WHISTLERS OBSERVED BY VOYAGER 1: DETECTION OF LIGHTNING ON JUPITER

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Abstract. During the Voyager 1 encounter with Jupiter a number of discrete signals were identified in the wideband plasma wave data with characteristics similar to whistlers generated by lightning. In this paper we show that the calculated whistler-mode travel times from Jupiter to the spacecraft are in good agreement with the measured dispersion characteristics, thereby confirming that the signals are caused by lightning on Jupiter and substantiating the Voyager 1 photographic evidence for lightning on Jupiter. A quantitative estimate of the north-south thickness of the Io plasma torus is also obtained from the measured whistler dispersion.

Introduction

The Voyager I spacecraft, which passed by Jupiter on March 5, 1979, included a plasma wave instrument which provided the first measurements of low frequency (10 Hz to 56 kHz) plasma waves and radio emissions in the magnetosphere of Jupiter. During the closest approach to Jupiter a number of dispersive signals were detected in the electric field waveform measurements which were tentatively identified as whistlers generated by lightning [*Scarf et al.*, 1979]. The purpose of this paper is to establish that these signals have the dispersion characteristics of whistlers produced by lightning at Jupiter and to analyze the implications regarding the plasma density in the Jovian magnetosphere.

The interpretation of these results relies heavily on our previous knowledge and understanding of whistlers in the earth's magnetosphere. Whistlers, as is well known, are low frequency electromagnetic waves generated by lightning which are guided along the magnetic field lines from one hemisphere to the other at frequencies below the electron gyrofrequency. The frequency dependence of the velocity of propagation in the magnetospheric plasma converts the impulsive lightning signal into a whistling tone, from which the name of this phenomenon is derived. The first comprehensive explanation of the propagation and dispersion of whistlers in the earth's magnetosphere was given by *Storey* [1953]. For a review of the observations and theory of whistlers, see *Helliwell* [1965].

Observations

Whistlers were detected by the Voyager 1 plasma wave instrument during two distinct periods near closest approach using the wideband 115 kb/s waveform measurements. See *Scarf and Gurnett* [1977] for a description of the instrumentation. Because the 115 kb/s telemetry system is normally used to transmit pictures from the imaging system, waveform data can only be obtained during a few selected intervals. The two specific intervals for which we have wideband data with whistlers are indicated by the regions marked A and B in Figure 1, which shows equatorial and magnetic meridian plane projections of the Voyager 1 trajectory by Jupiter. During the 12-hour period near closest approach a total of seven 48-second frames of wideband data are currently available for analysis, five frames in region A, and two in region B. In these seven frames of wideband data a total of 41 whistlers have been identified, 30 in region A on the inbound leg and 11 in region B on the outbound leg.

Representative frequency-time spectrograms of the whistlers observed in regions A and B are shown in Figure 2. All times are given as spacecraft event times (SCET). Each event is labeled by a letter indicating the region and a number (A-19, B-11, etc.), starting from the first event in each region. As can be seen, all of the events in Figure 2 have dispersion characteristics typical of whistlers observed in the earth's magnetosphere.

These events can be conclusively identified as whistlers by analyzing the frequency-time variation of the received signal. A well-known characteristic of whistlers at low frequencies is that the arrival time, t, at a specific frequency, f, is proportional to $1/\sqrt{f}$ [*Eckersley*, 1935],

$$t = D/\sqrt{f} + t_0 \qquad (1)$$

where D is a constant called the dispersion. The measured arrival times for two whistlers, A-22 and B-11, selected from Figure 2 are shown as a function of $1/\sqrt{f}$ in Figure 3. In both cases the measured arrival times fit the whistler dispersion law given by Equation 1, as indicated by the straight line fit through the data points. This close agreement provides strong evidence that these signals are whistlers produced by lightning.

