Lightning on Venus confirmed

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Venus, with its dense lower atmosphere and high surface temperature, has thick cloud cover containing aerosols and residual volcanic gases forming an admixture of concentrated sulphuric acid and water. This composite cloud cover has a high dielectric constant. Given sufficient atmospheric dynamics we would expect the occurrence of charge separation and resultant electrical discharges or lightning. The four Venera landers with onboard loop antennas measured electromagnetic signals near the Venus surface and these signals were interpreted as signals generated by cloud-to-cloud electrical discharges. Similar electrical signals were measured by electric field detectors aboard Pioneer Venus Orbiter in the Venus ionosphere. These observations confirmed the measurements of Venera landers. However, controversy about the lightning interpretation of PVO signals arose and mechanisms for generation of these waves by plasma processes were proposed. Amidst claims and counter-claims about Venus lightning, the Galileo spacecraft flew by the Venus nightside. The measurements made by Galileo at radio frequencies were consistent with the existence of Venus lightning with an amplitude and occurrence rate roughly similar to those often observed on earth. In this article, we review the evidence for the occurrence of lightning on Venus and the attempts to study this phenomenon quantitatively.

THE scientific study of the phenomena of thunder and lightning in the earth's atmosphere is over two centuries old, beginning with the demonstration by Benjamin Franklin[1] in the eighteenth century that lightning is a gigantic electrical discharge. The electrification of clouds in the earth's atmosphere and generation of lightning is one of the commonest and most spectacular terrestrial phenomena and has been the subject of numerous scientific investigations. Yet, in spite of investigation with modern theoretical and measurement techniques, lightning in the earth's atmosphere is not fully understood and remains one of the most complex, unsolved and elusive scientific problems.

Reference to lightning phenomena on the nightside of Venus originated from the speculative work of Meinel and Hoxie[2]. They attributed the faint flow of hot gases, on the nightside of Venus, known as Ashen light to Venus lightning. As the knowledge of planetary atmospheres started to develop, speculation about the presence or the absence of lightning discharges on other planets became more common-place[3]. The exploration of planetary lightning by *in situ* measurements was considered important by these authors because of its likely role in the formation of certain important trace gases, such as prebiotic material. The first measurements of signals, later to be interpreted as lightning, were provided by the visible spectrometer on the Venera 9 orbiter in 1975[4]. Seven frames containing intense optical flashes were seen covering 70 seconds of observing time. However, this one important optical observation, which is consistent with other constraints on the rate of lightning occurrence is generally forgotten in the Venus lightning debate. Lightning detectors were installed on the four Venera landers 11, 12, 13 and 14 (ref. 5). The first unambiguous evidence of the VLF signals from lightning came from Venera 11 and 12 landers which measured electric field signals on four narrow-band channels centered at 10, 18, at 36 and 80 kHz. These measurements were made using loop antennas of 250 mm in diameter which were sensitive only to the magnetic component of the lightning signals and they confirmed the electromagnetic nature of these waves. Contemporaneous with these observations, the Pioneer Venus Orbiter (PVO) carried a VLF receiver with four narrow-band channels centered at 100 Hz, 730 Hz, 5.4 kHz and 30 kHz. The PVO detector used dipole antennas. The nature of variation of these signals resembled those recorded by the Venera 11 and 12 landers.

The first observations of VLF signals interpreted as due to lightning aboard PVO were reported by Taylor and co-workers[6]. Because the Venus cloud system was thought to be less massive and perhaps less dynamic than its terrestrial counterparts, other possible sources were considered. One such source was the volcanic plume which on earth is known to produce electrical discharges[7]. Examining lightning data on 1185 orbits, Scarf and Russell[8] observed that 65 per cent of the 100 Hz signals were correlated with topographically high regions near Phoebe, Beta and Alta. The apparent escape of the VLF waves at all the four frequencies into the Venus ionosphere posed a problem because all frequencies between the electron gyrofrequency (about 500 Hz) and the electron plasma frequency (about 100 kHz) at minimum altitude should be excluded from the ionosphere according to magneto-ionic theory. The 100 Hz signals were interpreted to be propagating upwards in the whistler mode[9] and were extensively used

Table 1. Composition of the atmospheres of the terrestrial planets

Constituents	Fractional abundance or parts per million (ppm)		
	Venus	Earth	Mars
Carbon dioxide	0.96	0.0003	0.95
Nitrogen	0.035	0.77	0.027
Oxygen	0.0013	0.21	0.0
Argon	0.00007	0.0093	0.16
Neon	5.0 ppm	18.0 ppm	2.5 ppm
Sulphur dioxide	0.00015	0.20 ppm	0.0
Carbon monoxide	0.00004	0.12 ppm	0.0007
Water vapour	0.0001	0.01	0.0003

Table 2. Comparison of properties of clouds on terrestrial planets

			Mars		
Property	Earth	Venus	Dust	H_2O	CO_2
Percentage coverage	40	100	100	Small	Winter pole
Average optical depth	5–7	25–40	0.5	0.5	~1
Maximum optical depth	300–400	40	10	?	
Cloud vertical extent	Several km	25 km	40 km	?	Large
Composition	Solid and liquid H_2O	H_2SO_4 droplet, crystals plus contaminants	Dust	H_2O (solid)	CO_2 (solid)
Number density	100–1000 cm^{-3} (liquid) 0.1–50 cm^{-3} (ice)	50–300 cm^{-3} (liquid) 10–50 cm^{-3} (crystals)	5 cm^{-3}	< 5 cm^{-3}	?
Average mass loading (mass loading)	0.3–0.5 g m^{-3}	0.01–0.02 g m^{-3}	5×10^{-4} g m^{-3}	$< 5 \times 10^{-3}$ g m^{-3}	?
Maximum mass loading (mass density)	10–20 g m^{-3}	0.05 g m^{-3}	5×10^{-4} g m^{-3}	1×10^{-2} g m^{-3}	?
Distribution function	Normal-log normal bimodal (ice)	Multimodal	Unimodal	Unimoral	?
Typical background aerosol at cloud base 0.5 µm	1 cm^{-3}	100–200 cm^{-3}	–	5 cm^{-3}	< 5 cm^{-3}
Condensation process	Homomolecular	Heteromolecular	–	Homomolecular	Homo molecular
Average precipitable mass	0.03–0.05 mm	0.1–0.2 mm	1 µm	?	Large
Mean scattering size (diameter) (in the visible)	10 µm	2–4 µm	6 µm	4 µm	Large
Mean mass size (diameter)	30 µm	10 µm	8 µm	?	Large
Dominant optical cloud form	Stratiform	Stratiform	Haze	Wave cloud	Stratus
Dominant mass cloud form	Cumulus	Stratiform			
Potential latent instability	High	Low	Low	Low	Low
Temporal variability	High	Slight	High	High	High
Dominant cloud atmosphere heat-exchange process	Latent heat	Radiation	Radiation	Radiation	Latent heat/ radiation

(After Levin *et al.*, *Icarus*, 1983, 56, 80)

by Scarf and his co-workers in support of the hypothesis of Venus lightning. Taylor Jr and colleagues[10] soon questioned the lightning interpretation of VLF signals and their association with volcanic phenomena. They suggested that the VLF waves were locally generated by some undetermined plasma instability operating within the Venus ionosphere. The suggestion of Taylor *et al.*[10] became a nucleating centre for a continued controversy argued over a series of papers. An important development in this controversy was the re-examination PVO VLF lightning data and the conjecture that the observed VLF signals at all four PVO frequencies going from below the electron gyrofrequency to well above it were able to propagate some distance into the night ionosphere. These signals were shown to resemble the terrestrial lightning generated electromagnetic wave spectrum varying perhaps as steeply f^{-2} at lower frequencies and as f^{-1} at higher frequencies with a spectral peak around 6–8 kHz (refs. 11, 12). This further evidence put forward by Singh and Russell[11] was also questioned by Taylor and his co-workers[13–15]. This work was followed by extensive analyses of the VLF signals on all four frequencies by Russell and co-workers[16-23]. These studies established the properties and morphology of the VLF signals in detail and put the Venus lightning hypothesis on a solid footing.

The scientific vigour of comments and counter-comments on Venus lightning finally culminated with a decisive observation by the Galileo experimenters. Impulsive signals covering the frequency range 100 kHz to 5.6 MHz were observed by the high frequency receivers aboard Galileo during the Venus flyby as would be expected if lightning of terrestrial strength and frequency of occurrence existed in the nightside of Venus[24, 25]. In this article, we review the phenomena of Venus lightning and discuss the importance of some of the Venus atmospheric and ionospheric phenomena associated with the generation and propagation lightning-generated electromagnetic waves.

Venus atmosphere and its cloud cover

The Venus atmosphere has two striking differences compared with earth's atmosphere. The first difference is the natural gas density at the surface which is predominantly CO_2 with a density about 90 times greater than the density on the surface of the Earth whose atmosphere is predominantly nitrogen. The second striking difference is the surface temperature of Venus which is 743 K compared to earth's surface temperature of 288 K. Moreover, the high albedo of the thick Venus cloud cover (~ 80%) and the dense atmosphere allows only 16 per cent of solar radiation to reach the Venus surface. The variation of gas density with altitude is such that the gas density at Venus and earth becomes equal around 150 km and thereafter the Venus gas density becomes smaller than that found in earth's atmosphere. The atmospheric constituents of terrestrial planets is given in Table 1[26].

Although Venus has become the second best studied planet, very little is known about the Venus cloud composition and its dynamical processes. The properties of Venus clouds were penetrated by the large probe[27] and are summarized in Table 2 and are also compared with those of Earth and Mars[28]. Venus clouds cover 100 per cent of the surface as against 40 per cent for earth. The Martian cloud cover, its composition, and its morphology is quite variable. Another important difference comes from the composition of the clouds and number density of liquid and ice crystals per cm^3. Consequently, the dielectric constant of the Venus cloud is rather large and we expect it to play an important role in the process of charge separation and in the development of electrical discharge.

The composition and dynamics of Venus clouds are very important in sustaining the lightning activity within its cloud cover. The Venus cloud cover extends from about 45 to about 65 km above the surface, with haze layers above and below as shown in Figure 1. Within this cloud cover, the haze particle diameter ranges from 10 to 30 microns and the particle size distribution is trimodal: 'mode 1' distribution particles are of unknown origin and form aerosol haze extending throughout the cloud layer; 'mode 2' particles are intermediate in size and are measurable telescopically and for this mode a composition of 75% H_2SO_4 and 25% HO_2 has been determined by spectroscopic and polarimetric measurements; 'mode 3' contains most of the cloud mass and consists of the biggest size drops. These drops could be crystalline sulphur which interacts with HO_2 forming droplets of H_2SO_4 (refs. 26, 29). A counterpart of Venus clouds is found in the earth's atmosphere at about 20 km where the so-called Junge layer appears. The Junge layer is known to become enhanced and move downwards in response to major volcanic events.

