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Positively Drifting Structures During the 18 March 2003 Solar Flare

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Abstract We analyze the high-frequency drift radio structures observed by the spectrometer at Purple Mountain Observatory (PMO) over the frequency range of 4.5 – 7.5 GHz during the 18 March 2003 solar flare. The drifting structures take place before the soft X-ray maximum, almost at the maximum of hard X-ray flux at 25 – 50 keV. For the first time, the positive drift in this kind of radio structures is detected in such a high frequency range. Their global drifting rate is roughly estimated as 3.6 GHz s^{-1}. They appear in four groups, lasting in total for less than 6 s, and have a broad bandwidth of more than 2 GHz but a smaller ratio of the bandwidth of the drifting structures to mean frequency than that of the lower frequency range. The lifetime of each individual burst in this event can be derived by using the high temporal resolution of the spectrometer at PMO and has an average value of 36.3 ms. Since the negative drifting structures observed in the 0.6 – 4.5 GHz frequency range were interpreted to be a radio signature of a plasmoid ejected upward (moving out of the Sun), the present observation may imply that it is possible for a plasmoid to move downward during a solar flare. However, for a confirmation of this suggestion direct radio imaging observation would be needed.

Keywords Sun: flares · Sun: radio radiation

1. Introduction

High-frequency slowly drifting structures are one kind of temporal fine structures of radio bursts in the decimetric and microwave ranges. According to their appearances on the dynamic spectra, three sub-classes of these structures are defined: (a) slowly drifting structures, (b) slowly drifting pulsation structures (DPSs), and (c) slowly drifting pulsation-continuum structures (*e.g.*, Karlický, Fárník, and Mészárosová, 2002). The first sub-class has complex fine structure. The second one is generally composed of multi-pulsations, with each having an infinite frequency drift. In some cases, there are clouds

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of narrow-band dm spikes following them. The third sub-class shows continuum emission following the slowly drifting structures. This third sub-class was found to be generated simultaneously with metric type II bursts during the 12 April 2001 flare (Karlický *et al.*, 2005). The second sub-class is more generally observed than others. And most of the slowly drifting structures previously documented are so-called DSPs (Kliem, Karlický, and Benz, 2000). However, a typical feature of all three sub-classes is the slow frequency drift, which is thought to be associated with a common physical process during the eruptive flare. So such a common word as "drifting structures" is suggested to be the representative of the three sub-classes (Karlický, Fárník, and Mészárosová, 2002; Karlický, 2004).

Drifting structures are intensively studied in association with plasmoid ejection at the beginning of some eruptive solar flares (Karlicky and Odstrcil, 1994; Karlický, 1998, 2004; Kliem, Karlický, and Benz, 2000; Hudson *et al.*, 2001; Kundu *et al.*, 2001; Khan *et al.*, 2002; Karlický, Fárník, and Mészárosová, 2002; Karlický and Kosugi, 2004; Karlický *et al.*, 2005). One typical characteristic of these structures is slow drift with a negative rate between (-1.6) and (-30) MHz s^{-1}. They have a bandwidth in the interval 200 – 1000 MHz and a duration of 25 – 136 s (*e.g.*, Karlický, Fárník, and Mészárosová, 2002). These values can be extended in some solar flares. Using the Fourier method, Karlický *et al.* (2005) found the quasi-periods in the range between 0.9 and 7.5 s of the individual burst in the slowly drifting structures. In some cases, the shorter periods are in the interval of 0.06 – 0.2 s. Observationally, most drifting structures were associated with a plasmoid ejection. So they are interpreted by using the plasmoid ejection model of solar flares (*e.g.*, Shibata, 1999; Yokoyama and Shibata, 2001). Based on MHD numerical simulations, Kliem, Karlický, and Benz (2000) suggested that each individual burst in the drifting structures is generated by a beam of superthermal electrons accelerated by the electric field in the reconnection region. The global negative frequency drift of the structure was explained by a plasmoid propagation upward in the solar corona toward lower plasma densities.

Another observational property is that drifting structures are observed in series. Karlický (2004) suggested a series of drifting structures mapping the continuous reconnection in a solar flare. In such a scenario the drifting structures correspond to the radio emission from primary and secondary plasmoids, which are formed in the extended current sheet and move upward in the solar atmosphere. He interpreted the increase and decrease of the frequency drift of these structures in the initial and decay flare phases as due to an increase and decrease in the reconnection rate, respectively.

