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

M. Pulupa[1], S. D. Bale[1,2,3,4], S. M. Curry[1], W. M. Farrell[5], K. A. Goodrich[1], K. Goetz[6], P. R. Harvey[1], D. M. Malaspina[7,8], N. E. Raouafi[9]

[1]Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, USA
[2]Physics Department, University of California, Berkeley, CA 94720-7300, USA
[3]The Blackett Laboratory, Imperial College London, London, SW7 2AZ, UK
[4]School of Physics and Astronomy, Queen Mary University of London, London E1 4NS, UK
[5]Solar System Exploration Division, NASA/Goddard Space Flight Center, Greenbelt, MD, USA
[6]School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA
[7]Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder, CO, USA
[8]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA
[9]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA

Key Points:

- During the second Parker Solar Probe (PSP) Venus gravity assist, the PSP/FIELDS radio receiver recorded high cadence ‘burst mode’ spectra.
- We examined the burst mode data for lightning-associated emission. No lightning events were observed, consistent with prior observations.
- We can use this non-detection to place an upper limit on possible lightning emission from Venus.

Corresponding author: Marc Pulupa, `pulupa@berkeley.edu`

Abstract

The Parker Solar Probe (PSP) spacecraft completed its second Venus gravity assist maneuver (VGA2) on 26 December 2019. 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 '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 reported by Gurnett et al. (2001).

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 reported by Gurnett et al. (2001).

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 several Earth radii (Záhlava et al., 2019). At radio frequencies, lightning produces strong, transient broadband emissions commonly known as 'sferics' (Smith et al., 2002). Terrestrial sferics 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 observed at Jupiter, Saturn, Uranus, and Neptune (Aplin et al., 2020), its existence at Venus remains an open question. Lorenz (2018) reviewed claims of detections and nondetections of lightning at Venus, concluding that while some type of electromagnetic activity is present (Russell et al., 2008), its properties are different from terrestrial lightning. During three years in orbit, Akatsuki did not detect optical emission due to lightning flashes (Lorenz et al., 2019). During two Venus flybys in 1998 and 1999, with closest approach distances of 284 and 598 km from the surface, the Cassini Radio and Plasma Wave Science instrument did not detect lightning sferics (Gurnett et al., 2001).

Although the Cassini non-detection was statistically robust, the observations were limited in duration to approximately 2 hours during each flyby. Therefore, the existence of highly intermittent lightning remains a possibility. For this reason, during the second Venus flyby of the Parker Solar Probe (PSP, Fox et al. (2016)), the PSP radio receiver employed a mode designed to measure strong impulsive signals. This Letter describes these observations, which are consistent with the non-detection reported by Gurnett et al. (2001).

2 FIELDS Instrumentation and Venus Observations

The FIELDS instrument suite (Bale et al., 2016) provides electric and magnetic field measurements for the PSP mission. In this Letter, we present electric field data from the FIELDS Time Domain Sampler (TDS), Radio Frequency Spectrometer (RFS, Pulupa et al. (2017)), and Digital Fields Board (DFB, Malaspina et al. (2016)). These receivers are optimized for different phenomena, and differ in frequency range, sensitivity, and observing modes. The DFB measures electric fields from DC to 75 kHz, and generates a variety of waveform and spectral data products. The TDS captures waveforms of plasma waves (and dust) at high cadence. TDS data products include (a) TDS waveform snapshots selected by onboard algorithms, and (b) peak and RMS voltages, averaged over an interval of ∼7 seconds. The RFS is the highest frequency FIELDS receiver, measuring quasi-thermal noise and radio spectra from 10.5 kHz to 19.2 MHz. RFS measurements are detailed in the next section.

In order to achieve a final perihelion distance below 10 solar radii, the PSP spacecraft employs seven Venus Gravity Assist (VGA) maneuvers. Thus far, 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 26 December 2019. During VGA2, the spacecraft skimmed the edge of the Venus bow shock, reaching a closest approach distance of ∼3000 km above the surface. Figure 1 shows VGA2 in Venus Solar Orbital (VSO) coordinates, with lines indicating the PSP trajectory and a model bow shock using parameters determined in Malaspina et al. (2020).