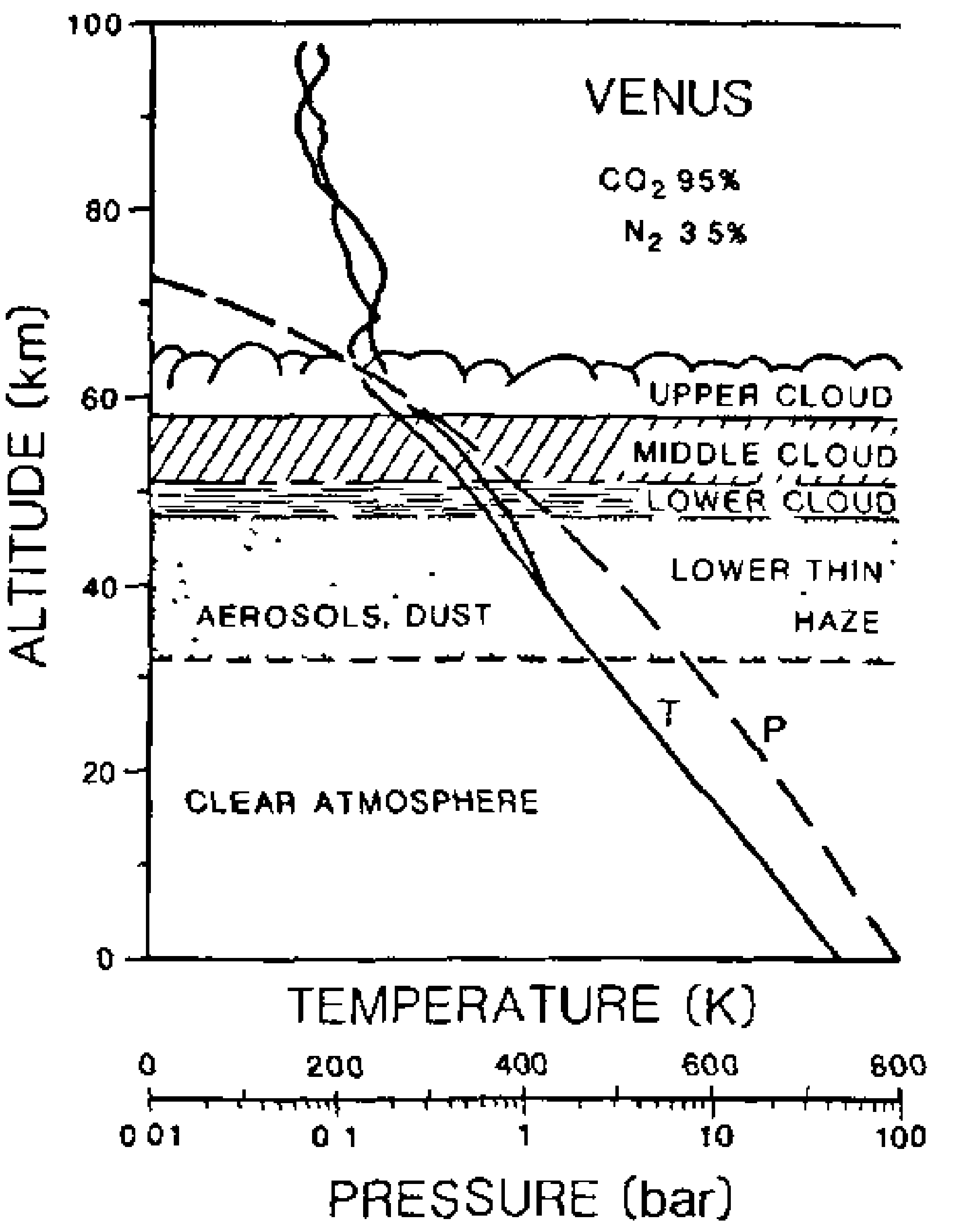

Figure 1. The height profile of the Venus cloud system and atmospheric temperature and pressure (after Rinnert 1982)[34]

The optical properties of the Venus cloud layers are not fully understood and explored. The incident visible and near-infrared light diffuses down to the Venus surface. Most of the infrared radiation from Venus into space comes from the cold top of the Venus clouds which are not strong radiators because of their low temperature, a key reason for the 'greenhouse' heating of the lower atmosphere. However, some of the infrared radiation from the lower atmosphere does diffuse upward and escapes through windows in the absorption spectrum of CO_2. The Galileo mission succeeded in mapping the cloud cover using these emissions. Carlson[30] analysing these optical measurements has shown large horizontal variations in the thickness of the main Venus cloud deck.

Observations of Venus lightning

The word lightning is used here in the context of the combined effects often times heard, seen and recorded namely: (i) the thunderous sound heard, due to pressure waves in the neutral gas; (ii) the visually observed optical light flashes; and (iii) the broadband electromagnetic waves generated by the electrical discharges and recorded by radio wave detectors. All these three effects have been extensively used for the study of lightning phenomena in the Earth's atmosphere. The efforts made in studying the lightning phenomena on other planets are highly limited and restricted by the instruments carried and the trajectories followed by our space probes. Thus, we often have to make compromise with less than ideal diagnostics and must rely on as few as one manifestation of lightning for its study. Venera measurements have provided the earliest evidence for Venus lightning. Most recently, the radio measurements aboard Galileo during its flyby through nightside of Venus measured high frequency electromagnetic waves and confirmed the occurrence of lightning on Venus[24, 25]. However, attempts to detect lightning with the Galileo images were unsuccessful because of poor viewing conditions and non-optimal gain settings[31]. The difficulty in obtaining optical evidence for lightning has caused some to remain skeptical about the claims of the existence of lightning on Venus. The importance of a definite and repeatable measurement of any kind providing direct support to certain phenomena cannot be scientifically undermined and ignored however, it is important for us to try to resolve these riddles. Lightning is a complex phenomena and it has not been completely understood even in the context of the Earth's atmosphere. We present below the details of efforts made to measure and understand the phenomena of Venus lightning.

Acoustic studies

One of the important effects produced by terrestrial lightning is acoustic wave generation. The magnitude, direction and the quality of lightning generated sound waves give an approximate idea of the distance and multiple flash nature of the lightning phenomena. Although the study of sound wave generation and propagation is a well known tool for terrestrial lightning, it cannot be used with equal ease in the study of planetary lightning. Venera 11 and 12 did carry acoustic sensors but these sensors were saturated aboard during the descent process possibly due to the noise of the air rushing by the probe. Venera 13 and 14 did not carry acoustic sensors. Thus a carefully planned and designed sound wave recording and analysis of the data is capable of providing definite information about lightning processes. So far' it has not been fully exploited for studying planetary lightning.

Optical studies

On 26 October 1975, the spectrometer in the visible range aboard Venera 9 detected a period of apparent optical flashes on the nightside of Venus at 1930 LT at 9°S latitude[32]. The flashes were seen over a period of 70 seconds corresponding to 7 sweeps of the instrument while the field of view moved 450 km. No such flashes were seen when the instrument pointed away from the planet. Figure 2 shows the details of optical observations made during this plot from ref. 32. Russell has corrected this plot from the original by applying the factor of 8 gain to the points indicated as being at reduced gain in the original figure. In doing so they assumed that the baseline was zero signal and the scales were linear. The dashed and dotted lines show the instrument response to a 1 W/A/km^2 signal. The dashed line shows the radiation background The narrow pulses at either end show calibration marks at 3000 and

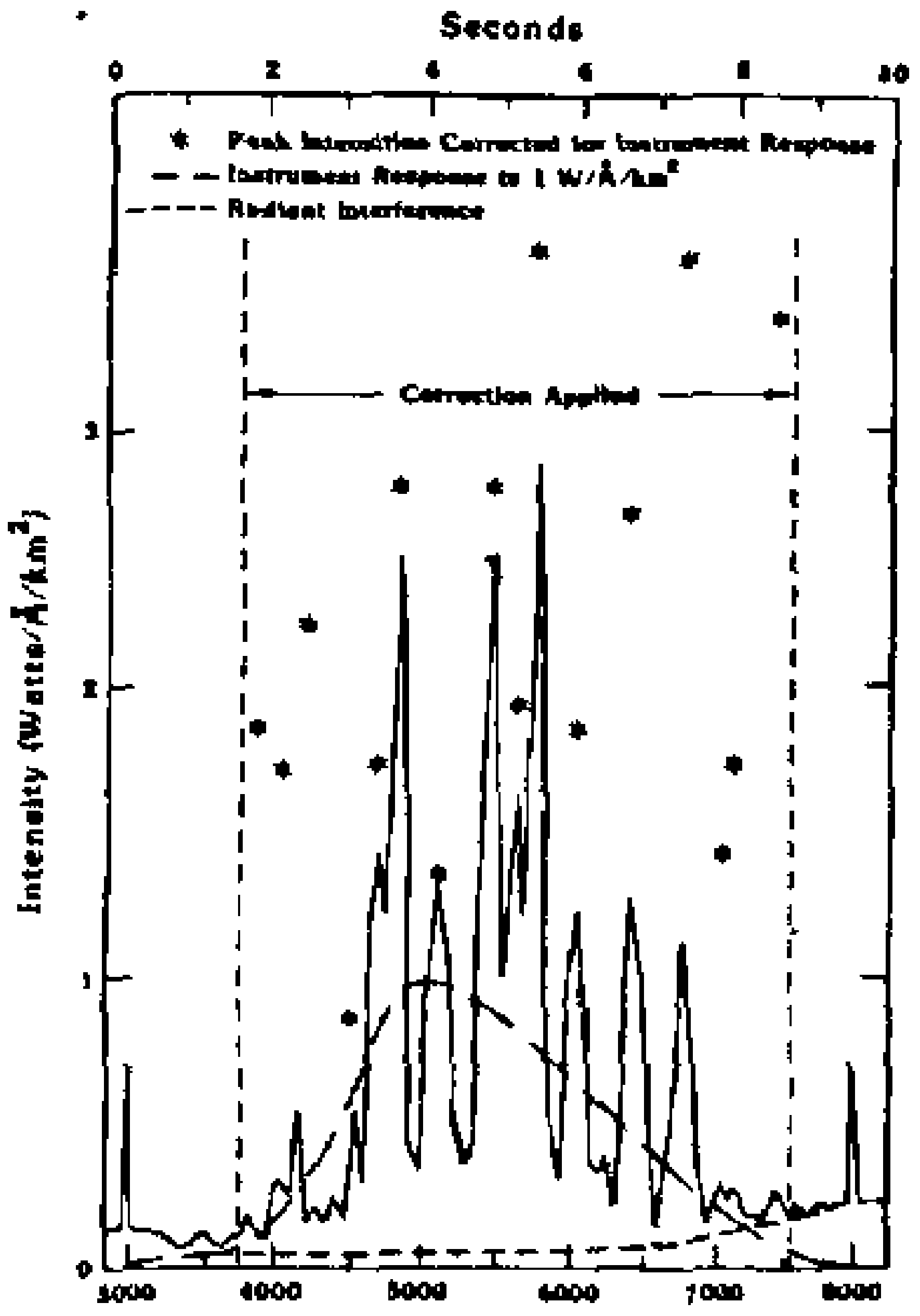

Figure 2. One sweep of the Venera 9 Spectrometer of 7 during which time flashes were observed No such flashes were observed when the instrument viewed space The short pulses at the start and end of the sweep are calibration pulses The lower dashed line is the radiative background noise observed by the instrument The dash-dot line is the response of the instrument to a 1 Watt/Å/km^2 energy source The instrument was operating in gain states 2 and 3 (of 4) at this time and we have accounted for the switching between gains in drawing this plot The asterisks show the peak amplitudes after correcting for the spectral response function (dot-dash curve) of the instrument (after Krasnopol'sky[32], V. A. Krasnopol'sky, private commun., 1991)

8000 Å The observations indicated by the solid lines clearly show impulsive signals of about 0.25 s duration, the amplitude of which mimic the instrument response indicating that they arise outside the instrument response indicating that these signals arise outside the instrument and not inside (possible errors 'inside' the instrument include telemetry 'bit errors'). The duration of each peak, lasting several samples, also indicates that signals are real and are not telemetry noise. The corrected peak amplitudes for the instrument response were obtained as indicated by the asterisks in Figure 2. These peak amplitudes seem to be much more uniform with wavelength. The slight weakening of amplitudes seen at shorter wavelengths is consistent with the greater atmospheric absorption expected in the UV. Both Borucki[33] and Krasnopol'sky[34] pointed out that the weakness of the absorption with wavelength is suggestive of high altitude lightning source. It is possible that optical signals generated at lower altitudes are absorbed and are not recorded by optical sensors aboard orbiting satellites. We note that this apparent 'spectrum' of lightning should be affected by both the temporal nature of the exciter, the lightning flash, and the spectral lines in the excited air. No comparison of this 'spectrum' with the expected spectrum[35] has been undertaken, nor have the remaining 6 disturbed spectra been published to our knowledge.

