flow if their nondimensional phase speed is $-0.26 < C_0/U_0 < 0$. [The E waves are solitary waves of elevation and the D waves solitary waves of depression (*1*).] On the basis of the jet profiles in (*3*), the latter criterion appears to be satisfied for all the features under consideration—the GRS and WO's and the spots at 41°S as E waves and their surrounding cyclonic flows as D waves.

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Lightning on Jupiter: Rate, Energetics, and Effects

Abstract. *Voyager data on the optical and radio-frequency detection of lightning discharges in the atmosphere of Jupiter suggest a stroke rate significantly lower than on the earth. The efficiency of conversion of atmospheric convective energy flux into lightning is almost certainly less than on the earth, probably near 10^{-7} rather than the terrestrial value of 10^{-4}. At this level the rate of production of complex organic molecules by lightning and by thunder shock waves is negligible compared to the rates of known photochemical processes for forming colored inorganic solids.*

The Voyager imaging team (*1*) reported the detection of lightning-like flashes in nightside observations of Jupiter. Cook *et al.* (*2*) analyzed the spacecraft images in order to map the locations of these flashes onto the cloud features observed during daylight. Twenty flashes were identified in a time exposure of 192 seconds (*2*). The flashes were estimated to generate $\sim 10^{17}$ ergs "comparable to terrestrial superbolts" (*1*). Ordinary lightning discharges on the earth are very variable in strength, but typical discharges dissipate roughly 0.5×10^{16} to 1×10^{16} ergs (*3*). The field of view of the television image containing the lightning flashes extends from ~ 30°N to 80°N, with most coverage between longitudes 25°W and 75°W. Although the area covered is in excess of 2×10^9 km^2, much of this is viewed at low grazing angles. All the observed flashes lie within an area of $\sim 1 \times 10^9$ km^2, which is about twice the surface area of the entire earth. Flashes are observed up to 55°N, with 19 of 20 lying within the complex polar region (> 45°N) (*1*).

The Voyager plasma-wave experiment (*4*) also reported evidence of lightning. While (and only while) the spacecraft was near 5.5 to 6.0 Jupiter radii (R_J) near the equatorial plane, a number of frequency-dispersed radio impulses were detected with an event rate of about one in 8 seconds (*5*). These impulses are whistlers, similar to those formed by propagation of electromagnetic burst noise from terrestrial lightning discharges roughly along field lines in the magnetosphere (*6*). The whistler rate observed by Voyager is well within the range of rates observed on the earth at middle to high magnetic latitudes (*6*). The Voyager planetary radio astronomy experiment also searched for evidence of lightning, but the evidence has so far not been conclusive (*7*).

Further analyses of the plasma-wave experiment data (*5, 8*) have shown that these whistlers originate at high latitudes (~ 66°N, the foot of the field lines near which the whistlers were observed) and follow paths which, aside from complications introduced by the high electron density in Io's plasma torus, roughly follow the magnetic lines of force in the relatively undistorted inner magnetosphere (near magnetic shell $L \simeq 6$).

I will now make estimates of the frequency of occurrence of both optical flashes and radio-frequency whistler bursts and the associated energy dissipation rates.

The 20 flashes observed over 10^9 km^2 in 192 seconds amount to 3×10^{-3} km^{-2} year^{-1}, which, at 10^{17} ergs per discharge, gives $\sim 10^{-3}$ erg cm^{-2} sec^{-1}. The convective energy flux averaged over Jupiter is 0.9×10^4 erg cm^{-2} sec^{-1}, so that the energy released by visible lightning flashes is $\sim 10^{-7}$ of the convective energy flux. I use here only the contribution to the atmospheric energy flux due to the turbulent upward transport of the internal heat of Jupiter, a conservative assumption applicable down to great depths in the troposphere (*9*). At pressures near 2 bars, deposition of solar heat can increase this figure by as much as a factor of ~ 2.5 at low latitudes, which, of course, would reduce the efficiency by the same factor.

The size of the area from which the plasma-wave experiment can detect lightning bursts is difficult to estimate precisely. Two effects contribute to the geographic spread of whistler signals. First, radio burst noise in the neutral atmosphere may be propagated for considerable distances, until it encounters an area where the critical frequency of the ionosphere is low and there passes through the ionosphere to initiate a whistler (*10*). Even low-altitude earth satellites can detect whistlers originating from discharges as far as 1000 km from the foot of the local field line (*6, 11*). Second, once a whistler originates in the ionosphere, it may propagate at a substantial angle with respect to the field lines (*12*). At frequencies very much less than the electron gyro frequency f_g (which was about 4.2 kHz at the point of whistler detection) the angle is about 19°; it decreases to 11° at $0.19 f_g$ and rises to allow all directions at f_g (*6*), where the signal is strongly attenuated. Ray tracing (*8*) shows that noticeably different paths

Table 1. Energy available for disequilibrating processes on Jupiter.

Process	Principal products	Available flux (erg cm^{-2} sec^{-1})	Reference
CH_4 photolysis (< 1600 Å)	C_2H_6, C_2H_2	0.2	(*15*)
NH_3 photolysis (< 2300 Å)	N_2, N_2H_4	10	(*16*)
PH_3 photolysis (< 2300 Å)	P_4 (red)	15	(*17*)
H_2S photolysis (< 2700 Å)	S_x (yellow → brown)	100	(*18*)
Lightning	CO, C_2H_2, HCN	< 0.003	(*14*)

connect a fixed lightning source to a fixed spacecraft location at different frequencies. Similarly, various lightning sources may be connected to any fixed spacecraft position.

