Solitary Wave Radiation and the Related Type IV-like Burst from Solar Wind Acceleration Region Observed by PSP

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Ma et al. (2025)

Chen et al. (2024)

Abstract

As the latest near-Sun spacecraft, Parker Solar Probe (PSP) supports a unique viewpoint to explore solar radio bursts generated from the solar wind acceleration region. We will report two significant types of solar radio bursts detected by PSP. One is the weak radio burst observed when PSP passed through a low-density magnetic channel. It has a starting frequency of about 20 MHz and a narrow frequency range from tens of MHz to hundreds of kHz. The relative frequency drift rate of this burst rapidly decreases from above 0.01 s^{-1} to below 0.01 s^{-1}. The other is a type IV-like radio burst. It lasts about 20 hours and consists of a series of short-time (ST) bursts with the central frequency slowly drifting from approximately 5 MHz to 1 MHz. By analyzing the empirical models of the solar atmosphere and the in-situ measurement data of PSP, it is found that the source regions of both types of radio bursts have similar characteristic plasma parameters. The electron cyclotron frequency in these regions is higher than the plasma frequency, which means that the source region is a low-β plasma environment and these radio bursts are likely to be generated by the electron cyclotron maser (ECM) emission mechanism. We proposed that both types of bursts may be generated by solitary kinetic Alfvén waves (SKAWs). In a low-β plasma, SKAWs can accelerate electrons to excite the electron cyclotron maser (ECM) instability and cause radiation. The frequency drift is related to the propagation of SKAWs and the movement of magnetic loops. However, due to the uncertainty of empirical models, further verification is needed with the help of PSP's future observations closer to the Sun and the possible local measurements in the source regions.

Introduction

The study of solar wind acceleration and coronal heating has been a major challenge in solar physics. Radio observation becomes main information sources of the coronal plasmas, instead of the spectral line observation, which is a main method of inferring the physical situation and processes in the photosphere and chromosphere.

In the data observed by the PSP/RFS during April 1-9, 2019 at a heliocentric distance of about 1/6 AU, we found that there are a large number of small-scale weak solar radio bursts (SRBs) when it passed through an open low-density magnetic channel (Fig. 1). Based on the commonly adopted empirical models of the solar atmosphere (Mariani & Neubauer, 1990; Hu et al., 1997; Leblanc et al., 1998; Wu & Fang, 2003), we analyzed further the radiation mechanism and evolutionary dynamics of these small-scale SRBs.