The optical energy in each flash was estimated to be about 2.5×10^7 J corresponding to a total energy of about 7×10^9 J (ref. 36). Venusian lightning strokes of longer pulse duration cause the peak optical power to be much less[28].

Two studies of Venus lightning using the star sensor aboard Pioneer Venus have been completed[36, 38]. The latter study of Borucki *et al.*[37] supercedes the earlier study due to a recalibration of the star sensor axial response function. They have shown that with a suitably designed study, the lightning generated optical radiation should be easily recorded. However, the sensitivity of the optical survey depends on the duration of the pulse relative to the filter bandwidth of the optical sensor. The data recorded during only one of the two seasons were obtained with the filter set to be sensitive to long duration pulses such as seen by the Venera 9 spectrometer. Also very few data were obtained over the local time sector identified as the 'lightning source' region by the VLF data which will be discussed below. The Venera 9 optical data on the other hand were obtained over the 'active' sector. Two other optical results should be mentioned. The first is the report of very bright, partially illuminated nitrogen band on two successive short wavelength scans of the instrument. While these two 'flashes' need further study their duration appears similar to the flashes shown in Figure 2 that the Vega balloon photometers saw no flashes as they moved from midnight to dawn in the Venus clouds.

Electromagnetic wave studies: VLF radio waves

Lander measurements. The first *in situ* measurement of Venus lightning was made by instruments carried aboard spacecraft of the former Soviet Union. Their Venera 11 and 12 landers carried a VLF wave detector GROZA with a high sensitivity loop antenna which could detect the magnetic component of electromagnetic waves. These VLF measurements provided the first unambiguous evidence of lightning generated electromagnetic signals[5, 39]. The GROZA VLF detecting system included 4 narrow-band channels centered at 10, 18, 36 and 80 kHz with a wide-band channel. The amplitude profiles obtained by Venera 11, 12 and two subsequent missions Venera 13, 14 looked very different from each other even though the descent trajectories were very similar. This clearly showed that the observed waves were not due to the interaction of the measuring probe with the Venus atmosphere. The measured signal variation was consistent with a temporally varying lightning-like source. The high resolution VLF data during weak activity at high altitudes on the Venera 12 landing are shown in Figure 3. Here the pulses occur sufficiently infrequently that they can be counted

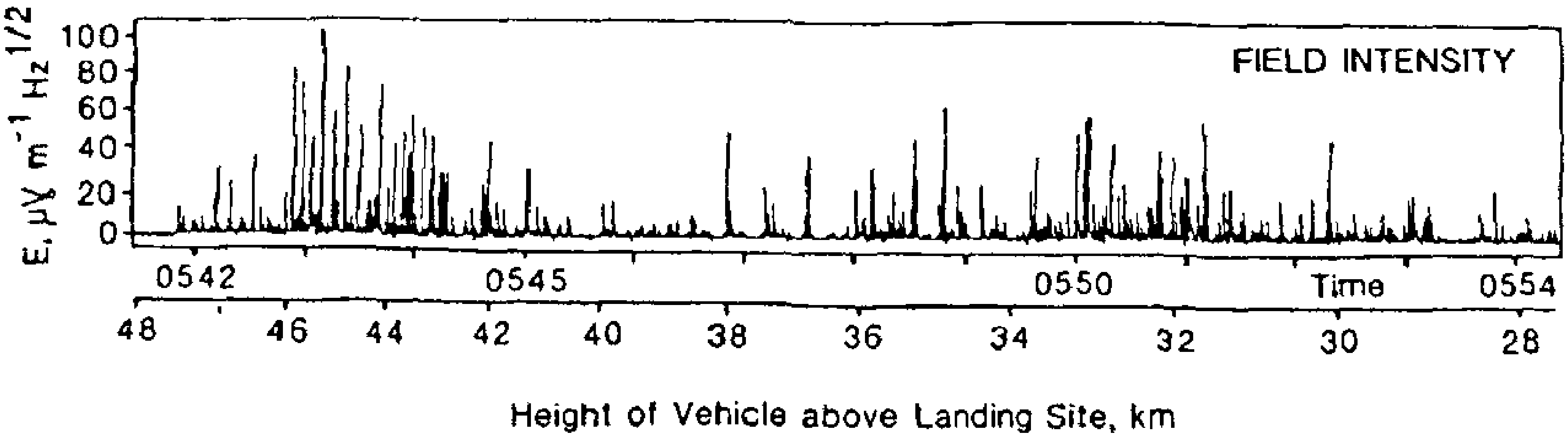

Figure 3. High resolution measurements of the wideband field intensity on Venera 12 (ref 40)

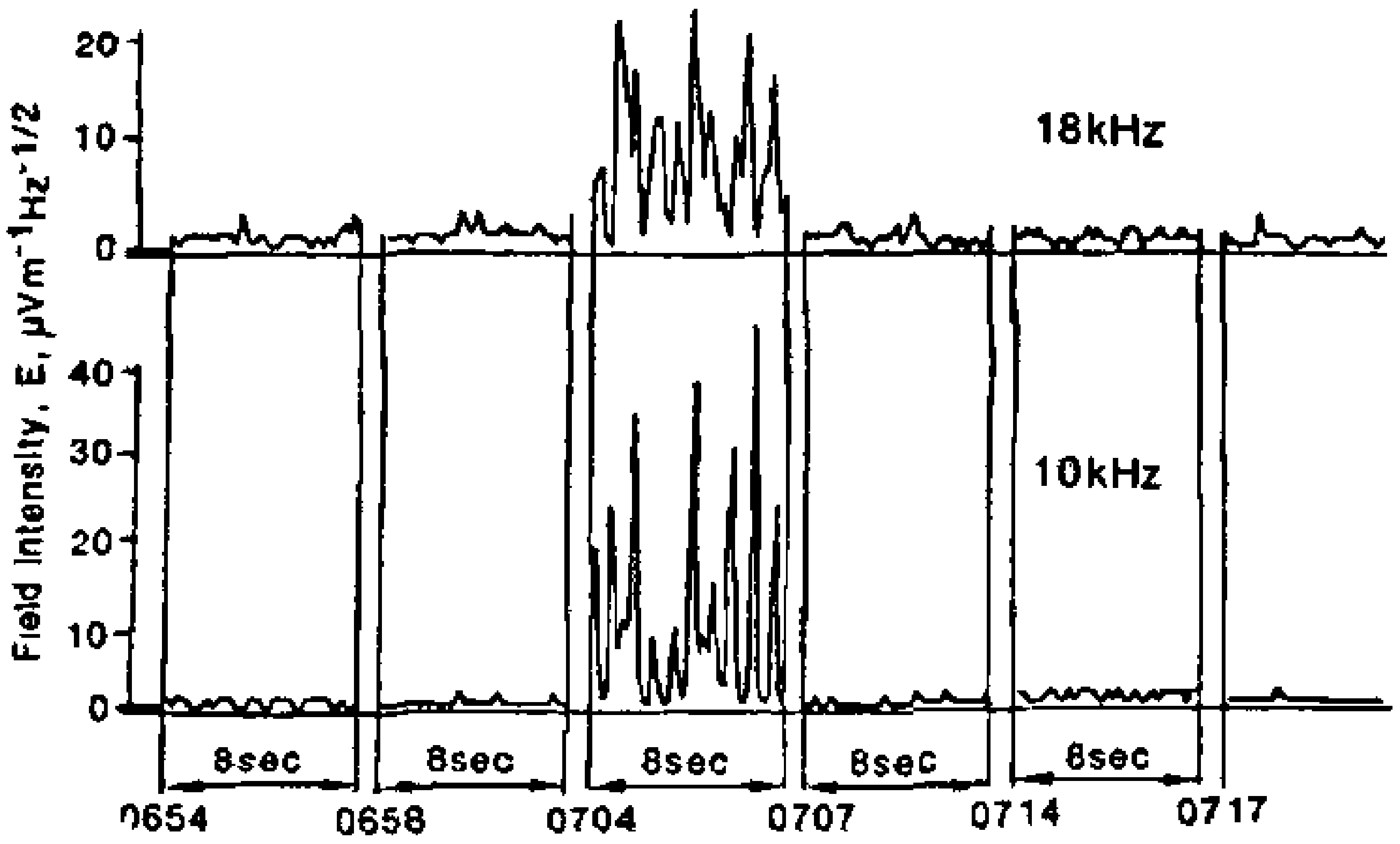

Figure 4. A burst of VLF noise while Venera 12 was sitting on the surface[40]

without sophisticated aids. In the interval shown in Figure 3, there is one burst about every 12 s on the average. Later during the descent, the rate of electrical burst became too large to be counted by eye. Venera 13 and 14 carried electromagnetic sensors similar to those aboard Venera 11 and 12. These probes also monitored the coronal discharge current from the spacecraft. However, no discharge currents were detected aboard Venera 13 and 14 (ref. 40). The lightning activity recorded aboard Venera 13 and 14 was similar to that recorded on Venera 12 and was found to be significantly less than that recorded aboard Venera 11. The landing area for the probes was close to the subsolar point and far away (~ 8000 km) from the late afternoon region in which terrestrial lightning is observed to be most frequent. On the Venus surface the instruments continued to operate but only Venera 12 recorded a burst of VLF noise for the brief period as shown in Figure 4. This was interpreted to indicate that the observed lightning was a distant phenomena and the landed spacecraft was 'shaded' from the source.

The mean rate recorded by the Venera VLF impulse counter was 16.5 s^{-1} overall. Below 20 km altitude the recorded impulse rate dropped to 13 s^{-1} and below 5 km it dropped to 10 s^{-1}. These impulse rates are much greater than the observed impulse rate in the terrestrial atmosphere. The impulse rates on the ground obtained during a test run on a clear day in the terrestrial atmosphere were similar to the lowest rates obtained on the Venera 12 entry from 25 to 12 km. On the Venera 11 descent the recorded impulse rates were an order of magnitude higher than the terrestrial rate until the vehicle landed on the Venus surface.