3 RFS burst mode

The RFS is a two channel receiver, measuring both auto and cross spectra. In its default 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) ranges. The number of individual spectra averaged together for a single measurement (n_{avg}) is commandable, and the measurement cadence depends on n_{avg}. During a typical solar encounter, n_{avg} is 80 and the RFS produces one LFR and one HFR averaged spectrum every 7 seconds. We will refer to this operating 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 perihelion. Burst mode has not yet been enabled during PSP solar encounters, 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 218 ms; and (3) burst mode is limited to the HFR frequency range. In both LFR/HFR and burst mode, 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.

The FIELDS suite includes four voltage sensors mounted near the PSP heat shield, referred to as $V1$, $V2$, $V3$, and $V4$. The two channels of the RFS receiver can each be configured to measure single-ended (monopole) voltage from any sensor, or differential (dipole) voltage between any two sensors. The $V1 - V2$ and $V3 - V4$ dipoles consist of two co-linear monopole antennas deployed in opposing directions. These two dipoles are nearly orthogonal, and the RFS "cross dipole" configuration uses $V1 - V2$ as input to one channel and $V3 - V4$ as input to the other channel.

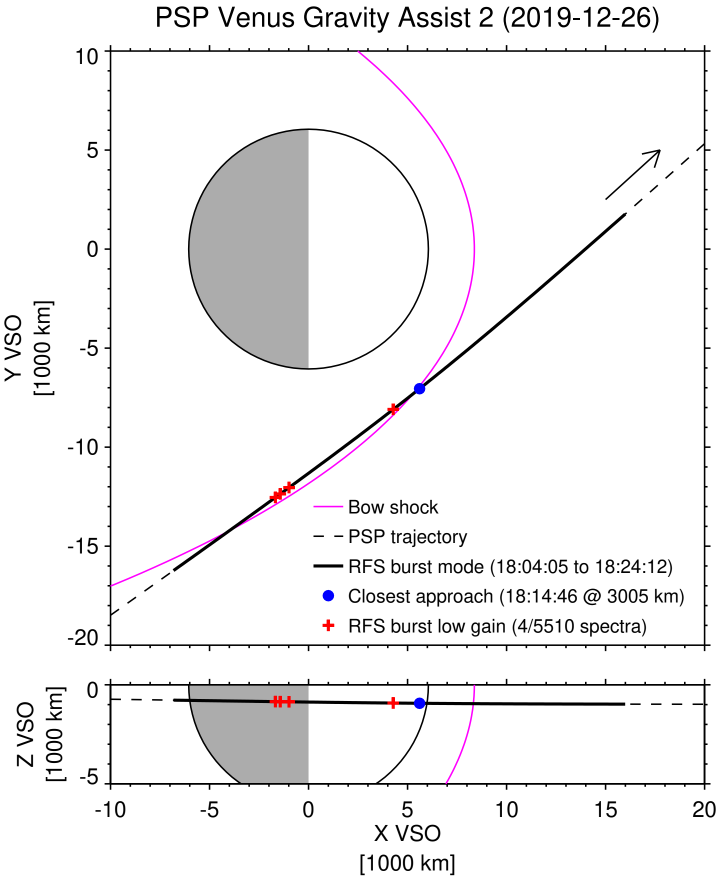

Figure 1. VGA2 in XY (top) and XZ (bottom) VSO coordinates. PSP trajectory is indicated with a dashed/solid line, with the thick solid segment indicating the interval when RFS was in burst mode. Closest approach and RFS burst low gain events are indicated with a blue circle and red crosses, respectively.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