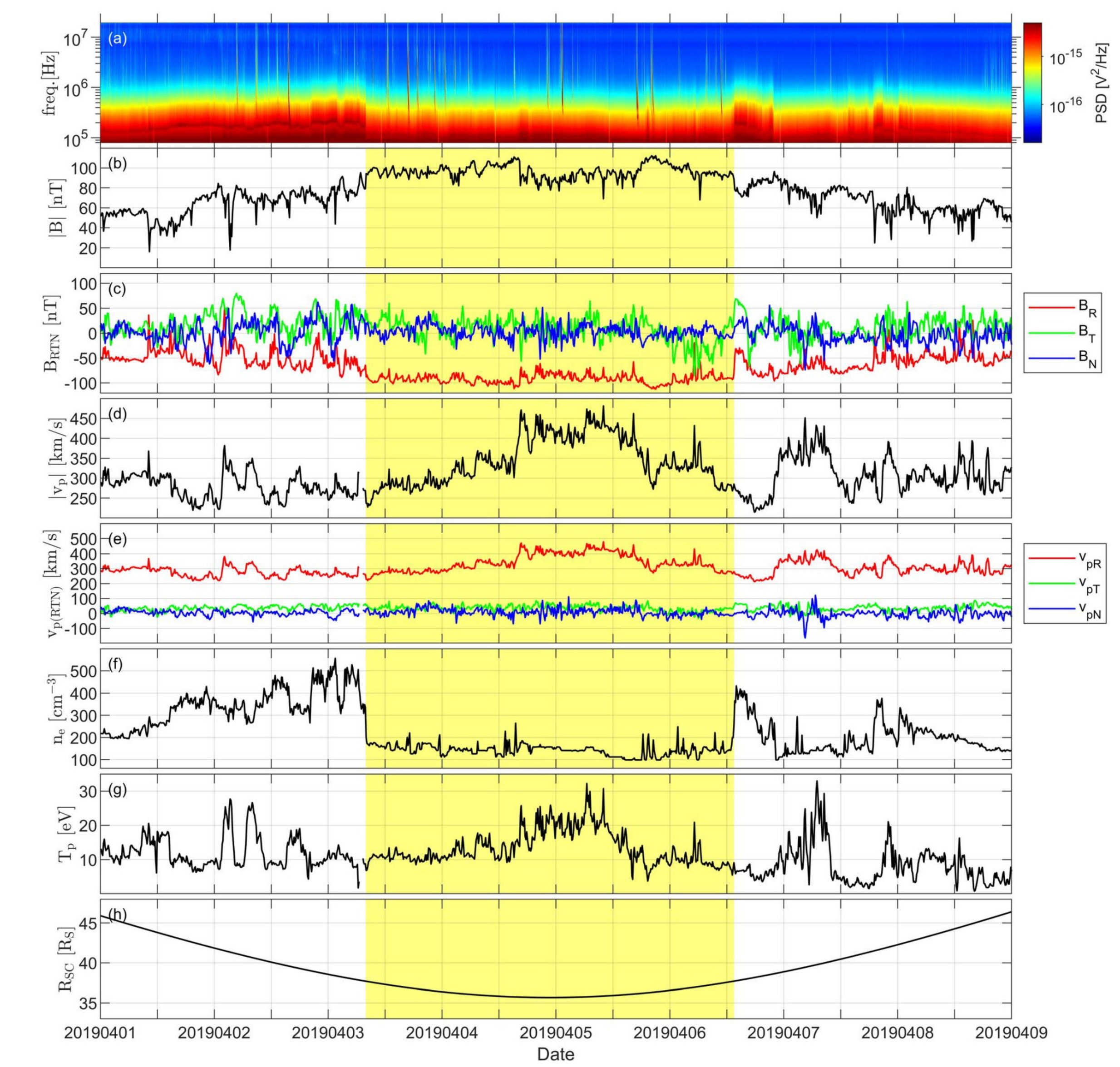

Fig. 1 The solar wind plasma parameters observed by PSP. From top to bottom, the panels are the PSD of the radio radiation (a), the magnetic field (b) and its components (c), the solar wind velocity (d) and its components (e), the plasma density (f) and temperature (g), and the heliocentric distance of PSP in units of solar radius, R_S (h). This figure is from Chen et al. (2024).

The results show that the radiation sources of these small-scale SRBs located in the high corona region with the heliocentric distance of 1.1 to 6.1 R_S, which belongs to the transition region between the quasi-static solar corona and the dynamic solar wind and hence is also the typical acceleration region of the solar wind.