The detection of spin modulation during descent of Venera indicates the presence of a small angular source as opposed to an extended source. Ksanfomaliti *et al*[40] estimated that Venera 11 and 12 were able to monitor lightning discharges from 7.5% of the planetary atmosphere. By extrapolating the number of discrete burst sites, they suggested that there were about 50 lightning sites at a given instant of time over the entire planet compared to about 2000 lightning events that one would detect on Earth. However, their extrapolation depends on the assumption that, thunderstorms are uniformly distributed and thus they ignore the possibility that lightning could be more frequent on Venus beyond the radio horizon of the Venera landers. It is very difficult to estimate the strength of an individual stroke from these measurements or even the rate of occurrence because the location and angular size of the lightning flashes responsible for the observed VLF pulses are not known precisely. Thus, the Venera data provide no reliable estimates of the strength and occurrence rate of Venus lightning. The differences in the rates of occurrence and the temporal pattern of lightning flashes during each descent through the atmosphere are reminiscent of the variability expected of lightning associated with terrestrial thunderstorms.

Orbital VLF studies

The Pioneer Venus Orbiter launched by NASA had among many other experiments on board a VLF receiver with 4 narrow-band frequency channels centered at 100 Hz, 730 Hz, 5.4 kHz and 30 kHz, called the Orbiter Electric Field Detector, OEFD. The recording of these signals for over a decade has enabled experimenters to carry out statistical sampling of both the source location and the rate of occurrence of lightning flashes. On Venus, the magnetic field magnitude is such that the 3 higher frequency channels are almost always above the local electron gyrofrequency. The waves at these higher frequencies do not propagate along the magnetic field in the whistler mode. If these signals are detected by the OEFD near periapsis, it may still indicate the presence of lightning but the entry of the wave energy into the ionosphere must be by a separate mechanism. At 100 Hz waves can propagate in the whistler mode, if the magnetic field is sufficiently inclined to the horizontal direction. However, when the ionospheric magnetic field is nearly horizontal the vertically propagating waves lie outside the resonance cone and, as with the higher frequency waves, these 100 Hz waves may also not propagate upwards in the whistler mode. In short, in studying the 100 Hz signals care must be taken to note both the strength and orientation of the local magnetic field. This was not always done in earlier studies.

At orbit injection, the Pioneer Venus periapsis was in sunlight and not until a month later did the spacecraft observe the first electric field signal that appeared to be due to lightning[6]. The signals had all the characteristics expected for lightning generated signals. These were intense, impulsive, broadband (i.e. occurred on all 4 frequency channels) and lasted for less than 0.5 s because the signals were shorter than the decay constant

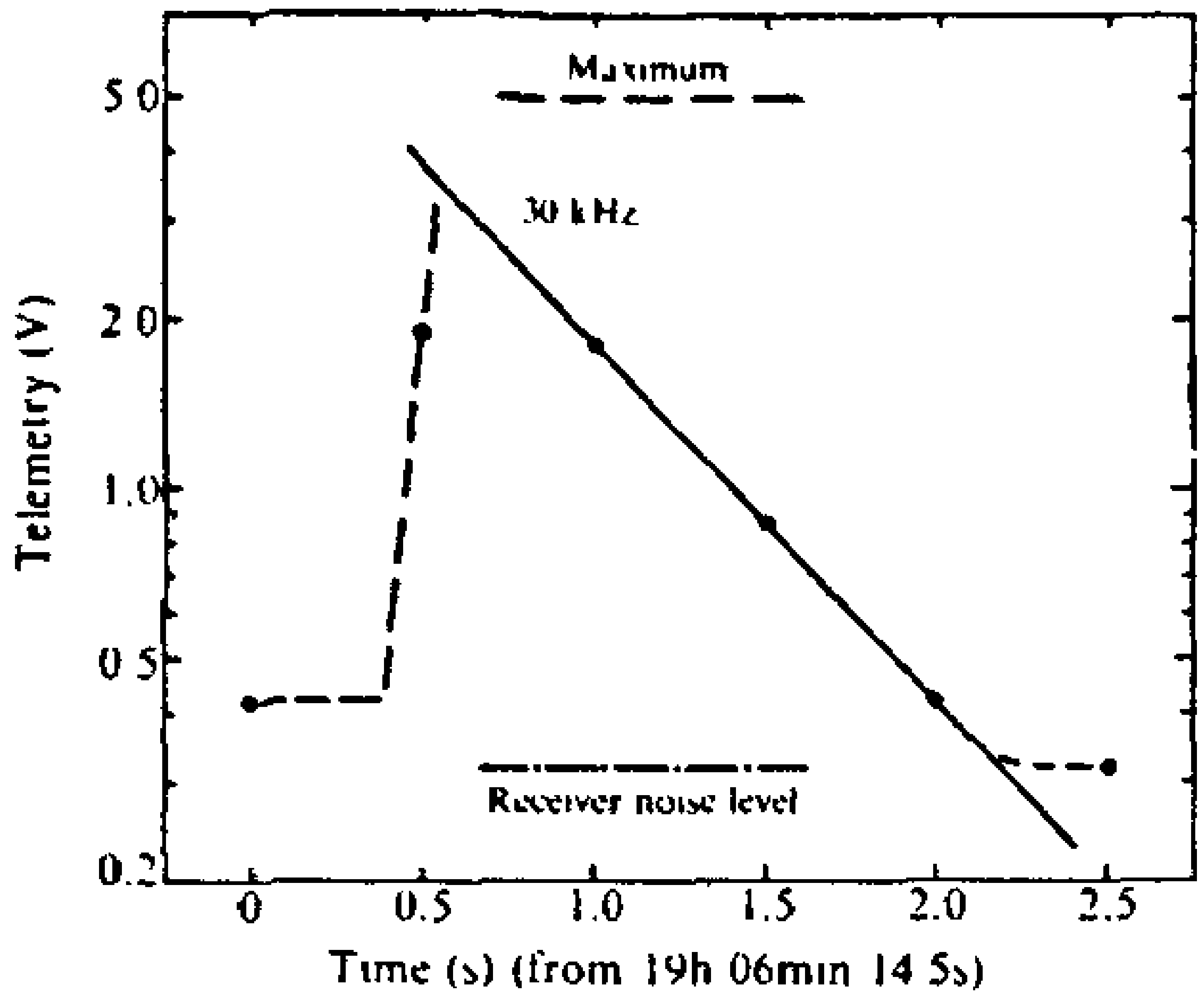

Figure 5. Decay of 30 kHz signal strength in Pioneer Venus plasma wave instrument due to naturally occurring signals in the night ionosphere Note the logarithmic voltage scale

of the instrument. This type of signal is illustrated in Figure 5 for the 30 kHz channel. The signals appeared to be more frequent at lower altitudes suggesting a low altitude atmospheric source.

After analysing a larger sample of data, Scarf and Russell[8] decided to use a more conservative definition of a possible lightning generated signal. Since signals above the electron gyrofrequency should not propagate to the spacecraft in a collisionless plasma, Scarf and Russell[8] counted as possible lightning events, only impulsive signals at 100 Hz which were unaccompanied by signals at other frequencies. Furthermore, the magnetic field had to be strong enough so that the electron gyrofrequency well exceeded 100 Hz. However, they did not check the orientation of the magnetic field. Since Venus clouds were 50 km above the Venus surface, it is unlikely that cloud-to-ground lightning strokes occur. However, since terrestrial volcanic plumes exhibit intense electrical discharges, Scarf and Russell[8] looked for a possible correlation of the emissions with regions suspected to be volcanic from the radar-derived cloud topography.

A larger sample of data was analysed by Scarf and Russell[8] who examined records for the first 1185 orbits of Pioneer Venus. These orbits covered 5 complete traversals of the nightside ionosphere (or observing seasons) plus a part of sixth. This survey covered 14% of the Venus surface. In this study 65% of the observed signals came from regions near Phoebe, Beta, and Atla which were topographically high regions where volcanism was suspected. These correlations lead Scarf and Russell[8] to propose a possible link between volcanism and the lightning events. The study reported a rate of 2.4 bursts/km^2/yr^1. However, this burst rate cannot be considered to be lightning flash rate both because there are many flashes in a burst and because many bursts were not counted because they failed to satisfy one of the conservative selection criteria. Furthermore, the area of the Venus surface monitored at one time was not known, nor the size of the lightning discharge which could cause a detectable electrical burst at Pioneer Venus. Scarf and co-workers later attempted to revise the definition of an event to make it more nearly equal to a flash by counting each impulse in a group of impulses. However, the time resolution of the instrument still restricted this approach and the flash rate was still underestimated. In this later study they chose a threshold just above that of the instrument of $2 \times 10^{-6}\ \text{Vm}^{-1}\text{Hz}^{-1/2}$ at 100 Hz. They required that the electron gyrofrequency be greater than *100 Hz* and that the magnetic field line through the spacecraft intersect the planet. Examining data from the first 2124 orbits (9.5 observing seasons), Russell *et al* [16–22] found 4240 bursts covering the altitude range from 150 to 2900 km. After the first three seasons, the periapsis altitude of Pioneer Venus was allowed to follow the rise caused by solar gravitational perturbations. As periapsis rose, the seasonal total number of bursts fell, indicating that the event rate was greatest at low altitudes. An attempt to show this altitude dependence using the rate versus altitude, independent of seasons, was flawed because of the non-uniform sampling of altitudes within any season. As before no attempt was made to normalize the occurrence rates to the observing time at any altitude or in any season.

Taylor *et al.*[6] ascribed all signals in their initial study to Venus lightning. Studies carried out later were restricted only to 100 Hz signals which could propagate upwards in whistler mode along the nightside Venus magnetic fields. Lightning in the Earth's atmosphere is known to generate broad-band electromagnetic waves with a power peak around 6–10 kHz. Singh and Russell[11] and Singh *et al* [12] analysed the OEFD data and showed that under suitable conditions signals at all the four frequencies are recorded and that these signals conform well with the general nature of the electromagnetic spectrum generated by lightning discharges. Soon after new evidence was put forward by Singh and Russell[11], the earlier objection of Taylor *et al* [10] developed into a controversy with varying suggestions and interpretations[13, 15, 21 41 42].

