

LIGHTNING AT PLANETS IN THE OUTER SOLAR SYSTEM

M. D. Desch*

Abstract

The Voyager spacecraft discovered lightning or lightning-like phenomena at each of the planets Jupiter, Saturn, Uranus, and Neptune, but at no planet did all of the relevant instruments onboard provide corroborating evidence. Is this a problem? Or are the observations really self consistent if the particular conditions at each planet are properly accounted for. We will examine the observations in this context. In addition we will review the upper-limit observations of lightning at Titan, re-evaluate the energetics of lightning at Jupiter and Saturn, and present initial estimates of the lightning flash energetics at Uranus and Neptune. Comparison with the terrestrial case shows that the properties of lightning at the outer planets have more in common with each other than they do with terrestrial lightning.

1 Introduction

In 1979, the Voyager program provided the first unambiguous detection of extraterrestrial electrification when the Voyager 1 cameras captured brilliant images of lightning flashes on the nightside of Jupiter. Ironically, while this discovery heralded future detections of lightning at all the outer planets, the imaging system made no further detections of lightning beyond Jupiter. At Saturn, Titan, Uranus and Neptune, either the planetary radio astronomy or plasma wave investigations provided the crucial observation establishing, or setting upper limits for, the existence of lightning. In fact, as Table 1 shows, at no planet did all three experiments detect lightning and only at Jupiter did two experiments detect lightning. While this amply demonstrates the importance of exploiting multiple windows of the electromagnetic spectrum, it also raises important questions concerning the interpretation of some, if not all, of the observations.

We will review the observations, focussing attention on those areas that present special problems with regard to interpretation. A complete survey of lightning energetics at each planet will be presented, including new calculations of flash rates, flash energies, and global dissipation rates. These will be compared with the rather better-known terrestrial lightning values. As we shall see, however, terrestrial lightning seems to provide a poor model in general for atmospheric electrification in the solar system.

*NASA/Goddard Space Flight Center, Greenbelt, MD, USA

Table 1: Summary of Lightning Measurements

Body	Optical	Radio	Plasma Wave
	<i>ISS</i>	<i>PRA</i>	<i>PWS</i>
Jupiter	Yes	No ¹	Yes
Saturn	No ²	Yes	No ³
Titan	No	Upper Limit	No
Uranus	No ⁴	Yes	No ⁵
Neptune	No ⁶	No ^{7†}	Yes

Explanations for lack of detection: (See text)

¹Combination of ionosphere and receiver attenuation

²Light scattering due to bright rings

³Appropriate magnetic field lines not sampled

⁴Thick atmospheric haze

⁵Spacecraft–planet distance too great

⁶Atmospheric attenuation

⁷Ionospheric attenuation

[†]A few very tentative events

2 Jupiter

2.1 ISS and PWS observations

If for no other reason, the detection of lightning at Jupiter by two independent experiments makes it the most unequivocal case among all the planets. Evidence of localized flashes from the imaging (ISS) experiment (Fig. 1) on both Voyagers 1 and 2 [Smith et al., 1979; Cook et al., 1979] and Voyager 1 PWS observations of whistlers [Gurnett et al., 1979] support the conclusion that intense lightning discharges exist in Jupiter’s atmosphere. There is additional agreement, within rather broad observational constraints, regarding the localization of the flashes in latitude. Specifically, an analysis by Magalhaes and Borucki [1991] of all suitable Voyager images showed that the flashes were confined to northern latitudes near 13°, 49° and 55°–60°. The Voyager 1 trajectory was such that a remote detection of lightning via whistlers only permitted observations on magnetic L shells north of about 55°–60°, but it was on L shells that map to this approximate latitude range that the majority of the whistlers were seen [Menietti and Gurnett, 1980]. An independent analysis of the whistlers by Tokar et al. [1982] led to a somewhat different conclusion, namely that the whistler source locations mapped down to the foot of the Io flux tube; however, they assumed perfect ducting of the whistlers which is questionable since no multiple hop whistlers were observed [Kurth et al., 1985]. In contrast, the analysis by Magalhaes and Borucki showed that the visible flashes were aligned in bands of constant jovigraphic latitude, as would be expected of a phenomenon arising out of an essentially atmospheric, as opposed to magnetospheric, process. The majority of flashes, both in terms of number and brightness, were seen at 49° latitude which Magalhaes



Figure 1: Voyager 1 ISS image of Jupiter's nightside showing evidence of lightning flashes (bright patches below center) and aurorae (curved arcs at top).

and Borucki associate with moist convective regions deep in Jupiter's atmosphere. The apparent restriction of lightning to specific latitude bands explains why there was no detection of whistlers by Voyager 2 whose greater perigee distance prevented the sampling of whistlers at the appropriate latitudes.

2.2 Lack of Jovian sferics

Inappropriate viewing geometry does not, however, explain the lack of detection of lightning at Jupiter by the planetary radio astronomy (PRA) experiment. In the radio astronomy frequency bands, lightning is detected as a sferic, a freely propagating wave that originates at the discharge site and as a consequence of it. There is no need for the spacecraft to be on the closed magnetic field line that is conducting the whistler, so that lightning can be detected remotely, sometimes at great distances. Yet despite this advantage, and the fact that lightning characteristics were taken into account in the design of the PRA receiver and was an anticipated result [Warwick et al., 1977], no Jovian sferics were detected by either Voyager 1 or 2.

Two effects contrived to prevent the detection of lightning by PRA at Jupiter. Because extremely high signal levels were expected from Jovian magnetospheric noise, 15 dB attenuators were inserted to reduce noise levels near closest approach. This effect alone would have made detection of even intense Saturn-like discharges (SED) difficult at Jupiter. Second, spheric attenuation in Jupiter's lowest ionospheric layers was shown by Zarka [1985] to be many tens of dB, even at high radio frequencies. While this result depends critically on the unconfirmed existence of a single, low altitude ionospheric ledge (L_7) observed by Pioneer 10 [Fjeldbo et al., 1975], it seems likely that the combination of reduced receiver sensitivity and at least some attenuation adequately explains the non detection of lightning by PRA.

2.3 Lightning flash rates at Jupiter

At Earth, lightning occurs on average at a global rate of about 100 flashes/sec, equivalent to a flash rate R of about 5 flashes $\text{km}^{-2}\text{yr}^{-1}$. Comparisons with Jupiter remains elusive, however, because estimates of the Jovian flash rate derived from the ISS and PWS observations (see Table 2) vary over 56 dB, from 10^{-4} to $40 \text{ km}^{-2}\text{yr}^{-1}$.

