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On some characteristics of Radio-Loud and Radio-Quiet front side full Halo-CMEs and Their associated Flares during Solar Cycles 23 and 24

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On some characteristics of Radio-Loud and Radio-Quiet front side full Halo-CMEs and Their associated Flares during Solar Cycles 23 and 24

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Abstract: We have studied differences between the characteristics of radio-loud (RL) and radio-quiet (RQ) front side full halo coronal mass ejections (FFHCMEs) (angular width 360^0) during the period 1996 – 2014. In our study, we have examined the properties of FFHCMES as: (i) RL and RQ CMEs, (ii) slow and fast CMEs among RL and RQ CMEs (iii) associated flares and (iv) associated radio bursts. During the study period, we found that 26% of slow CMEs are RL and 82 % of fast CMEs are RL. The average speeds of RL and RQ CMEs are 1370km/s and 727 km/s respectively. Most of the RQ CMEs occurs around the disc centre. The mean acceleration value of RL-CMEs is more than twice that of RQ-CMEs and mean deceleration value of RL CMEs is very less compare to RQ events. RQ events are associated with C-and M-class flares, while RL events are associated with M- and X-class flares, which imply RQ CMEs are less energetic than RL CMEs. The average bandwidth of type II radio burst associated with FFHCMEs and solar flares is larger than general population of km and DH type II radio bursts.

Keywords: CME; Radio burst; Solar corona; Solar flare

Introduction

Coronal mass ejection (CME) is an eruption of magnetized plasma from the Sun into the interplanetary medium and it is among the main Heliospheric disturbances (Mittal and Narain, 2010). Type II bursts are produced by shocks which are driven by CMEs accelerated electrons. A CME can produce an IP shock only when its speed exceeds both the Alfvén speed and the solar wind speed. Type II radio bursts contain information about the shock and ambient medium in which the shock propagates when shocks accelerate electrons in the ambient medium to form type II radio burst in the energy range 0.2 – 10 keV (Bale *et al.*, 1999; Mann and Klassen, 2005; Kahler *et al.*, 2005, Gopalswamy *et al.*, 2010). The type II radio burst formation may take place at any height in the inner or outer corona, which defines limits in its wavelength between metres and kilometres. Zhang *et al.*, (2001), shows CMEs are mainly accelerated below 3 *R*s where m type II radio bursts are generated. The study of type II solar radio bursts and their properties in association with CMEs have been studied by solar physicist for more than half century (Kundu, 1965, Nelson and Melrose, 1985, Cane, 2000, Goplaswamy, 2008 and references therein, Sharma et al., 2008, 2012, 2015).

CMEs, flares and radio burst have been a major field of research in solar physics and space science for several decades. CMEs are believed to be the causes of many geo-effective activities such as geomagnetic storms (Mittal and Narain, 2010). Front side full halo CMEs, are good potential candidates, which drive hazardous space weather in the form of intense solar energetic particle (SEP) events and severe geomagnetic storms because they can directly affect the Earth's magnetosphere but all front side HCMEs are not geoeffective (Gopalswamy, 2004, Moon et al., 2005). CMEs at solar disk centre, those accompanied by decametric-hectometric (DH) type II radio bursts are identified as sources of space-weather disturbances (Prakash et al., 2014). CMEs associated with type II radio bursts with m and DH wavelengths are more energetic than most CMEs, those are associated with SEPs (Gopalswamy, 2003; Cliver et al., 2004). CMEs associated with type II radio bursts in metric and DH wavelengths are characterised as radio-loud (RL) and as radio-quiet (RQ) when they are not associated with type II radio bursts in metric and DH wavelengths (Sheeley et al., 1984). Gopalswamy et al., (2002) and Sharma et al, (2015) shows that CMEs which produce type II radio emission in DH wavelength is known as radio rich or radio loud CMEs. Gopalswamy *et al.* (2008), suggested that the reason for the radio-quietness of CMEs are (1) the lower kinetic energy within the fast and wide CME population, (2) smaller soft X-ray flare sizes, and (3) the eruption at large angles from the Sun – observer line. Here we are interested to study DH and km type II burst associated full front side halo coronal mass ejections (FFHCMEs). CME energy and Alfvén speed profile of the ambient medium are primarily responsible for the radio quietness of fast and wide CMEs (Gopalswamy, 2004). Properties of general population of CMEs compared to CMEs which are associated with metric, DH and m-to-km type II bursts for period 1997-2004 are studied by Gopalswamy et al., (2005). Gopalswamy et al., (2008) again study RL and RQ CMEs for the period 1996-2005. RL CMEs are twice as wide as the RQ CMEs and RQ CMEs have a narrow expanding bright part with a large extended diffusive structure (Michalek et al., 2007). The particle acceleration in RQ shocks occurs predominately in a quasi-perpendicular shocks. Energetic storm particle (ESP) events associated with RQ shocks are also weaker than those associated with RL shocks. Hence, studying RL and RQ CMEs helps in better understanding the physical mechanism behind the CME-shock association and other related phenomena (Mäkelä et al., 2009). The shocks that generate metric type II radio bursts become sub-Alfvénic for some distance and then become strong enough to produce type II radio bursts at a later time in the DH or km wavelength domain (Gopalswamy *et al.*, 2010). Here, we study type II burst associated full front side halo CMEs (FFHCMEs; width 360 degree) and their association with solar flares, which we analyzed from two different aspects (slow FFHCMEs and fast FFHCMEs). Prakash et al. (2009), studied relationship between m-type-II radio burst and DH- type-II radio burst for 38 events observed by Caugoora radio observatory and found that those DH- type-II radio burst are not continuation of m- type-II radio burst are well correlated with flares and CMEs in their energy release. Prakash et al. (2012) examined acceleration characteristics of 61 limb events assuming that CMEs to be RL CMEs when they had a signature in DH wavelengths that occurs in the period from 1997 to 2008 of Solar Cycle 23. In their study Prakash et al., (2014) found that RL CMEs produces more energetic storms than RQ CMEs.

Properties of flares and CMEs associated with metric and DH type II radio bursts have been studied by several authors (Lara et al., 2003, Gopalswamy et al., 2005, Prakash et al., 2009, Suresh and Shanmugaraju, 2015). Gopalswamy *et al.* (2001, 12) show that CMEs associated with long-wavelength type II radio bursts like DH type radio bursts and large flares are decelerated in the field of view of the SOHO/LASCO. Lara et al. (2003) found that m-CMEs were more energetic than general population of CMEs but less energetic than DH CMEs. Suresh and Shanmugaraju (2015) examined 552 fast RL and RQ CMEs and found that there is no considerable difference between accelerated and decelerated RL CMEs and RQ CMEs respectively, but there is significant difference in their properties when they are associated with flare.

In this paper we investigated various characteristics of both RL and RQ halo CMEs for the period between 1996 and 2014, which covers solar cycle 23 and 24. We refer CMEs as RL which produce type-II bursts in DH and km wavelength. The paper is organized in 4 sections. Section 1 is introduction, section 2 contains data analysis, section 3 contains the results and discussion, and conclusions are summarized in the last section 4.

2. Data Analysis

In present study we have analysed only 310 FFHCMEs selected from 657full halo CME events observed during the period 1996 – 2014 by SOHO/LASCO. CME data were collected from the SOHO/LASCO online catalogue http://cdaw.gsfc.nasa.gov/CME_list/index.html (Brueckner *et al.*, 1995). These events are selected on the basis of following criteria:

i) The source location of the event should be clear and back side events are neglected. The source location is identified from the corresponding flare location.

ii) Events without speed data in the SOHO/LASCO catalogue were also neglected.

Flare events were searched and selected within a time window of one hour when the CME was first detected. Flare events were taken from the GOES. The radio quietness is defined as the absence of type II radio bursts in km and/or DH wavelength domain.

We have used the following criteria in the classification of events.