In light of these controversies, the analysis of PVO signals was refined and the magnetometer data were examined to eliminate periods in which telemetry errors occurred. Figure 6 shows typical signals classified in this study. The signals labelled 'b' are interference associated with the motion of the antenna into the spacecraft wake. The signals labelled 'a' and 'c' are typical of those thought to be associated with lightning. As we discuss below, the broadband nature of the 'a' signals implies that they are probably from a source immediately below the satellite. Such signals are seen at

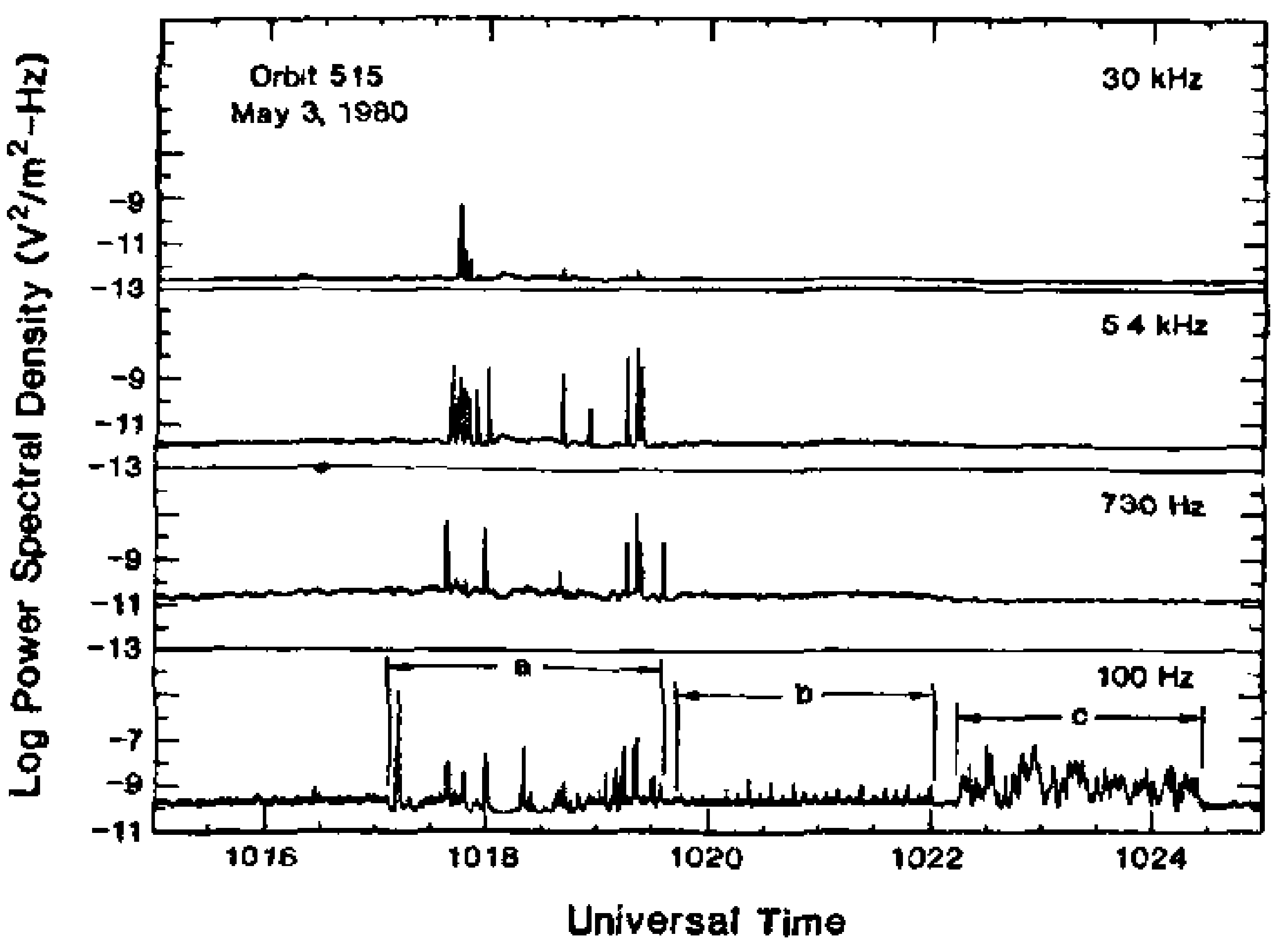

Figure 6. Plasma wave amplitude versus time on orbit 515 showing types of signals observed Type 'b' is due to the interaction of the antenna or the spacecraft with the local plasma environment[22] (Russell *et al* 1990)

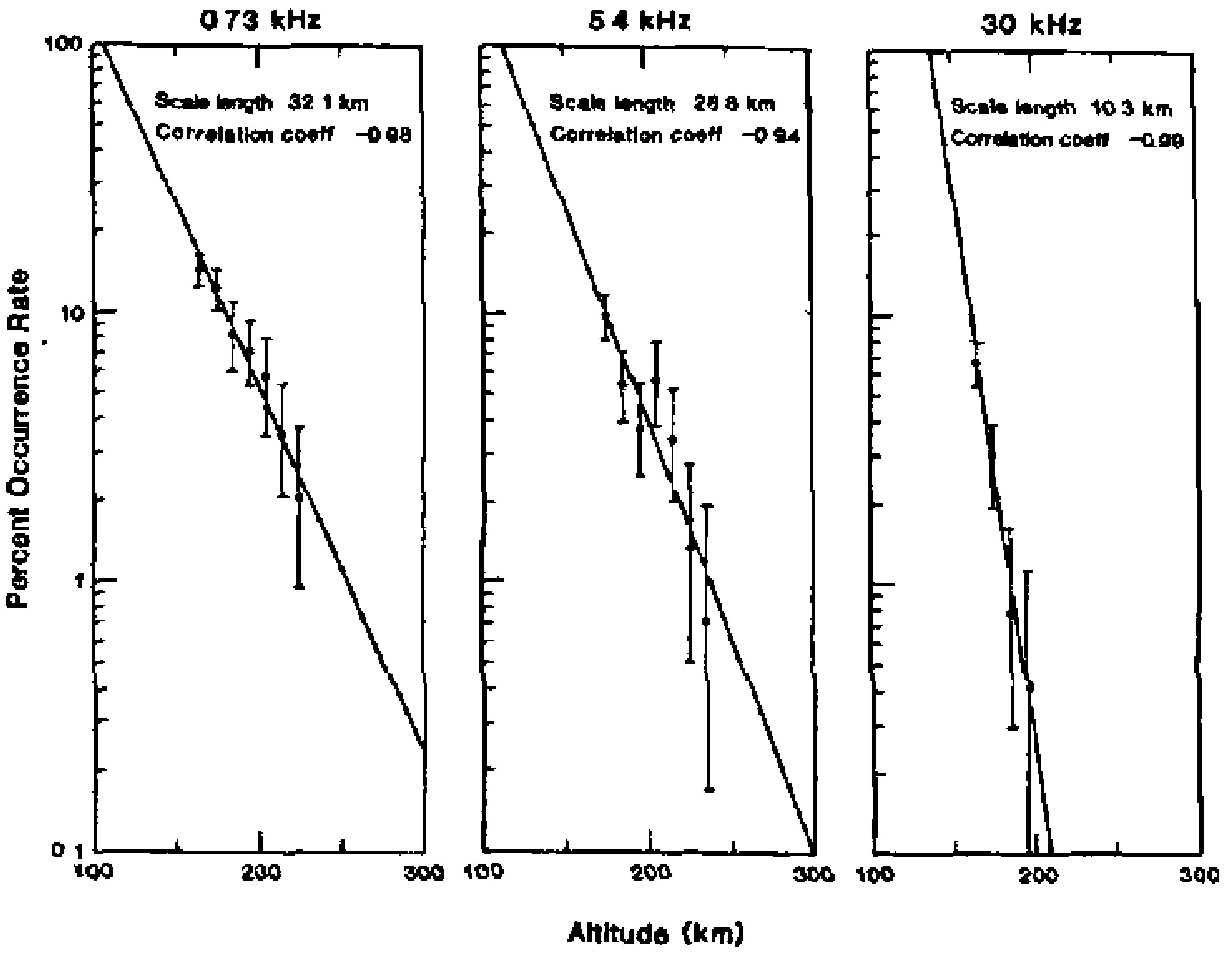

Figure 7. Altitude dependence of the occurrence rate of impulsive bursts in the Venus nightside ionosphere above the local electron gyrofrequency An occurrence is defined as at least one impulsive signal rising above a threshold value in a 30 s period[19]

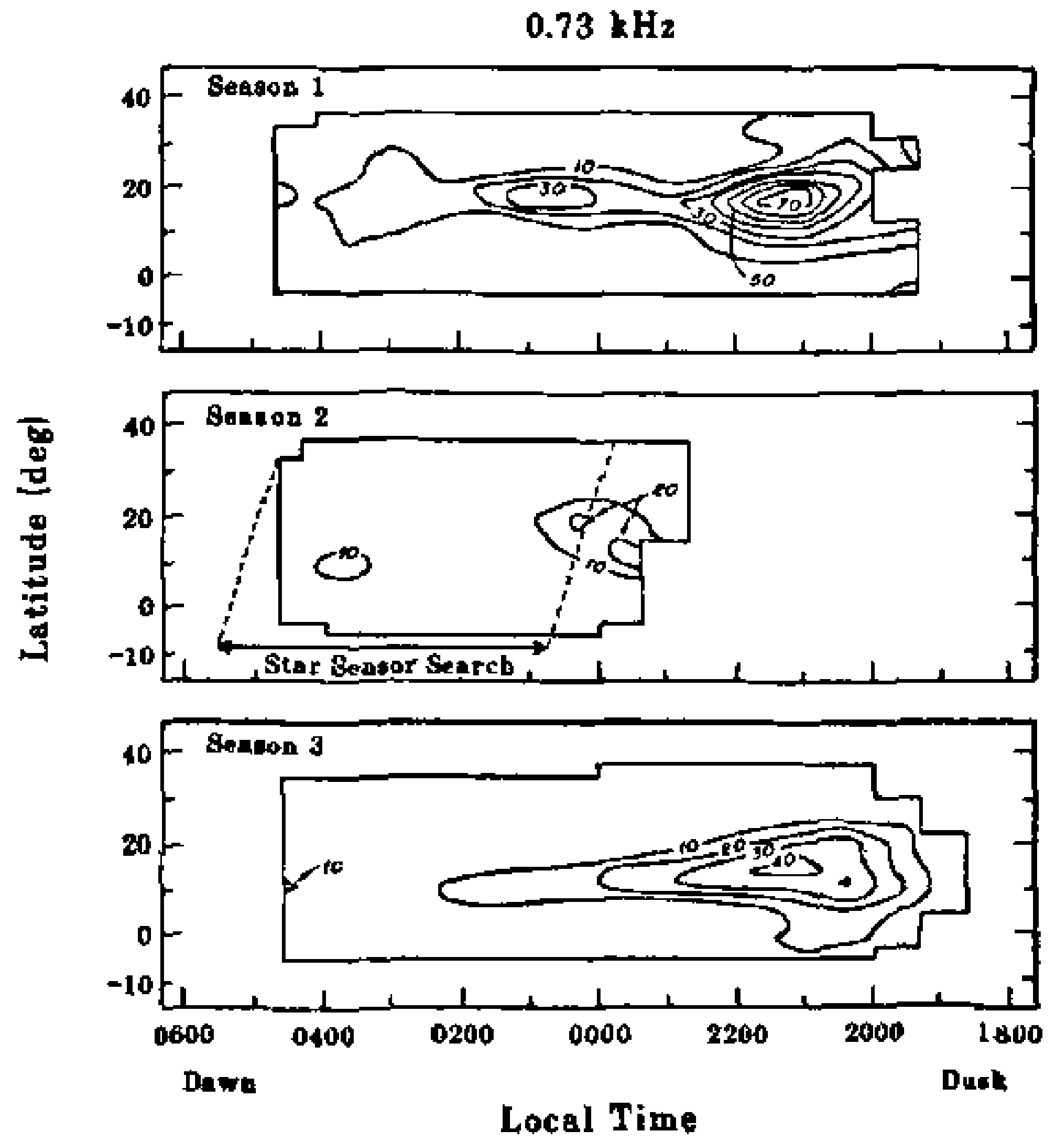

Figure 8. Contour maps of the occurrence rate bursts at 730 Hz in local time and latitude for each of the three observing seasons The interval during the second observing season over which the star sensor search was conducted is also shown[19]

lowest altitudes. Since 'c' signals occur only on the 100 Hz channel, the spacecraft does not appear to be in the near field of the lightning stroke. Probably these signals have propagated a large distance to the spacecraft and come from an extended region. The initial examination of these data showed that the occurrence rate of lightning signals decreased with increasing altitude at all frequencies, suggesting that at least some of the signals present were generated below the ionosphere. It also showed that the occurrence rate varied from year to year[16]. The altitude dependence of the signals at the 3 highest frequencies is shown in Figure 7 (ref. 19). The magnetic field strength affects the occurrence rate of these signals but the direction of the magnetic field has only a small or negligible effect[17]. The signals above the electron gyrofrequency are useful for mapping the source locations precisely because they attenuate rather rapidly. The occurrence rate at 730 Hz as a function of latitude and local time for each of the first three seasons is shown in Figure 8 (ref. 19). During the first half of the second season Venus passed behind the Sun, preventing telemetry transmission to Earth. Thus, only 2.5 seasons of low altitude data are available. In the middle panel the region covered by the star sensor survey[37] is also indicated. The first and third seasons show a very strong local time dependence with a region of highest occurrence rate on the dusk side which is confirmed during the second season by the relative absence of signals on the dawn side. The 100 Hz signals, which generally occur below the electron gyrofrequency, behave in some respects in the same way and in some respects in different ways than those above 100 Hz.