Tracing back the cone of possible ray paths from the spacecraft (distance $R = 6\ R_J$; colatitude = 90°) to Jupiter ($R = R_J$) with the conservative assumption of a half-angle of 10° for the cone leads to an acceptable source area at high latitudes with a radius of ~ 16,000 km, extending from 54°N to 79°N. This gives an area of $\sim 9 \times 10^8$ km^2 in each hemisphere: we will consider only whistlers originating in the north polar regions because, at 6 R_J, south polar whistlers pass through (and are greatly dispersed by) the Io plasma torus, and hence would appear different from the observed "fast" whistlers which have not traversed the torus. The whistler count rate of ~ 0.12 sec^{-1} corresponds to an occurrence frequency of 4×10^{-3} km^{-2} year^{-1}, very similar to the rate of optical flashes. Since lightning is normally associated with electrification processes due to the freezing of liquid droplets and is observed (*2*) to be associated with upwelling regions on Jupiter, the most reasonable locale for typical Jovian lightning discharges is in the water condensation region near 0°C and 6 bars. The water cloud layer, unlike the topmost NH_3 cloud layer, is expected to be optically thick (*13*), so that observations from above could reveal a higher frequency of whistlers than of optically visible flashes.

The lightning rate deduced from the whistler data is, of course, very imprecise. It could be argued that the interval of jovicentric distance over which whistlers were observed was so small that the true global average rate is much lower than the figure estimated above—that is, that lightning is associated only with a particular narrow latitude interval, or that only isolated regions of intense thunderstorm activity were present, making up no more than ~ 10 percent of the surface area of Jupiter. Alternatively, it could be argued that only a small fraction of the lightning discharges (say 10 percent or less) generate whistlers, and that the region of relatively intense activity is fairly representative of the rest of the planet. Thus an average lightning stroke rate as high as 4×10^{-2} or as low as 10^{-4} km^{-2} year^{-1} cannot be ruled out. Making the very generous assumption that every discharge generating a whistler is a "superbolt" dissipating about 10^{17} ergs, we could then have a total lightning energy dissipation rate as low as 3×10^{-5} erg cm^{-2} sec^{-1}. At the other extreme, if 90 percent of the bolts are only of conventional size (10^{16} ergs) and are not detected because they are not large enough to generate whistlers, then extension of the high level of activity observed between 5.5 and 6.0 R_J to the entire surface of Jupiter would provide 3×10^{-3} erg cm^{-2} sec^{-1}. The conversion efficiency of convective energy into lightning is thus probably between 3×10^{-7} and 3×10^{-9}.

The whistler data, while difficult to interpret quantitatively, are reasonably consistent with the idea that the whistlers and the optical flashes are produced by the same population of discharges, dissipating $\sim 10^{-3}$ erg cm^{-2} sec^{-1} (efficiency, 10^{-7}). If further interpretation of the Voyager plasma-wave data leads to a higher estimate of the stroke rate, then we must conclude that most of the lightning occurs deep within the atmosphere, beneath the optically thick water cloud layer. The Voyager data do not provide any evidence for extensive lightning activity at high altitudes, near the NH_3 cloud tops; however, if all the observed flashes and whistlers were arbitrarily attributed to the NH_3 cloud region, the rate of energy dissipation by lightning and thunder would be only 10^{-4} of the rate of deposition of energy by ultraviolet photolysis of NH_3 and PH_3 in the same region.

A detailed treatment of the chemical consequences of lightning discharges in the Jovian atmosphere has appeared (*14*). For the present, it suffices to compare the energy fluxes available for each of several competing processes for forming complex organic molecules and colored solids. This comparison, given in Table 1, demonstrates that known photochemical processes involving formation of inorganic chromophores are far more important than lightning-induced synthesis on Jupiter.

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Fluoride Distribution and Biological Availability in the Fallout from Mount St. Helens, 18 to 21 May 1980

Abstract. *Concentrations of fluoride in the ash fallout in central Washington from the 18 May 1980 eruption of Mount St. Helens varied severalfold, but none are high enough to constitute any immediate hazard to animal life. The heaviest fallout (Moses Lake) contained 113 parts per million (ppm) of acid-labile fluoride, but of this only 11 ppm was water-soluble and 20 ppm was available to rats. The fluoride concentrations in the urine of cattle feeding for 4 days on hay contaminated with this ash were essentially normal. Samples of ash from other areas generally had higher concentrations of acid-labile fluoride but lower concentrations of water-soluble fluoride. The concentration of water-soluble fluoride was inversely correlated with the coarseness of the fallout.*

The distribution and biological availability of fluoride in the ash from Mount St. Helens are of interest since some volcanic ash has caused heavy loss of livestock as a result of fluorosis (*1*). Stoiber *et al.* reported that the ash that fell on 4 and 12 April 1980 contained 8 parts per million (ppm) of fluoride (*2*). This concentration, which corresponds to the water-soluble fraction (*3*), is not alarming, but it is not known whether water-soluble fluoride is the only form that is biologically important or whether the concentrations vary. In an effort to shed some light on these questions, I carried out preliminary experiments on ash samples collected from central Washington after the large eruption of Mount St.

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