:08	2015-07-01	20:47	1000–150	0.051	14:36	360	1435	1385	−19.8
157	2015-08-22	7:07	2015-08-22	7:18	14000–7300	10.152	7:12	360	547	0	**
158	2015-09-18	4:54	2015-09-18	9:52	14000–400	0.761	5:00	131	823	1030	35.5
159	2015-09-20	18:23	2015-09-21	1:46	14000–300	0.515	18:12	360	1239	1240	0.2
160	2015-11-04	14:07	2015-11-04	15:14	14000–440	3.373	14:48	360	578	701	**
161	2015-11-09	13:21	2015-11-09	13:27	14000–9000	13.889	13:25	273	1041	1000	−10.2
162	2015-12-16	8:45	2015-12-16	8:57	5300–3800	2.083	9:36	360	579	487	**
163	2015-12-23	1:18	2015-12-23	1:23	12000–6700	17.667	1:25	89	520	531	1.6
164	2015-12-28	11:50	2015-12-28	21:45	14000–180	0.387	12:12	360	1212	1228	**
165	2016-01-02	0:55	2016-01-02	3:08	1100–300	0.100	23:24 (01/01)	360	1730	1755	12.7
166	2016-02-05	20:28	2016-02-05	23:31	1650–500	0.105	*	*	*	*	*
167	2016-02-05	22:35	2016-02-05	22:55	5200–1900	2.750	21:24	155	445	448	0.2
168	2016-05-04	14:20	2016-05-04	14:34	14000–10500	4.167	14:12	134	390	339	−3.4
169	2016-05-24	17:00	2016-05-24	20:50	1500–700	0.058	*	*	*	*	*
170	2016-08-15	18:21	2016-08-15	18:28	11000–3400	18.095	17:24	98	633	584	−9
171	2017-04-23	6:00	2017-04-23	6:13	15000–8300	8.590	6:00	77	955	838	−19
172	2017-07-14	1:18	2017-07-14	21:30	14000–70	0.192	1:25	360	1200	1200	−0.1
173	2017-07-23	5:27	2017-07-23	6:12	4400–900	1.296	4:48	360	1848	1790	−40.1
174	2017-09-04	20:27	2017-09-05	4:54	14000–210	0.453	20:12	360	1418	1611	47.5
175	2017-09-06	12:05	2017-09-07	8:00	16000–70	0.222	12:24	360	1571	1570	−0.3
176	2017-09-10	16:02	2017-09-11	6:50	16000–150	0.297	16:00	360	3163	2868	−232
177	2017-09-12	7:38	2017-09-12	7:43	16000–13000	10.000	8:03	96	252	0	**
178	2017-09-17	11:45	2017-09-17	12:35	16000–900	5.033	12:00	360	1385	1308	−32.8
179	2017-10-18	5:48	2017-10-18	12:40	16000–400	0.631	8:00	146	1001	928	−44.3
180	2019-05-03	23:52	2019-05-04	0:16	13000–2300	7.431	23:24	113	692	744	4.9

Note. Note that the “*” indicates missing data in the catalog and “***” indicates the accelerations are unreliable whenever based on only three measurements.

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