If terrestrial-like lightning sferics are present at Venus, they would be detectable by RFS in burst mode. Gurnett et al. (1991) scaled the peak electric fields reported by Venera (Ksanfomality et al., 1983), which are given as $\sim 100\ \mu\mathrm{V\ m^{-1}\ Hz^{-1/2}}$ 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 $\sim 4\times10^{-15}\ \mathrm{V^2\ m^{-2}\ Hz^{-1}}$, at a frequency of 1 MHz, for lightning observations during the Galileo Venus flyby on 10 February 1990. During the Galileo flyby, radio observations were performed at distances of ∼24,000-30,000 km. During PSP VGA2, burst mode was enabled at distances of ∼3,000-11,500 km. At these distances, a similar scaling yields estimates of power spectral density of $\sim 2\times10^{-14}$ to $\sim 4\times10^{-13}\ \mathrm{V^2\ m^{-2}\ Hz^{-1}}$ at ∼1 MHz, well above the RFS noise level. We note that for this estimate we have used a nominal effective length of 1 m for the FIELDS dipoles.

The integration time for a single burst mode spectrum is 0.853 ms, and the cadence is 218 ms, for a duty cycle of 0.4%. If Venus lightning occurred at similar rates to terrestrial lightning, the rate of flashes would be ∼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 ∼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). 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 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 RFS observations during VGA2 have adequate sensitivity, time resolution, and duration to detect signals of terrestrial-like lightning on Venus.

However, we note that the occurrence rate of Venus lightning could also differ significantly from Earth. Using ground-based optical measurements, Hansell et al. (1995) estimated a rate of 0.02 events/million km^2-hr, $\sim 1/3.5\times10^4$ lower than the rate at Earth. Should lightning on Venus occur at these significantly lower rates, it would be unlikely that RFS would observe an event during a flyby.

4 Results

During VGA2, the RFS inputs were in cross dipole configuration, and burst mode was enabled from 18:04:05 to 18:24:12 UTC. During this interval, 5506 burst mode spectra were recorded in high gain and 4 in low gain. The four low gain spectra are signatures of brief, high amplitude signals. However, they are unlikely to be lightning-related for two reasons: (1) there is no frequency structure similar to the f^{-2} and f^{-4} power laws observed in terrestrial sferics, and (2) they occur simultaneously with strong *in situ* plasma waves, pointing to saturation of the RFS high gain stage by these 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 shock crossings, which occur at approximately 18:07 and 18:14 UTC.

Figure 2 shows a section 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 mode. Figure 2b shows 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 $V1-V2$ data, covering the full frequency range of RFS burst mode observations.

