Non-detection at Venus of high-frequency radio signals characteristic of terrestrial lightning

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The detection[1,2] of impulsive low-frequency (10 to 80 kHz) radio signals, and separate very-low-frequency (~100 Hz) radio 'whistler' signals[3–5] provided the first evidence for lightning in the atmosphere of Venus. Later, a small number of impulsive high-frequency (100 kHz to 5.6 MHz) radio signals, possibly due to lightning, were also detected[6]. The existence of lightning at Venus has, however, remained controversial[7–13]. Here we report the results of a search for high-frequency (0.125 to 16 MHz) radio signals during two close fly-bys of Venus by the Cassini spacecraft. Such signals are characteristic of terrestrial lightning, and are commonly heard on AM (amplitude-modulated) radios during thunderstorms. Although the instrument easily detected signals from terrestrial lightning during a later fly-by of Earth (at a global flash rate estimated to be 70 s^{-1}, which is consistent with the rate expected for terrestrial lightning), no similar signals were detected from Venus. If lightning exists in the venusian atmosphere, it is either extremely rare, or very different from terrestrial lightning.

The Cassini spacecraft, which is on its way to Saturn, made two gravity-assisted fly-bys of Venus, the first (Venus-1) on 26 April 1998, and the second (Venus-2) on 24 June 1999. During these fly-bys the Radio and Plasma Wave Science instrument[14] (RPWS) conducted a search for impulsive high-frequency radio signals from lightning. Impulsive signals of this type are commonly heard on AM radios during terrestrial thunderstorms, and are called spherics[15,16]. Because spherics are always produced by terrestrial lightning, the detection of spherics by a spacecraft flying over another planet provides strong evidence of lightning. To be detected the signals must pass through the ionosphere. Such line-of-sight propagation can only occur at frequencies above the maximum plasma frequency in the ionosphere, which on the dayside of Venus is about 5 MHz, and on the nightside is about 1 MHz, or less[17]. The spectrum of lightning generally decreases with increasing frequency, approximately as $1/f^2$ for terrestrial lightning; the best place to search for lightning is therefore on the nightside, where the ionospheric plasma frequency is low. Lightning can also be detected on the dayside, but the frequency must be above 5 MHz. To illustrate the region sampled by Cassini, the trajectories of the two Venus fly-bys are shown in Fig. 1. As can be seen the trajectories are quite complementary. The Venus-1 fly-by provided a low-altitude pass over the nightside of Venus, and the Venus-2 fly-by provided a low-altitude pass over the dayside of Venus. When the two fly-bys are combined, line-of-sight coverage is provided over 61% of the surface (in a Sun-fixed coordinate system) at radial distances less than 2 Venus radii, R_V, and 88% at radial distances less than 5 R_V. The coverage is reduced somewhat by refraction if the frequency is near the ionospheric plasma frequency.

The electric field intensities observed by the RPWS during the Venus-1 fly-by are shown in Fig. 2. The nearly constant background in all except the 0.125-kHz channel is due to galactic radio noise[18]. About a dozen impulsive events can be seen near closest approach that could possibly be attributed to lightning. The strongest such event (with a peak intensity 4.1 dB above the galactic background) occurs in the 2.225-MHz channel at about 13:46 UT. Although at first glance this event looks like lightning, a detailed examination shows that it consists of a series of consecutive points in a single-frequency channel, with no corresponding response in the adjacent frequency channels (see the expanded panel in Fig. 2). But lightning produces radiation over a broad range of frequencies, so this event cannot be lightning. Several of the other events observed around closest approach have similar narrowband characteristics, and cannot be caused by lightning.

