Non-detection of lightning during the second Parker Solar Probe Venus gravity assist

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Key Points:

- During the second Parker Solar Probe (PSP) Venus gravity assist maneuver, the radio receiver on PSP recorded high cadence 'burst mode' spectra.
- If Venus lightning exists and produces MHz radio emission, it is highly likely that signals would have been detected.
- No significant radio signals above background were observed, consistent with prior non-detection of lightning at Venus.

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Abstract

The Parker Solar Probe (PSP) spacecraft completed its second Venus gravity assist maneuver (VGA2) on 2019 December 26. For a 20 minute interval surrounding closest approach, the PSP/FIELDS Radio Frequency Spectrometer (RFS) was set to 'burst mode', recording radio spectra from 1.3–19.2 MHz at sub-second cadence. We analyze this burst mode data, searching for signatures of radio frequency EMP or 'sferic' emission from lightning discharges. During the burst mode interval, only 4 spectra were observed with strong impulsive signals, and all 4 could be attributed to saturation of the RFS high gain stage by *in situ* electrostatic plasma waves. These RFS measurements during VGA2 are consistent with previous non-detection of radio frequency lightning signals from Venus.

Plain Language Summary

The Parker Solar Probe (PSP) studies the physics of the solar wind, using an elliptic solar orbit which brings it much closer to the Sun than any other spacecraft. PSP uses seven Venus flybys to change its orbital trajectory via gravitational assist, lowering the distance of closest solar approach after each flyby. During Venus Flyby 2 in December 2019, the PSP radio receiver was set to a special operating mode, which is sensitive to possible lightning signals from the Venus atmosphere. During the flyby, no lightning signals were detected. This is consistent with previous non-detection of Venus lightning at radio frequencies.

1 Introduction

Lightning is an atmospheric electric discharge between two locations that have been charged to a large differential potential. In the terrestrial atmosphere, lightning occurs frequently (30-100 times per second worldwide) and produces a broad range of phenomena, including bright optical flashes and thunder (Dwyer & Uman, 2014). Lightning also generates electromagnetic whistlers, which can propagate into Earth's magnetosphere, and are detectable out to a distance of several Earth radii (Záhlava et al., 2019). At radio frequencies, lightning produces strong, transient broadband EMP emission commonly known as 'sferics' (Smith et al., 2002). Terrestrial sferic discharges typically exhibit a f^{-2} power spectrum at frequencies below a few MHz, steepening to f^{-4} at higher frequencies (Levine & Meneghini, 1978).

While extraterrestrial lightning has been definitively observed at Jupiter and Saturn (Zarka et al., 2008), the existence and nature of lightning at Venus remains an open question. Lorenz (2018) reviewed observations of potential detection (and non-detection) of lightning at Venus, concluding that while some type of electromagnetic activity is present on Venus (Russell et al., 2008), its properties are likely different from those occurring on Earth. During three years in orbit, the Akatsuki spacecraft did not detect optical emission due to lightning flashes (Lorenz et al., 2019). During two Cassini Venus flybys in 1998 and 1999, with closest approach distances of 284 and 598 km from the Venus surface, the Cassini Radio and Plasma Wave Science instrument did not detect lightning sferics (Gurnett et al., 2001).

While the Cassini observations were highly sensitive and the non-detection was statistically robust, the observations were limited in duration to two short flyby intervals (several hours during each flyby). Therefore, the existence of highly intermittent lightning activity (with terrestrial sferic-like emissions) on Venus remains a possibility. For this reason, during the second Venus flyby of the Parker Solar Probe (PSP), the PSP radio receiver was commanded to a high rate mode that is sensitive to strong impulsive signals. This Letter describes these observations, concluding that they are consistent with the non-detection reported by Gurnett et al. (2001).