Estimates of R at Jupiter tend to fall into two categories, those computed in a straightforward manner from the observed flash rate, and those derived from some estimate of the fraction of unobserved flashes. The appropriate figure in the former case, using the most recent data: 41 flashes observed over an area of $\sim 10^9 \text{ km}^2$ and total exposure time of 319 sec, yields $R \sim 0.004 \text{ km}^{-2}\text{yr}^{-1}$. The derived figures yield far higher total flash rates, and refer to the flash rate for conventional lightning. Values derived in this way range from 3–30 flashes $\text{km}^{-2}\text{yr}^{-1}$. The most accurate estimate for the conventional lightning flash rate comes from a recalculation of the number derived by Borucki et al. [1982], modified by a re-evaluation [Borucki and McKay, 1987] of the optical efficiency of Jupiter's atmosphere. This yields a flash rate of $28 \text{ km}^{-2}\text{yr}^{-1}$.

The greatest disparity in R is in the interpretation of the whistler data owing to large

Table 2: Jupiter Lightning Flash Rates

VOYAGER EXPERIMENT	FLASH RATE R ($\text{km}^{-2}\text{yr}^{-1}$)	COMMENT
ISS	0.003	(a) Direct calculation
	0.1	(b)
	3–30	(c) Assumes $10^{-3} - 10^{-4}$ of flashes observed
	4	(d) Assumes 10^{-3} of flashes observed
	28	(e) Re-estimate of (d) from Lab experiment
PWS	0.0001–0.04	(a) Direct calculation = $0.002 \text{ km}^{-2}\text{yr}^{-1}$
	40	(f) Upper bound assuming ducting

^aLewis, 1980

^dBorucki et al., 1982

^bWilliams, 1986

^eBorucki and McKay, 1987

^cWilliams, 1983

^fScarf et al., 1981

uncertainties in (1) the area from which the whistlers originate, and (2) the fraction of lightning flashes that produce detectable whistlers. Starting with the observed rate [Gurnett et al., 1979] of $0.12 \text{ whistlers sec}^{-1}$, Lewis [1980] calculated that $R = 0.004 \text{ km}^{-2}\text{yr}^{-1}$ by allowing for (non-ducted) whistler ray paths within a 10° half angle of $\vec{B}$ but allowing for only a single hemisphere on the planet's surface from which the whistlers are 'visible'. This yields a total surface area, extending from 54° – 79° latitude, of $\sim 9 \times 10^8 \text{ km}^2$. We might call this the large source area model. The assumption restricting whistler visibility to a single hemisphere is probably incorrect since Tokar et al. [1982] showed that whistlers from both northern and southern hemispheres are detectable, effectively doubling the source area; therefore, the most direct calculation of R from the whistler data yields $R = 0.002 \text{ km}^{-2}\text{yr}^{-1}$ as noted in Table 2. This value assumes that all of the flashes yield detectable whistlers. Allowing further for the possibility of a selection effect in which active regions were preferentially sampled, or conversely that only a fraction (10%) of the lightning strokes produce detectable whistlers, Lewis derived the range $0.0001 \leq R \leq 0.04$.

Beginning with the same observed occurrence rate (0.12 sec^{-1}) as Lewis, Scarf et al. [1981] assumed that the whistlers were ducted along field lines from a source footprint extending over no more than 10^6 km^2 – the small source area model. In addition, comparison with terrestrial whistler field intensities led Scarf et al. to conclude that only about 10% of the whistlers were being detected. These estimates led Scarf et al. to an upper bound for the lightning flashes of $40 \text{ km}^{-2}\text{yr}^{-1}$, considerably higher than even the upper limit set by Lewis [1980], but consistent with the $28 \text{ km}^{-2}\text{yr}^{-1}$ upper bound computed here from an extrapolation of the results of Borucki and McKay [1987] using imaging data. The main driver for this large estimate is the assumption that the whistlers are ducted, which leads to an extremely small area from which the whistlers can originate. The small-area hypothesis may yield an unreasonably large number, however, since the ducting hypothesis has been called into question by Menietti and Gurnett [1980] based on the fact that no multiple-hop whistlers were ever observed. Despite this, we include in Table 3 the range 28–40 flashes $\text{km}^{-2}\text{yr}^{-1}$ as the most likely range of conventional lightning flash rates for Jupiter.

3 Saturn

3.1 PRA observations of SED

Beginning several days before the Voyager 1 encounter with Saturn, the planetary radio astronomy experiment began detecting highly unusual, impulsive signals at frequencies above about 5 MHz and extending up to the receiver's 40-MHz cutoff [Warwick et al., 1981]. The signals appeared in quasi-random fashion in frequency and time, lending a peppered appearance to the radio spectrograms (Fig. 2) that had never previously been encountered. The gross envelopes of the signals, defining major hours-long episodes, repeated with a period of 10.17 hr [Evans et al., 1981], significantly less than the planet's intrinsic 10.65 hr rotation period [Desch and Kaiser, 1981]. Between episodes, virtually no signals were detectable.