If the intensity scale in Fig. 2 is further magnified, a continuous level of fluctuations can be seen with a standard deviation of about $\sigma = 0.23$ dB. A detailed analysis of these fluctuations has been carried out by counting the number of peaks whose intensity, I, exceeds a threshold, I^*, that is a fixed number of standard deviations,

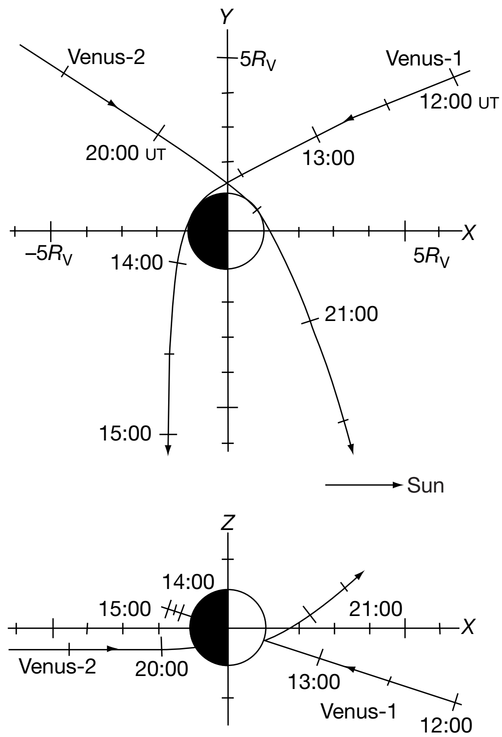

Figure 1 The trajectories of the Venus-1 and the Venus-2 fly-bys in a Venus-centred coordinate system. The $+x$ axis is directed toward the Sun, the $+y$ is in the plane of Venus' orbit, and the $+z$ axis completes the orthogonal coordinate system. The closest approach for Venus-1 occurred at an altitude of 284 km, and the closest approach for Venus-2 occurred at an altitude of 598 km. For the lightning search, measurements were made using a 18.5-m tip-to-tip electric dipole antenna. Intensities were measured in 20 quasi-logarithmically spaced frequency channels from 0.125 to 15.975 MHz, each with a bandwidth of 25 kHz. The receivers provided outputs proportional to the logarithm of the signal intensity, with response times of about 0.1 to 0.4 ms for rising signals and about 0.5 to 1.0 ms for falling signals. During the Venus-1 fly-by the receiver outputs were digitally averaged over 80-ms intervals, with 1 sample from each channel every 1.94 s. Data were collected from 12:58:17 Universal Time (UT) to 15:12:39 UT, giving a total of 81,920 measurements. During the Venus-2 fly-by the lowest 12 channels (0.125 to 3.975 MHz) were digitally averaged over 21-ms intervals and the upper 8 channels (5.475 to 15.975 MHz) were digitally averaged over 12-ms intervals, with 1 sample from each channel every 0.625 s. Data were collected from 19:15:57 UT to 21:19:49 UT, giving a total of 172,160 measurements. In addition, for the Venus-2 fly-by three frequency channels, 1.525, 5.325 and 9.125 MHz, were sampled at a rate of 1,000 samples per second (called the millisecond mode), with one block of 1,024 samples every 1.375 s. The millisecond-mode data were collected from 20:00:17 UT to 20:59:55 UT, giving a total of 1,307,648 measurements in the millisecond mode.

N_σ, above a locally averaged background, I_0. The open squares in Fig. 3 shows the number of events with $I > I^*$ as a function of N_σ. The solid line is the expectation for a gaussian distribution. As can be seen, the intensities are in good agreement with simple random fluctuations in the galactic background. Only 12 peaks exceed four standard deviations, some of which are the previously mentioned narrowband signals. To search for very weak lightning signals we investigated the number of peaks above three standard deviations as a function of frequency and time for the entire data set. The resulting distribution shows no evidence of the $1/R^2$ radial dependence or the $1/f^2$ frequency dependence that would be expected for lightning. Also, there is no evidence of a local time variation in the occurrence rate, as one might expect from the day/night asymmetry in the ionospheric plasma frequency.