1. We have selected FFHCMEs as RQ and RL based on their association with type II radio bursts identified in data from the *Wind*/Plasma and Radio Waves (Bougeret *et al.*, 1995) spacecraft in the frequency range equal or below than 16 MHz. WIND/WAVES data is available online at http://www-lep.gsfc.nasa.gov/waves/data_products.html. Classifying on basis of type II radio bursts, 178 events out of the 359 FFHCME events are RL and 181 events are

RQ. Since WIND/WAVES did not detect any event during June-2013 to Dec-2014, so we left out 49 events and considered only 310 events for the analysis. In total, 57% of the sample are RL CMEs (178/310) and 43 % are RQ CMEs (132/310).

2. We divided FFHCMEs into two groups: (i) slow and moderate FFHCMEs (*v<900 km/s*) and (ii) fast FFHCMEs (v>900 km/s). Out of 310 front side full halo CMEs, 173 events (56 %) are fast. The remaining 137 CMEs (44 %) are slow and moderate events (hereafter we have used only slow word for slow and moderate). Since we have grouped total events into two groups; fast and slow FFHCMEs. So there are 142 events are RL FFHCMEs out of 173 fast events i.e. 82%, and 31 events are RQ FFHCMEs, i.e. 18%. Out of the remaining 137 slow events, 26% (36/137) are RL and 74 % (101/137) are RQ FFHCMEs.

3. Results and Discussion

In this section, the various physical properties of RL and RQ FFHCMEs are analyzed without making any duty cycle correction and projection effect correction.

3.1 CMEs Speed

We have investigated 310 FFHCMEs during 1996-2014 to determine the mean speed which is 1097 km/s, where as the mean speed of general population of CMEs is 435 km/s (Mittal et al., 2009 and Mittal and Narain 2009). Speed of FFHCMEs is 2.5 times of general speed of CMEs. Figure 1 shows the speed distribution of 310 FFHCMEs and shows that distribution of speed ranges from 200 km/s to more than 2500 km/s and peak occurs at 500 km/s. Figure 2 compares the speed distribution for RL & RQ events. The average speed of RL events is 1370 km/s which is consistent with the mean speed 1358 km/s as reported by Suresh and Shanmugaraju (2015) and average speed of RQ events is 727 km/s which is much small in compare to results given by Gopalswamy et al. (2008) and Suresh and Shanmugaraju (2015). The speed of RL events is larger than speed of FFHCMEs while the speed of RQ is smaller than speed of FFHCMEs.

With respect to the RQ FFHCMEs the average speed of RL CMEs is much higher for fast CMEs and lower for slow CMEs.

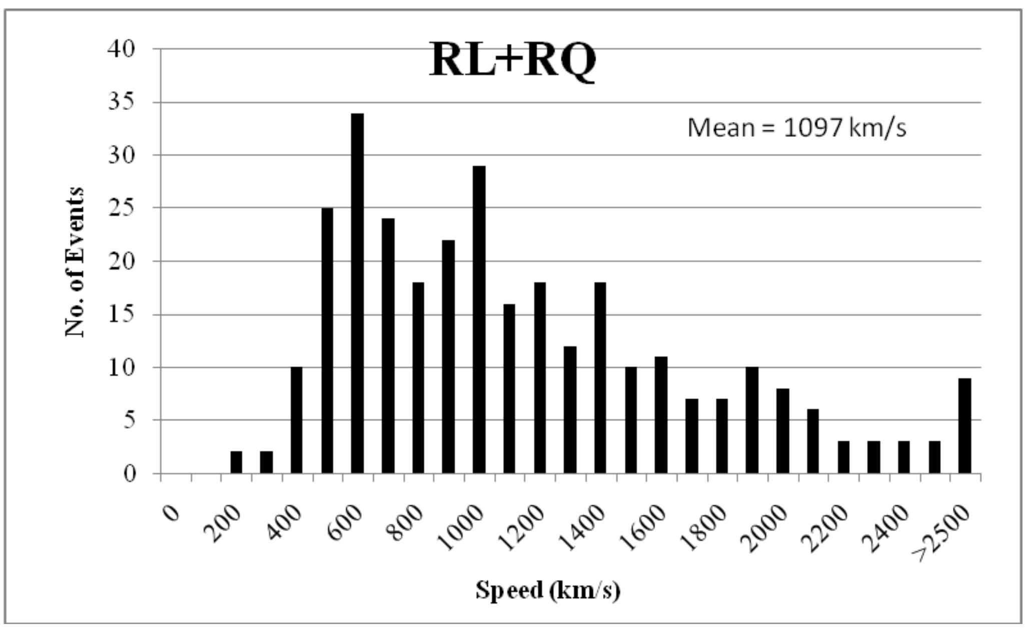

Figure 1: Histrogram shows speed distribution of RL and RQ CMEs for 310 events.

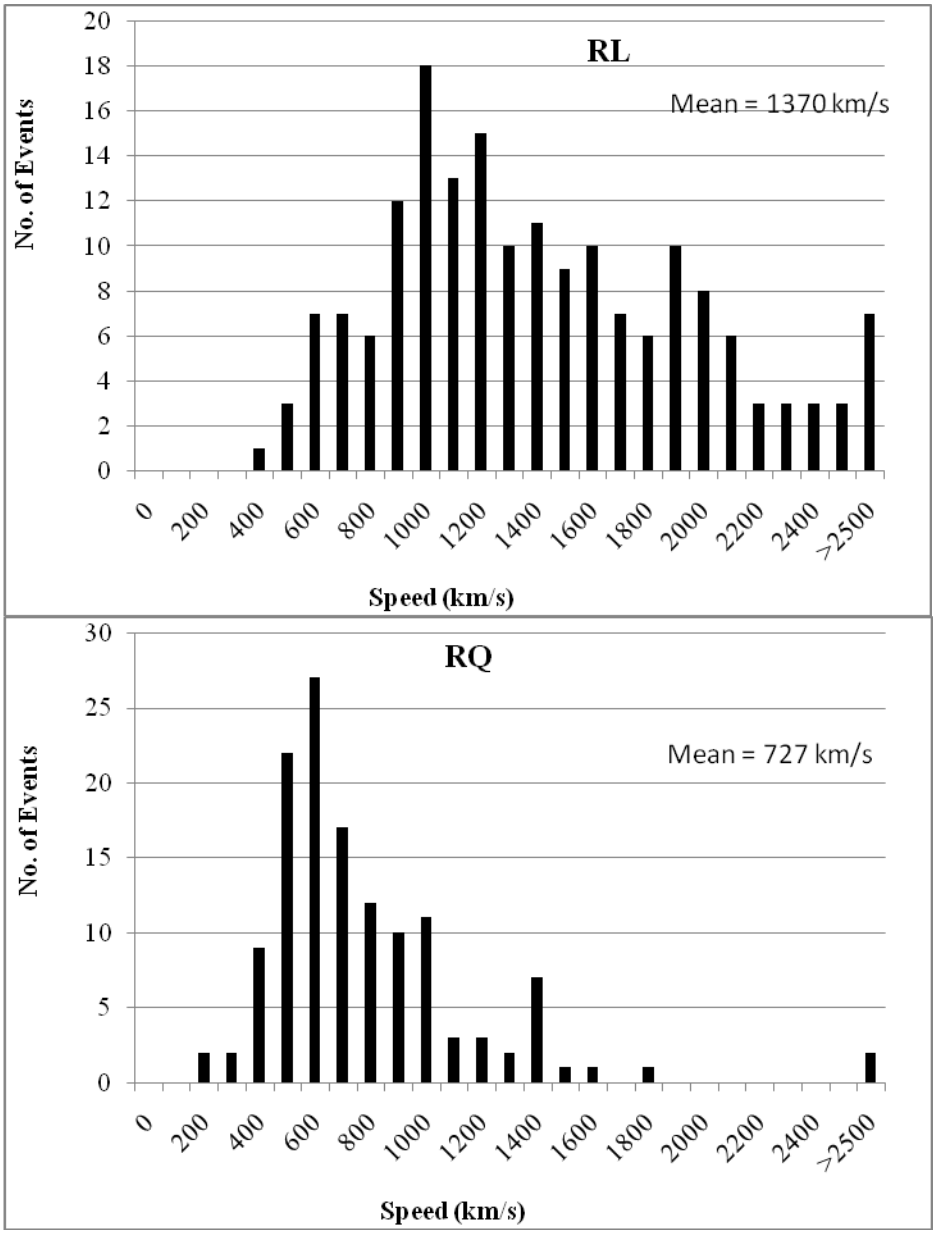

Figure 2: Upper shows distribution of speed for RL events while lower shows distribution of speed for RQ events.