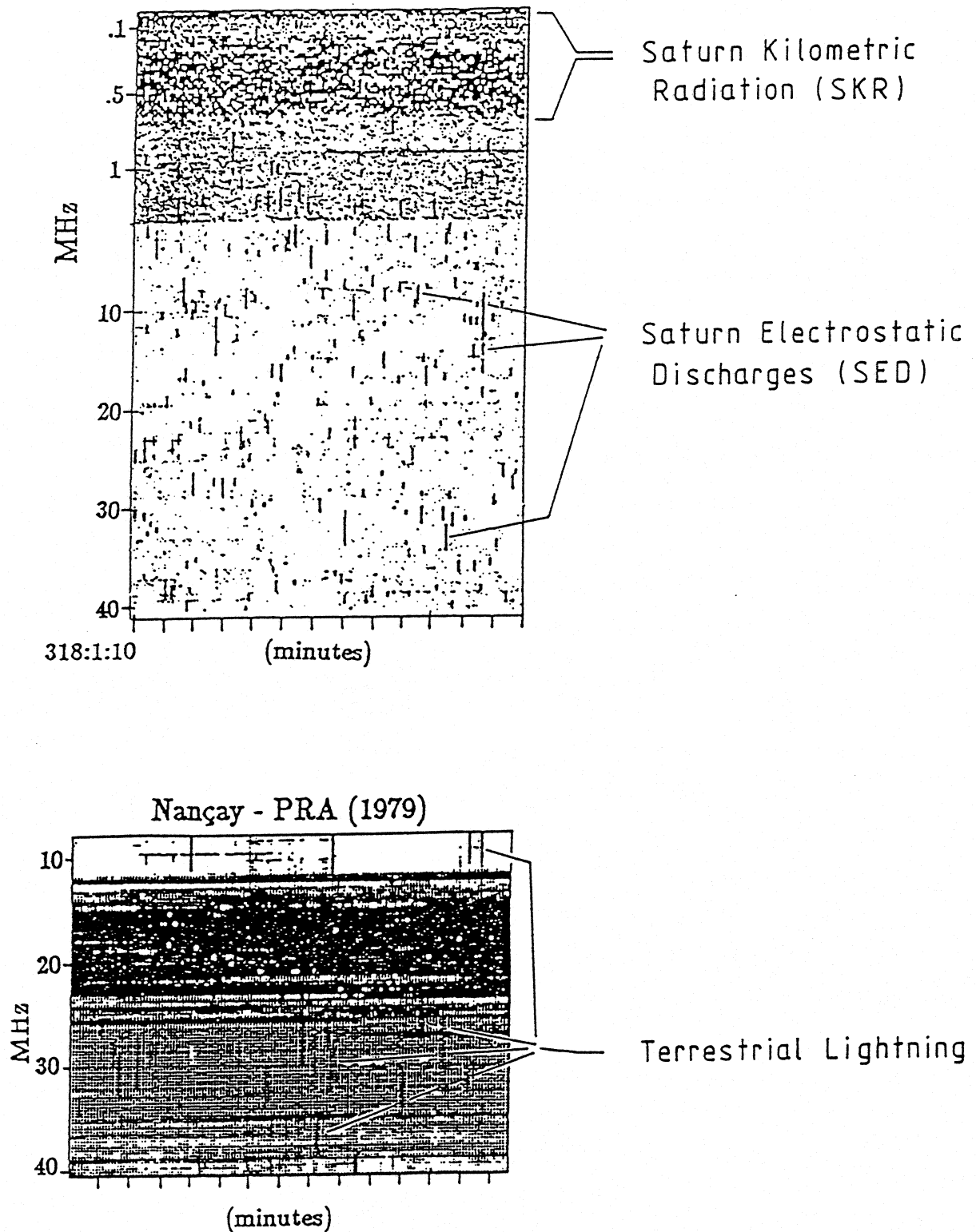


Figure 2: (Top) Radio spectrogram from the planetary radio astronomy (PRA) experiment on Voyager 1 shows evidence of Saturnian lightning in the form of Saturn electrostatic discharges (SED). (Bottom) Spectrogram made at Nançay, France during a local terrestrial thunderstorm with the PRA backup receiver shows terrestrial sferics [from Desch et al., 1991].

Warwick et al. [1981] labelled the bursts *Saturn Electrostatic Discharges*, or SED. The origin of the SED was a mystery, although it was realized early on that they resembled the radio signatures of lightning [Evans et al., 1981]. However, since they were often detected outbound at frequencies as low as a few hundred kHz, an atmospheric origin could be ruled out: Such signals could not propagate through Saturn's ionosphere. Further, since the SED also extended up to 40 MHz (and certainly beyond), well above any characteristic frequency in the planet's magnetosphere, a magnetoionic source originating in a wave-particle interaction could also be excluded. The one remaining region in the Saturn system where the SED period could be matched was in the planet's B ring at a radial distance of about $1.81R_S$. Evans et al. [1982] and Warwick et al. [1982] hypothesized a source at this radial distance; however, without invoking exotic phenomena, a mechanism for generating SED in the planet's rings remained elusive.

In the face of this problem, Burns et al. [1983], pointed out that if the discharges were lightning-like and originated in the region of the ring shadow on Saturn, the ionospheric electron density might be low enough to permit the escape of very low frequency sferics. Such signals would also be expected to extend to very high frequencies. Subsequently, Kaiser et al. [1983] verified that virtually all of the key observables of the SED, including the overall organization of the major episodes in time and the systematic variation of the low-frequency cutoffs, were consistent with discharges from a stable, long-lived atmospheric storm on Saturn, rotating with the planet's cloud system at equatorial latitudes. Exploiting this fact, Kaiser et al. [1984] used the SED as a remote probe of the planet's ionosphere. By examining how the low frequency cutoff varied with time they determined the global ionosphere density in the equatorial plane. In agreement with the atmospheric discharge hypothesis, there was close agreement with an independent estimate of the electron concentrations from the radio science experiment [Tyler et al., 1982] at the two local times where the observations overlapped.

3.2 Lack of visual or whistler evidence

If the SED are really due to extraordinarily intense discharges in the planet's atmosphere, it is a fair question to ask why no whistlers or optical flashes were observed. An examination of the circumstances of the trajectory, ring brightness, and the physical state of Saturn's atmosphere shows why this was the case.

Saturn's atmosphere is colder than Jupiter's so that a given temperature level in Saturn's atmosphere is reached at a higher pressure, that is, greater depth than on Jupiter. Additionally, because of the reduced gravity, atmospheric features at the same pressure level will have five times the mass density in Saturn's atmosphere as compared with Jupiter. Thus an obscuring layer of haze on Saturn will have about 5 times the mass of a similar layer in Jupiter's atmosphere [Smith et al., 1981], leading to substantially higher optical depth and attenuation of outward propagating light. In addition to the problem of detecting flashes through the relatively high opacity of Saturn's atmosphere, the overwhelming degree of scattered light from the planet's bright rings compounded the detection problem. An excellent example of how this can prevent detection of atmospheric flashes can be seen in Figure 2 of Magalhaes and Borucki [1991] which shows how, even at Jupiter,

the scattered light from that planet's relatively insignificant rings was brighter than the nightside flashes. Only the fact that the discharges were far from the scattered-light portion of the image allowed detection of the Jovian images.

The detection of whistlers associated with lightning requires that the spacecraft intercept magnetic field lines that are connected to the point at the atmosphere-ionosphere boundary where the original low frequency sferic couples to the whistler-mode wave. According to Kaiser et al. [1983], in order to explain not only the SED repetition period but also the fact that the period is probably stable to within about 5 min, the source must be tightly confined to near-equatorial latitudes. Within the uncertainty in the SED period, the SED source matches Saturn's zonal wind speeds [Smith et al., 1982] over a range of ± 80 m/sec, equivalent to latitudes of about 2° – 6° N. On Earth, the original low frequency sferic can propagate in a ground-ionosphere wave guide up to 1000 km from the discharge site. At the outer planets it is difficult to see how such a wave guide could exist; however, even allowing for propagation up to 10 000 km from a discharge site as in the Jovian case [Rinnert et al., 1979], the maximum latitude reached by such a wave propagating due north in Saturn's atmosphere would be $\sim 18^\circ$ N, corresponding to a magnetic L shell of ~ 1.11 . Near closest approach, Voyager 2 reached a minimum L of only ~ 2.8 , not nearly close enough to detect the whistlers associated with SED.

