Whistlers in the Solar Vicinity That Are Spiky in Time and Frequency

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Received 2020 October 2; revised 2020 November 21; accepted 2020 November 24; published 2021 February 9

Abstract

Spiky whistlers are short duration chirps of electric field that have fine structures in both frequency and time. They are observed on the Parker Solar Probe for the first time. From the limited available data, they appear to be accompanied by low-frequency ion waves and to occur relatively frequently. The origin of these wave pairs and their correlations are not understood.

Unified Astronomy Thesaurus concepts: Solar wind (1534); Solar physics (1476); Solar electromagnetic emission (1490)

1. Introduction

The term “spiky” is used to describe whistlers in several contexts. In a context that is relevant to this article, spiky whistlers may be the result of either nonlinear, modulation instabilities with respect to low-frequency perturbations (Yu & Shukla 1982; Shukla et al. 1984), two-dimensional self-modulation (Karpman & Washimi 1977; Eliasson & Shukla 2005; Krafft & Volokitin 2018), or other processes. In the present paper, the term “spiky” is expanded to describe sharp, narrow bursts in both time and frequency of whistlers that are observed for the first time by the Parker Solar Probe.

2. Data

On 2020 June 4 the Parker Solar Probe was about 36 solar radii from the Sun on its fifth orbit, measuring the two components of electric field in the plane perpendicular to the Sun–satellite line (Bale et al. 2016; Mozer et al. 2020). The power of the X-component electric field, measured during a 1 minute interval, is illustrated in the lower panel of Figure 1, in which more than a dozen impulsive electric field bursts were observed over the frequency range of 280–500 Hz. (The large wave power at lower frequencies is not shown in order to emphasize the power at the frequencies shown). That these spikes are chirps with the initial pulse occurring at all frequencies rather than frequency dispersed incident waves is clear from the occurrence of power at all frequencies at the beginning of each spike.

The upper panel of Figure 1 describes the phase relationship of EX to EY, covering phase differences from 0° to 180°. Because the phase difference was typically 90 degrees with EX leading EY and the background magnetic field was in the +Z-direction, the observed waves were right-hand-polarized whistler mode waves. For these assumed parallel propagating whistlers, their frequencies in the plasma frame were identical to their frequencies in the spacecraft frame to within about 20% and they were between 0.13 and 0.24 times the electron gyrofrequency of 2100 Hz.

To obtain the electric field from the measured potential differences, the potential measurements were divided by 3.5 m, the geometric half-length of the antennas. It has been shown (Mozer et al. 2020) that this is the best estimate of the effective antenna length at the measured frequencies.

The data of Figure 1 were obtained by Fourier (not wavelet) analyses, such that the time and/or frequency resolution of the plots may be adjusted over a wide range. Figure 2 presents the same data as in Figure 1, at a time resolution of 27 ms. At this higher resolution, the individual chirps of Figure 1 are seen, in the bottom panel of Figure 2, to consist of many, short duration, discreet pulses of whistler energy. These spiky temporal features are better seen in the EX time domain waveform of Figure 3 as 11 discreet, 10 ms (three cycles) to 20 ms (six cycles) whistler pulses in 220 ms. (The amplitude of the electric field may be overestimated by a factor of about two because the dc electric field exceeded –vxB by a similar factor).

In Figure 4, the same data is plotted with a frequency resolution of 4.6 Hz. The bottom panel of this figure shows that the wave energy was largely contained in discrete frequency pulses. This result is further illustrated in the spectrum of 0.8 s of data in Figure 5. In this figure, there are seven peaks with peak-to-valley ratios of one to two orders of magnitude in a 100 Hz interval.

3. Discussion

The self-modulation that produces spiky whistlers is accompanied by relative density fluctuations (Karpman & Washimi 1977; Eliasson & Shukla 2005; Krafft & Volokitin 2018). To test the existence of such density fluctuations, the relative density, Δn/n, is plotted in the bottom panel of Figure 6, where the density was obtained from a linear least-squares fit of the logarithm of the 2.8 Hz electron density versus the spacecraft potential over a 30 minute interval at the time of interest. The fluctuations, during both this time and generally throughout this orbit, were one or a few percent. Thus, the less than 1% density fluctuations that might be expected from the self-modulation instability are not measurable.