2 PSP Instrumentation and Venus Observations

The PSP spacecraft (Fox et al., 2016) launched in August 2018 on a mission to study the inner heliosphere, addressing long-standing questions related to the origin of the solar wind and heating of the solar corona. The FIELDS instrument suite for PSP (Bale et al., 2016) provides electric and magnetic field measurements for the mission. The FIELDS data products employed in this Letter come from the FIELDS Time Domain Sampler (TDS), the Radio Frequency Spectrometer (RFS, Pulupa et al. (2017)), and the Digital Fields Board (DFB, Malaspina et al. (2016)).

In order to achieve a final perihelion distance below 10 solar radii, the PSP mission employs seven Venus Gravity Assist (VGA) maneuvers, scheduled over a six year period from 2018 to 2024. As of fall 2020, the first three VGA maneuvers have been successfully executed, lowering the PSP perihelion to 20 solar radii.

This Letter focuses on FIELDS observations during the second gravity assist (VGA2), which occurred on 2019 December 26. During VGA2, the spacecraft skimmed the edge of the Venus bow shock, reaching a closest approach distance of $\sim$3000 km above the surface of the planet. Figure 1 shows an overview plot of VGA2 in XY and XZ Venus Solar Orbital (VSO) coordinates, with lines indicating the PSP trajectory and a model bow shock. The bow shock shown in the figure uses a conic model, with parameters determined by Malaspina et al. (2020).

3 RFS burst mode

The RFS is a two channel receiver, measuring both auto and cross spectra. In its default operational mode, the RFS produces averaged spectra, in 64 logarithmically spaced bins, in both the Low Frequency Receiver (LFR, 10.5 kHz–1.7 MHz) and High Frequency Receiver (HFR, 1.3–19.2 MHz) frequency ranges. The number of individual auto and cross spectra averaged together for a single LFR or HFR measurement is commandable, and the cadence of the LFR and HFR data depends on the number of commanded averages n_{avg}. During a typical solar encounter, n_{avg} is 80 and the RFS produces one LFR and one HFR spectrum every 7 seconds. For purposes of comparison with the special 'burst mode' enabled near VGA2, we will refer to this default RFS mode as 'LFR/HFR mode'. Details of the LFR/HFR algorithms are described in Pulupa et al. (2017), and examples of typical RFS performance in LFR/HFR mode are described in Pulupa et al. (2020).

During VGA2, RFS 'burst mode' was enabled, to search for possible signals of lightning. RFS burst mode is a special high cadence mode, designed for rapid observations of solar radio bursts near PSP perihelion. Burst mode has not yet been enabled during PSP solar encounters, primarily due to low solar activity during the first two years of the mission. The primary differences between burst mode and LFR/HFR mode are: (1) $n_{avg} = 1$, i.e. burst mode returns individual spectra, not averaged spectra; (2) burst mode cadence is significantly higher–during VGA2, cadence is 0.218 seconds; and (3) burst mode is limited to only the HFR frequency range.

In both LFR/HFR and burst mode, the two channels of the receiver can be configured to use any combination (monopole or dipole) of the $V1$–$V4$ FIELDS antennas. In both modes, the RFS selects the gain stage automatically–attempting first to record high gain spectra, but returning low gain spectra if the high gain stage is saturated.

Some approximate scaling and timing arguments can be used to demonstrate that, if lightning sferics are present on Venus, they would likely be detected by RFS in burst mode. Gurnett et al. (1991) scaled the peak electric fields reported by Venera observa-