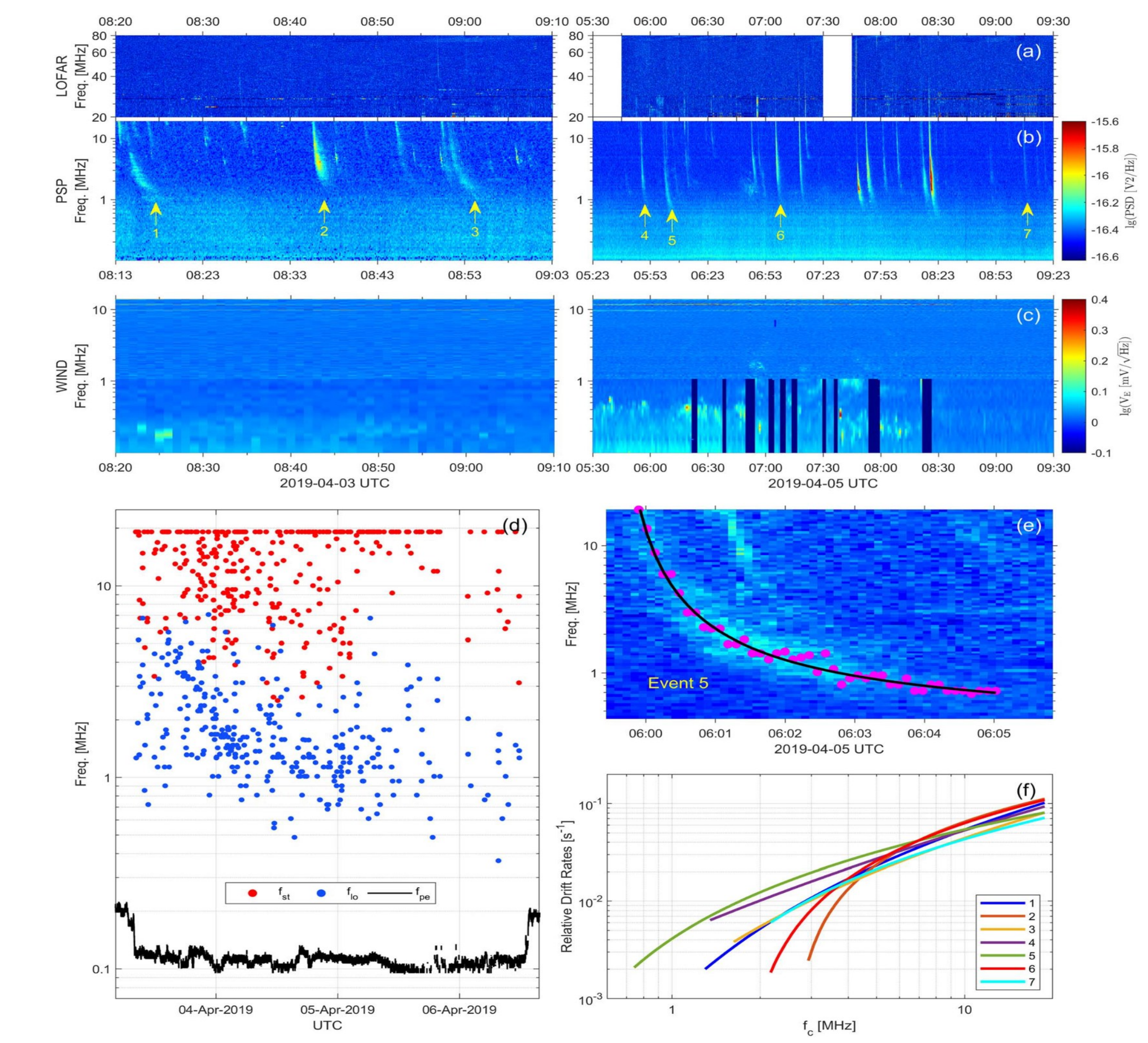

Fig. 2 The weak SRBs observed by PSP during its crossing of the low-density magnetic channel. The top three rows show PSD measured by LOFAR (a), PSP (b), and WIND (c) in two intervals, 08:13–09:03 on 2019 April 3 (left) and 05:23–09:23 on 2019 April 5 (right). (d) The starting (f_{st}; red circles) and ending (f_{lo}; blue circles) frequencies for the 385 weak SRBs and the local plasma frequency f_{pe} (back line) along the PSP orbit. (e) The fitting curve (black curve) of maximal PSD for event 5 marked by an arrow in panel (b) through the least-squares fit, where the magenta dots are the location of maximal PSD in the dynamic spectrum. (f) The relative frequency-drift rate for the several typical bursts as marked by arrows in panel (b). This figure is from Chen et al. (2024).

Table 1. the observation features of the weak solar radio bursts

Observation time	PSP's 2nd encounter phase (3-6 April 2019)
Plasma environment	An open magnetic channel with low electron density
Features of events	Weak emission intensity (only can be observed by PSP)
	Low start frequency (< 20 MHz for 64% events)
	Short duration (< 10 min)
	Fast decreasing frequency drift rate (from ~0.1/s to <0.01/s)

We found that solitary kinetic Alfven waves (SKAWs), which are easily generated in the high solar corona (Wu & Chen, 2020), can self-consistently explain the generation mechanism and strong evolution behavior of the dynamic spectrum of these small-scale SRBs, in which the electric field of SKAWs accelerates electrons to energies of a few tens of keV and the accelerated energetic electrons are trapped in the potential well of SKAWs and move together with SKAWs.