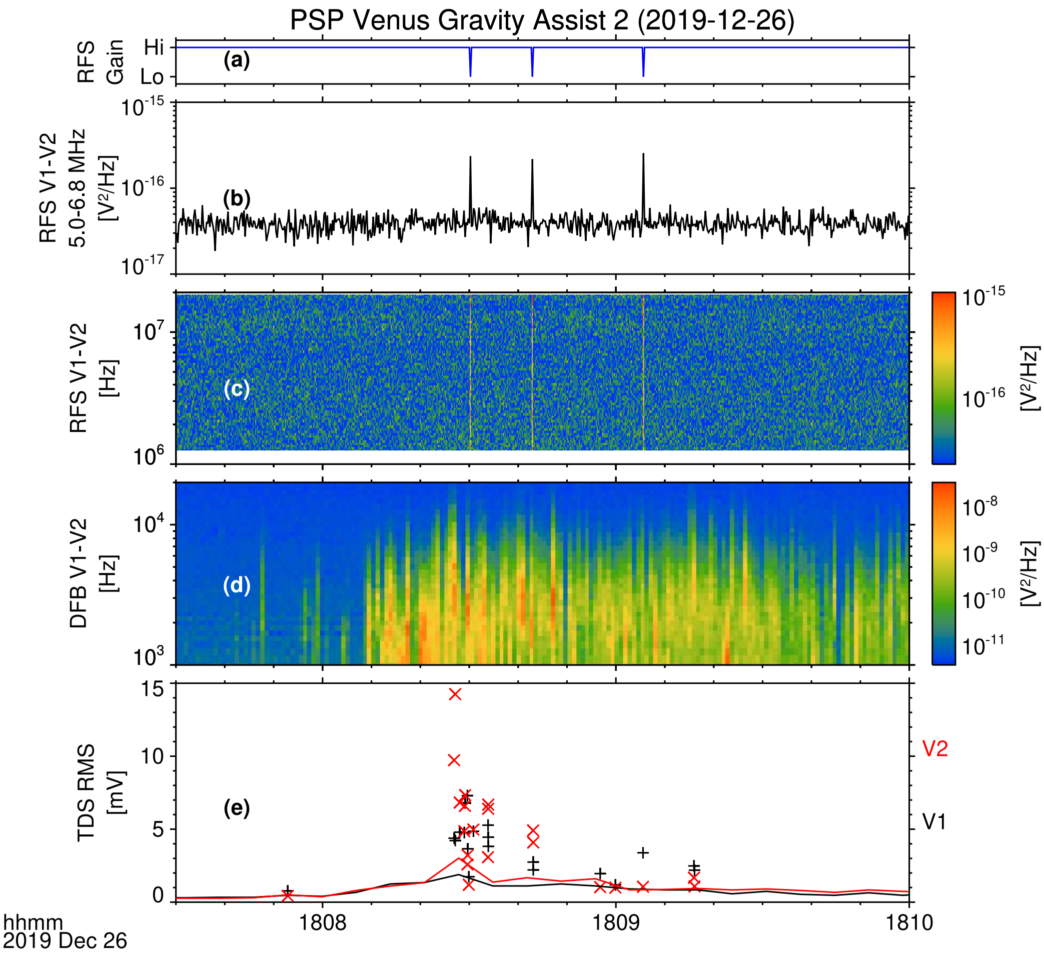

Figure 2. FIELDS measurements during VGA2. (a) Gain indicator for RFS burst mode. (b) RFS burst mode data from $V1 - V2$, averaged over 5.0-6.8 MHz. (c) Spectrogram of RFS burst mode data. (d) DFB spectra from $V1 - V2$. (e) TDS waveform RMS measurements, for the $V1$ and $V2$ monopoles.

Figure 2d shows DFB AC-coupled spectra from the $V1$–$V2$ dipole. The duty cycle of the DFB AC spectra is 12.5%, and the cadence is 874 ms. Figure 2e shows TDS data, with measurements from the $V1$ and $V2$ monopoles shown in black and red, respectively. The RMS values measured by TDS and averaged over 7 second intervals (with 100% duty cycle) are shown with solid lines. TDS also captures high amplitude waveform snapshots, sampled at a rate of 1.92 MSa/s, with a duration of 17 ms. An onboard algorithm, optimized for identification of intense plasma waves, selects the "best" waveforms for downlink. RMS values of these selected waveforms are indicated by crosses.

Due to the differing duty cycles and observing configurations among the three receivers, it is not possible to identify a one-to-one correspondence between RFS low gain spectra and specific plasma waves observed by DFB and TDS. However, Figure 2 does indicate that RFS low gain observations correspond to periods of strong waves. The TDS 7 second data show that the RMS amplitude in $V1$ and $V2$ is enhanced near the RFS low gain measurements. The DFB spectra demonstrate that this enhancement corresponds to plasma waves in the kHz to $\sim$10 kHz frequency range. Individual TDS waveform captures show that high amplitude waves are measured near each of the three low gain measurements shown in Figure 2.

Although the plasma waves measured by DFB and TDS are lower in frequency than the lowest RFS burst mode frequency (1.3 MHz), a sufficiently high amplitude plasma wave can saturate the RFS high gain stage, causing the RFS to return a low gain spectrum. This is consistent with observations from PSP Encounter 4, where RFS (in LFR/HFR mode) switched to low gain when exceptionally high amplitude plasma waves were observed near perihelion.