The statistical distribution of the intensity peaks for the Venus-2 fly-by is shown by the open circles in Fig. 3. Again the fluctuations closely follow a gaussian distribution, with no statistically significant peaks. In the high time-resolution millisecond-mode data (see the caption of Fig. 1 for a description of the millisecond mode), approximately 40 small widely scattered pulses were found with durations of about 1 to 2 milliseconds. Although these pulses are suggestive of lightning, they do not display the $1/R^2$ radial intensity variation and the $1/f^2$ frequency dependence that would be expected for lightning. Furthermore, a substantial number of the pulses occurred near closest approach on the dayside of Venus at a frequency (1.525 MHz) that is well below the plasma frequency (~5 MHz) in the dayside ionosphere. These millisecond-mode pulses cannot be due to lightning, as the signals cannot propagate through the ionosphere. Most probably they are caused by interference from on-board electrical systems.

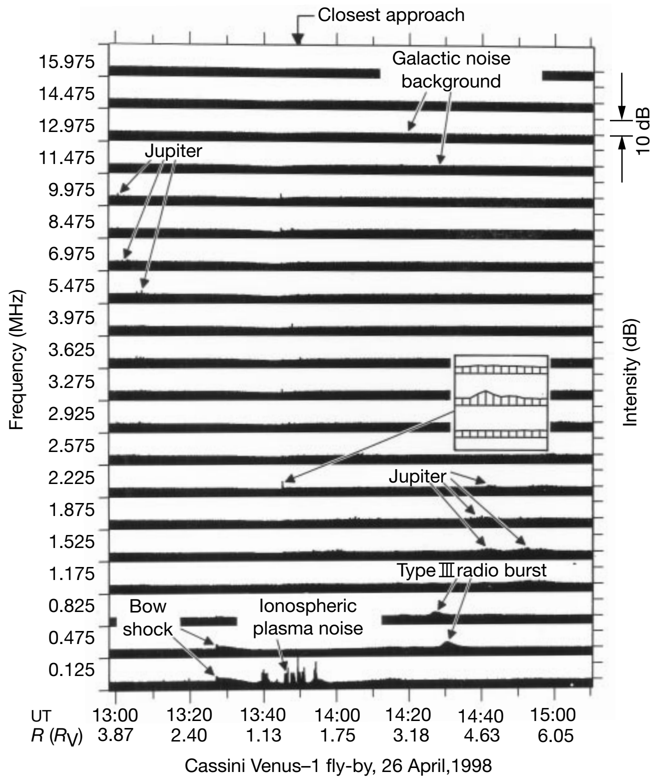

Figure 2 A 20-channel plot of the electric field intensities as a function of time during the Venus-1 fly-by. The frequencies are shown on the left, and the intensities in decibels are shown on the right. The UT and radial distance (R) from Venus, in Venus radii (R_V), are shown at the bottom of the plot. The background noise levels in all except the 0.125 kHz channel are due to galactic radio noise[18], and have been adjusted to the same level in each channel (5 dB above the bottom of the plot). Features not associated with lightning that can be easily identified included some very weak emissions from Jupiter in the 5.475 to 9.975 MHz channels from about 13:00 to 13:10 UT, and again in the 1.175 to 2.225 MHz channels from about 14:35 to 15:00 UT (these can be seen in similar spectrograms from Earth-orbiting spacecraft), a type III solar radio burst in the 0.475 and 0.825 MHz channels from about 14:23 to 14:35 UT, and various types of ionospheric plasma wave noise in the 0.125 and 0.475 MHz channels from about 13:24 to 13:55 UT.