3.3 Saturn lightning: Comparisons with Earth and Jupiter

Based on a source area of 2.6×10^8 km² and an observed frequency of 0.17 SED sec⁻¹, a direct estimate of the global lightning flash rate from the SED data leads to a value of 0.02 km⁻²yr⁻¹ (Table 3). The source area is derived from the inferred $60^\circ \times 4^\circ$ extent of the atmospheric 'storm' in longitude and latitude. Of course, this value refers to the flash rate for supposed Saturnian superbolts, and is somewhat higher than the equivalent superbolt values for Earth and Jupiter. The median flash duration was 60 msec, with each flash apparently made up of many ~ 1 -msec duration strokes [Evans et al., 1983]. Assuming that the power is isotropically radiated, the typical value for the observed energy per flash at radio wavelengths is about 10^8 J for 60 msec pulses [Zarka, 1985]. An estimate of the energy radiated over the entire spectrum requires some estimate of the efficiency with which power is radiated at RF. The efficiency below 100 kHz, where most of the terrestrial radio emission appears, is between 10^{-5} and 10^{-6} [Taylor, 1963]. However, considering the extreme flatness and bandwidth of the SED, the efficiency for Saturn has been variously estimated at between 10^{-3} and 3×10^{-5} [Williams, 1983; Zarka, 1985]. Using a conservative figure of between 10^{-4} and 10^{-5} , we obtain a total energy per flash of 10^{12} – 10^{13} J.

Recognizing that the distribution of SED flashes is log-normal, we can put broad limits on the global flash rate at Saturn for lightning of all energies, F_c , by assuming an Earth-like distribution. Following Borucki et al. [1982], we note that the ratio of F_s/F_c , where F_s is the superbolt flash rate, is

$$\frac{F_s}{F_c} = \frac{1}{\sqrt{2\pi}} \int_{t_0}^{\infty} \exp\left(-\frac{1}{2t^2}\right) dt \quad (3.1)$$

where

$$t \sim \log \frac{E}{\bar{E}}, \quad (3.2)$$

t_0 is the value of t calculated for the lowest energy per flash, E is the total energy per flash, and $\bar{E}$ is the median value of the energy. Evaluation of F_s/F_c for the range of $\bar{E}$ in Table 3 yields $20 < F_c < 385$. The lower limit encompasses the Jovian flash rate for lightning of all energies; the upper limit, however, is far greater than that seen elsewhere in the solar system.

The higher values for Jupiter in Table 3 compared with earlier studies reflects the recent work of Borucki and McKay [1987] which showed that the optical conversion efficiency for lightning in a Jovian atmosphere is a factor of 3.8 lower than previously thought. This forces the flash rate for conventional lightning up by a factor of about 7 and the total energy/flash up by a factor of 3.8. Most of the terrestrial lightning figures are nominal values from Borucki et al. [1982] with the ratio of dissipation rate to convective energy flux reflecting the range of values quoted by Williams [1983] and Borucki et al. [1982].

In questions about the atmospheric storm explanation, much has been made of the supposed unrealistically large power radiated by SED. In Table 3 we compare the flash rates and various forms of the lightning power levels, measured and inferred, at Earth, Jupiter and Saturn. Where possible, we compare superbolt (s) values with same, and conventional (c) lightning values with same. In comparing the planetary values in each category, it is clear that there is a systematic trend of increasing magnitudes from Earth to Saturn. But in no case does Saturn stand out as statistically anomalous. In fact the global lightning dissipation rate, derived from the product of the total energy/flash and flash rate, is greatest for Jupiter. In terms of the ratio of the dissipation rate to the convective energy flux, it appears that, in fact, the Earth is in a category by itself, with Jupiter and Saturn together possessing rather high efficiencies for the conversion of convective heat into lightning. It may well be that, to first order, the dissipation rates, D , scale with the atmospheric pressures, P , where the lightning occurs.

4 Titan

Saturn's largest moon Titan has an extensive hydrocarbon atmosphere composed primarily of nitrogen, methane, and hydrogen. Based on its atmospheric constituents and the deposition of significant amounts of solar energy at its surface, Borucki et al. [1984] estimated that Titan could support lightning discharges with an energy dissipation rate somewhat less than that at Earth. The Voyager 1 encounter with Saturn in November of 1980 offered a unique opportunity to search for lightning discharges in Titan's atmosphere owing to the extremely close flyby of the satellite (Fig. 3). The trajectory took Voyager 1 within $1.72 R_T$ ($R_T=2575$ km) of Titan's surface, and during the ± 50 min interval around closest approach $\sim 98\%$ of the satellite was 'visible'. While visual investigation of the satellite for evidence of lightning was precluded by the highly opaque nature of its atmosphere, radio wave attenuation in the UV- and cosmic-ray induced Titan ionospheres was shown to be negligible [Desch and Kaiser, 1990], permitting exploitation of a radio window deep into the atmosphere.

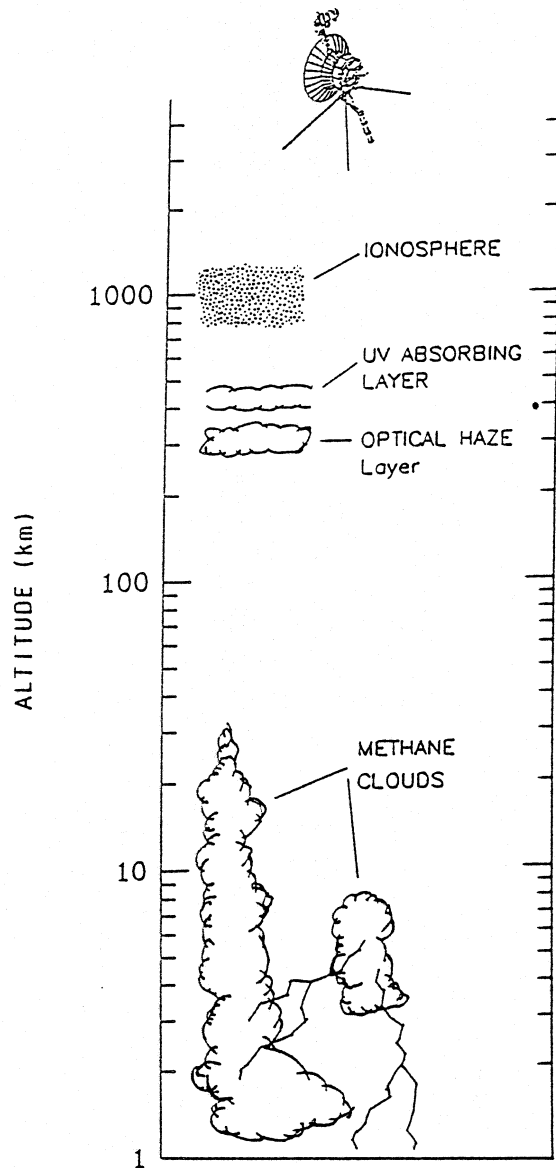


Figure 3: Figure drawn to scale shows close approach of Voyager to Titan with cloud layers, ionosphere, and hypothetical lightning flashes.