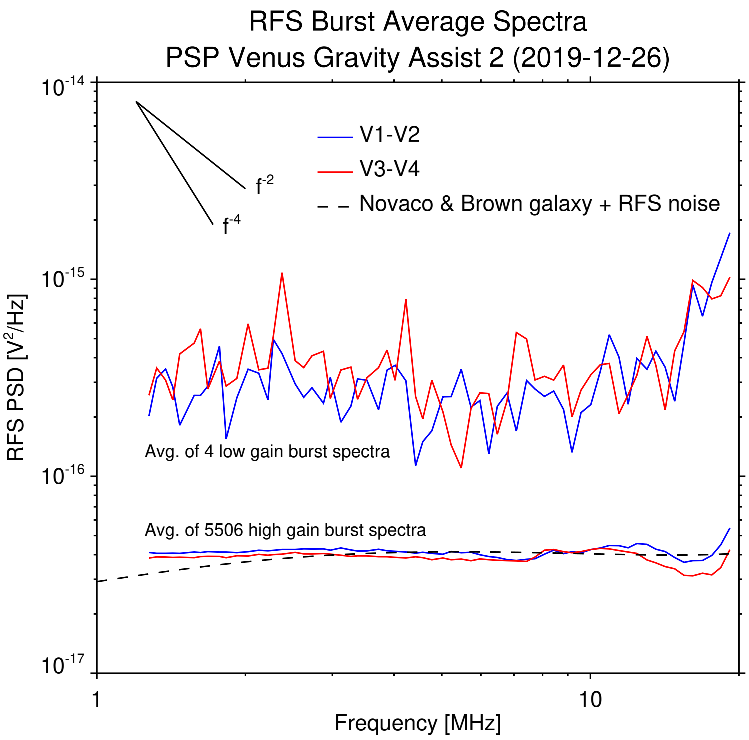

Figure 3. Averaged RFS burst mode spectra during VGA2. Blue and red lines indicate $V1 - V2$ and $V3 - V4$ dipole measurements, respectively.

Figure 3 shows averaged RFS burst mode spectra. Data from $V1-V2$ and $V3-V4$ are shown in blue and red, respectively. The high gain spectra, with typical PSD values of $\sim 4\times10^{-17}$ V^2/Hz, are consistent with quiet time solar wind measurements, where the primary signal is the galactic synchrotron spectrum. A nominal background, consisting of the galactic spectrum 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 dashed line and the measured spectra are comparable. The small differences between the measurements and background are due to several effects not taken into account here, including frequency-dependent antenna effective length, anisotropic galactic emission (Manning & Dulk, 2001), and occultation of the galaxy by Venus during VGA2.

The low gain RFS measurements have a higher background level, consistent with the measured PSD of $\sim 2\times10^{-16}$ V^2/Hz. The noisier low gain spectra in Figure 2 reflect the smaller number of measurements included in the average. For both high and low gain spectra, a rise in PSD above $\sim$16 MHz is due to aliased power from above the RFS Nyquist frequency of 19.2 MHz. Lines in the upper left indicate spectral slopes consistent with the f^{-2} and f^{-4} power laws characteristic of terrestrial lightning. No such frequency structure is seen in any spectrum during the RFS burst mode interval.

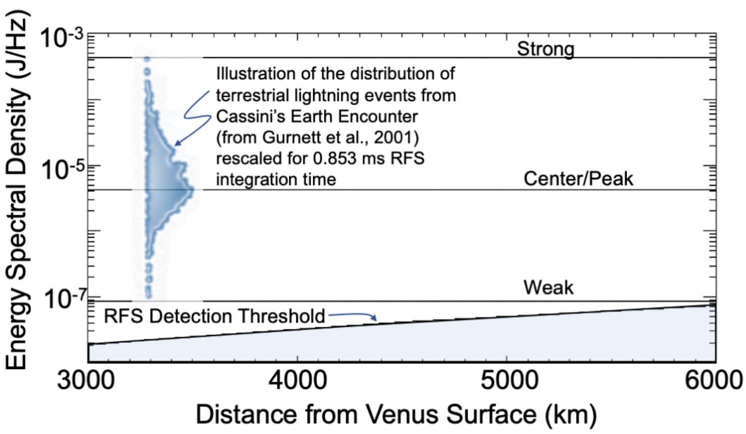

Figure 4. Threshold for detection of lightning by the RFS receiver at distances comparable to PSP VGA2 closest approach. The vertical histogram of data shows terrestrial lightning events observed during the Cassini–Earth flyby, rescaled to the RFS integration time. Histogram from Gurnett et al. (2001) adapted by permission from Springer Nature.