It is the trapped energetic electrons that excite the radio radiation of the observed small-scale SRBs, and the frequency drift may be attributed to the propagation of SKAWs. The strongly evolutionary behavior in the dynamic spectra can be reasonably explained by the kinetic dissipation and dynamic evolution of SKAWs.

Observation

Fig. 3 shows the radio observation by PSP/RFS from 2021 April 26 10:00 to 27 09:00 and the frequency drift features of eight weak radio bursts during this interval. In Fig. 1(a), an intense type III radio burst was detected from 11:00 to 12:00 on 2021-04-26. After that, a long-time radio storm consisting of numerous weak radio bursts with fast frequency drift appear and last for about 20 hours.

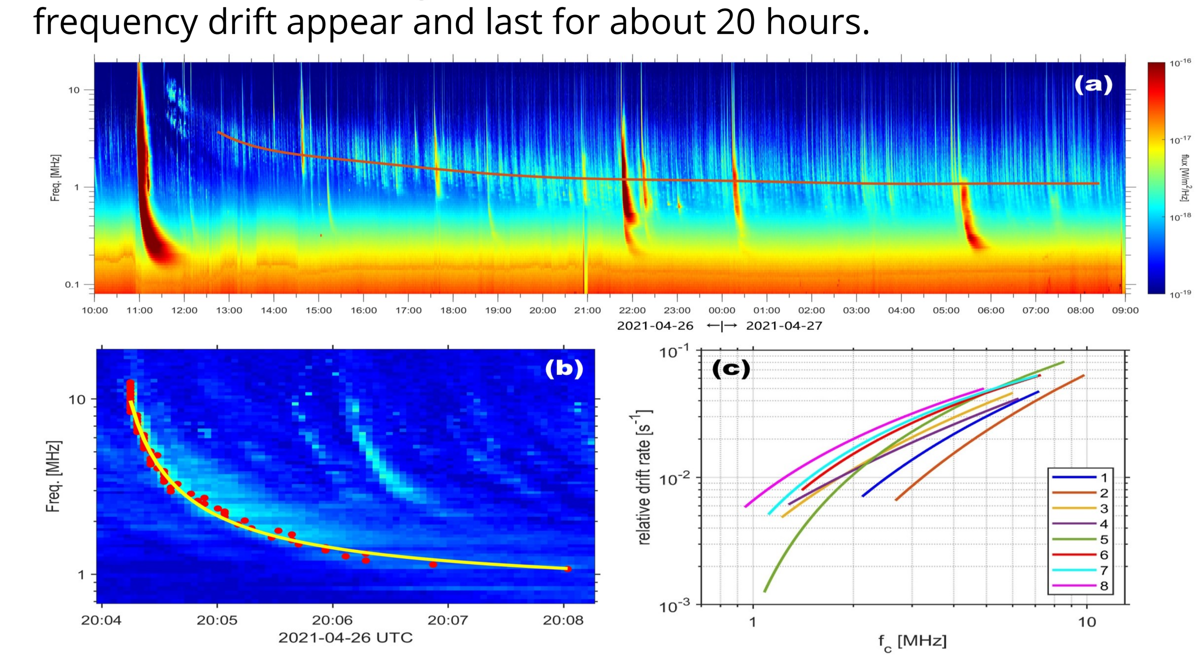

Fig. 3 Dynamic spectrum observed by PSP, the example of drift curve fitting and the frequency drift rates of 8 weak radio bursts. This figure is from Ma et al. (2025).

The weak bursts exhibit three special spectral features: (1) each of them has a shorter duration of about 1-4 min; (2) the start frequency for most of them is below 15 MHz; (3) their peak frequency decrease with the time.