Since the whistler mode ray path cannot make an angle of more than 19° from the local magnetic field [*Helliwell*, 1965] the lightning source must lie somewhere along the magnetic field line through the spacecraft. For the whistlers in region A the only object known to be within the whistler mode propagation cone is Jupiter, so we conclude that the lightning is located at Jupiter. For the whistlers in region B, the satellite Io is also located within the propagation cone. Consequently, the lightning in this case could be located either at Io or Jupiter. Since Io has

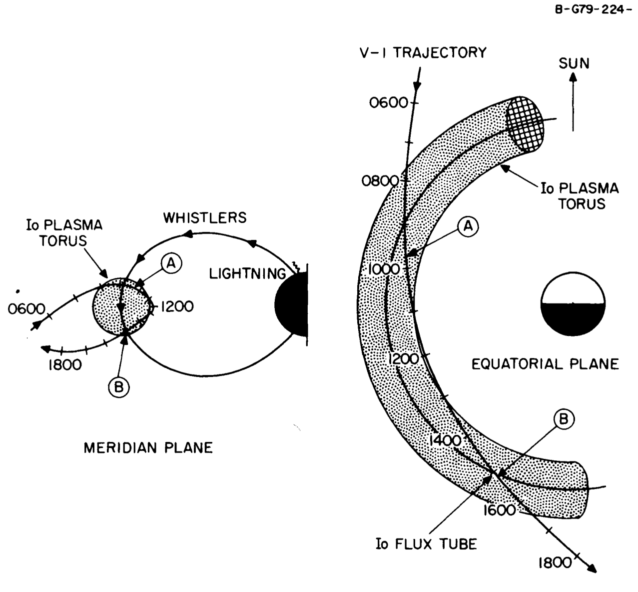

Fig. 1 The Voyager 1 trajectory near the closest approach to Jupiter. Whistlers were detected in regions A and B as the spacecraft passed through the Io plasma torus.

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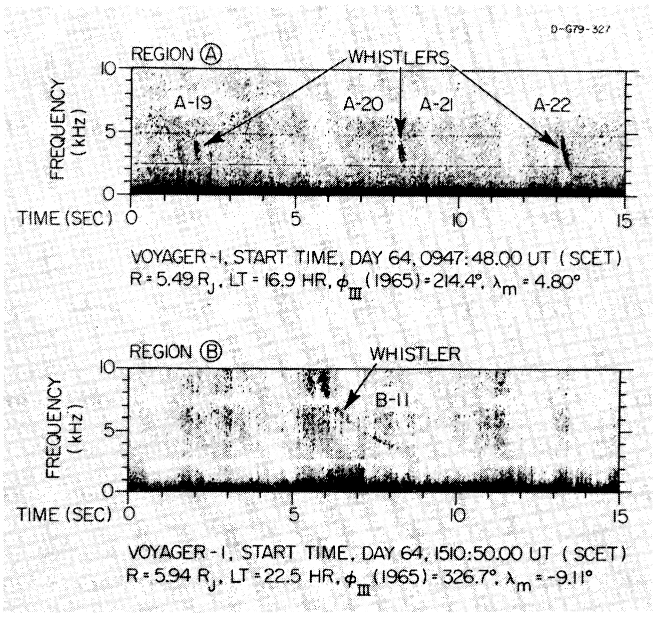

Fig. 2 Frequency-time spectrograms of representative whistlers from regions A and B in Figure 1. The larger dispersion of the whistlers in region B is believed to be due to the extra travel time caused by propagation through the high densities in the Io plasma torus.

active volcanos [*Smith et al.,* 1979], and volcanos on the earth have been known to produce lightning, the possibility of lightning on Io cannot be completely dismissed. However, the most likely interpretation is that Jupiter is also the source of the whistlers in region B, since lightning must be present on Jupiter to explain the whistlers in region A. Further evidence for the common source of the whistlers observed in regions A and B is given by the fact that the whistler rates, approximately one whistler every 8 seconds, and intensities, approximately 30 μV m^{-1} peak electric field intensity, are very similar to the two regions. Later we also show that in both regions the computed dispersions are consistent with lightning on Jupiter.