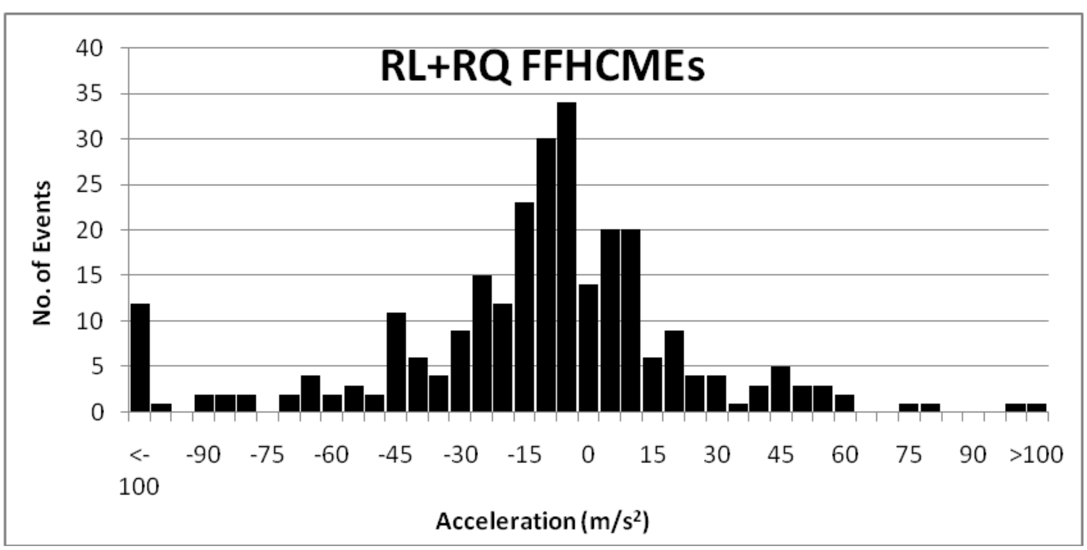

Figure: 3 Histrogram shows distribution of acceleration.

3.2 CMEs Acceleration

Figure 3 shows acceleration distribution of 274 FFHCMEs. We left out 36 events whose accelerations were uncertain due to three point data set. Average acceleration of these events is -13.3 m/s^2 and a peak occurs at -5 m/s^2. About 64% events are deceleration and 31% events are accelerating only 5% events have little or zero acceleration.

Figure 4 shows the distribution of acceleration for RL and RQ FFHCMEs, whereas figure 5 shows acceleration distribution for fast and slow FFHCMEs. Average acceleration of RL events is 27.51 m/s^2 and average deceleration of RL events is -37.4 m/s^2. Average acceleration of RQ events is 11.92 m/s^2 and average deceleration of RQ events is -13.3 m/s^2, as shown in table 1. On an average, fast CMEs are decelerated down to -17.17 ms^{-2}, while slow CMEs are decelerated up to -5.35 ms^{-2}. The average acceleration of 111 slow CMEs is found -5.35 m/s^2, while average acceleration of 163 fast CMEs is -17.17 m/s^2. There are 40 accelerated events and 71 events are decelerated in RQ and 49 events are accelerated and 114 events are decelerated in RL during the study period.

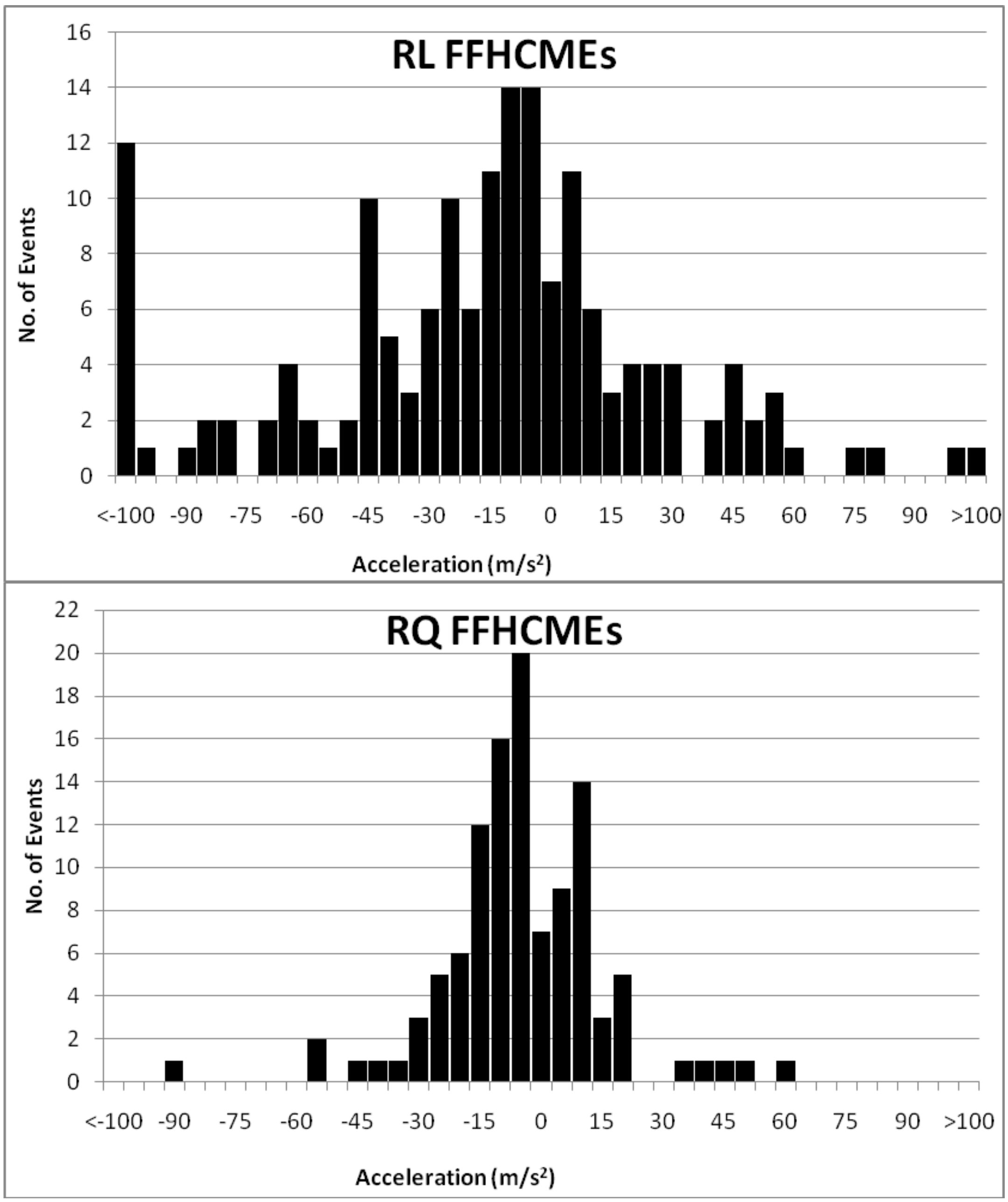

Figure: 4 Histrogram shows distribution of acceleration. Upper shows for RL events and lower shows for RQ events.