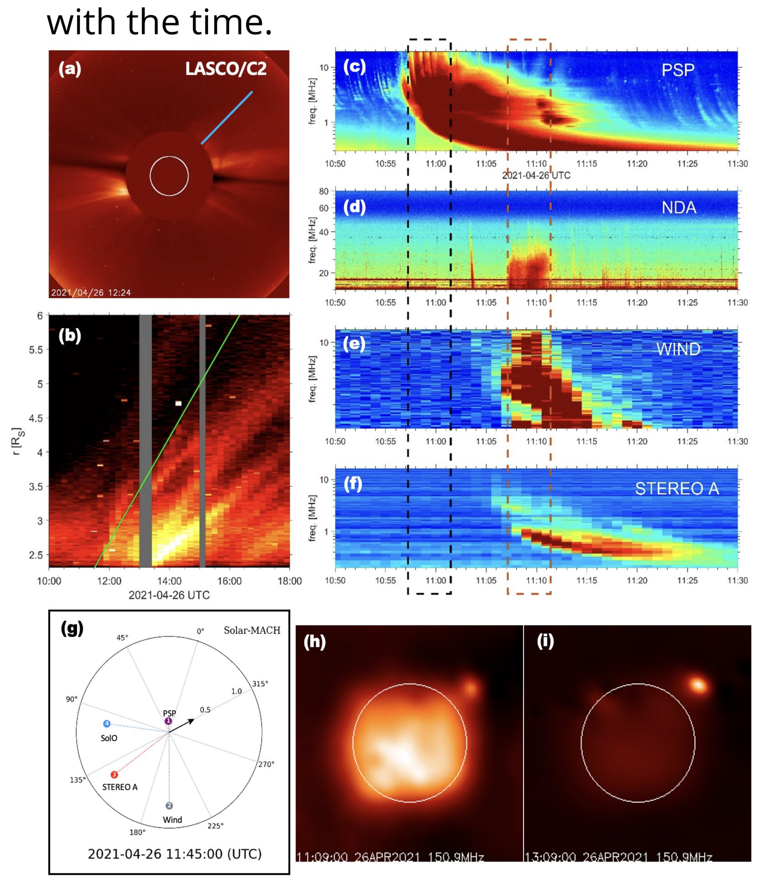

Fig. 4 shows that a weak CME is the unique eruption event associated with the latter radio bursts. The time difference (>9 min) of the intense type III radio bursts by PSP and NDA implies that the correlative CME may originate from the back of solar limb.

The image observation from NRH at 150.9 MHz shows that a obvious radio source at same direction of the weak CME, which also implies the active region is possibly behind the northwestern solar limb.

Fig. 4 CME observation by LASCO/C2 and the time difference of intense type III radio burst by different instruments. The NRH images are also shown here. This figure is from Ma et al. (2025).