It is evident from a comparison of the whistlers in the top and bottom panels of Figure 2 that the whistler in region B has a much larger dispersion than the whistlers in region A. This marked difference in the dispersion is characteristic of all the whistlers observed in these two regions. The average dispersion of all the whistlers in region A is 53.8 sec Hz$^{1/2}$ with a standard deviation of 18.9 sec Hz$^{1/2}$, and in region B is 473 sec Hz$^{1/2}$ with a standard deviation of 127 sec Hz$^{1/2}$. The whistlers in region B typically have ten times the dispersion of those observed in region A. Since the whistlers in both regions have propagated over comparable path lengths, the larger dispersion in region B indicates that these whistlers have propagated through a region of greater electron density. The proximity to the Io plasma torus provides the simplest explanation for this marked difference in dispersion. As is now known from the ultraviolet spectrometer [*Broadfoot et al.,* 1979] and planetary radio astronomy measurements [*Warwick et al.,* 1979], a high density plasma torus, magnetically locked to the rotation of Jupiter, is present around the orbit of Io. As shown in Figure 1, the spacecraft passed through the northern portion of the torus on the inbound leg, crossed the magnetic equator near the inner edge of the torus, and passed through the southern portion of the torus on the outbound leg. If the lightning source responsible for the whistlers detected by Voyager is assumed to be located in the northern hemisphere, as illustrated in Figure 1, then the dispersion in region B would be much larger than in region A, as is observed, since the whistlers must pass through the high density torus to reach the spacecraft at B.

Dispersion Analysis

Since the propagation velocity of the whistler mode depends on the electron density it is evident that measurements of the whistler dispersion can provide important information on the plasma density distribution in the outer magnetosphere. For purposes of providing an initial analysis we will assume that the whistler waves are propagating parallel to the magnetic field. Separate ray tracing analyses which will be published later indicate that this approximation gives very good results for single hop whistlers, even though the wave vector direction may deviate substantially from parallel to the magnetic field. [See also, *Helliwell,* 1965]. For parallel propagation the group index of refraction, n_g, which is the speed of light divided by the group velocity, can be written in the following exact form,

$$n_g = \frac{1 + \frac{1}{2}\,\frac{f_p^2 f_g}{f(f_g - f)^2}}{\left[1 + \frac{f_p^2}{f(f_g - f)}\right]^{\frac{1}{2}}} \qquad (2)$$

where f_g is the electron gyrofrequency and f_p is the electron plasma frequency ($f_p = 9\sqrt{n}$ kHz, where n is the electron density in cm^{-3}). The arrival time is given by the following integral,

$$t = \frac{1}{c}\int n_g\, ds \quad , \qquad (3)$$

along the ray path, which in this analysis is assumed to be the magnetic field line. For purposes of understanding the observed whistler dispersion, this integral can be thought of in the following simple terms. Because the ionosphere is very thin only a negligible dispersion occurs as the whistler passes through the ionosphere. Above the ionosphere, in the region where the gyrofrequency is very large and the plasma density is very small ($f << f_g$ and $ff_g \gtrsim f_p^2$) the group index of refraction is close to one, so very little dispersion occurs in this region. As the whistler propagates farther away from the planet, the gyrofrequency decreases until the condition $ff_g \gtrsim f_p^2$ is no longer satisfied. At this point the group index of refraction starts to increase and approaches the following form in the limit $ff_g << f_p^2$ (still assuming $f << f_g$)

$$n_g \simeq \frac{1}{2}\,\frac{f_p}{\sqrt{ff_g}} \quad . \qquad (4)$$

It is in this region, where $ff_g << f_p^2$, that the primary contribution to the dispersion occurs. This region includes the magnetospheric plasma near the equatorial plane and the Io torus. The $1/\sqrt{f}$ dependence of the travel time is readily evident in Equation 4 and the dispersion is given approximately by

$$D \simeq \frac{1}{2C}\int \frac{f_p}{\sqrt{f_g}}\, ds \quad , \qquad (5)$$

where the integral extends only over that portion of the path for which $ff_g < f_p^2$. In comparison to the earth, whistler propagation at Jupiter is somewhat different because of the extremely low plasma densities expected away from the magnetic equator [*Goertz,* 1976]. Normally, at the earth, Equations 4 and 5 would be valid over the entire ray path.