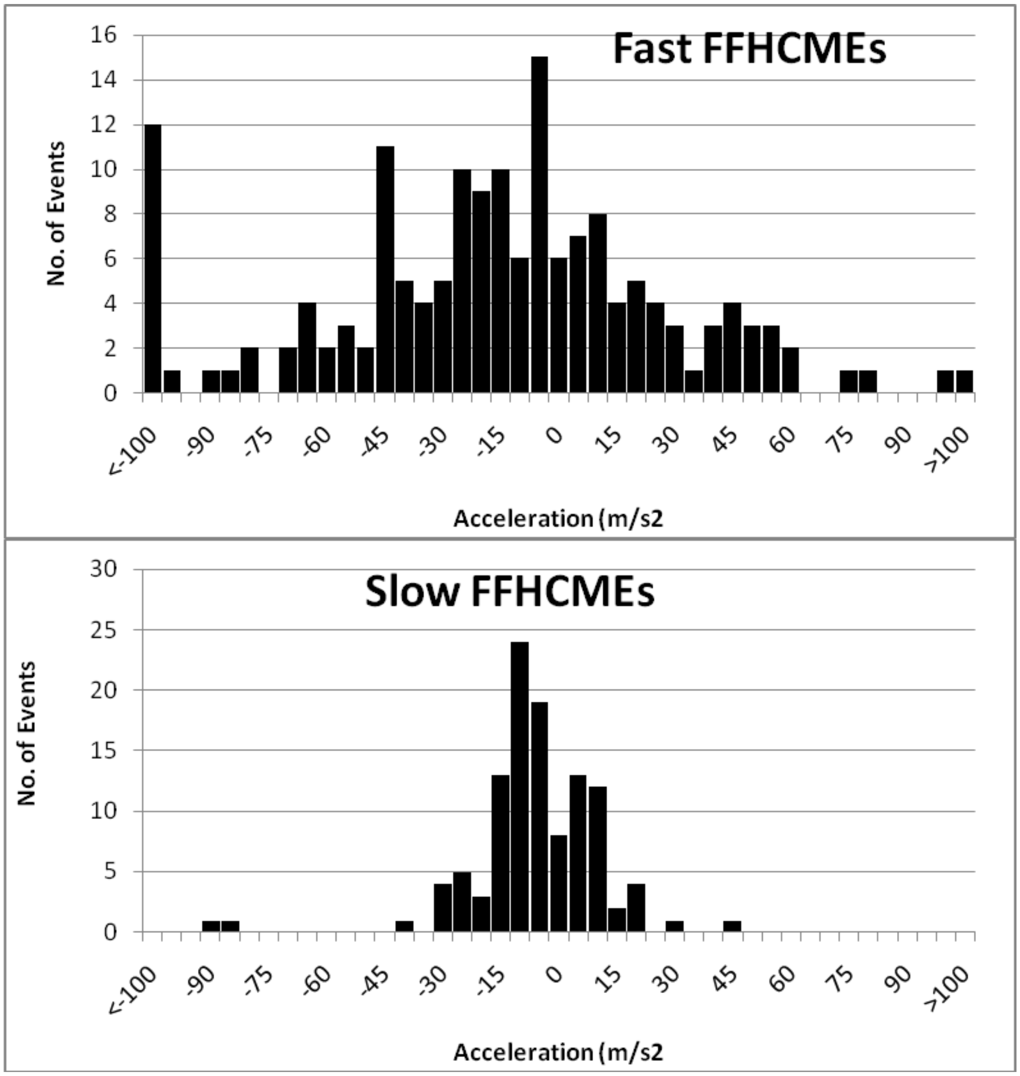

Figure: 5 Histrogram shows distribution of acceleration. Upper shows for fast events and lower shows for slow events.

From figure 4 it is clear that RL FFHCMEs decelerate much more in compare to RQ FFHCMEs. Figure 5 shows fast CMEs decelerate much more. From figure it is clear that fast FFHCMEs decelerate down to less than -100 m/s^2, while slow FFHCMEs decelerate down to -45 m/s^2.

The correlation between speed and acceleration of FFHCMEs is shown in figure 6. From figure it is clear that there is no correlation between speed and acceleration of FFHCMEs. Figure 7 and 8 shows relation between speed and acceleration of FFHCMEs for RL and RQ and fast and slow events respectively. We found that faster events decelerate more with correlation coefficient r = 0.32 between speed and acceleration of FFHCMEs, while slow FFCMEs decelerate with correlation coefficient r = 0.10. We found that (48/163) 30% events of RL events accelerate and (108/163) 66% decelerate while (36/111) 33% of RQ events accelerate and remaining (68/111) 61% decelerate.

The scatter plot may show that more FFHCMEs decelerate than accelerate, and that more of the faster CMEs have a large deceleration than a large acceleration.

Table 1 shows average acceleration and deceleration for fast and slow RL and RQ FFHCMEs.

Table 1: Average acceleration and deceleration of RL CMEs and RQ FFHCMEs

	Fast RL CMEs	Fast RQ CMEs	Slow RL CMEs	Slow RQ CMEs	RL CMEs	RQ CMEs
Ave. acceleration (m/s^2)	30.12	26.69	14.16	6.32	27.51	11.92
Ave. deceleration (m/s^2)	-41.69	-26.4	-19.36	-8.86	-37.4	-13.3

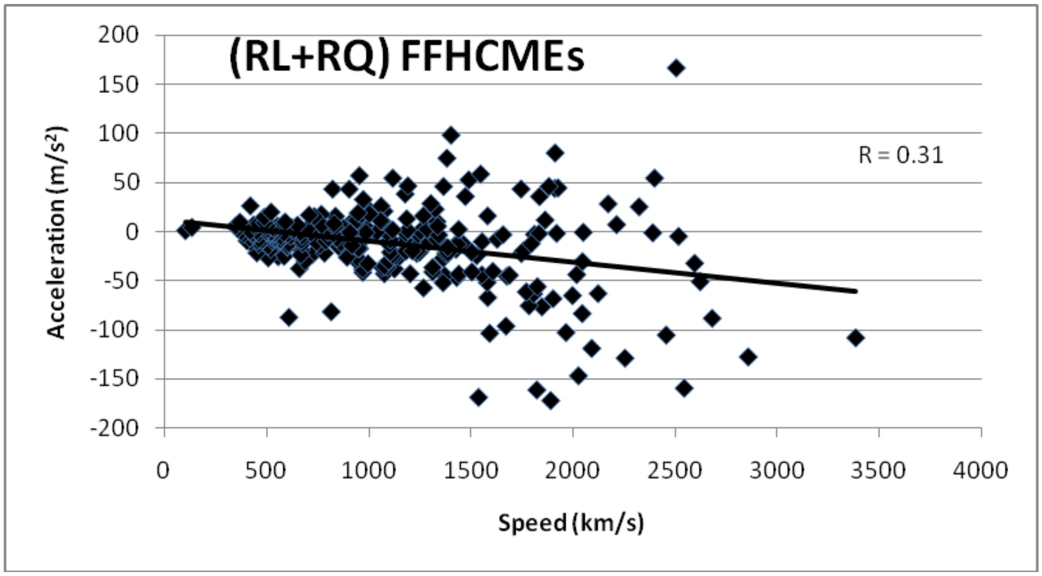

Figure: 6 Relation between speed and acceleration of FFHCMEs.