The local time of occurrence of the 100 Hz signals when the magnetic field is greater than 15 nT, together with the occurrence rate of fields greater than 15 nT and with the occurrence rate of signals above the electron gyrofrequency is shown in Figure 9. This latter quantity was inferred earlier to be a good indicator of the source region of the lightning radiation because of the rapid decrease in occurrence (and amplitude) with altitude. The 100 Hz occurrence rate does not resemble this curve nor does it resemble the occurrence of strong fields. If it did resemble, we would infer that the

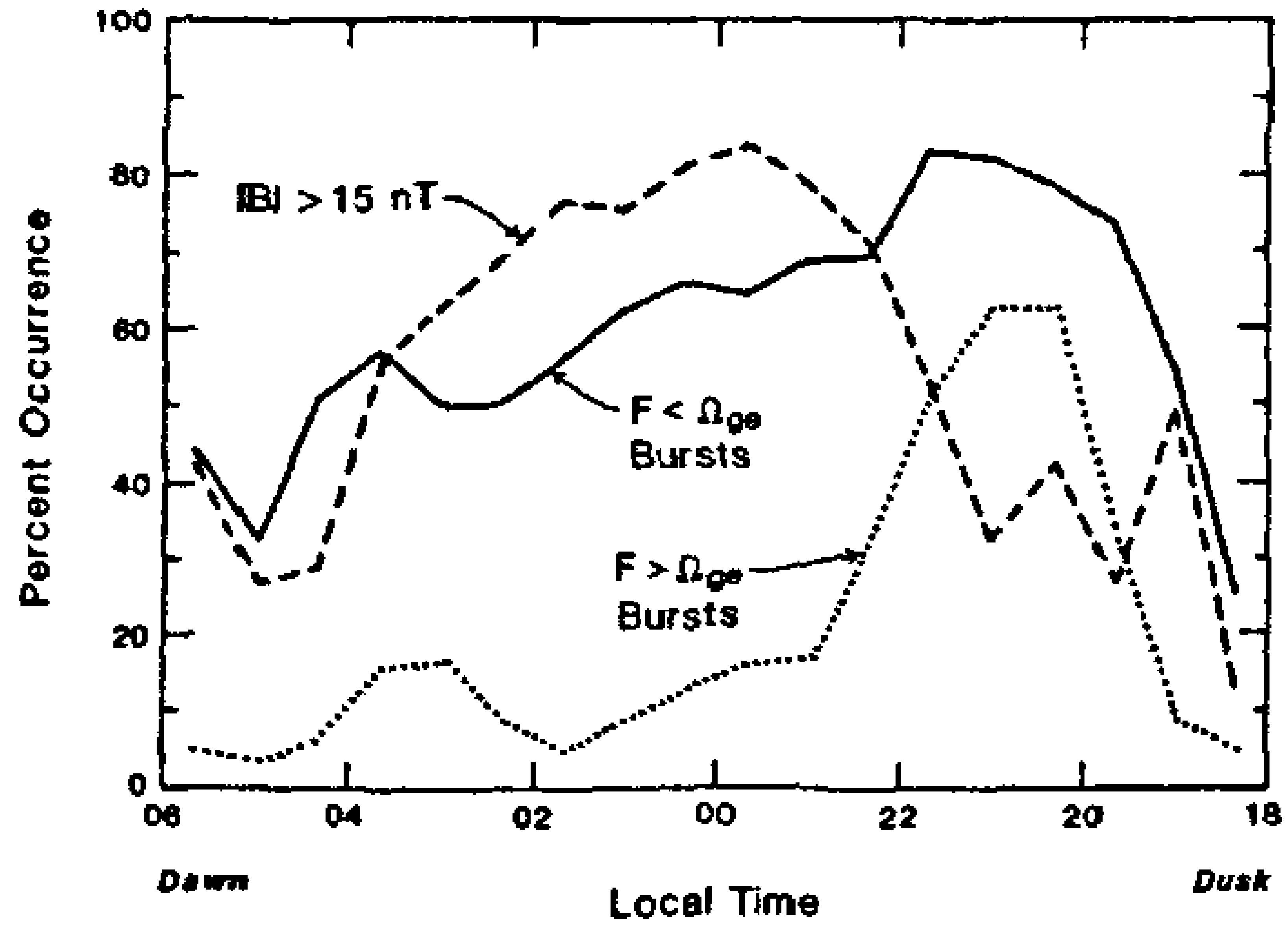

Figure 9. Local time dependence of the low altitude ULF bursts observed by Pioneer Venus when the magnetic field strength at the satellite was greater than 15 nT. Solid line shows per cent active 30 s intervals for 100 Hz channel, dotted line for higher 3 channels.

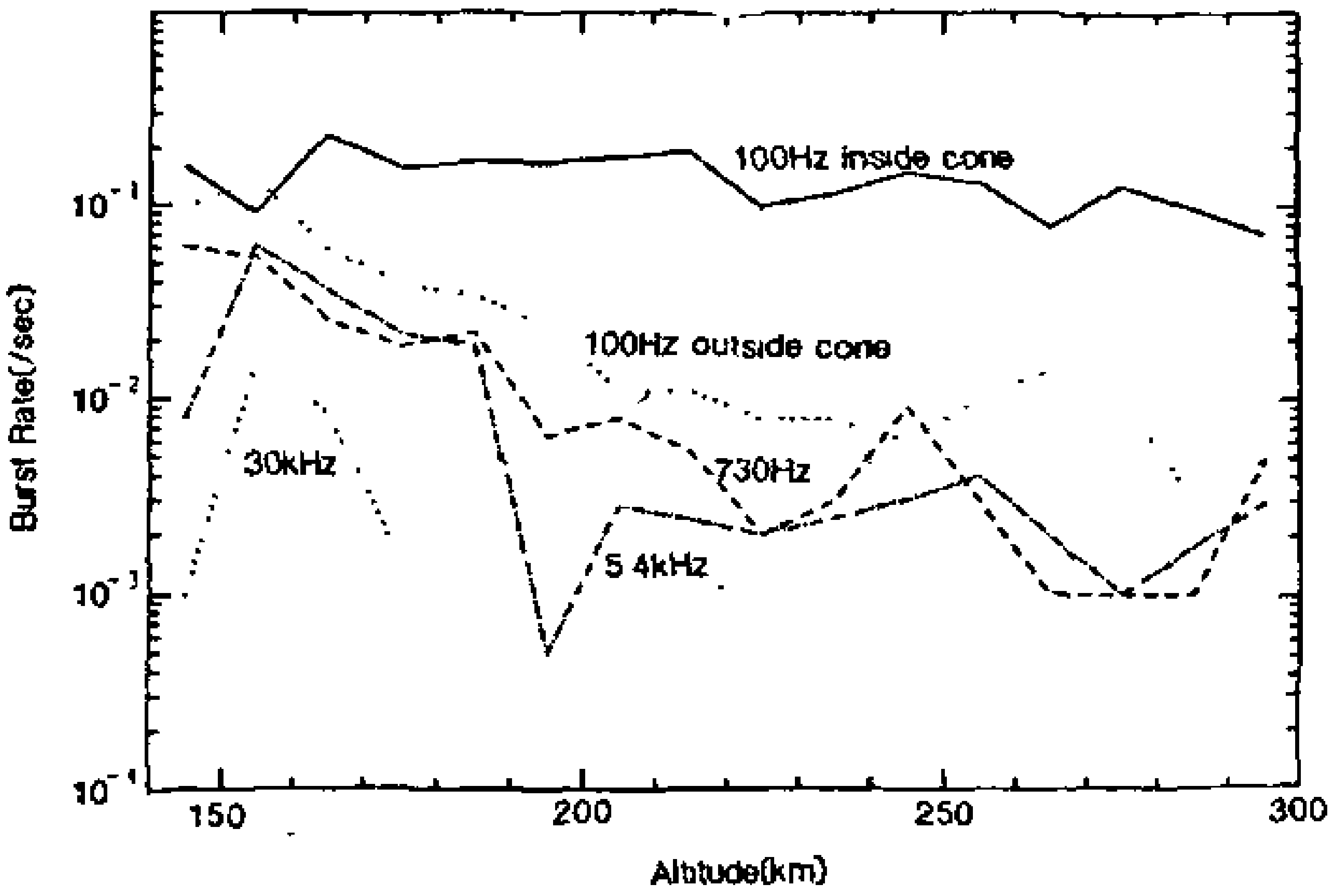

Figure 10. The altitude dependence of the rate of individual VLF pulses as a function of altitude for signals above the local gyrofrequency at 730 Hz, 5.4 kHz and 30 kHz, together with the rate of occurrence of 100 Hz bursts inside the resonance cone and outside the resonance cone. The only assumption used deriving the direction of propagation of these 100 Hz waves is that the source of the waves was in atmosphere. This resonance cone appears to be quite successful in separating propagating waves (top curve) from non-propagating waves (dotted line).

occurrence of 100 Hz waves was controlled solely by the magnetic field. Rather the 100 Hz waves peak over the so-called 'source region' and also extend far across the nightside gradually decreasing in occurrence. We deduce from this that the 100 Hz signals may be generated in the 'source region' and then propagate a long way in the Venus-ionosphere wave-guide before they enter the ionosphere. We find that it is not possible to map out the extension of the source region into the afternoon sector because the changes in the ionospheric density appears to control the access of signals to the spacecraft.