To demonstrate that the observed whistler dispersion is consistent with the dispersion expected for reasonable magnetospheric plasma parameters we have computed the travel times for several simple models by numerically integrating Equation 2 along the ray path. In all cases the ray path is assumed to be a dipole magnetic field line through the spacecraft. Since the measured dispersion characteristics do not define a unique density

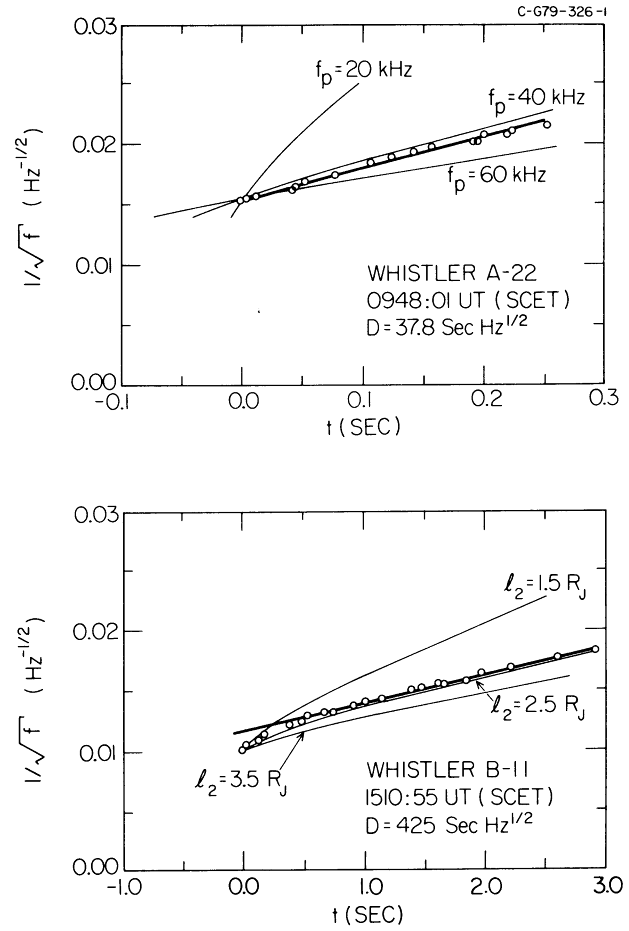

Fig. 3 A plot of $1/\sqrt{f}$ vs. the measured arrival time, t, for whistlers A-22 and B-11 in Figure 2. The linear relationship provides convincing evidence that these signals are whistlers produced by lightning.

distribution, a simple model has been used for the electron density along the magnetic field line. Inside of the Io torus the density is assumed to be constant with a value given by the local electron density at the spacecraft. The path length, l, through the torus is considered an adjustable parameter. Outside of the Io torus the electron density is assumed to be a different constant value characteristic of the magnetospheric plasma from the boundary of the torus to the ionosphere. This plasma density is also considered an adjustable parameter.

Models M-1 and M-2, shown at the top of Figure 4, represent two extreme cases which give a good fit to whistler A-22 in region A. The low dispersion of this whistler indicates that it could not have propagated very far through the Io torus, and must have originated from the northern hemisphere as illustrated in Figure 1. Model M-1 represents a limiting case in which the propagation path through the torus is assumed to be zero. By successive iteration the plasma frequency outside of the torus is adjusted until the best fit is obtained. The solid curves in the top panel of Figure 3 show the computed arrival times for various frequencies. The best fit plasma frequency is 40 kHz, which corresponds to an electron density of 19.7 cm^{-3}. This plasma frequency can be regarded as an upper limit to the average electron plasma frequency in the magnetosphere outside of the torus, since any additional contribution by the torus would only lower the density outside the torus.

Model M-2 represents the opposite limiting case for whistler A-22 in which we assume that the plasma frequency outside of the torus is as small as possible and adjust the path length through the torus, l_1, to give the best fit. An absolute lower limit to the plasma frequency is given by the highest frequency of the whistler, 4.2 kHz, since the whistler mode cannot propagate above the plasma frequency. The plasma frequency inside the torus is assumed to be 300 kHz, which is the local plasma frequency determined from the Planetary Radio Astronomy experiment [*Warwick et al.*, 1979]. The best fit travel time obtained using these parameters gives a path length, l_1, through the torus of 0.30 R_J. This path length is the maximum effective path length through the torus, since any increase in the plasma frequency outside the torus can only decrease l_1. The actual plasma density profiles will, of course, differ significantly from these simplified models, which are only intended to give a rough indication of the density distributions compatible with the observed whistler dispersion. Model M-2 probably underestimates the plasma density outside the torus, since it is unlikely that the plasma frequency could be as low as 4.2 kHz without causing a detectable deviation from the whistler dispersion law given by Equation 1.