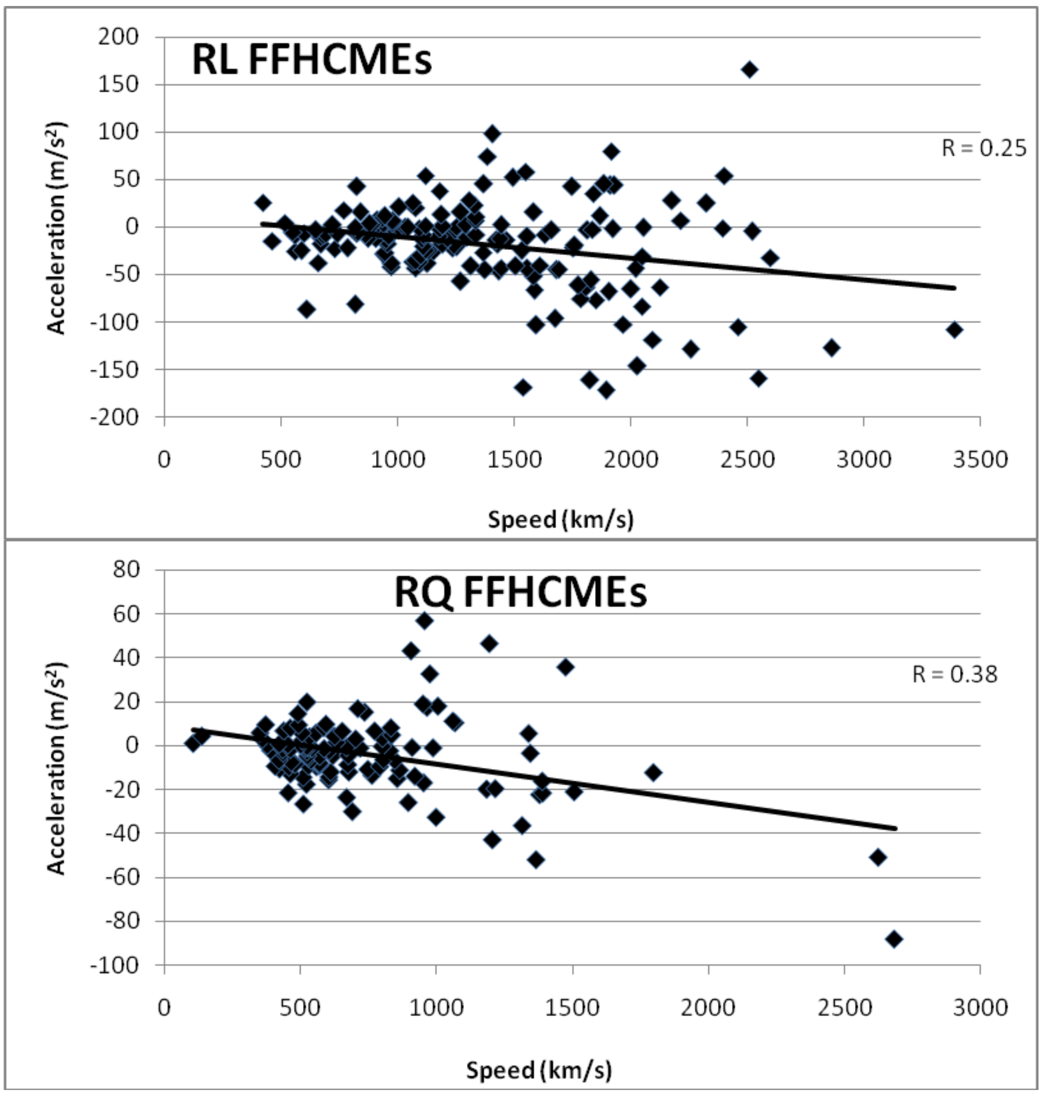

Figure: 7 Relation between speed and acceleration of RL FFHCMEs and RQ FFHCMEs

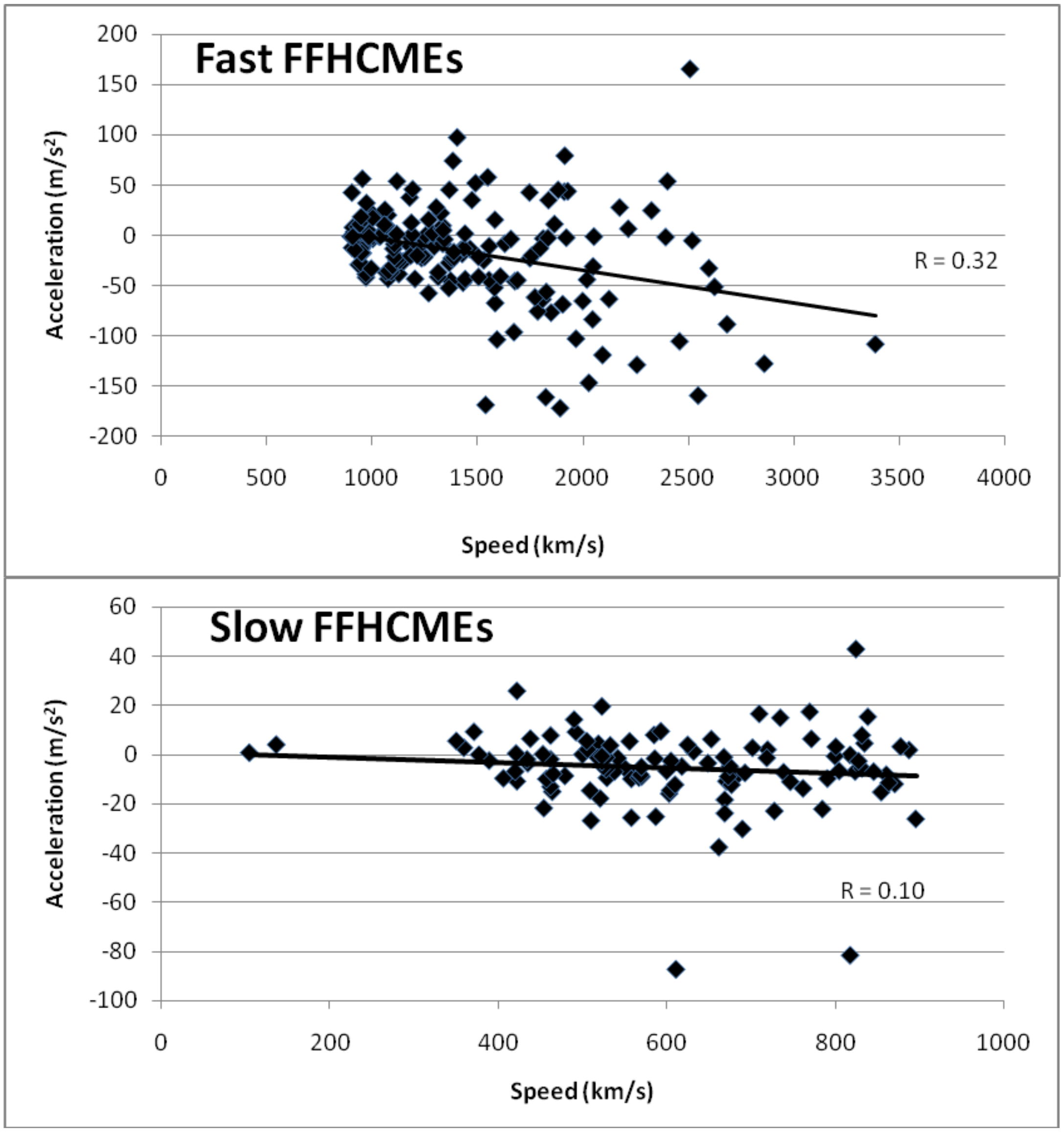

Figure: 8 Relation between speed and acceleration of fast FFHCMEs and slow FFHCMEs

3.3 Flare Properties

The heliographic distribution of RL and RQ FFHCMEs based on their location on the Sun where the associated flares were observed. Figure 9 shows heliographic distribution of flare associated FFHCMEs. Figure 10 shows that the heliographic distribution of flare associated RL CMEs is more uniform than that of RQ CMEs. There are few RQ and RL CMEs close to the eastern and western limb. The latitudinal distribution ranges in around $\pm 30^0$ for both RL and RQ CMEs. Figure 11 (a-d) shows heliographic distribution for fast and slow RL and RQ events. From figure 11 it is clear that for RL CMEs sources are distributed throughout the disc but in case of RQ CMEs sources are centered at disc. If we see the distribution of source for fast and slow RL CMEs than it is clear from figure that fast RL CMEs have longitudinal range $\pm 90^0$, while slow RL CMEs have their longitudinal distribution between $\pm 45^0$. For fast and slow RQ FFHCMEs source location is spread out longitudinally in range $\pm 90^0$, but it is clear from figure that most of the slow RQ FFHCMEs have their source location near to centre of solar disc. So we can conclude that fast RL CMEs or fast RQ FFHCMEs have their source throughout the solar disc in longitudinal range, while slow RL FFHCMEs and slow RQ FFHCMEs originate in the $\pm 45^0$ longitudinal range. There seems to be no sources for slow RL FFHCMEs close to the eastern and western limb, while there are several sources for slow RQ CMEs at eastern limb.