Whether or not the observed spiky whistlers result from a nonlinear, modulation instability with respect to low-frequency perturbations (Yu & Shukla 1982; Shukla et al. 1984) can be tested by examining low-frequency signals such as those...
illustrated in the top panel of Figure 6. A time domain segment of this observed 5 Hz signal is shown in Figure 7, in which the top panel gives the three components of the magnetic field and the bottom panel gives the two measured components of the electric field, both presented in spacecraft coordinates. As seen in this figure, the X-components of both fields lead the Y-components by 90°. Because the background magnetic field was in the +Z-direction, this is a right-hand polarized wave in the spacecraft frame. In the plasma rest frame, this wave may be either an outward moving whistler or an inward moving electromagnetic ion wave, depending on the direction of propagation in the rest frame. To determine this direction from the wave speed in the spacecraft frame, the hodogram of $E_Y$ versus $B_X$ is plotted in Figure 8. The least-squares slope of this curve gives an outward wave speed of 284 km s$^{-1}$ in the spacecraft frame. Because the solar wind flow speed was 301 km s$^{-1}$, the wave speed in the plasma rest frame was $-17$ km s$^{-1}$, i.e., the wave was inward moving in the plasma rest frame. In this frame and for an assumed parallel propagating wave, its speed should be equal to $\omega/k$ obtained from the dispersion relation for an ion wave. Because $\omega/k = 18$ km s$^{-1}$, this requirement is satisfied and the wave is an inward moving ion wave.

This low-frequency ion wave is associated with the spiky whistler, as is shown in Figure 9. The top panel is the familiar spiky whistler plot and the bottom panel gives the 3–10 Hz bandpass filtered power as a function of frequency and time. The bottom curve is offset from the top curve by 6 s to provide a better visual correlation between the two quantities. This 6 s time lag may be interpreted as the difference in travel times of the two waves from their common source. Because the whistler speed in the spacecraft frame was about 1400 km s$^{-1}$ (as determined from the spacecraft measured $E/B$), while the ion...
wave speed was 284 km s$^{-1}$, the distance, $D$, that the two waves traveled is given by

$$D = 1400T = 284(T + 6),$$

where $T$ is the travel time of the whistler wave. From this equation, the waves were generated at a distance $D = 2100$ km from the spacecraft at the time $T = 1.5$ s before the whistlers were observed. This analysis assumes that both waves were formed as pulses in the same location, at the same time, and that no other high-frequency waves formed during the subsequent propagation of the low-frequency wave. Because not all wave pairs might satisfy this restriction, the correlation between the data in the two panels of Figure 9 is not expected to be quantitative. However, the observed correlation suggests that the whistler spikes and the few Hz ion waves are related.

During the 12 hr period of high rate wave data, there were 24 bursts of lower band whistler waves. About half of these bursts were associated with few Hz electromagnetic ion waves and about one-third of the events had spiky whistlers. Thus, it
appears that lower band whistlers are often associated with low-frequency ion waves. The observed ion waves are electromagnetic, parallel propagating, Alfvén/ion-cyclotron waves, which are known to be incompressible so they do not produce density fluctuations. In contrast, the modulation instability involves ion-acoustic electrostatic fluctuations, which are produced by the ponderomotive force of a high-frequency whistler wave. Thus, the observed ion waves are not those in the theory of modulation instability of Yu & Shukla (1982) and Shukla et al. (1984). The mechanism, which results in quasi-periodic appearance of spiky whistler waves, and the relation of this quasi-periodicity to the low-frequency electromagnetic fluctuations remains to be addressed theoretically.

One can also imagine a three-wave parametric instability that creates a daughter whistler and the low-frequency wave from an incident whistler. The requirement that $\omega_1 = \omega_1 + \omega_2$ is met for the daughter whistler having a frequency that is about 4 Hz less than the incident whistler and this can explain the high time resolution data of Figures 2 and 3 as being due to beating between the incident and daughter whistlers. However, the full requirement for the parametric instability is that $\partial \omega / \partial k = \omega_{IW}/k_{IW}$, where $\partial \omega / \partial k$ was obtained from the whistler dispersion relation and $\omega_{IW}/k_{IW}$ is the phase velocity of the ion wave. Because these two quantities differ by an order of magnitude, this instability does not work for the data of interest.

The ∼1 s resolution archive electron data has been examined. It could not be determined whether the electron distribution functions were unstable with respect to whistler wave generation because the fitting did not allow unambiguous determination of the drift velocity of the halo population (Halekas et al. 2020).

In summary, interesting spiky whistlers accompanied by low-frequency inward propagating ion waves have been observed, but their origins and correlations are not understood.

This work was supported by NASA contracts NNN06AA01C and NASA-G-80NSSC1. The authors acknowledge the extraordinary contributions of the Parker Solar Probe spacecraft engineering team at the Applied Physics Laboratory at Johns Hopkins University. Our sincere thanks to P. Harvey, K. Goetz, and M. Pulupa for managing the spacecraft commanding and data processing, which has become a heavy load thanks to the complexity of the instruments and the orbit. The work of I.V. was supported by NASA grant 80NSSC18K0646. The data used in this paper are publicly available at http://fields.ssl.berkeley.edu/data.

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Figure 9. Comparison of the timing of pulses observed in the whistlers (upper panel) and those observed in a higher time resolution plot of the low-frequency ion wave (lower panel). The lower panel contains data that is bandpass filtered from 3 to 10 Hz and that is offset from the data in the upper panel by 6 s. There was negligible low-frequency power outside the immediate time interval that is illustrated.