Figure 4 shows a PRA radio spectrogram centered on the time of Titan closest approach. As discussed by Desch and Kaiser [1990], only waves of magnetospheric origin – the Saturn kilometric radiation (SKR) – is detectable. No lightning sferics attributable to Titan were observed during the 100-minute interval centered on the Titan encounter. Because the flyby was so close, a significant upper limit for the total energy per flash, 10^6 J, was set by these observations. Given a lightning flash rate comparable to or greater than that at Earth, this figure is about 10^3 times weaker than that typical for terrestrial lightning flashes.

The presence or absence of lightning on Titan has important consequences for the generation of trace hydrocarbons in Titan's atmosphere. For example while the observed abundances of hydrogen cyanide, acetylene, ethane and propane are in agreement with the calculated abundance derived from photochemistry [Yung et al., 1984], the model prediction for ethylene falls short of the observations by an order of magnitude, and cannot be accounted for except by a significant level of lightning activity [Borucki et al., 1988].

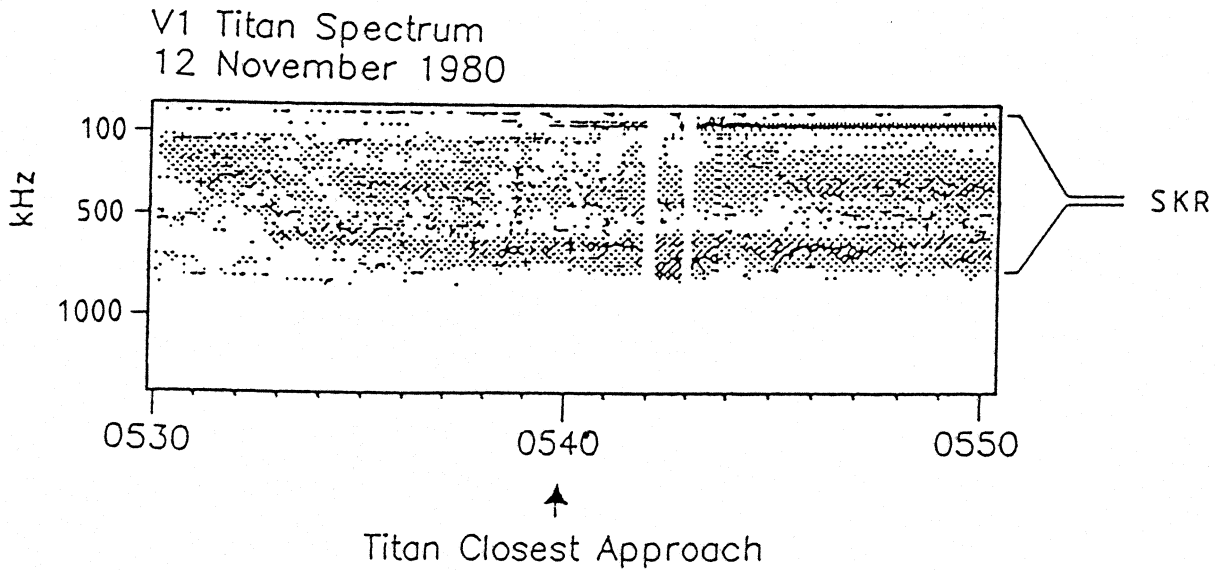


Figure 4: PRA radio spectrogram showing lack of evidence for Titan lightning [from Desch and Kaiser, 1990].

The absence of lightning suggests that certain aspects of the chemical kinetics of organic synthesis in Titan's atmosphere should be re-evaluated.

5 Uranus

5.1 PRA observations of lightning

As at Saturn, Uranian lightning in the form of sferics (UED) were detected only at radio wavelengths [Zarka and Pedersen, 1986]. The UED (Fig. 5) were observed within $\pm 20 R_U$ of the planet, but owing to detection threshold effects, the bulk of the emission, especially at higher frequencies, was only observed during a 90-min interval soon after closest approach. In the PRA radio spectrograms the UED appeared very much like the SED and like terrestrial lightning detected on the ground with the PRA engineering backup instrument (Fig. 2). However, the flash rate of UED is very much less than that of the SED. While tens of thousands of SED were detected, only about 140 UED were seen, all within about 24 hr of closest approach. The power spectrum falls off very approximately as $1/f^2$; although weighted by the events observed near 1 MHz, the spectrum is better fit by a $1/f$ falloff. Mean flash durations were ~ 120 msec, compared with ~ 60 msec for the SED. Also unlike the SED, no periodicity was apparent in the repetition of UED episodes so that the source of the UED could not be confined to any particular range of latitudes in the atmosphere.

By analogy with SED, UED clearly represent the superbolt component of Uranian lightning. We may estimate the superbolt flash rate by taking the 30-min interval near Voyager closest approach, when detection threshold effects were minimized. During this time, 41 bursts were identified by Zarka and Pedersen, 1986. From this we estimate a global flash

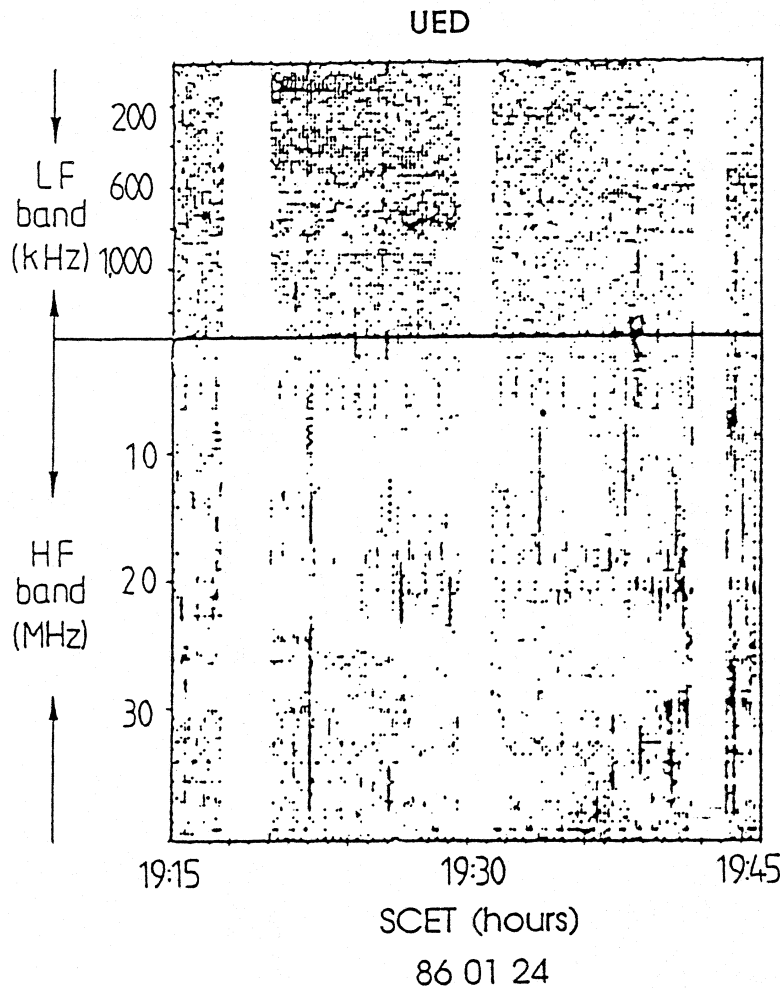


Figure 5: PRA Voyager 2 radio spectrogram of sferics showing evidence for Uranus lightning (UED) [adapted from Zarka and Pedersen, 1986].

rate of $9 \times 10^{-5} \text{ km}^{-2} \text{ yr}^{-1}$ (Table 3). This flash rate is lower than that at Earth or among any of the outer planets, but as we shall see, it is surprisingly close to the rate at Neptune inferred in this paper from the whistler data.