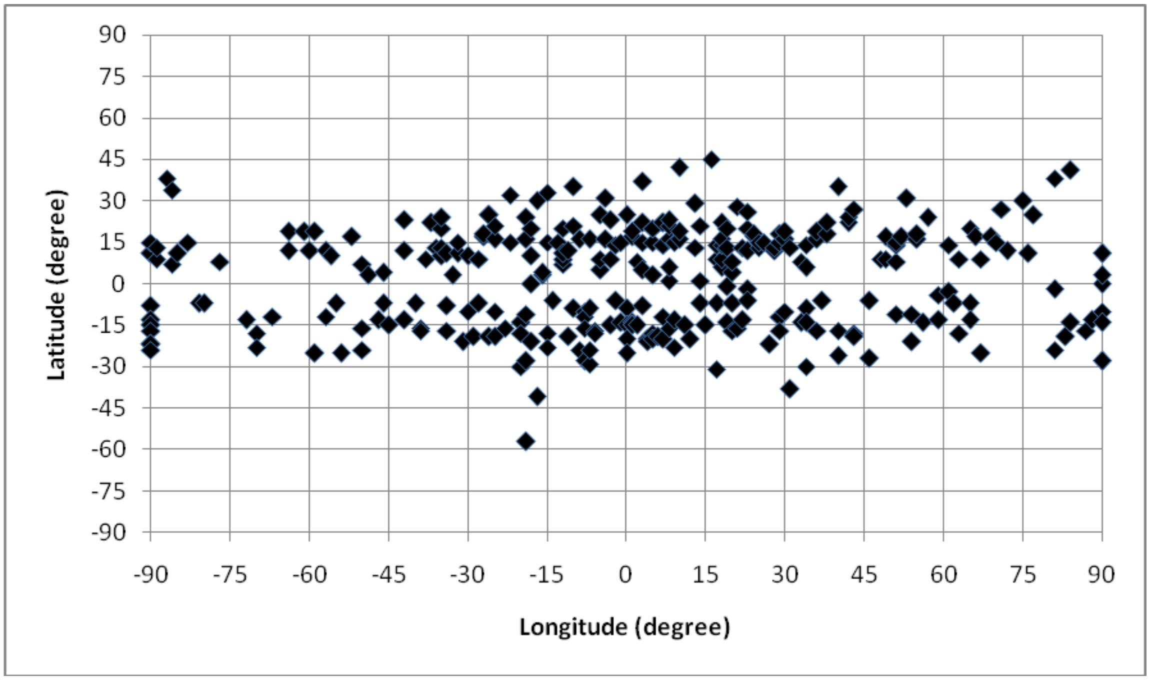

Figure: 9 Heliographic Latitudinal and longitudinal distribution of flare location associated with FFHCMEs.

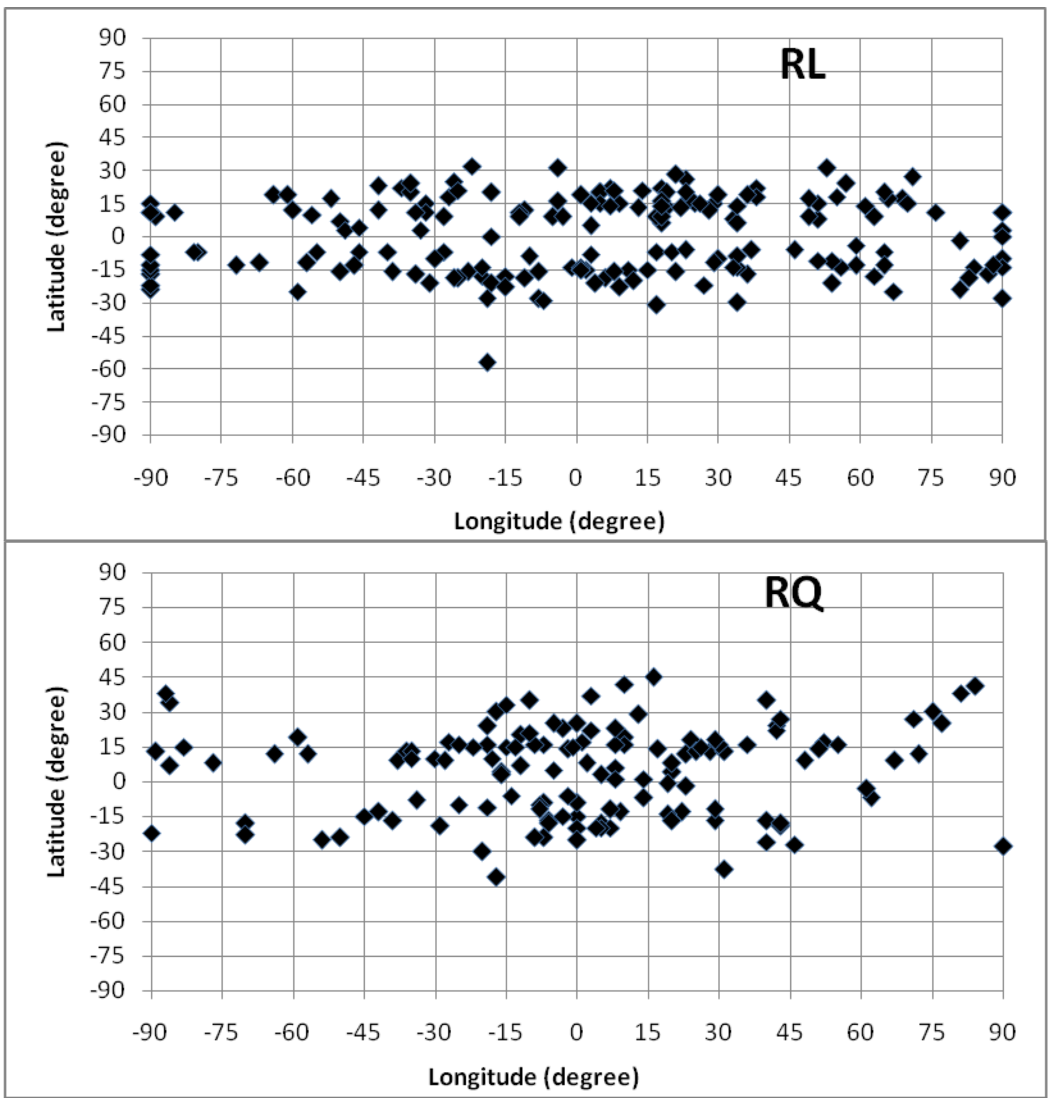

Figure: 10 Comparison between heliographic Latitudinal and longitudinal distribution of flare location associated with RL and RQ FFHCMEs.