Up to now, drifting structures have been well studied and documented in the frequency range of 0.6 – 4.5 GHz (*e.g.*, Karlický, 2004; Karlický, Fárník, and Mészárosová, 2002; Karlický and Kosugi, 2004; Karlický *et al.*, 2005). However, observational properties of the drifting structures in the frequency range above 4.5 GHz are still poorly known. In this paper, we will analyze an example of drifting structures detected by the Purple Mountain Observatory (PMO) spectrometer in the high-frequency range between 4.5 and 7.5 GHz during the 18 March 2003 solar flare.

2. Observations

For a detailed study of the fine structures in the high-frequency part of microwave bursts, a radio spectrometer with high time and frequency resolution at PMO has been developed to record solar bursts in the frequency range of 4.5 – 7.5 GHz. It has 300 frequency channels of 10 MHz bandwidth each and a time resolution of 10 ms. This spectrometer has recorded

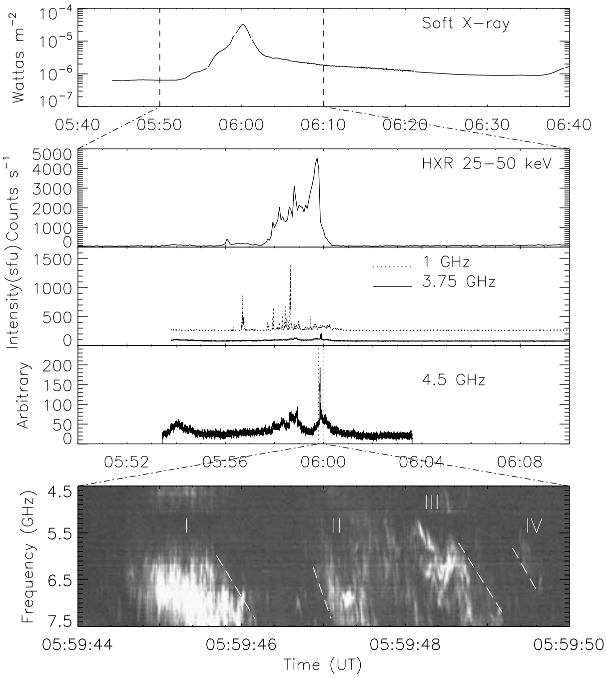

Figure 1 An overview of a solar flare detected by soft X-ray, hard X-ray, and microwave emissions on 18 March 2003. Top panel: Flux of GOES soft X rays at 1 – 8 Å. Second panel: RHESSI observations of hard X-ray flux at 25 – 50 keV. Third panel: Nobeyama radio flux at frequencies of 1 (dotted) and 3.75 (solid) GHz. Fourth panel: PMO radio bursts at a frequency channel of 4.5 GHz. Bottom panel: Dynamic spectra of a series of positively drifting structures observed by the PMO spectrometer.

much valuable data during the last solar maximum cycle (*e.g.*, Xu and Wu, 2004; Wu, Xu, and Huang, 2004; Ning *et al.*, 2003, 2005). Its daily working time is between 01:00 and 09:00 UT. A good description of this instrument can be found in the paper by Xu *et al.* (2003).

On 18 March 2003, the GOES satellite observed a soft X-ray flare that started at 05:51 UT, had its maximum at 06:00 UT, and ended at 06:02 UT. This event is classed as M2.5 and is localized at the active region NOAA AR 10314. According to Hα observations the 1N flare was detected at an interval of 05:54 UT (start) to 06:00 UT (max) to 06:21 UT (end) at a position of S15W46. An overview of this flare observed in the soft X-ray, hard X-ray, and microwave ranges is given in Figure 1. Four continuous groups (marked by I, II, III, and IV) of drifting structures (bottom panel) are detected by the PMO spectrometer between 05:59 and 06:00 UT. They are observed before the soft X-ray maximum, almost at the maximum of the hard X-ray emission. Group I is the most intensive emission while group IV is the faintest one. These structures are also observed by the Nobeyama radio polarimeter at 3.75 GHz.

Figure 2 shows the flare images around the soft X-ray maximum detected by TRACE 171 Å and RHESSI 25 – 50 keV. The RHESSI hard X-ray instrument detects a single flare source while TRACE 171 Å shows loop-like structures at 05:59:52 UT, which could be caused by the different spatial resolutions. So this event could be a compact flare. The drifting radio structures are observed at the same time as the maximum of 171 Å and hard X-ray emissions. Hard X-ray radiation disappears rapidly after the end of the drifting structures, while TRACE 171 Å still presents faint emission. The radio sources observed by the Nobeyama radioheliograph (NoRH) at 17 and 34 GHz at 05:59:43 UT are overplotted on the figure.

