An Upper Bound to the Lightning Flash Rate in Jupiter's Atmosphere

Lewis (*1*) discussed Voyager optical measurements and low-frequency radiowave observations related to lightning discharges in the atmosphere of Jupiter. He used a specific set of assumptions together with whistler measurements from the plasma-wave system to arrive at estimates of the average planetary lightning stroke rate *r* ranging between 10^{-4} and 4×10^{-2} flashes per square kilometer per year. Here we show that when the same Voyager whistler data are combined with different physical assumptions about the source area, the whistler paths, and the whistler amplitude distributions over the paths, a planetary lightning rate as high as several tens of flashes per square kilometer per year cannot be ruled out.

The Voyager 1 wave instrument detected lightning whistlers only when the spacecraft was at a Jovicentric distance of about 5.5 to 6.0 Jupiter radii (R_J) near the equatorial plane. The Voyager event rate was about 0.12 whistlers per second (*2*), and the ray-tracing analysis by Menietti and Gurnett (*3*) confirmed that these whistlers originate at high latitudes ($\approx 66°$) near the feet of the field lines passing through the Io torus. The geometric situation is indicated in the upper part of Fig. 1, which shows Jupiter, some

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representative magnetic field lines, and preliminary Io torus density contours deduced by Bagenal *et al.* (*4*) from the Voyager 1 plasma probe measurements.

We assume, with Lewis, that each whistler launched upward from an area A produces a magnetospheric signal that propagates without amplification or damping toward the equator; we also assume that the Voyager wave instrument detects a fraction F of these. Then for one whistler per 8 seconds, the lightning flash rate is

$$r = 4 \times 10^6/A\,F \text{ km}^{-2} \text{ year}^{-1} \qquad (1)$$

Lewis considered only possible conditions that would yield minimum combinations of $A\,F = 10^8 \text{ km}^2$, but we do not agree that this estimate provides an upper bound.

Our upper-bound evaluation is based on the concept that the lightning whistlers were detected only in a specific subsection of the Io torus because of special conditions that were present locally and along the magnetic field lines leading from the Voyager position down to the ionosphere. We therefore assume that the whistler waves propagated strictly along the field lines from Jupiter to Voyager, so that A in Eq. 1 simply represents the area below the ionosphere that illuminates the foot of the appropriate field line. This leads to a relatively small value for A, because Rinnert *et al.* (*5*) recently showed that at Jupiter the continuously increasing density with increasing atmospheric depth limits propagation of waves with frequency $f \lesssim 100$ kHz to line of sight and to one-hop reflection from the ionosphere. Thus, there is no Jovian analog of the terrestrial surface-ionosphere waveguide effect for radiation from lightning.

The atmospheric ray-tracing calculations of Rinnert *et al.* also provide a useful basis for a numerical estimate of A. Rinnert *et al.* considered a cloud source located 50 km below the 1-bar level within the neutral atmosphere, with a lower ionosphere boundary 200 km above the clouds. They showed that for this source location all upward rays in the cone defined by initial elevation angles greater than about +10° would illuminate an ionospheric area having a circular cross section and a radius of approximately 1000 km. Realistic restrictions to subsets of ray path angles suitable for propagation all the way out to Voyager lead to values of A on the order of 10^6 km^2.

To evaluate F, we have to consider the large distance from Jupiter to the spacecraft, the varying index of refraction over the path, and the high level of local Io torus plasma-wave activity that masks all the weaker signals from the planet. The Voyager 1 observations (*2*) suggest that we should take $E \simeq 5 \times 10^{-5}$ V/m as a representative amplitude within the Io torus. In the torus, the index of refraction n is high, and the wave E field must be reduced from its free-space value because $E(n) \approx 1/\sqrt{n}$ (*6*), with n given by

$$n^2 = 1 + f_p^{\,2}/f(f_c - f) \qquad (2)$$

Here, $f_p = 9000\sqrt{N}$ is the electron plasma frequency and $f_c = 28\,B$ is the electron cyclotron frequency (N is density in electrons per cubic centimeter and B is magnetic field strength in gammas). At 0912:36 on 5 March 1979, when two clear whistlers were detected, N was approximately 2250 cm^{-3}, B was about 2000 gammas, and for a 1-kHz wave the local n value was approximately 58. Thus, in the presumed low-density region just above the Io torus, the amplitudes of these whistler signals were near 3.8×10^{-4} V/m.

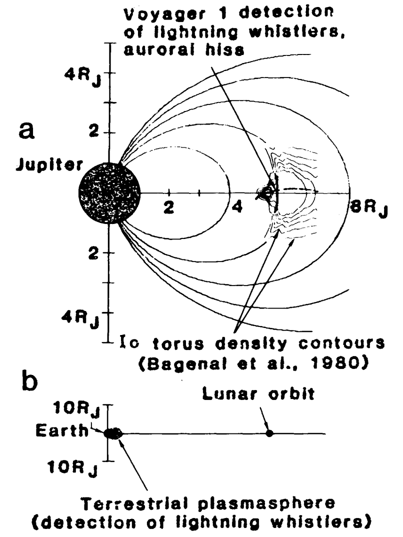

Fig. 1. (a) Position of Voyager 1 with respect to Jupiter, its magnetic field, and the Io plasma torus during the period when lightning whistlers were detected. (b) Earth and its plasmasphere to the same scale.

We must also consider the divergence of the wave energy and the changing wave amplitude over the huge high-latitude path. A possible geometry would have $DE(D) \approx$ constant, where D is the diameter of a magnetic field flux tube. Since the diameter of a flux tube leaving radius $R = 1\,R_J$ and 66° latitude expands by a factor of more than 28 at the equator, this implies that the whistlers detected on Voyager had field strengths comparable to or exceeding 10^{-2} V/m as they started upward from the top of the ionosphere. At Earth the dayside ionospheric transmission introduces an additional loss of about 12 dB for waves with $f \simeq 1$ to 3 kHz (*6*), and in this upper-bound model the cloud source is taken to be 200 km below the bottom of the ionosphere. When these factors are all inserted, we arrive at an estimate that the Voyager plasma-wave instrument detected only lightning signals with E_0 at least as high as 0.85 V/m, at a distance of 10 km from the source.

Pierce (*7*) showed that the peak amplitudes for signals radiated by terrestrial lightning are somewhat lower than this. For instance, with a 200-Hz bandwidth, Pierce's peak would be near 0.2 V/m at 10 km, and thus our conservative model indicates that Voyager detected only lightning whistlers with power levels at least ten times greater than those typically generated at Earth. This suggests that it might be appropriate to use $F \simeq 0.1$ (the lowest value used by Lewis), leading to $r \approx 40$ flashes per square kilometer per year, as stated above. Indeed, since at Earth the fractional number of lightning bolts drops off very rapidly with increasing power level (*8*), an even smaller value of F would be consistent with a strict earthlike model. This introduces the possibility that the r value may even be larger than the "upper bound" discussed above. However, as Lewis noted, all these high r values would imply that the lightning developed deep within the atmosphere beneath the optically thick cloud layer, and therefore his discussion of the chemical effects is not affected.

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References and Notes

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