In the absence of a lightning detection, it is possible to estimate an upper limit on lightning discharge events, based on the sensitivity and integration time of the RFS receiver. Our estimate is based on the method presented in Gurnett et al. (2001) and Gurnett et al. (2010), which describes 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}). These units are appropriate for the impulsive character of lightning events, and are also normalized to remove the effect of source to spacecraft distance.

We use 3σ as a threshold for event detection, where σ is the noise fluctuation level in the burst spectra. Over the RFS burst mode frequency range, $\sigma \approx 2.5\times10^{-17}\mathrm{V}^2/\mathrm{m}^2/\mathrm{Hz}$, using an effective length of 1 m. 5506 spectra were observed during the burst mode interval, not counting low gain measurements associated with plasma waves. The observed distribution is modeled well by a Gaussian, so $\sim$10 individual observations at any given frequency will lie above the 3σ threshold. However, we expect lightning emission to be broadband, so valid signals will exhibit increased amplitude in several consecutive frequencies. If we set a criterion of a 3σ increase in a minimum of 3 consecutive frequencies to consider a spectrum a candidate for lightning detection, the likelihood of a single spectrum rising above the threshold is extremely small ($\sim$ .1%). During the burst mode interval, none of the 5506 high gain spectra satisfied this criterion.

The 3σ threshold for detection expressed in J/Hz is 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 integration time, and R is the distance from the source to the spacecraft. Figure 4 shows the results of the threshold calculation for RFS observations during VGA2. For comparison, Figure 4 also shows a histogram of terrestrial lightning amplitude, adapted from Gurnett et al. (2001). The histogram has been scaled to the RFS receiver integration time, via the same scaling method used for MARSIS data in Gurnett et al. (2010). At closest approach, RFS is sensitive to events $\sim$200 times smaller than typical terrestrial lightning.

Our results demonstrate non-detection for terrestrial-like lightning at Venus. However, if lightning on Venus occurs at a much lower rate than on Earth, as suggested by Hansell et al. (1995), a single flyby interval with a duration of tens of minutes may not contain a single event. Lightning discharges with different amplitudes or time scales than those observed on Earth could also go undetected. Figure 5 presents one scenario, comparing a typical terrestrial-like lightning spectrum (Levine & Meneghini, 1978) with a 'slow discharge' spectrum. At several MHz, the PSD of the terrestrial-like spectrum is $\sim$200 times the sensitivity of the RFS receiver during VGA2, consistent with the description above. The slow discharge spectrum in Figure 5 represents an event with the same amount of transferred charge, but a discharge rate slower by a factor of 10. Thus the peak spectral density is unchanged, but peak frequency is shifted by 10. The slow discharge lies well below the RFS sensitivity, by a factor of $\sim$50. Figure 5 illustrates only one specific scenario—other differences from terrestrial-like conditions, such as decreased total charge, could also result in non-detection.

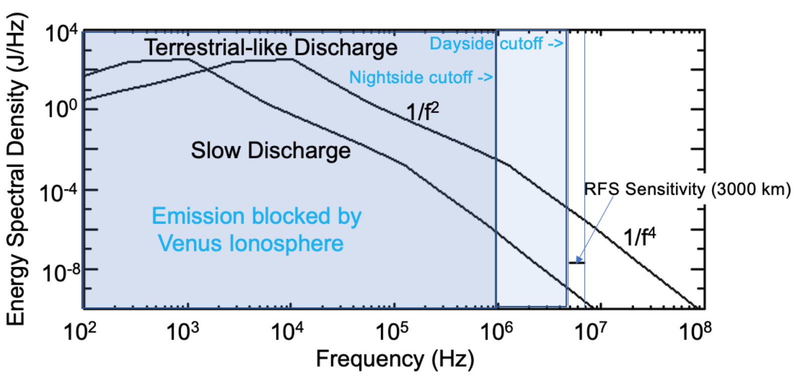

Figure 5. Possible effects of a slow discharge lightning scenario. While a typical terrestrial-like discharge event is well above the RFS detection threshold, an event differing only by the discharge rate could lie below the threshold.