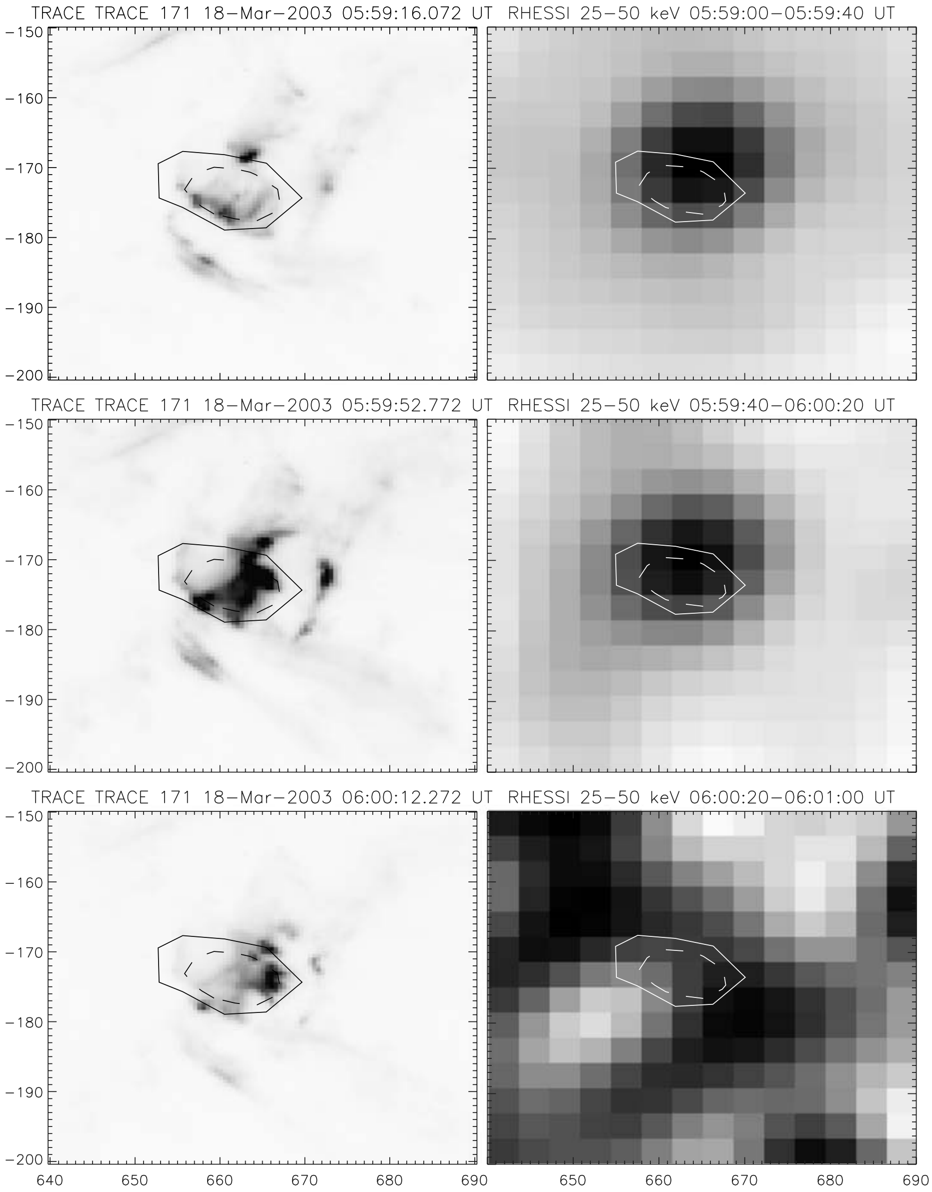

Figure 2 Flare images taken around the soft X-ray flare maximum observed by TRACE 171 Å (left) and RHESSI 25 – 50 keV (right). The contours are radio sources at 17 GHz (solid lines with a level of 6×10^6 sfu) and 34 GHz (dashed lines with a level of 2×10^6 sfu) at 05:59:43 UT.

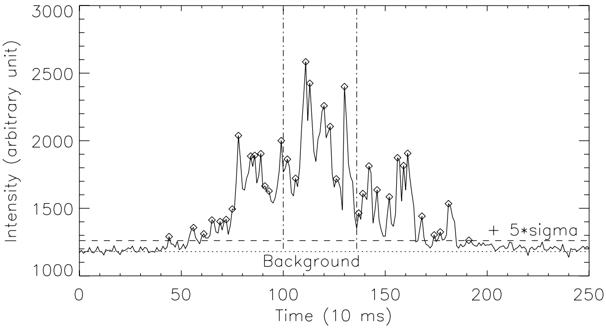

Figure 3 Time profile of group I (between 05:59:44.200 and 05:59:46.700 in Figure 1) of drifting structures at 6.8 GHz. The points marked with diamonds are identified as being the peaks of 35 individual burst profiles (for details see text).