5.2 UED energetics

Table 3 summarizes the Uranus lightning energetics. Zarka and Pedersen [1986] quote a total power per flash in the RF of 10^8 W ; however, this value is strongly dependent on assumptions regarding the unseen, primarily lower-frequency, portion of the spectrum. While integration of the observed spectrum alone (Fig. 4 of Zarka and Pedersen [1986]) yields a flash power of $\sim 10^8 \text{ W}$, if one assumes that the spectrum is terrestrial-like and peaks near 10 kHz, the integrated power is between about $2 \times 10^8 \text{ W}$ for a $1/f$ spectrum and 10^{10} W for a $1/f^2$ spectrum. For 100-msec duration flashes, this yields a range of 10^7 – 10^9 J for the energy per flash in the RF. With a nominal efficiency of 10^{-5} for the conversion of energy into radio waves, the total energy per flash is 10^{12} – 10^{14} J , which is in the range of values found at the other planets. Because the observed flash rate is rather low, the global dissipation rate, D , is correspondingly small also: 3×10^{-6} – $3 \times 10^{-4} \text{ W/m}^2$,

tending toward the lower end of the dissipation rates of the other planets. Relative to the internal heat flux, we quote a lower limit owing to the fact that only an upper limit to the Uranus heat flux ($\sim 0.09 \text{ W/m}^2$) has been determined from the Voyager observations [Pearl et al., 1990]. This lower limit, 3×10^{-3} , for the ratio of the dissipation rate to internal heat flux, is, however, consistent with the upper limit values reported here for both Jupiter and Saturn.

5.3 Lack of detection of lightning flashes and whistlers

The reason for the failure to detect visual evidence of lightning flashes at Uranus is clear from the nature of the planet's atmosphere. The existence of a thick photochemical haze in the planet's lower stratosphere, at altitudes above a few hundred km above the 1 bar level [Pollack et al., 1987], not only prevented detection of flashes but also resulted in rather low contrast images altogether with only a few observations of atmospheric cloud features even under highly stretched conditions. Lightning, which would have originated at altitudes $\sim 200\text{--}400$ km below the 1 bar level in the ammonia–water cloud [Weidenschilling and Lewis, 1973], would be completely obscured.

An explanation for the failure to detect whistlers at Uranus is somewhat more problematic. Kurth et al. [1985] noted that the whistler occurrence rate at Jupiter was highly dependent upon the integrated electric field strength background level in the range 56 Hz to 10 kHz. Even though the Jovian whistlers were fairly strong, no whistlers were detectable when the background level was above a certain value. Scarf et al. [1987] noted that the most intense whistler mode signals were detected at Uranus. Such signals would act as a noisy background against which the detection of lightning whistlers might be difficult, particularly at the relatively remote approach distance of the Uranus encounter.

6 Neptune

6.1 PWS measurements of whistlers

Neptune is the only planet visited by Voyager where lightning manifested itself solely in the form of whistlers (e.g. Fig. 6). During the Neptune flyby, Gurnett et al. [1990] detected 16 whistler-like events whose dispersion characteristics fit the Eckersley law for lightning-generated whistlers. While the frequency–time shapes conformed with that expected from lightning, the magnitudes of the dispersions were typically $26\,000 s \sqrt{Hz}$, which is extremely large compared with the more familiar range of dispersions ($50\text{--}500 s \sqrt{Hz}$) seen at Jupiter [Kurth et al., 1985]. According to Menietti et al. [1991], the extraordinary dispersion measures are attributable to a large cold plasma population which drives the whistlers to propagate near the resonance cone angle over much of its ray path. In the absence of propagation near the resonance cone angle, the most reasonable path length is one in which most of the propagation occurs in a region of the ionosphere where the field strength is small, 10^4 nT, and the mean density is $6 \times 10^5 \text{ cm}^{-3}$ [Gurnett et al., 1990]. Then the minimum ray path required to account for the observed dispersions