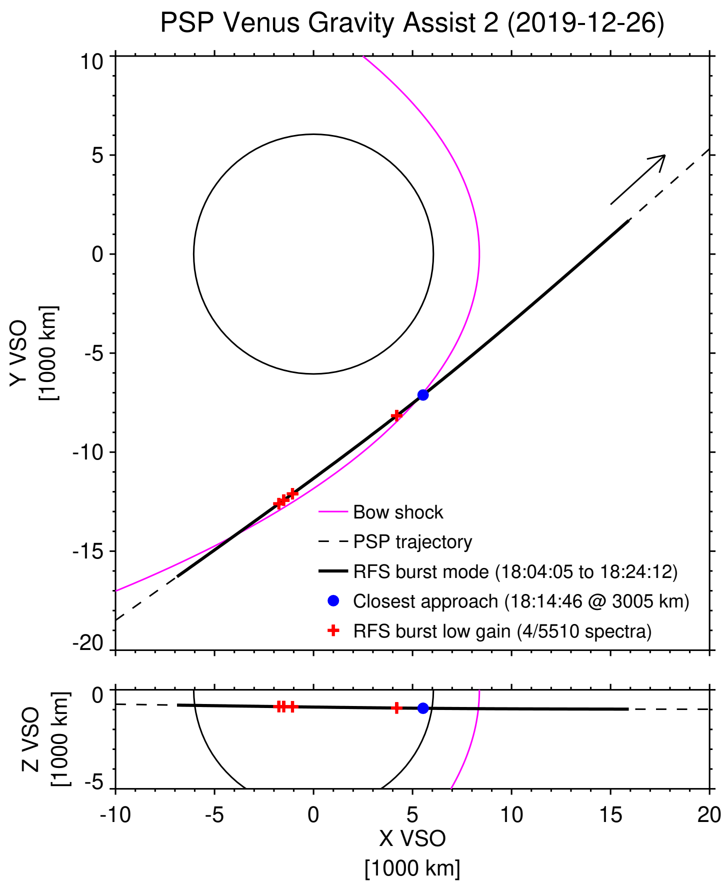

Figure 1. Flyby trajectory for PSP VGA2, in XY (top) and XZ (bottom) VSO coordinates. PSP trajectory is indicated with a dashed/solid line, with the thick solid segment indicating the interval when RFS was in burst mode. Closest approach and RFS burst low gain events are indicated with a blue circle and red crosses, respectively. The magenta line indicates the best fit conic bow shock model from Malaspina et al. (2020).

tions (Ksanfomality et al., 1983), which are given as $\sim$100 μV m^{-1} Hz$^{-1/2}$ at a frequency of 10 kHz and an estimated source distance of 1200-1500 km. Gurnett et al. (1991) used $1/f^2$ and $1/R^2$ scaling in frequency and radius to estimate an amplitude of $\sim 4\times10^{-15}$ V^2 m^{-2} Hz^{-1}, at a frequency of 1 MHz, for lightning observations during the Galileo Venus flyby. The Galileo flyby occurred on 10 February 1990, and radio frequency observations were performed at typical distances of 4-5 Venus radii ($\sim$24,000-30,000 km). Since PSP VGA2 is somewhat closer than the Galileo flyby, a similar scaling yields estimates of power spectral density of $\sim 7\times10^{-14}$ V^2 m^{-2} Hz^{-1} at $\sim$1 MHz, well above the noise level of the RFS receiver (in either high or low gain mode). We note that for this estimate we have used a nominal effective length of 1 m for the PSP/FIELDS antennas.

The integration time for a single burst mode spectrum is 0.853 ms, and the cadence of measurements is 218 ms, for a duty cycle of 0.4%. If Venus lightning occurred at similar rates for terrestrial lightning, the rate of flashes would be $\sim$100 per second. RFS burst mode was implemented for 20 minutes, and for approximately half of this interval, the night side of Venus was visible to PSP. (On the night side, the density of the ionosphere is lower, allowing radio waves with frequencies of $\sim$1 MHz to escape the atmosphere. On the day side, radio signals can also escape, but the ionospheric cutoff is higher, at several MHz (Brace & Kliore, 1991).) Given the previous estimate of lightning amplitude, and under the assumption that lightning occurrence on Venus is similar to Earth, we might expect to observe

$$10\,\text{minutes} \times 100\,\frac{\text{events}}{\text{second}} \times 0.4\% \approx 240\,\text{events}. \tag{1}$$

While the PSP mission design does not include an Earth flyby, flybys of Earth using instruments with similar sensitivity have observed many lightning signals (Gurnett et al., 2001). From these comparisons and the above calculations, it is reasonable to claim that PSP/RFS observations during VGA2 have adequate sensitivity, time resolution, and duration to detect possible signals of terrestrial-like lightning on Venus.