5 Summary and Conclusions

During PSP VGA2, the RFS receiver 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.

Our non-detection result agrees with the Cassini flyby non-detection, and adds support to the conclusion (Lorenz, 2018) that 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 radio signals comparable to emissions observed at Earth.

The PSP mission has completed three VGA maneuvers. Four more are planned, including the seventh and final VGA in 2024, with a closest approach <400 km from the surface. Although future encounters may enable more sensitive searches for lightning, there are tradeoffs to enabling RFS burst mode to perform an additional test. With the current flight software, burst mode is limited to the HFR range (1.3–19.2 MHz), with no measurements in the LFR range (10.5 kHz–1.7 MHz). This limitation is significant, as VGA3 observations indicate that LFR measurements near the Venus ionosphere are of considerable scientific interest.

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References

Angelopoulos, V., Cruce, P., Drozdov, A., Grimes, E. W., Hatzigeorgiu, N., King, D. A., . . . Schroeder, P. (2019, January). The Space Physics Environment Data Analysis System (SPEDAS). Space Sci. Rev., *215*(1), 9. doi: 10.1007/s11214-018-0576-4

Aplin, K. L., Fischer, G., Nordheim, T. A., Konovalenko, A., Zakharenko, V., & Zarka, P. (2020, March). Atmospheric Electricity at the Ice Giants. Space Sci. Rev., *216*(2), 26. doi: 10.1007/s11214-020-00647-0

Bale, S. D., Goetz, K., Harvey, P. R., Turin, P., Bonnell, J. W., Dudok de Wit, T., . . . Wygant, J. R. (2016, December). The FIELDS Instrument Suite for Solar Probe Plus. Measuring the Coronal Plasma and Magnetic Field, Plasma Waves and Turbulence, and Radio Signatures of Solar Transients. Space Sci. Rev., *204*(1-4), 49-82. doi: 10.1007/s11214-016-0244-5

Brace, L. H., & Kliore, A. J. (1991, March). The Structure of the Venus Ionosphere. Space Sci. Rev., *55*(1-4), 81-163. doi: 10.1007/BF00177136

Dwyer, J. R., & Uman, M. A. (2014, January). The physics of lightning. Phys. Rep., *534*(4), 147-241. doi: 10.1016/j.physrep.2013.09.004

Fox, N. J., Velli, M. C., Bale, S. D., Decker, R., Driesman, A., Howard, R. A., . . . Szabo, A. (2016, December). The Solar Probe Plus Mission: Humanity's First Visit to Our Star. Space Sci. Rev., *204*(1-4), 7-48. doi: 10.1007/s11214-015-0211-6

Gurnett, D. A., Kurth, W. S., Roux, A., Gendrin, R., Kennel, C. F., & Bolton, S. J. (1991, September). Lightning and Plasma Wave Observations from the Galileo Flyby of Venus. *Science*, *253*(5027), 1522-1525. doi: 10.1126/science.253.5027.1522

Gurnett, D. A., Morgan, D. D., Granroth, L. J., Cantor, B. A., Farrell, W. M., & Espley, J. R. (2010, September). Non-detection of impulsive radio signals from lightning in Martian dust storms using the radar receiver on the Mars Express spacecraft. Geophys. Res. Lett., *37*(17), L17802. doi: 10.1029/2010GL044368

Gurnett, D. A., Zarka, P., Manning, R., Kurth, W. S., Hospodarsky, G. B., Averkamp, T. F., ... Farrell, W. M. (2001, January). Non-detection at Venus of high-frequency radio signals characteristic of terrestrial lightning. Nature, *409*(6818), 313-315. doi: 10.1038/35053009

Hansell, S. A., Wells, W. K., & Hunten, D. M. (1995, October). Optical detection of lightning on Venus. *Icarus*, *117*(2), 345-351. doi: 10.1006/icar.1995.1160

Ksanfomality, L. V., Scarf, F. L., & Taylor, W. W. L. (1983). The Electrical Activity of the Atmosphere of Venus. In D. M. Hunten, L. Colin, T. M. Donahue, & V. I. Moroz (Eds.), *Venus* (p. 565-603). Tucson, Arizona: The University of Arizona Press.