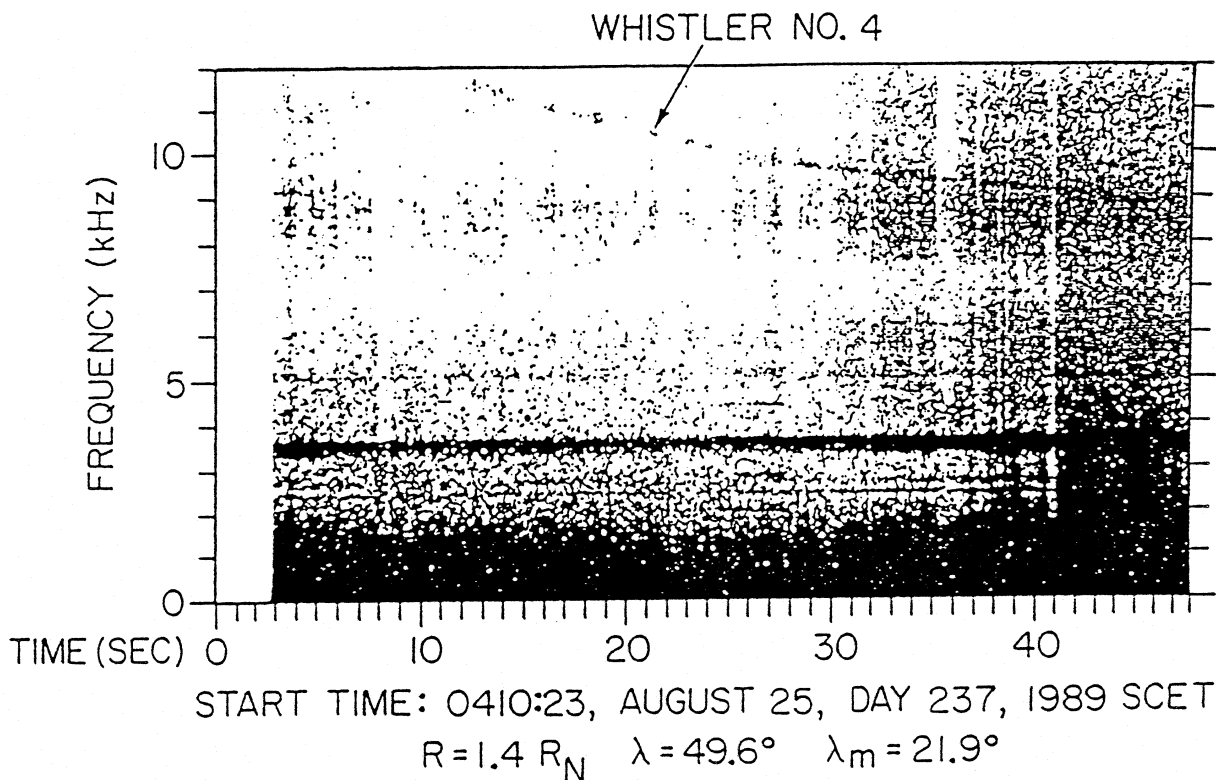


Figure 6: Evidence for lightning on Neptune in the form of whistlers from the plasma wave (PWS) experiment on Voyager 2 [from Gurnett et al., 1990].

is unrealistically large, involving multiple bounces from one hemisphere to the other of length $\sim 48 R_N$.

An estimate of the lightning flash rate can be made by noting that Gurnett et al. [1990] detected 16 whistlers within a total observing span of 10 min (17 partially complete PWS high-rate frames). Since the observed events were possibly multiple-hop whistlers, effectively the entire surface area of the planet was sampled. The resultant global flash rate (see Table 3) is 1.1×10^{-4} flashes $\text{km}^{-2} \text{yr}^{-1}$, a factor of only 1.8 lower than that predicted by Borucki [1989] based on the level of lightning activity at Jupiter and on the assumption that lightning dissipates energy at a constant fraction of the dissipation rate of the convective energy flux. Just as at the other major planets, the observed flash rate no doubt refers only to the most energetic component of the lightning flashes and therefore represents the analog of the terrestrial superbolts.

6.2 Sferics, lightning flashes, and lightning energetics at Neptune

No observations were made of lightning by any other instruments on Voyager 2. The four sferics tentatively identified by Kaiser et al. [1991] using the planetary radio astronomy experiment were so marginal that the authors could only rule out the possibility of lightning as strong as that at Saturn or Uranus. By an extension of the Kaiser et al. upper limit observations and arguing by analogy with terrestrial lightning, an upper limit for the energy per flash in the RF can be set at about 10^7 J, corresponding to a total

flash energy of 10^{12} J for a typical RF conversion efficiency of 10^{-5} . Taking the observed flash rate into account, this is equivalent to a global dissipation rate (upper limit) of only 3×10^{-6} W/m², consistent with the lower limit estimate of D at Uranus. This, and the upper limit energy-per-flash estimates, are consistent with the observation by Gurnett et al. [1990] who noted that the Neptune whistlers were extremely weak, implying that the lightning sources may be of very low intensity. The internal heat flux driving convective motions in Neptune's deep atmosphere is ~ 0.433 W/m² [Pearl et al., 1991] which leads to a dissipation rate to convective heat flux ratio of 7×10^{-6} , consistent with lower limit estimates of 10^{-5} for the terrestrial lightning dissipation ratio (see Table 3).

Despite attempts to sight lightning flashes in Neptune's atmosphere, no lightning was observed. Since there were multiple opportunities to image portions of the nightside at fairly close range [Borucki, 1989], one must look to possible signal attenuation at some overlying optically thick layer for the explanation. The planet's atmosphere is dominated by a vivid sky-blue aspect which is due to a relatively transparent layer of methane near the 1 bar level. If the lightning originates in a water cloud, it must be at much deeper layers, probably 300–400 km below the 1 bar level at pressures in the range 50–100 bar [Weidenschilling and Lewis, 1973]. In this case, it is probably the hydrogen sulfide or ammonia cloud deck at the 3-bar level, about 30 km below 1 bar [Smith et al., 1989], that accounts for a high proportion of the light absorption. This layer of clouds is thick enough and global enough in extent to delineate the shadows cast upon it from the higher elevation methane ice clouds. Deeper cloud layers may exist (e.g., Weidenschilling and Lewis, 1973) that also contribute to the absorption of lightning flashes but none could be directly observed by Voyager owing to the opacity of the H₂S/NH₃ cloud deck.

7 Summary

With the benefit of hindsight, we have shown that the detection or lack of detection of lightning at each of the outer planets is consistent with the conditions of each of the relevant observations. At Jupiter, the failure to detect sferics is explained by the combined effects of receiver attenuation and radio frequency attenuation of the sferics in the upper atmosphere and ionosphere. At Saturn, the failure to detect lightning whistlers and flashes was due to the inaccessibility to Voyager of the requisite whistler-ducting field lines and the strong light scattering by rings compounded by atmospheric attenuation. Similarly at Uranus, the atmosphere's thick obscuring haze concealed any visual evidence of lightning, while the high noise background and distant close approach probably contributed to the absence of whistlers. At Neptune, ionospheric attenuation of sferics prevented detection of all but a few highly tentative events, but the close encounter distance permitted the establishment of closely constrained upper limits on the lightning energetics. While Neptune's high altitude haze layer has an insignificant optical depth, the underlying H₂S/NH₃ cloud deck is optically thick and probably accounts for the masking of light flashes from the lower elevation H₂O clouds.

New estimates of the energetics of lightning at the outer planets change somewhat our view of lightning as an analog of the terrestrial phenomenon. A re-examination of the Jovian and Saturnian cases shows that, in terms of the conventional lightning flash rates,

total energy per flash, global dissipation rates and ratio of dissipation rates to internal heat flux, Jupiter and Saturn are far more similar to each other than either is to Earth. In each case, there is a one to two order of magnitude difference between Jupiter and Saturn on the one hand and Earth on the other. In short, Jupiter and Saturn stand out as energetically prominent relative to the Earth, not unlike the magnetospheric components of their radio emissions. The Uranus and Neptune total flash energies are also more in league with Jupiter and Saturn, within rather broad measurement uncertainties.

The majority of terrestrial lightning statistics are based on the common cloud-to-ground discharge. It is widely recognized, however, that cloud-to-cloud and cloud-to-stratosphere lightning [e.g., Williams et al., 1983; Farrell and Desch, 1992] manifest very different characteristics and may involve different physical processes. Outer planets lightning not only must be of a cloud-to-cloud nature, but must also occur at atmospheric pressures that are far in excess of anything experienced in the Earth's atmosphere. It is not surprising then that lightning at the outer planets appears different from terrestrial lightning. These differences should spur further research into the nature of discharge processes taking place under highly unusual atmospheric conditions.