4 Results

FIELDS/RFS was commanded to burst mode during a 20 minute period near VGA2 closest approach, from 18:04:05 to 18:24:12 UTC. The RFS inputs were configured for cross dipole measurements, with one channel set to observe $V1$–$V2$ and the other channel set to $V3$–$V4$. The PSP trajectory during this burst interval is indicated in Figure 1, plotted as a thick solid line.

During this period, 5510 burst mode RFS spectra were recorded. Of these, 5506 spectra were taken in high gain and 4 were in low gain. The high gain spectra were consistent with quiet time measurements in the solar wind, with a background signal consisting of galactic synchrotron emission and intrinsic receiver noise. Aside from a decrease in the synchrotron spectrum near close approach, consistent with occultation of a fraction of the radio sky by Venus, signal levels remained steady throughout the burst mode interval.

The four low gain spectra are signatures of brief, high amplitude RFS signals. However, they are unlikely to be related to lightning for two reasons: (1) there is no decreasing frequency structure similar to the f^{-2} and f^{-4} decrease observed in terrestrial sferics, and (2) they tend to occur simultaneously to wave activity in lower frequency bands, pointing to saturation of the RFS high gain stage by strong *in situ* plasma waves as a more likely origin. The times of low gain spectra are indicated in Figure 1 with red crosses. All four low gain spectra were recorded close to the model shock crossings, which occur at approximately 18:07 and 18:14 UTC.

Figure 2 shows a subsection of the burst interval near 18:08 UTC, when three of the four low gain spectra were observed. Figure 2a shows the gain state for the RFS burst