Models M-3 and M-4, shown at the bottom of Figure 4, provide good fits to the dispersion of whistler B-11 in region B. The large dispersion of this whistler can be almost entirely accounted for by propagation through the Io torus. In both models the plasma frequency inside the torus is assumed to be 380 kHz, which is the local plasma frequency determined from the Planetary Radio Astronomy experiment [*Warwick et al.*, 1979]. Model M-3 assumes a plasma frequency of 40 kHz outside of the torus, corresponding to the maximum average plasma frequency determined from whistler A-22. Model M-4 assumes a plasma frequency of 10 kHz outside of the torus, which is the lowest possible plasma frequency compatible with the upper frequency limit (10 kHz) of this whistler. The computed arrival times for various effective path lengths, l_2, through the torus are shown by the solid curves in the bottom panel of Figure 3. The best fit is for $l_2 = 2.6$ R_J, essentially independent of which model is used for the plasma density outside of the torus. This relatively long path length also provides added justification for the assumption that whistler B-11 originates from Jupiter and not from Io, since it is very difficult to reconcile the effective path length $l_2 = 2.6$ R_J with the distance between Io and the spacecraft, which at this time is about 0.29 R_J.

Since the spacecraft at the time of whistler B-11 is about 1.0 R_J below the equatorial plane (see Figure 1) the total thickness of the torus along the magnetic field line, assuming symmetry with respect to the magnetic equator, is estimated to be 2(2.6 - 1.0)

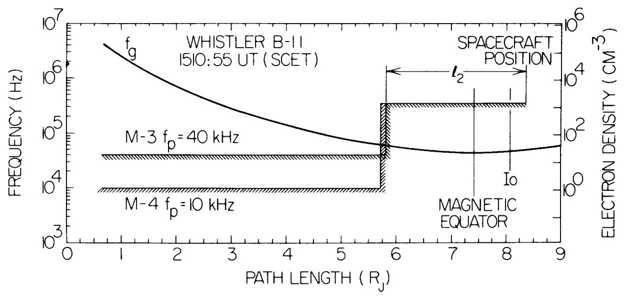

Fig. 4 Representative plasma density profiles which give good fits to the dispersion characteristics of whistlers A-22 and B-11 in Figure 3.

= 3.2 R_J. This thickness is in acceptable agreement with the initial results from the ultraviolet spectrometer observations which indicate a total north-south thickness of about 2 R_J. Note that the thickness would be reduced if the plasma density is increased near the center of the torus. Other trial density profiles can be constructed using Figure 4 by keeping a constant area under the f_p vs. path length curve. For whistler A-22 the corresponding north-south thickness estimated from models M-1 and M-2 ranges from about 1.0 to 1.6 R_J, depending on the plasma density assumed outside of the torus. The smaller north-south thickness in this case is probably related to the fact that the ray path passes much closer to the edge of the torus in region A compared to region B, which goes almost exactly through the center of the torus (see Figure 1).

Discussion

The Voyager 1 observations of whistlers during the encounter with Jupiter provide strong evidence of the existence of lightning in the atmosphere of Jupiter. No other source is known which can so accurately and consistently reproduce the dispersion characteristics of whistler-mode signals excited by lightning. The measured dispersion characteristics are in good agreement with the travel times computed using reasonable models for the magnetospheric plasma density. These observations, together with the photographs of lightning obtained from the Voyager 1 imaging instrument [*Smith et al.*, 1979], provide the final confirmation of various analyses and interpretations which strongly indicated the presence of lightning on Jupiter [see *Bar-Nun*, 1975]. The presence of lightning in a planetary atmosphere has been thought for some time to be an important factor in the production of certain minor constituents and organic compounds which require energetic processes, and possibly a necessary step in the development of biological activity [*Sagan et al.*, 1967].

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