About two months after the Venus-2 fly-by, on 18 August 1999, the Cassini spacecraft made a close fly-by of Earth. To demonstrate that the RPWS can detect lightning, a search was conducted for impulsive signals from terrestrial lightning. More frequency channels (75) were used to aid in eliminating signals from terrestrial radio stations. Otherwise the analysis procedure was essentially the same as for the Venus-1 and Venus-2 data. The statistical distribution of intensity peaks is shown by the black dots in Fig. 3. As can be seen, many impulsive signals were detected above the gaussian background noise (1,101 events greater than three standard deviations). These impulsive signals were observed essentially continuously at all radial distances inside of about 14 Earth radii (R_E). The maximum rate occurred on the nightside of the Earth at about 4.5 R_E, and was about 30 pulses per minute. After correcting for the instrument dead time and various other effects, such as obscuration by other types of radio signals, the global average flash rate is estimated to be about 70 s^{-1}, which is consistent with the global average flash rate expected for terrestrial lightning, that is about 100 s^{-1}. Some of the peaks were as much as 40 dB above the background noise level, and the intensities increased systematically with decreasing radial distance and frequency, varying approximately as $1/R^2$ and $1/f^2$, as would be expected for terrestrial lightning. Also, a strong day/night asymmetry is present in the low-frequency cut-off of the frequency spectrum, as would be expected from the day/night variation of the ionospheric plasma frequency.

The above comparisons between Venus and Earth show that if lightning exists on Venus it is either extremely rare, or very different from terrestrial lightning. Because instrumental characteristics play an important role in the ability to detect lightning, it is important to quantify the constraints implied by this study. Radio signals cannot propagate through the ionosphere at frequencies below the maximum plasma frequency in the ionosphere, which at its lowest is about 1 MHz on the nightside of Venus, so no definitive statement can be made about the lightning spectrum at frequencies below about 1 MHz. However, above 1 MHz, the constraints implied by this study are very restrictive, and are summarized by the diagram in

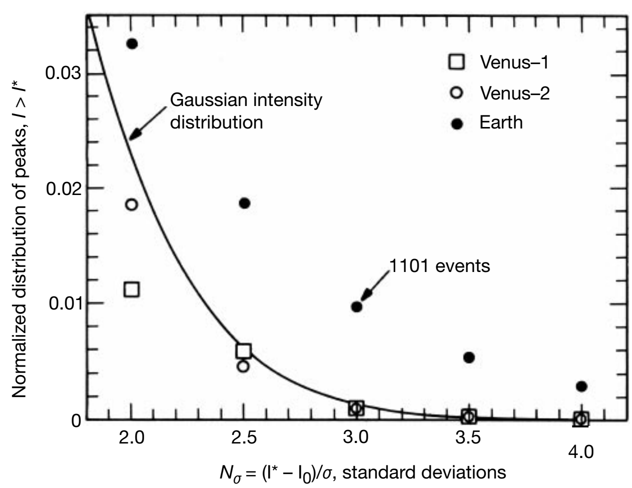

Figure 3 A plot of the number of intensity peaks greater than a fixed number of standard deviations above the background noise level, for the Venus-1, Venus-2, and Earth fly-bys. For the Venus-1 and Venus-2 fly-bys the number of peaks at each level is consistent with a gaussian distribution of fluctuations in the background noise. For the Earth fly-by a large number of impulsive events were detected over the entire region within about 13 R_E, some with intensities as much as 40 dB above the background noise level. These impulses are consistent with the detection of terrestrial lightning.