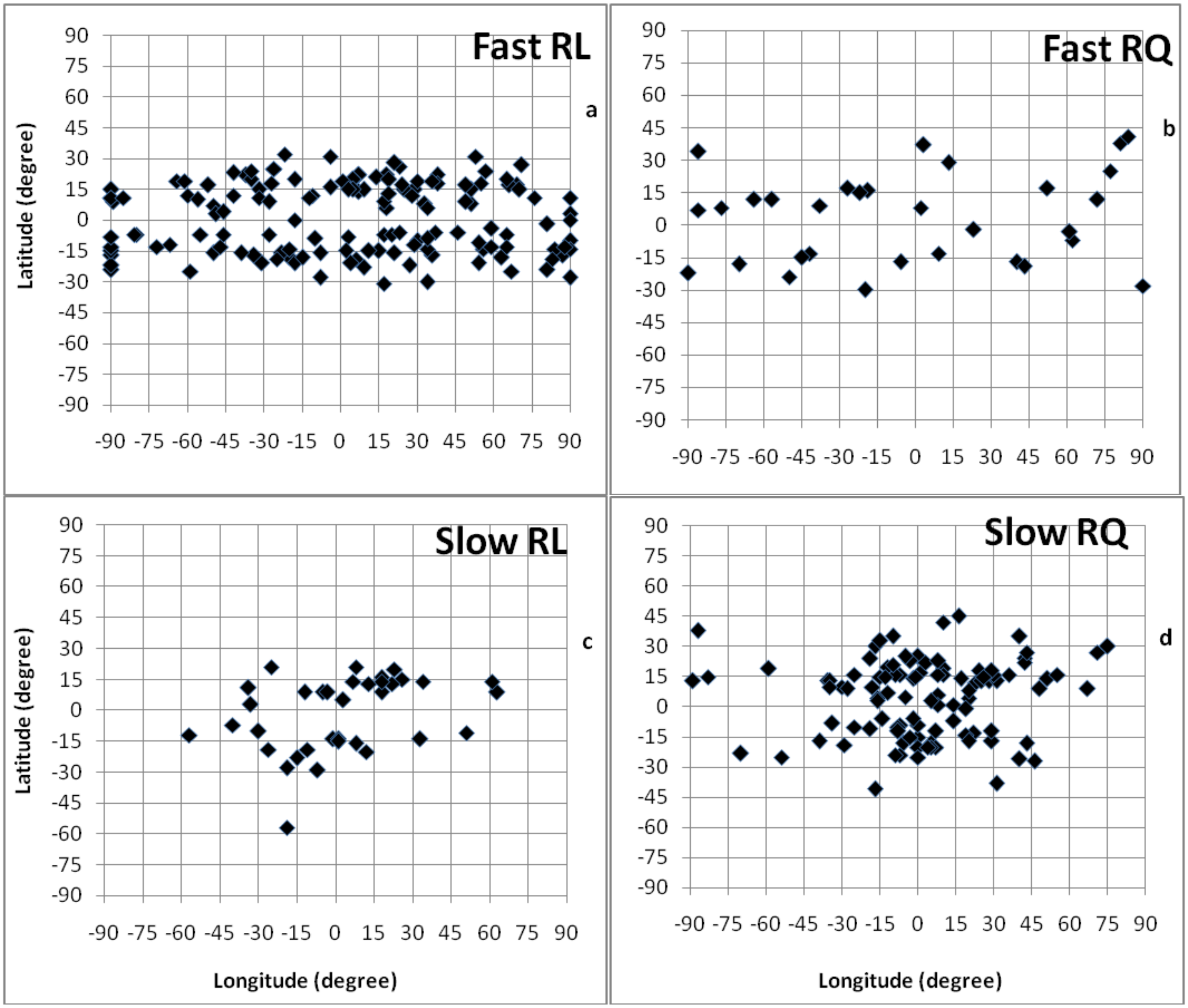

Figure: 11 (a-d) Comparison b/w heliographic Latitudinal and longitudinal distribution of flare location associated with fast and slow RL and RQ FFHCMEs.

The distribution of flare intensity between fast and slow events is shown in figure 12. From figure 12 it is clear that RL CMEs are associated mostly with M-class and X-class flares that occurs in the study period; while the RQ CMEs are mostly associated with M- and C-class flares. The distribution of flare intensity is slightly different for slow and fast events as shown in table 2. Most of fast RL CMEs are associated with M- and X-class flares. But for slow RL events, most CMEs are associated with M-class flares, while the remaining are associated equally with C- and X-class flares. From table 2 it is also clear that fast RQ CMEs are associated with M- and C- class flares while most slow RQ CMEs are associated with C- class flares and M-class flares. Some of slow RQ CMEs are also associated with B-class flares, which shows slow RQ CMEs are less energetic. There is only one B-class event associated with RL events; whereas 13 B-class flares are associated with RQ HCMEs. X-class flares have nearly equal number for fast RQ and slow RL events. Our analysis of type II associated HCMEs that occurs during study period indicates that RL CMEs are more often associated with intense flares compare to RQ HCMEs. We found that RL CMEs are faster, wider, and more often associated with intense X-ray flares than RQ CMEs and slow RL CMEs and fast RQ CMEs are associated with approximately equally strong X-ray flares which supplement the results obtained by Gopalswamy *et al.* (2008).

Table 2: Table shows intensity of flares for RQ and RL events

Intensity of flare	Fast RL CMEs	Fast RQ CMEs	Slow RL CMEs	Slow RQ CMEs
A	0	0	0	1
B	0	0	1	13
C	16	11	9	41
M	68	15	17	29
X	56	5	8	3

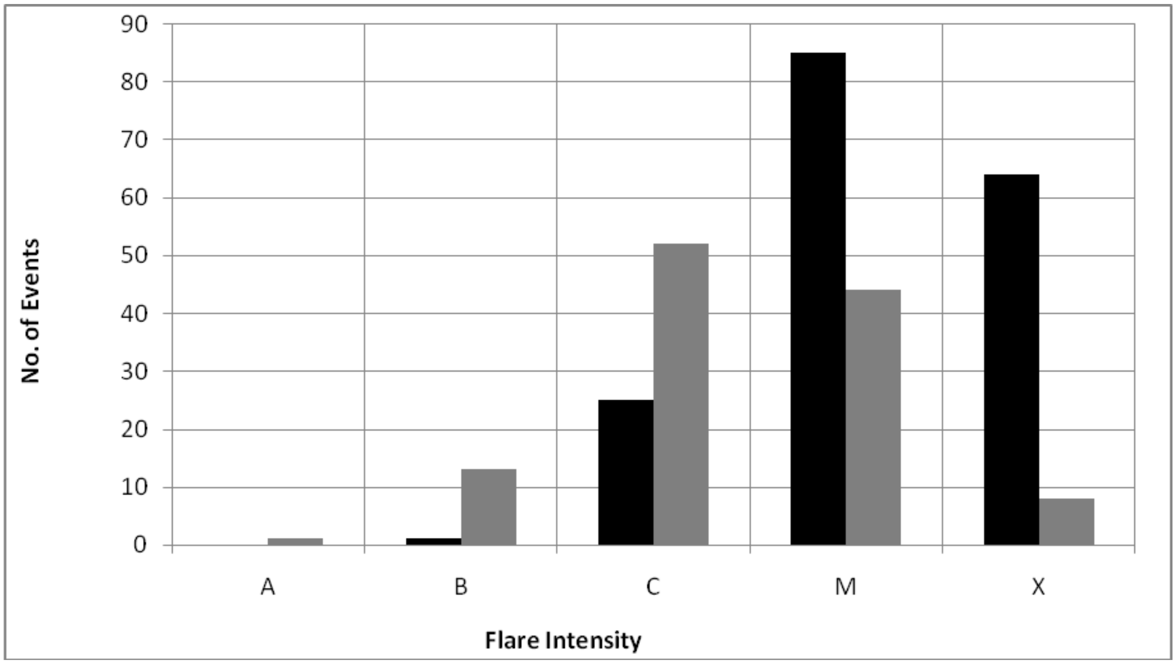

Figure: 12 Flare intensity distribution for RL (dark bar) and RQ (light bar) HCMEs.