Plasma Models and Theoretical Explanation

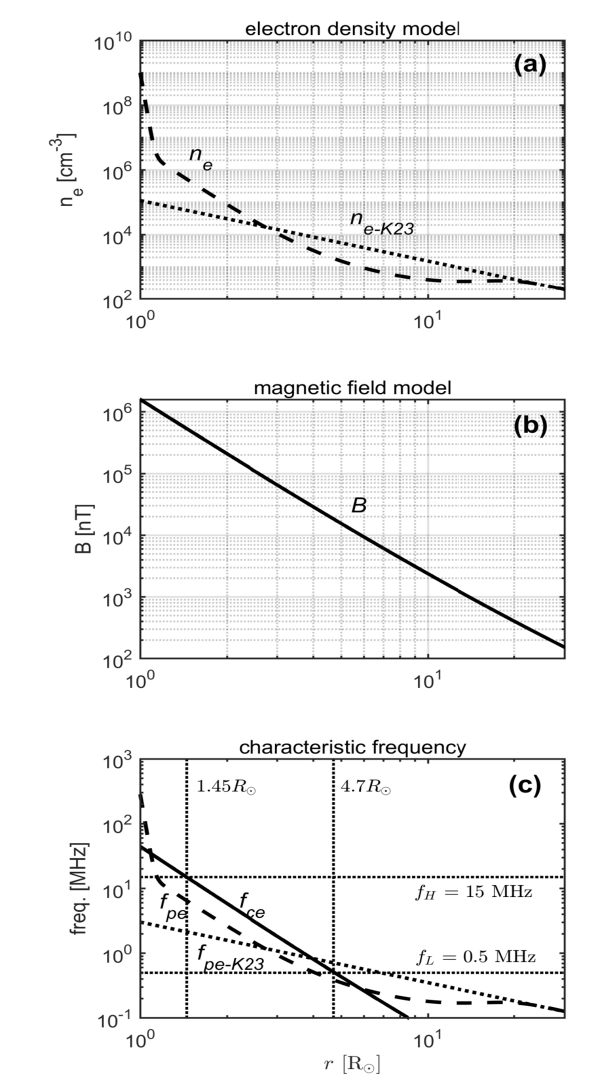

Fig. 5 Models of electron density and magnetic field and their corresponding characteristic frequencies. This figure is from Ma et al. (2025).

The data measured in situ by PSP and empirical models are used to fit the following models:

$$n_e(r) = \frac{n_0}{1 + 9e^{-(r-1)^2/100}}, \tag{1}$$

$$n_0 = \frac{10^{10}}{e^{50(r-1)}} + 0.63\left(\frac{680}{r^4} + \frac{35}{r^2} + 2.8\right)\frac{10^5}{r^2}\ [\mathrm{cm}^{-3}], \tag{2}$$

$$B(r) = 15r^{-3} + 0.87r^{-2}\ [\mathrm{G}], \tag{3}$$

$$n_{e-K23}(r) = 113525 \cdot r^{-1.87}. \tag{4}$$

Fig.5 shows the characteristic frequencies of the models of equation (1)-(4) can cover well the frequency range of radio bursts.

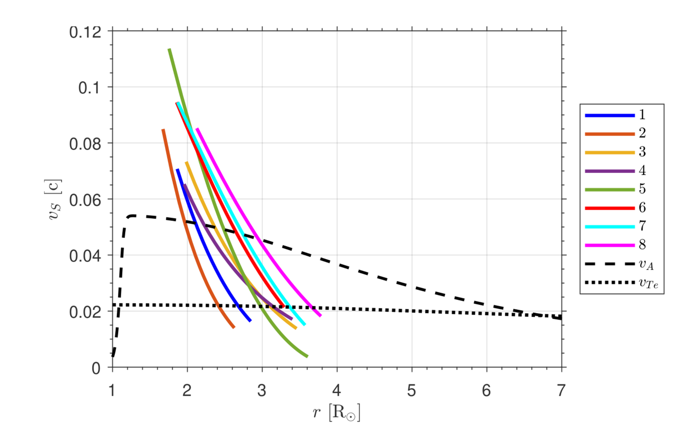

Fig. 6 Drift speed of 8 weak radio bursts (colorful curves), Alfvén speed and electron thermal speed versus the heliocentric distance. This figure is from Ma et al. (2025).

It means that these events may originate from solar wind acceleration region with the heliocentric distance between 1.45 – 4.7 R⊙.

These weak radio bursts have fast decreasing frequency drift rates, short duration and narrow frequency band. These features imply that the weak bursts may originate from small-scale emitting sources at high corona rather than the energetic electron beams accelerated in low corona. All the features of the bursts mentioned above are consistent with the solitary wave radiation (SWR) presented by Chen et al. (2024).

Conclusion

We propose a model to explain the long-time radio storm including many weak bursts. In a close magnetic structure within a weak CME erupting behind the solar limb, intense Alfvén turbulence can form the non-linear SKAWs. The electrons can be trapped in the potential well of SKAWs and accelerated to super-Alfvénic speed. The electrons with crescent-shaped VDF scattered by AWs excite ECM emission, called solitary wave radiation (i.e. SWR). The numerous SWRs present a long-time radio storm, which can reflect the movement of whole close magnetic structure behind the CME leading edge, called type IV-like radio burst.

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