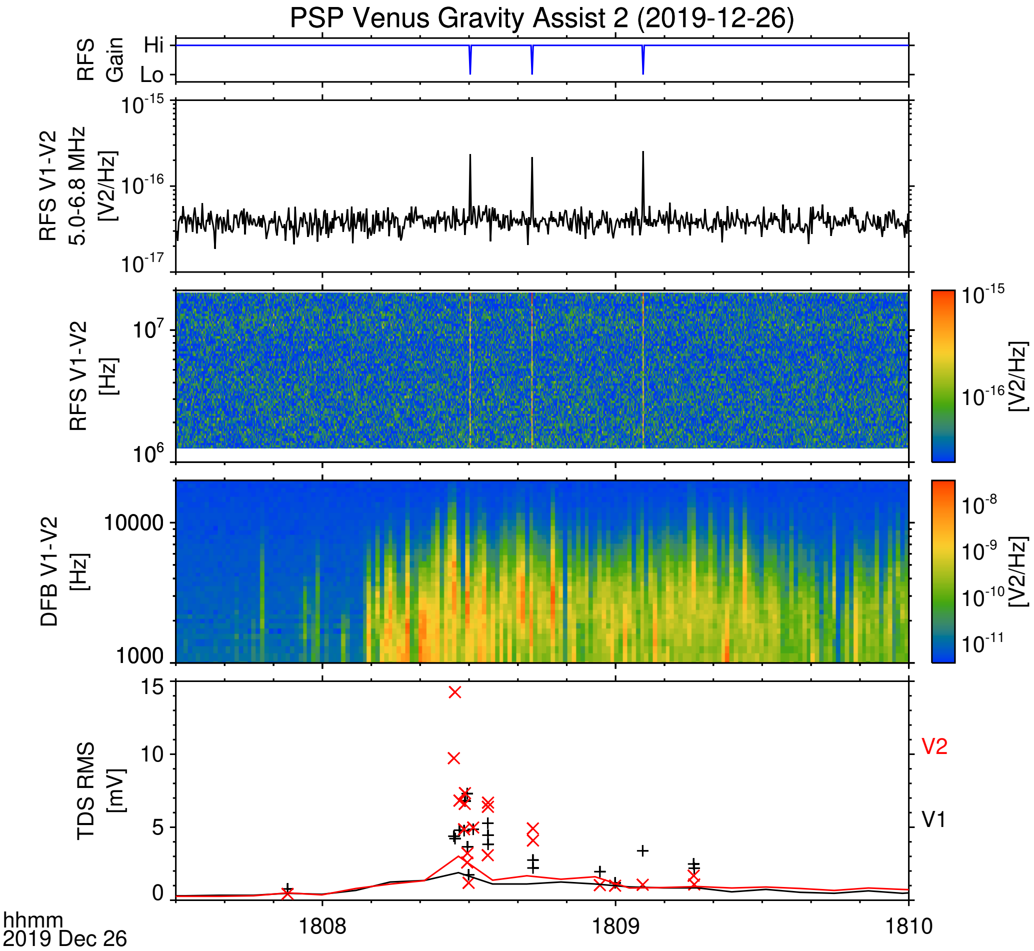

Figure 2. Interval of FIELDS measurements near VGA2 close approach. (a) Gain indicator (high or low) for RFS burst mode spectra. (b) Measured power spectral density from the RFS V1-V2 dipole auto spectra, in the frequency range 5.0-6.8 MHz. (c) Spectrogram of the RFS burst mode data for the V1-V2 dipole. (d) DFB spectra from the V1-V2 dipole. (e) TDS waveform RMS measurements, for the V1 and V2 monopole channels.

mode. Figure 2b shows the averaged power spectral density (PSD) from the $V1$–$V2$ dipole, averaged over a range of frequencies from 5.0 to 6.8 MHz. Figure 2c shows a spectrogram of $V1$–$V2$ PSD data, covering the full frequency range of the RFS burst mode observations. Figure 1d shows the DFB AC coupled spectra in the kHz to tens of kHz range, also using the $V1$–$V2$ dipole as the source. Figure 2e shows data from the TDS receiver, which recorded several high amplitude waveforms during the interval. The RMS values of the TDS waveform captures are shown with crosses, while the average RMS values measured over 7 second intervals are shown with solid lines. TDS measurements from the $V1$ antenna are shown in black, and those from the $V2$ channel are shown in red.

The low gain RFS burst spectra times are apparent in Figure 2a-c, and clearly correspond to high amplitude signals in the lower frequency DFB and TDS data. This is consistent with observations from PSP Encounter 4, where RFS (in LFR/HFR mode) switched to low gain when exceptionally high amplitude electrostatic plasma waves were observed near perihelion.

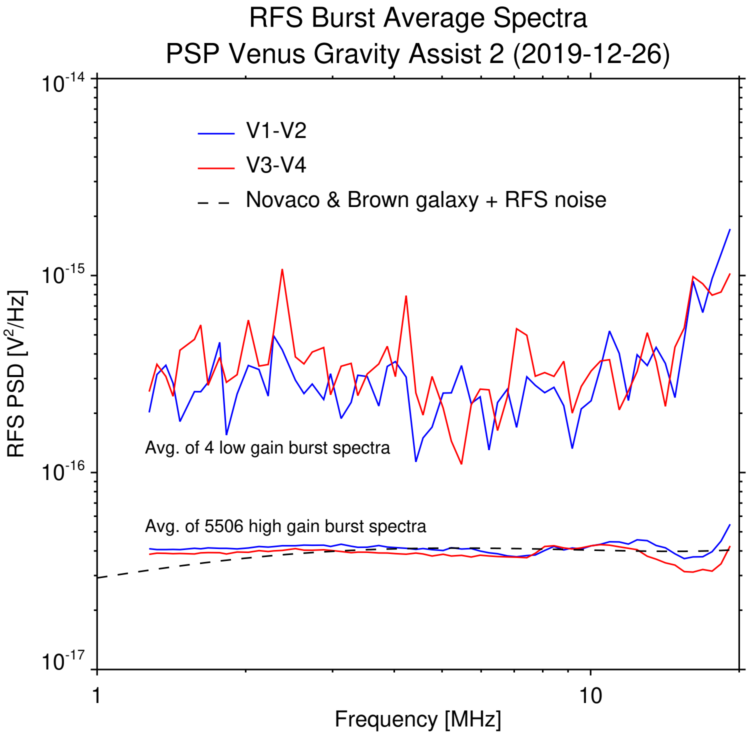

Figure 3. Averaged spectra during RFS burst mode interval during VGA2. The black and red lines indicate V1-V2 and V3-V4 dipole measurements, respectively.