3.4 Type II burst properties

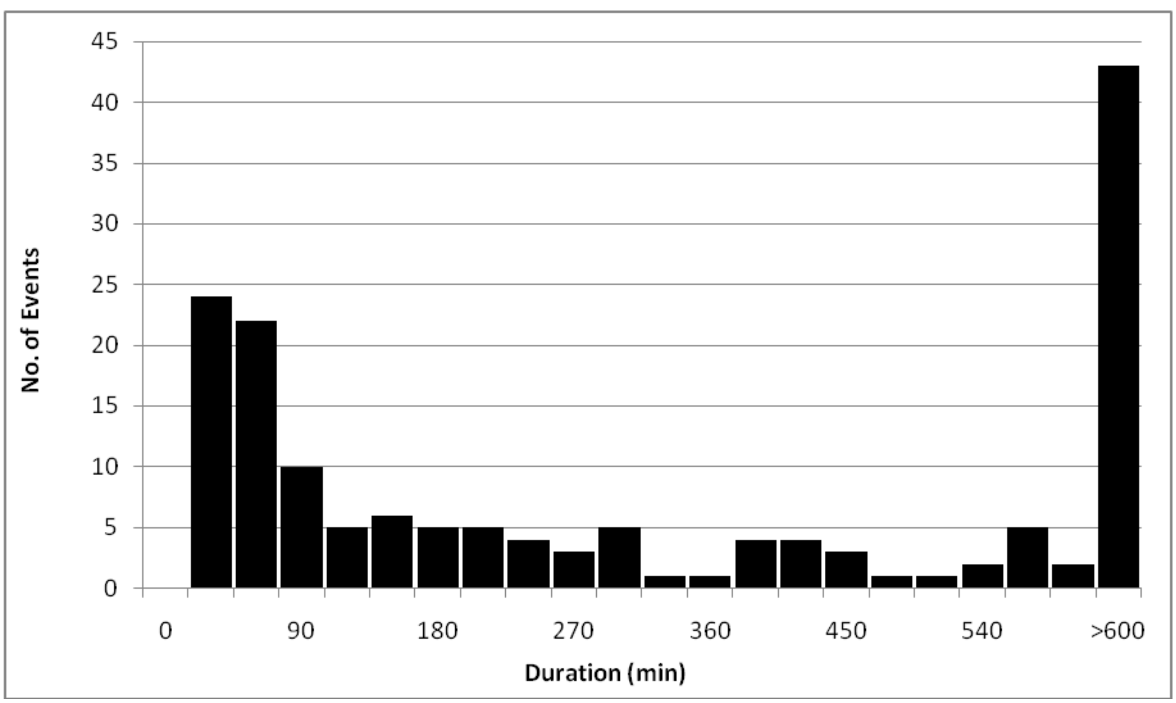

Figure: 13 Histogram shows duration of type II radio bursts

Duration of type II burst those associated with FFHCMEs and solar flares is shown in figure 13. Average duration of events is 499 minute. From figure 13 it is clear that maximum events have their duration longer than 600 minute. Duration of type II radio events lie in the range 20-2000 minute. It is clear from figure 58% events have their duration within the range of less than 360 minute (4-360 minutes) and remaining 42% events have their duration larger than 360 minute (370-3915 minutes). Average duration of type II events those associated with FFHCMEs is 549 minute. Average duration of type II events those are associated with slow FFHCMEs is 299 minute which is much smaller than the duration of type II events those associated with fast FFHCMEs.

Average bandwidth of associated events is 10.14 MHz and distribution of bandwidth is shown in figure 14. From figure it is clear maximum number of type-II bursts those associated with FFHCMEs have their bandwidth at 14 MHz. Average bandwidth of type II radio burst that associated with FFHCMEs and flares is larger than general population of km and DH- type II radio bursts. Figure 14 shows 57% type II radio bursts have bandwidth in the range 10 MHz-16 MHz and remaining 43 % have their bandwidth 20 KHz-10 MHz.

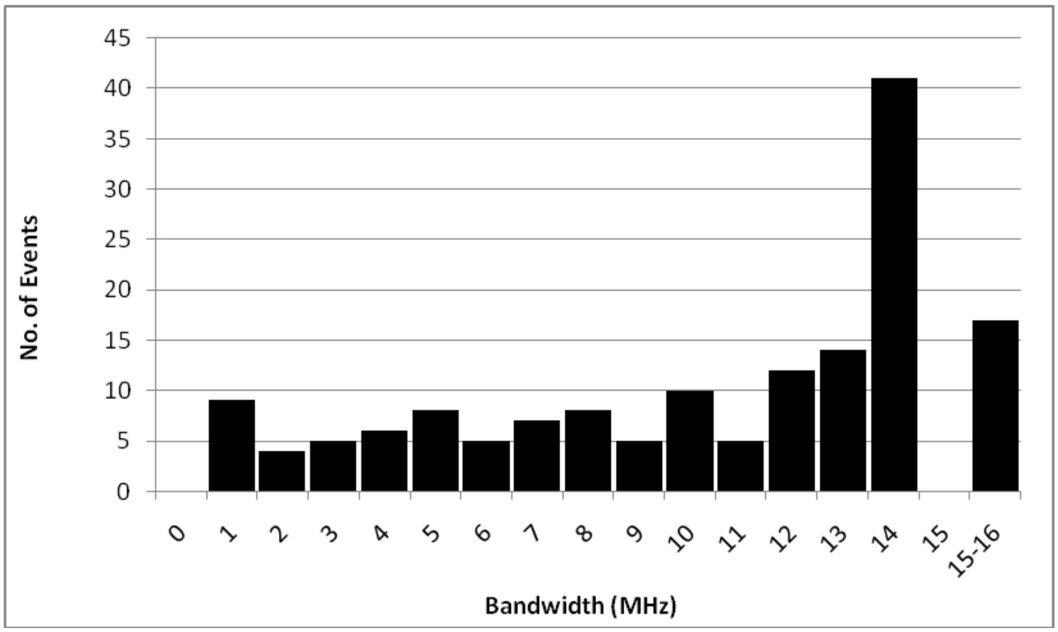

Figure: 14 Histogram shows bandwidth of type II radio bursts

4. Conclusion

We have studied a set of 310 FFHCME events, which is about 2% of all CMEs (24000) detected by SOHO/LASCO coronagraph during the period 1996 – 2014. We considered only front side full halo CMEs that generated disturbances in Earth environment. We have analysed the properties of CMEs and their associated flares based on the CME radio loudness (RL) or quietness (RQ) and their classification into slow (137 events) and fast (173 events) FFHCMEs.. The average values of properties of RL FFHCMEs were found to be much different than those of RQ FFHCMEs. Radio loud (RL FFHCMEs) are faster and wider than radio quiet (RQ) FFHCMEs. The mean speed of RL FFHCMEs is about 1370 km/s. The mean speed of RQ FFHCMEs is found to be 727 km/s. RQ CMEs do not often exceed the critical Alfvén speed of 1000 km/s in the outer corona to produce type II radio bursts (Gopalswamy *et al.*, 2008). The fraction of slow FFHCMEs is higher for RQ FFHCMEs because RQ CMEs are narrower on average (Michalek, et al., 2007). Out of 310 events 59% have speed greater than 900 km/s, which shows FFHCMEs associated with type II radio bursts are faster and wider as reported by Gopalswamy et al., (2000) and Yashiro et al, (2004). RL and RQ FFHCMEs have similarity in their acceleration and deceleration. About 70% RL FFHCMEs are decelerating, whereas 64% of RQ FFHCMEs are decelerating. Since we have divided FFHCMEs into slow and fast events, the mean values of acceleration and deceleration are different. Fast events decelerate more in compare to slow events in RL, which is in agreement with Vasanth, and Umapathy,(2013). In RQ slow and fast both are biased towards deceleration. For RQ events fast CMEs are decelerate down to -6.25 m/s^2, while slow CMEs decelerate down to -3.49 m/s^2. For RL events, fast events have an average deceleration down to −19.5 m/s^2, while slow events have mean deceleration down to 25 m/s^2. In RL FFHCMEs, a large number of fast (69 %) and slow (73

%) events were decelerating; where as in RQ FFHCMEs also an equally large number of fast (62 %) and slow (65 %) events were decelerating.
High-speed CMEs are accelerated at relatively low heights in the solar corona and decelerated in the SOHO/LASCO field of view. In contrast, slower CMEs accelerate up to greater heights. In other words, a more accurate estimation of either the acceleration or the deceleration of CMEs is essential for better understanding the kinematic behaviour of CMEs. The flare rising phase coincides with the impulsive acceleration phase of CMEs as shown by several investigators, (Zhang *et al.*, 2001; Chen and Krall, 2003; Shanmugaraju *et al.*, 2003), During this phase, the speed of the shock preceding the CME becomes greater than the speed of the ambient solar wind flow, and type II radio bursts are generated at super-Alfvénic speeds.

There is a difference in the properties of flares associated with RQ and RL FFHCMEs. Fast events are more often associated with X-class flares than slow events. Slow events are more often associated with C-class flares than fast events. 48% fast events are associated with M-class flares while only 34% slow events are associated with M-class flares. Figure 12 shows that small flares are more often associated with RQ CMEs than with RL CMEs. RQ FFHCMEs were found to be less energetic than RL CMEs and are less often associated with intense X-ray flares. Type II radio bursts those associated with FFHCMEs and solar flares have their mean duration 499 minutes and average bandwidth 14 MHz.

The mean values of the RL FFHCME main parameters are different in both fast and slow events than those of RQ CMEs. For RL CMEs, the percentage of accelerating CMEs is 29-30% in the case of slow and fast events. Summarizing the results found in the analysis of 310 RL and RQ CMEs that occurred in the period between 1996 and 2014; the RL FFHCMEs are decelerating more in compare to RQ FFHCMEs, because RL events are much faster in compare to RQ events. Since RL events are faster and wider than RQ events so they are more energetic.

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