3. Results

3.1. Observational Properties

The drifting structures of the 18 March 2003 flare are characterized by a positive frequency drift. Some examples with positive drifting have been previously documented (*e.g.*, Jiřička *et al.*, 2001; Karlicky and Barta, 2007), but these were around 1 GHz. This is the first time that such positive drifting structures have been detected over such a high frequency range. Their drifting rate is roughly estimated by the structure border (long-dashed lines on the dynamic spectra) and has an average value of 3.6 GHz s^{-1}, which is 100 times higher than the rate found previously (1.6 – 30 MHz s^{-1}). Another feature of this event is its short duration (less than 6 s) and its broad bandwidth of more than 2 GHz. Group I of these structures is extended to frequencies higher than 7.5 GHz. The broadest bandwidth of the drifting structures reported before is 1000 MHz (between 500 and 1500 MHz) in the 12 April 2001 flare (Karlický *et al.*, 2005). Although the drifting structures increase their bandwidth with higher frequency, the ratio of the bandwidth of these structures to the mean frequency decreases with higher frequency. For example, the ratio of the 12 April 2001 event is about 1 around 1 GHz, while it is about 0.77 for this event around 6.5 GHz.

3.2. Time Scale of the Individual Burst

The high temporal resolution of the PMO spectrometer makes it possible to detect the complete profile of the individual burst in the drifting structures on a single frequency channel. The shortest period of individual burst previously reported is 0.06 s (*e.g.*, Karlický *et al.*, 2005). So at least 6 points can be recorded by the PMO spectrometer if the individual burst has a profile with a lifetime greater than 0.06 s. First, we have to determine the peak of each individual burst. To rule out instrument noise, 5σ is used as the criteria of individual burst peaks, as shown in Figure 3, where the group I flux of drifting structures is plotted at 6.8 GHz. The value of σ is computed from the quiet Sun emission at this frequency channel. The background refers to the average value. If a point represents a local maximum of the flux above the 5σ level, it is identified as the flux peak of an individual burst profile. So in total 35 individual bursts are determined (with peaks marked by diamonds in Figure 3). Then, we have to determine the start and end times of each individual burst. For a given burst profile, if there is only one point following its peak before the flux rises again, this point is thought to be the end time of this burst. Otherwise, if there are two or more points following this peak before the flux starts increasing again, we choose the end of a burst as the point that has the half-peak flux value after background subtraction. The start time of an individual burst

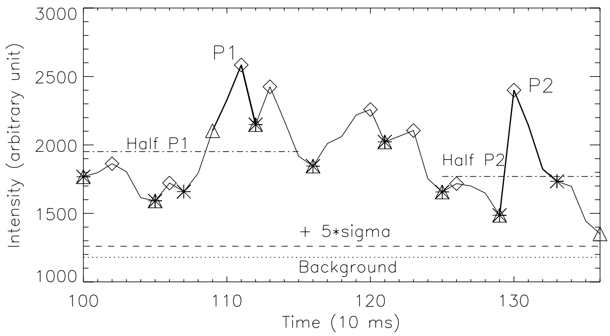

Figure 4 Time profile at 6.8 GHz between two dotted lines in Figure 3. The points marked with stars after the peak are identified as the end times of individual bursts, while the triangles before the peak are the start times.

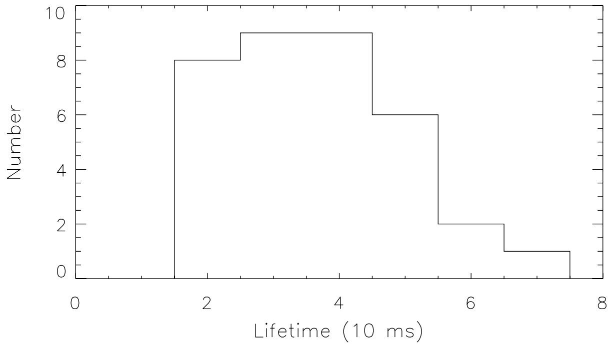

Figure 5 Histogram distribution of the lifetime of 35 individual bursts shown in Figure 3.