Figure 3 shows RFS burst mode spectra recorded during the burst mode interval. Data from the $V1-V2$ channel are shown in blue, and data from $V3-V4$ are shown in red. The high gain spectra, with typical PSD values of $\sim 4^{-17}$ V^2/Hz, are consistent with quiet time values observed in the solar wind, where the primary signal is the galactic synchrotron spectrum. A nominal background signal, consisting of the galactic spectrum as measured by Novaco and Brown (1978) and a constant term of 2.1×10^{-17} V^2/Hz (approximate RFS receiver noise in the HFR frequency range) is plotted in Figure 3 with a dashed line.

The low gain RFS measurements have a higher intrinsic background than high gain mode, consistent with the higher measured PSD of $\sim 2^{-16}$ V^2/Hz. The noisier low gain spectra in Figure 2 simply reflects the smaller number of measurements included in the average. There is no apparent frequency structure (f^{-2} and f^{-4} power law behavior) in the low gain spectra, consistent with the interpretation of these measurements as the result of high gain saturation by strong lower-frequency waves, and inconsistent with lightning. For both high and low gain spectra, a rise in spectral amplitude above ∼16 MHz corresponds to aliased power from above the RFS Nyquist frequency of 19.2 MHz.

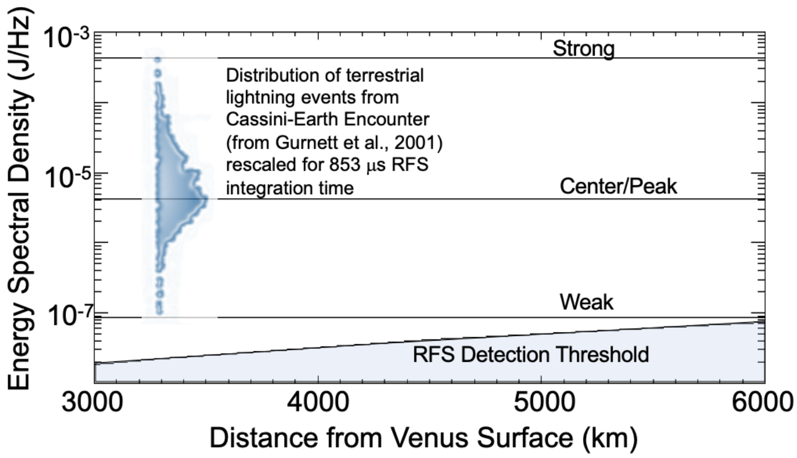

Figure 4. Threshold value for detection of lightning by the RFS receiver at distances comparable to those observed during VFB3. The vertical histogram of data shows terrestrial lightning events observed during the Cassini–Earth encounter, rescaled for the RFS integration time.

In the absence of a positive lightning detection, it is possible to place an upper limit on lightning discharge events, based on the sensitivity and integration time of the RFS receiver in burst mode. The estimate presented here is based on the method presented in Gurnett et al. (2001), using the Cassini flybys, and in Gurnett et al. (2010), which describes a similar non-detection of lightning at Mars using the MARSIS radar receiver. These studies defined the detection threshold in units of energy spectral density per discharge (Joules Hz^{-1}). This expresses the threshold in units appropriate for the impulsive character of lightning events, and is normalized to remove the effect of radial distance from the source to the spacecraft.

We use 3σ as a threshold for event detection, where σ is defined as the noise fluctuation level in the burst data. Using the data shown in Figure 2c, we calculate this level as $\sigma \approx 2.5 \times 10^{-17}$ V^2/m^2/Hz in the HFR frequency range (using an effective length of 1 m). The threshold value for detection in J/Hz is then given by $3\sigma/Z_0 \times t_{int} \times 4\pi R^2$, where Z_0 is the impedance of free space, t_{int} is the 0.853 ms RFS integration time, and R is the distance from the source to the spacecraft (assuming the source is directly beneath the spacecraft on the surface of Venus, and emission is isotropic).