The lightning study carried out by Russell and co-workers of the occurrence of VLF bursts treated only 30-second intervals of data. If an interval had a single impulse or was continually active, the study did not distinguish. Thus, these results essentially depict the frequency of lightning activity rather than an occurrence rate of lightning flashes or strokes. Ho *et al*[43] developed a new method to count individual VLF bursts or impulses on each of the four channels of the PVO plasma wave instrument. This study showed that the burst rate decreased rapidly with altitude above the electron gyrofrequency (with a scale length of about 20 km) and less rapidly below. The local time distribution of the high frequencies remained the same as reported before. However, the postmidnight sector had higher 100 Hz occurrence rates, possibly in part due to the magnetic field geometry in this region being more favourable to the leakage of the 100 Hz noise from the 'earth-ionosphere' wave-guide. Most importantly the authors were able to estimate a global flash rate of $250\ \mathrm{s}^{-1}$, a rate 2.5 times larger than the reported terrestrial global flash rate. However, this estimate depends on the size of the lightning generation region which extends an unknown distance into the dayside of the planet. The Poynting flux inferred from the 100 Hz radiation was found to be 10^7 Watts/m^2 over the active region[19]. Strangeway[44, 45] showed that the 'VLF' signals measured by OEFD could not be generated by plasma processes as proposed by Maeda and Grebowsky[46] and Huba[47].

Recently more sophisticated tests of the low frequency OEFD measurement aboard PVO have been used extensively to support the lightning hypothesis. Sonwalker *et al.*[48] and Ho *et al.*[49] have carried out the tests to show that recorded signals are consistent with a lightning origin. The altitude distribution of VLF burst rate is shown in Figure 10. Inside the resonance cone, at allowed whistler mode propagation angles, the waves have little altitude dependence as expected for whistler mode wave propagation. However, outside the resonance cone where whistler waves do not propagate, the 100 Hz waves decrease rapidly in a manner similar to non-propagating waves above the electron gyrofrequency namely 730 Hz and 30 kHz. Thus, there appears to be two mechanisms for VLF signals to appear in the Venus ionosphere. The first mechanism is propagation in the whistler mode from below the ionosphere. The second mechanism involves a nonpropagating signal and is restricted to low ionospheric altitudes.

High frequency electromagnetic radiation from Venus lightning

Experimental measurements have shown that the terrestrial lightning signals fall as f^{-1} at high frequencies.

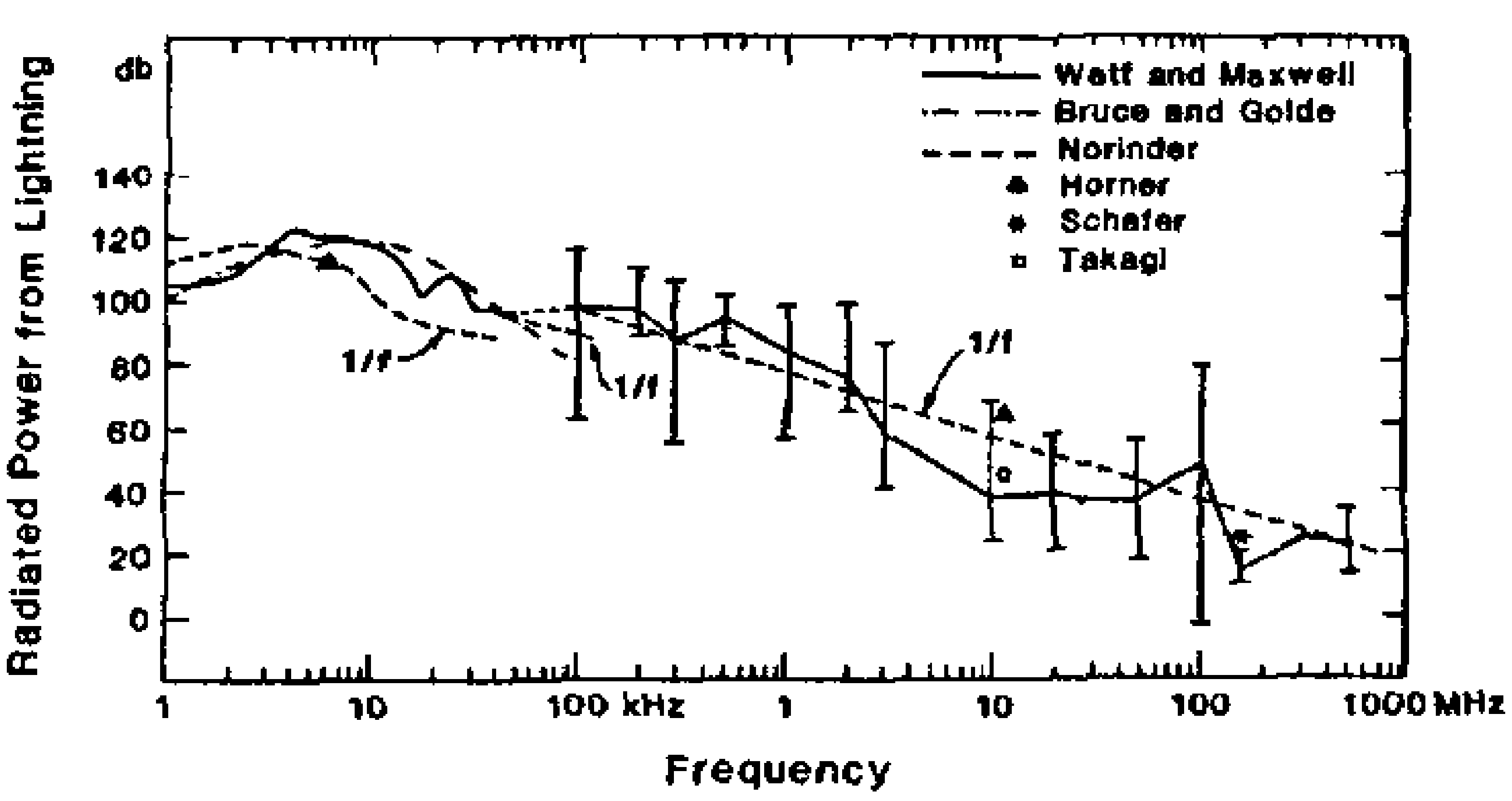

Figure 11. The variation of lightning generated electric field intensity measured by ground-based system with a bandwidth of 1 kHz A slowly varying tail extending up to very high frequencies are seen Some of the measurements are shown by the data points[48]

Measurements extending up to hundreds of megaHertz are shown in Figure 11. The OEFD measurements aboard PVO at four frequencies suggest that the peak of the power spectrum lies around 6–8 kHz consistent with the terrestrial spectrum[11]. The measured strengths of signals by OEFD aboard PVO at higher frequencies were shown to vary more slowly with frequency than the signals at lower frequencies[11]. Thus we might expect Venus signals to also extend into the hundreds of megaHertz range.

Signatures of lightning generated signals have been detected on Jupiter, Saturn, Uranus and Neptune[50–54] and for three of these planets only electromagnetic evidence is available. On Earth lightning has been mapped using electromagnetic waves both in space and on the ground. The generation of electromagnetic signals by lightning discharges has been mapped on the ground by Volland *et al*[55], while the high frequency signals escaping out of the earth's atmosphere have been mapped globally using the RAE-1 satellite at 9 MHz. The contours of lightning events measured by RAE-1 satellite and shown by Stone[56] are shown in Figure 12. The monitoring of lightning by radio frequency signals by satellites has provided reliable information on Earth and the only information about lightning on both Saturn and Uranus. In the absence of similar radio frequency measurements above ionized layer, the existence of Venus lightning had been countered by suggesting one or another plasma process that could generate electromagnetic waves. Thus the measurements at radio frequencies, up to 5.6 MHz, carried aboard Galileo during the flyby of the nightside of the Venus were very important in settling this controversy. These measurements showed the expected signature of lightning in the Venus clouds[24, 25]. The nature of the recorded signals is shown in Figure 13. With this latest evidence in favour of Venus lightning, all forms of electromagnetic evidence for planetary lightning have been found: optical, radio and whistler. It is now no longer a question of the existence of Venus lightning, but what are the occurrence rate and the source mechanisms. It is possible that some unique and hitherto unknown processes are at work in the dense and comparatively hot Venus clouds. The attenuation and cascading of solar and galactic cosmic-ray flux in the dense Venus atmosphere could play an important role in introducing additional charge in the thick Venus cloud cover. The cosmic-ray ionization of Venus lower atmosphere is shown in Figure 14 and we find that significant ionization is present at Venus cloud altitude[57]. The detailed knowledge of the dynamical processes in this region should be studied to determine the charge separation processes leading to Venus lightning.

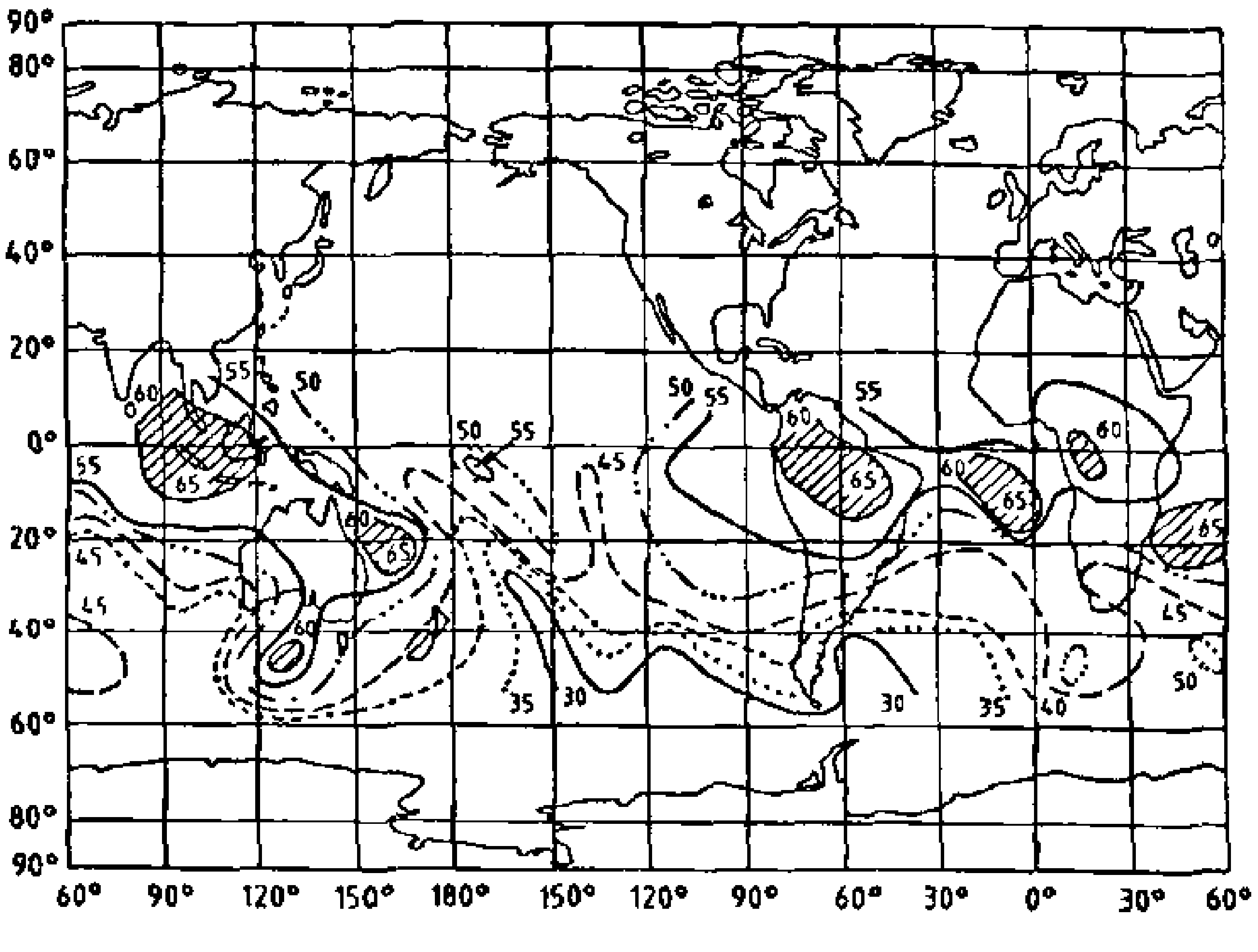

Figure 12. Global distribution of terrestrial lightning generated wave at 9 MHz as measured by RAE-1 satellite[56] The contours of equal wave intensity are superimposed on a world map to show their relation to land masses in the equatorial zone