Levine, D. M., & Meneghini, R. (1978, September). Simulation of radiation from lightning return strokes: The effects of tortuosity. *Radio Science*, *13*(5), 801-809. doi: 10.1029/RS013i005p00801

Lorenz, R. D. (2018, December). Lightning detection on Venus: a critical review. *Progress in Earth and Planetary Science*, *5*(1), 34. doi: 10.1186/s40645-018-0181-x

Lorenz, R. D., Imai, M., Takahashi, Y., Sato, M., Yamazaki, A., Sato, T. M., ... Nakamura, M. (2019, July). Constraints on Venus Lightning From Akatsuki's First 3 Years in Orbit. Geophys. Res. Lett., *46*(14), 7955-7961. doi: 10.1029/2019GL083311

Malaspina, D. M., Ergun, R. E., Bolton, M., Kien, M., Summers, D., Stevens, K., ... Goetz, K. (2016, June). The Digital Fields Board for the FIELDS instrument suite on the Solar Probe Plus mission: Analog and digital signal processing. *Journal of Geophysical Research (Space Physics)*, *121*(6), 5088-5096. doi: 10.1002/2016JA022344

Malaspina, D. M., Goodrich, K., Livi, R., Halekas, J., McManus, M., Curry, S., ... Whittlesey, P. (2020, October). Plasma Double Layers at the Boundary Between Venus and the Solar Wind. Geophys. Res. Lett., *47*(20), e90115. doi: 10.1029/2020GL090115

Manning, R., & Dulk, G. A. (2001, June). The Galactic background radiation from 0.2 to 13.8 MHz. A&A, *372*, 663-666. doi: 10.1051/0004-6361:20010516

Novaco, J. C., & Brown, L. W. (1978, April). Nonthermal galactic emission below 10 megahertz. ApJ, *221*, 114-123. doi: 10.1086/156009

Pulupa, M., Bale, S. D., Badman, S. T., Bonnell, J. W., Case, A. W., de Wit, T. D., ... Whittlesey, P. (2020, February). Statistics and Polarization of Type III Radio Bursts Observed in the Inner Heliosphere. ApJS, *246*(2), 49. doi: 10.3847/1538-4365/ab5dc0

Pulupa, M., Bale, S. D., Bonnell, J. W., Bowen, T. A., Carruth, N., Goetz, K., ... Sundkvist, D. (2017, March). The Solar Probe Plus Radio Frequency Spectrometer: Measurement requirements, analog design, and digital signal processing. *Journal of Geophysical Research (Space Physics)*, *122*(3), 2836-2854. doi: 10.1002/2016JA023345

Russell, C. T., Zhang, T. L., & Wei, H. Y. (2008, May). Whistler mode waves from lightning on Venus: Magnetic control of ionospheric access. *Journal of Geophysical Research (Planets)*, *113*(E5), E00B05. doi: 10.1029/2008JE003137

Smith, D. A., Eack, K. B., Harlin, J., Heavner, M. J., Jacobson, A. R., Massey, R. S., ... Wiens, K. C. (2002, July). The Los Alamos Sferic Array: A research tool for lightning investigations. *Journal of Geophysical Research (Atmospheres)*, *107*(D13), 4183. doi: 10.1029/2001JD000502

Záhlava, J., Němec, F., Santolík, O., Kolmašová, I., Hospodarsky, G. B., Parrot, M., ... Kletzing, C. A. (2019, August). Lightning Contribution to Overall Whistler Mode Wave Intensities in the Plasmasphere. Geophys. Res. Lett., *46*(15), 8607-8616. doi: 10.1029/2019GL083918