Figure 4 shows the results of the threshold calculation for RFS observations during VGA2. The vertical histogram shows the distribution of terrestrial lightning events from the Cassini flybys described in Gurnett et al. (2001), with the distribution scaled to the RFS receiver integration time, as the same data set was scaled for comparison to MARSIS data in Gurnett et al. (2010). At closest approach, the RFS receiver is sensitive to events ∼200 times smaller than typical terrestrial-like lightning.

Although the results presented here exhibit non-detection for terrestrial-like lightning at Venus, it is possible that lightning signals significantly different than those on Earth could be below our detection threshold. Figure 5 compares a typical terrestrial-like lightning spectrum (Levine & Meneghini, 1978) to RFS sensitivity, showing (as in the previous paragraphs) a signal ∼200 times the sensitivity. In addition to the terrestrial-like spectrum, the spectrum for a discharge which transfers the same amount of charge but at a slower rate (slower by a factor of 10) is also plotted. Thus the spectral peak intensity is the same as the terrestrial case, but the peak frequency is shifted by a factor of 10. Under this assumption, such a discharge would lie well below the RFS sensitivity, by a factor of ∼50. However, this "slow discharge" spectrum might be detectable at closer distances.

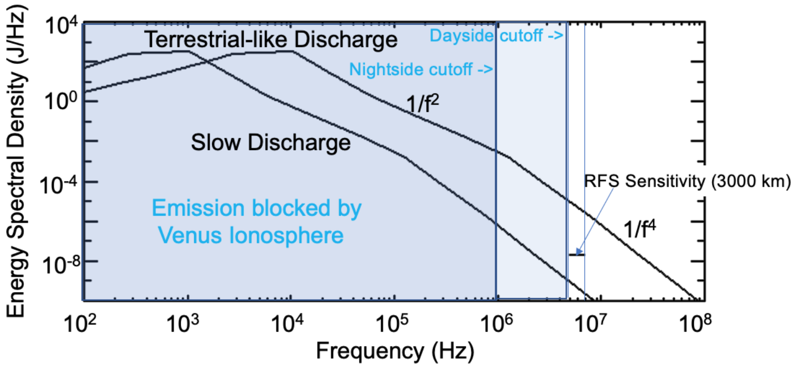

Figure 5. Illustration of possible effects of slow discharge on lightning spectra. While a typical terrestrial-like discharge event would be well above the detection threshold determined by RFS sensitivity, a similar event which differed only by the discharge rate could be below the threshold.

5 Summary and Conclusions

During PSP VGA2, the RFS instrument employed its rapid cadence burst mode, in an effort to detect possible radio frequency lightning signatures. No such signatures were detected. Near the bow shock, several high amplitude burst mode spectra were observed, however, the lack of power law frequency structure and concurrent high amplitude measurements at lower frequencies indicate plasma waves, not lightning, as a likely source.

These results are in agreement with observations from two Cassini flybys (Gurnett et al., 2001). Addition of a third flyby non-detection from an independent observatory adds additional support to the conclusion (Lorenz, 2018; Lorenz et al., 2019) that the electromagnetic activity observed at Venus does not resemble terrestrial lightning—in particular, that whistler mode waves observed at Venus (Russell et al., 2008) are not associated with optical and radio emission, as they are on Earth.

The PSP mission has completed three VGA maneuvers. Four more are planned, including the seventh and final VGA7, with a closest approach distance <400 km from the Venus surface. Although the closer encounter distances may enable more sensitive searches for possible lightning-like spectra, there are tradeoffs to enabling RFS burst mode to perform an additional test. With the current flight software, enabling burst mode disables measurement of spectra in the LFR range (10.5 kHz–1.7 MHz), and recent measurements from VGA3 indicate that LFR measurements in and near the Venus ionosphere are of considerable scientific interest.

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