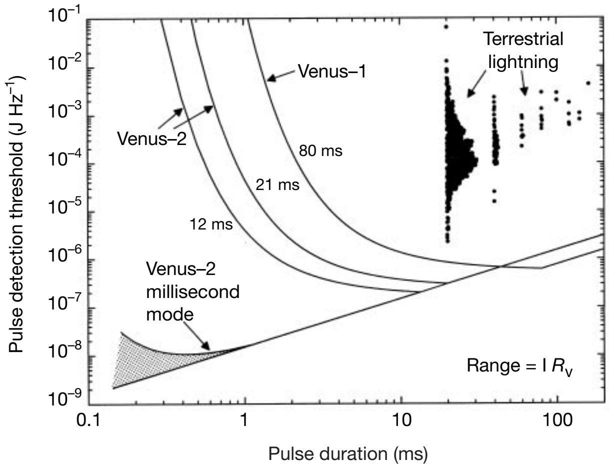

Figure 4 A plot of the pulse-detection threshold for the RPWS, in units of $\mathrm{J\,Hz^{-1}}$, as a function of the pulse duration at a representative range of one Venus radii (1 R_V). The pulse detection threshold has been computed by multiplying the galactic noise level, in units of Watts $\mathrm{m^{-1}\,Hz^{-1}}$, by $4\pi(R_V)^2$, by the pulse duration, and then by a factor of 0.236, which sets the pulse detection threshold at four standard deviations above the fluctuation level of the galactic noise background. The galactic noise level has been taken to be $7.5\times10^{-20}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$, which is typical for the frequency range from about 1 to 10 MHz. Four curves are shown, one for Venus-1, with an integration time of 80 ms, and three for Venus-2, two with integration times of 12 ms (for the 0.125 to 3.975 channels) and 21 ms (for the 5.475 to 15.975 MHz channels) and one for the millisecond mode. Because of the logarithmic response of the receiver, the detection threshold rises steeply for pulse durations shorter than the integration time. The detection threshold for the millisecond mode depends somewhat on the pulse shape and is difficult to quantify for very short pulses (less than 1 millisecond). This uncertainty is indicated by the shaded region. Also shown are the energy spectral densities, in units of $\mathrm{J\,Hz^{-1}}$, of the terrestrial lightning detected during the Earth fly-by. These energy spectral densities are plotted as a function of the observed pulse duration, which are at multiples of the 21 ms integration/sampling time used during the Earth fly-by. To indicate the amplitude distribution the points have been stacked to the right whenever multiple points occur at a given energy spectral density.

Fig. 4. This diagram shows the RPWS pulse-detection threshold, expressed in energy spectral density (in units of $\mathrm{J\,Hz^{-1}}$), as a function of the duration of the pulse. Because the detection threshold depends on the distance to the source, a range of 1 R_V has been assumed. The threshold can be easily adjusted to other ranges using a simple $1/R^2$ law. Also shown for comparison are the energy spectral densities and pulse durations of the 1,101 lightning events detected during the Earth fly-by. As can be seen, the energy spectral density of terrestrial lightning extends as much as 40 dB above the energy detection thresholds at Venus for a range of 1 R_V, and even more near closest approach. If terrestrial-like lightning were occurring in the atmosphere of Venus within the region viewed by Cassini, it would have been easily detectable.

Since the atmosphere of Venus is very different from that of Earth, it is perhaps not surprising that electrical activity on Venus might be very different from lightning in the Earth's atmosphere. Earth lightning can be divided into two broad types, cloud-to-ground, and cloud-to-cloud (including intra-cloud). Because clouds over Venus are at very high altitudes of 40 km or more, it is likely that lightning at Venus, if it exists, is primarily cloud-to-cloud. Terrestrial cloud-to-ground lightning is generally more intense (by about 10 to 20 dB) than cloud-to-cloud lightning, so it is possible that the absence of impulsive high-frequency radio signals during the Venus fly-bys could be owing to the dominance of very weak cloud-to-cloud lightning at Venus. The detection threshold imposed by the RPWS measurements, however, (see Fig. 4) imposes severe constraints on the intensity of any cloud-to-cloud lightning that might exist on Venus; such lightning would thus have to be much weaker than on Earth. As the previous reports of impulsive low-frequency (100 Hz to 80 kHz) radio signals by the Venera and Pioneer-Venus spacecraft indicate that some type of electrical activity is taking place in the atmosphere of Venus[1–5], we wonder what type of electrical activity might be involved. Because the ionospheric plasma effectively blocks these low frequency signals from reaching Cassini, we can draw no definitive conclusion about the presence or absence of such signals. However, rough comparisons of the reported Venera intensities[2] with the intensity limits imposed by the Cassini RPWS indicate that the spectrum must decline much more steeply than the typical $1/f^2$ spectrum of terrestrial lightning. Such a steep spectrum would indicate a relatively slow rise time for the discharge, possibly similar to the cloud-to-ionosphere discharges (sprites) that were recently discovered on Earth[19,20]. □

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