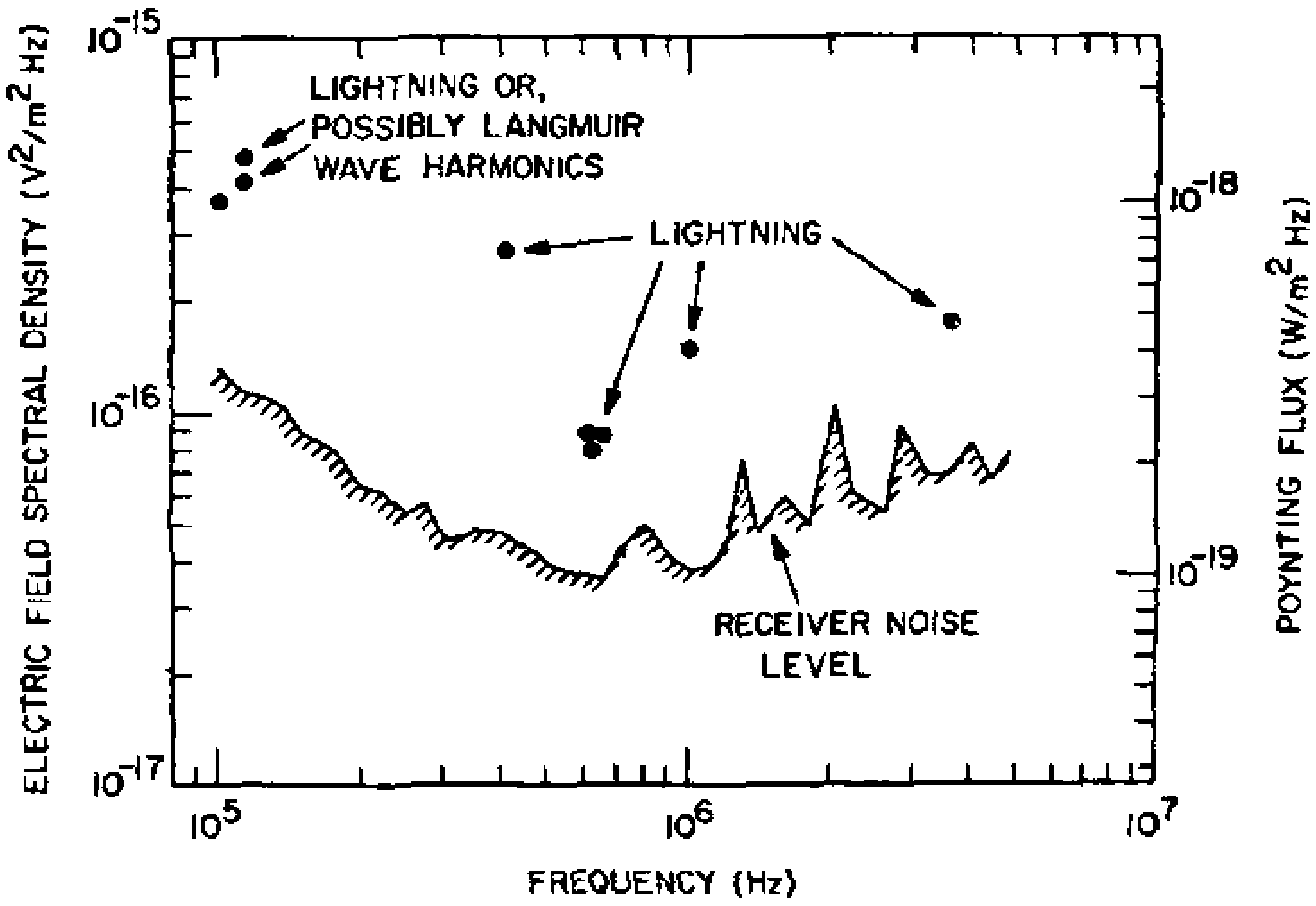

Figure 13. Amplitude of radio wave impulses seen by the plasma wave instrument on Galileo as it passed Venus on 10 February 1990

Summary

From the foregoing discussions, we find that the series of Venera lander experiments and the OEFD aboard

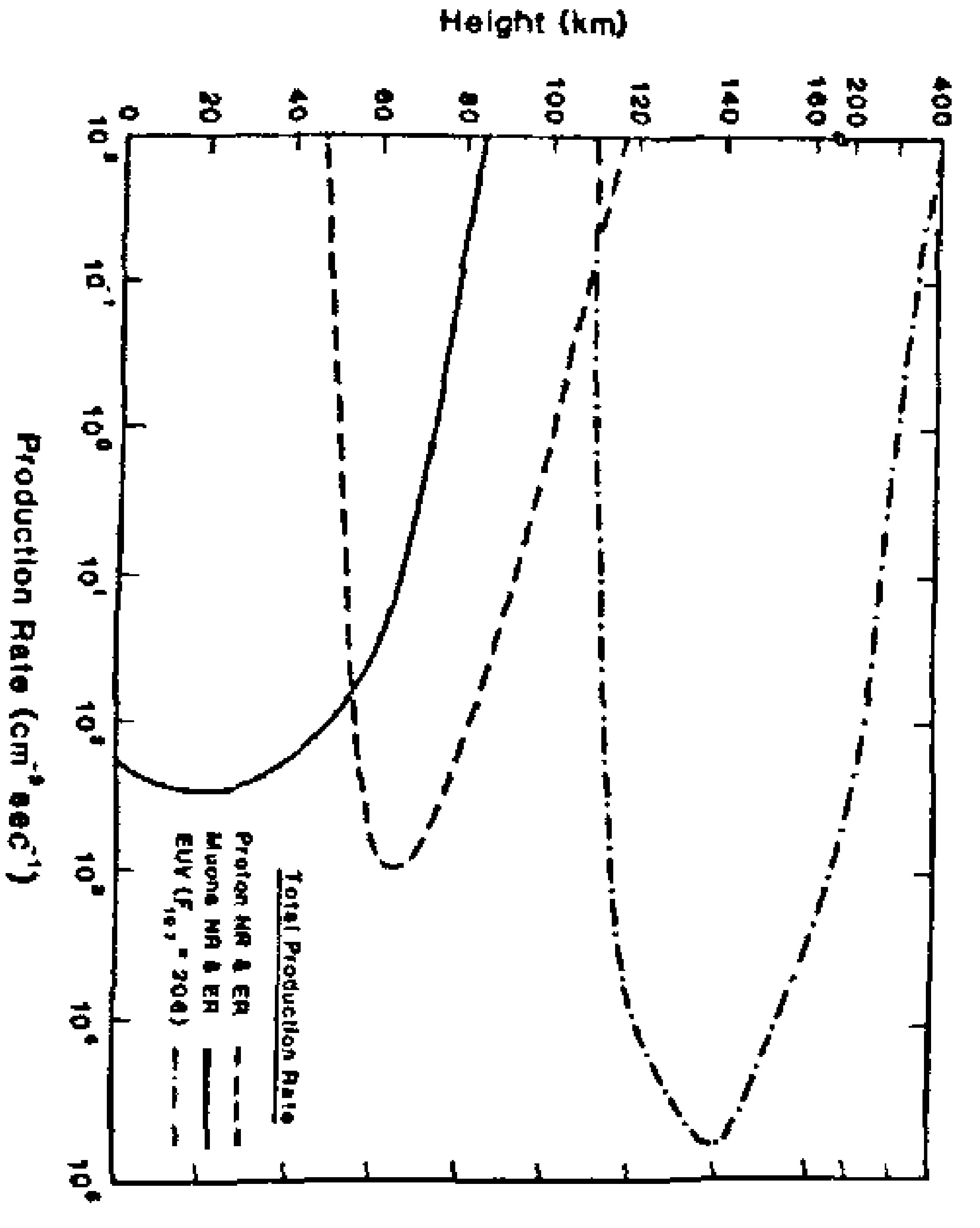

Figure 14. The electron–ion pair production rate produced by the cosmic-ray attenuation and decay processes in the Venus lower atmosphere[37]. Non-relativistic (NR) and extremely relativistic (ER) particles have been included in this calculation

PVO measured lightning generated very low frequency signals. These signals under suitable conditions escaped out of the nightside Venus atmosphere into the ionosphere, and were easily recorded whenever PVO travelled below a critical altitude. This interpretation originally met with some criticism of varying nature, associating these signals with either electrostatic wave modes or spacecraft interference signals. However no alternate mechanism has been proposed to explain the totality of signal characteristics observed and to counter the lightning origin of these signals. As do terrestrial lightning signals, they exhibit definite wave polarization, an impulsive nature, and broadband spectral features including a radio frequency component. Also, they freely enter the ionosphere, possibly through density depletions, possibly due to density inhomogeneities or possibly due to some interaction of the electric field in the clouds with the structure of the ionosphere above it, a process we little understand at present. Various likely processes of VLF wave generation have been suggested including volcanic plumes, plasma processes, signal interference, etc. However, the detailed statistical analyses of OEFD signals seem to favour charge separation arising from cloud dynamical processes and leading to lightning generation of broad band electromagnetic wave. In this article we have briefly discussed the role of the cosmic-ray flux which enhances the ionization at lower altitudes. Cloud dynamics is likely to play an important role in charge separation. Recent measurements of high frequency electromagnetic waves by Galileo during its flyby through nightside of Venus has at last confirmed the existence of lightning in the Venus clouds[24, 25]. What is not yet understood is the source of charge generation in the Venus clouds and the charge separation processes giving rise to large electric fields which generate cloud-to-cloud lightning discharges. The confirmation of Venus lightning by Galileo's measurements should provide the much needed incentive for researchers to work out the charging and charge separation processes in the Venus clouds. These processes are most probably global phenomena and the observation of VLF signals from lightning only above the nightside of Venus may be due to ionospheric control of the processes of escape of electromagnetic waves and their propagation to the orbiting satellite. The dayside ionopause seems to shield the low frequency signals but the highest frequency signals escape out and are recorded on the dayside as well. Future observations of both the physics of the clouds as well as radio observations, at all local times, are needed to help solve the present day mystery of the global rate of occurrence now that Venera, Pioneer, Venus and Galileo have established the existence of Venus lightning.

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