is determined by the same method. Figure 4 shows the details of how to determine the start and end times of a given burst. The start and end points are marked by triangles and stars, respectively. For example, the end time of the burst with peak P1 ($X = 111$) is the following point marked with a star ($X = 112$), which is the only point after P1 before the flux starts increasing again. However, the end time of the burst with peak P2 ($X = 130$) is the point at $X = 133$, which is chosen from the following six points ($X = 131; 132; 133; 134; 135; 136$) whose flux values are monotonically decreasing after P2, because the point $X = 133$ has the closet flux to the half-peak value of P2 after background subtraction. It is possible that the end time of the preceding burst is the same as the start of the following one, as shown in Figure 4. Finally, the lifetime of an individual burst is calculated by a subtraction of the end and start times. In Figure 5 the histogram of the lifetime distribution from the 35 individual bursts is plotted.

We obtain 13 181 individual bursts from the four groups of drifting structures on all 300 frequency channels using this method, although some of them belong to the same individual pulsation on the different channels. Figure 6 gives the lifetime distribution of all individual bursts. The average lifetime is about 36.3 ms.

4. Discussion and Conclusions

High-frequency drift structures observed by the PMO spectrometer over a frequency range of 4.5 – 7.5 GHz during the 18 March 2003 solar flare are studied in this paper. TRACE and RHESSI observations show that this event is a compact flare. NoRH observations also display the compact microwave radio sources at 17 and 34 GHz, although they are generated

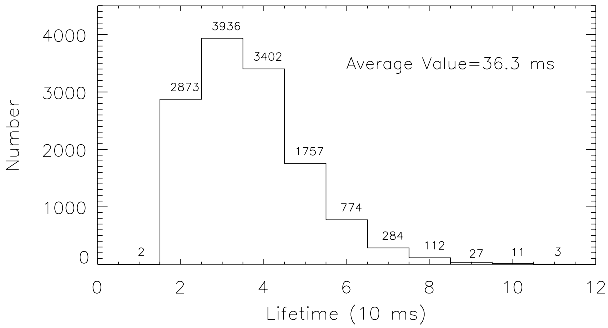

Figure 6 Histogram of the lifetime distribution of 13 181 individual bursts in these four series of drifting structures on 300 frequency channels. Burst numbers with corresponding lifetimes are marked. The average lifetime is about 36.3 ms.

by the gyro-synchrotron emission mechanism, whereas a different mechanism (*i.e.*, plasma emission) is proposed for the drifting structures. The compact flare implies that all the phenomena during this flare, *i.e.*, the drifting radio structures and hard X-ray bursts, could be produced by the same electron population.

Although some examples of positive drifting radio structures have been reported before (*e.g.*, Jiřička *et al.*, 2001; Karlicky and Barta, 2007), for the first time, the positive drift in the radio structures is detected in such a high frequency range. This event exhibits four continuous groups, and with a bandwidth more than 2 GHz, which is much broader than events previously reported (200 – 1000 MHz). However, the ratio of the bandwidth of the drifting structures to mean frequency is smaller than that at the lower frequency range. Their total duration is less than 6 s, which is much less than the events studied before (25 – 136 s) as well. We develop a method to determine the lifetime of individual bursts in the drifting structures on a single frequency channel. We assume every peak above 5σ corresponds to the peak of the standard profile of an individual burst. Because of the high temporal resolution of the PMO spectrometer, a lifetime as short as 36.3 ms is obtained.

The present observation is one example of positively drifting structures around 6 GHz. The search for more examples is work for the future.

As noted earlier, the drifting structures observed in the eruptive solar flares are thought to be the radio signature of plasmoid ejection upward in the outer solar corona. Hence, this observation of positively drifting structures suggests that a plasmoid is traveling downward into the inner corona during the 18 March 2003 flare. Simulation results show that the downward motion of the plasmoid is also possible during flare eruption (*e.g.*, Karlicky and Barta, 2007). This is in agreement with the observed positively drifting structures. But the present observations do not show any observational evidence of the downward plasmoid in this event. The time resolution of present image observations is not sufficient to detect a downward-directed plasmoid in a time scale of less than 6 s. So new spectral observations with high resolution of time, frequency, and space are needed. This is one of the scientific aims of the solar radioheliograph developed by the solar radio astronomy community in China. Nonetheless, the present observations show that the positive drifting structures take place at the maximum of REHSSI hard X-ray flux, corresponding to the hardest spectral index. Because the hard X-ray flux is negatively proportional to the spectral hardness (*e.g.*, Grigis and Benz, 2004), this implies that these structures could be associated with higher energy electrons with downward motion.

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