References

- Borucki, W. J., Predictions of lightning activity at Neptune, *Geophys. Res. Lett.*, **16**, 937, 1989.
- Borucki, W. J., A. Bar-Nun, F. L. Scarf, A. F. Cook, II, and G. E. Hunt, Lightning activity on Jupiter, *Icarus*, **52**, 492, 1982.
- Borucki, W. J., C. P. McKay, and R. C. Whitters, Possible production by lightning of aerosols and trace gases in Titan's atmosphere, *Icarus*, **60**, 260–273, 1984.
- Borucki, W. J., and C. P. McKay, Optical efficiencies of lightning in planetary atmospheres, *Nature*, **328**, 509, 1987.
- Borucki, W. J., L. P. Giver, C. P. McKay, T. Scattergood, and J. E. Parris, Lightning production of hydrocarbons and HCN on Titan: Laboratory measurements, *Icarus*, **76**, 125, 1988.
- Burns, J. A., M. R. Showalter, J. N. Cuzzi, and R. H. Durisen, Saturn's electrostatic discharges: Could lightning be the cause?, *Icarus*, **54**, 280, 1983.
- Cook, A. F., T. C. Duxbury, and G. E. Hunt, First results on Jovian lightning, *Nature*, **280**, 794, 1979.
- Desch, M. D. and M. L. Kaiser, Voyager measurement of the rotation period of Saturn's magnetic field, *Geophys. Res. Lett.*, **8**, 253, 1981.
- Desch, M. D., and M. L. Kaiser, Upper limit set for level of lightning activity on Titan, *Nature*, **343**, 442, 1990.
- Desch, M. D., M. L. Kaiser, P. Zarka, A. Lecacheux, Y. Leblanc, M. Aubier, and A. Ortega-Molina, Uranus as a radio source, in *Uranus*, edited by J. T. Bergstrahl, E.

- D. Miner, and M. S. Matthews, p. 894, Univ. of Arizona Press, Tucson, Arizona, 1991.
- Evans, D. R., J. W. Warwick, J. B. Pearce, T. D. Carr, and J. J. Schauble, Impulsive radio discharges near Saturn, *Nature*, **292**, 716, 1981.
- Evans, D. R., J. H. Romig, C. W. Hord, K. E. Simmons, J. W. Warwick, and A. L. Lane, The source of Saturn electrostatic discharges, *Nature*, **299**, 236, 1982.
- Evans, D. R., J. H. Romig, and J. W. Warwick, Saturn's electrostatic discharges: Properties and theoretical considerations, *Icarus*, **54**, 267, 1983.
- Farrell, W. M. and M. D. Desch, Cloud-to-stratosphere lightning discharges: A radio emission model, *Geophys. Res. Lett.*, submitted, 1992.
- Fjeldbo, G., A. Kliore, B. Seidel, D. Sweetnam, and D. Cain, The Pioneer 10 radio occultation measurements of the ionosphere of Jupiter, *Astron. and Astrophys.*, **39**, 91, 1975.
- Gurnett, D. A., R. R. Shaw, R. R. Anderson, W. S. Kurth, and F. L. Scarf, Whistlers observed by Voyager 1: Detection of lightning on Jupiter, *Geophys. Res. Lett.*, **6**, 511, 1979.
- Gurnett, D. A., W. S. Kurth, I. H. Cairns, and L. J. Granroth, Whistlers in Neptune's magnetosphere: Evidence for atmospheric lightning, *J. Geophys. Res.*, **95**, 20967, 1990.
- Kaiser, M. L., J. E. P. Connerney, and M. D. Desch, Atmospheric storm explanation of saturnian electrostatic discharges, *Nature*, **303**, 50, 1983.
- Kaiser, M. L., M. D. Desch, and J. E. P. Connerney, Saturn's ionosphere: Inferred electron densities, *J. Geophys. Res.*, **89**, 2371, 1984.
- Kaiser, M. L., P. Zarka, M. D. Desch, and W. M. Farrell, Restrictions on the characteristics of Neptunian lightning, *J. Geophys. Res.*, **96**, Supplem., 19043, 1991.
- Kurth, W. S., B. D. Strayer, D. A. Gurnett, and F. L. Scarf, A summary of whistlers observed by Voyager 1 at Jupiter, *Icarus*, **61**, 497, 1985.
- Lewis, J. S., Lightning on Jupiter: Rate, energetics, and effects, *Science*, **210**, 1351, 1980.
- Magalhaes, J. A., and W. J. Borucki, Spatial distribution of visible lightning on Jupiter, *Nature*, **349**, 311, 1991.
- Menietti, J. D., and D. A. Gurnett, Whistler propagation in the Jovian magnetosphere, *Geophys. Res. Lett.*, **7**, 49, 1980.
- Menietti, J. D., D. Tsintikidis, D. A. Gurnett, and D. B. Curran, Modeling of whistler ray paths in the magnetosphere of Neptune, *J. Geophys. Res.*, **96**, Supplem., 19117, 1991.
- Pearl, J. C., B. J. Cowrath, R. A. Hanel, J. A. Pirraglia, and A. Coustenis, The albedo, effective temperature, and energy balance of Uranus, as determined from Voyager IRIS data, *Icarus*, **84**, 12, 1990.

- Pollack, J. B., K. Rages, S. K. Pope, M. G. Tomasko, P. N. Romani, and S. K. Atreya, Nature of the stratospheric haze on Uranus: Evidence for condensed hydrocarbons, *J. Geophys. Res.*, **92**, 15037, 1987.
- Rinnert, K., L. J. Lanzerotti, E. P. Krider, M. A. Unran, G. Dehmel, F. O. Gliem, and W. I. Axford, Electromagnetic Noise and Radio Wave Propagation below 100 kHz in the Jovian atmosphere, 1. The equatorial region, *J. Geophys. Res.*, **84**, 5181–5188, 1974.
- Scarf, F. L., D. A. Gurnett, W. S. Kurth, R. R. Anderson, and R. R. Shaw, An upper bound to the lightning flash rate in Jupiter's atmosphere, *Science*, **213**, 684, 1981.
- Scarf, F. L., D. A. Gurnett, W. S. Kurth, F. V. Coroniti, C. F. Kennel, and R. L. Poynter, Plasma wave measurements in the magnetosphere of Uranus, *J. Geophys. Res.*, **92**, 15217, 1987.
- Smith, B. A., L. A. Soderblom, R. Beebe, J. Boyce, G. Briggs, M. Carr, S. A. Collins, A. F. Cook II, G. E. Danielson, M. E. Davies, G. E. Hunt, A. Ingersoll, T. V. Johnson, H. Masursky, J. McCauley, D. Morrison, T. Owen, C. Sagan, E. M. Shoemaker, R. Strom, V. E. Suomi, and J. Ververka, The Galilean satellites and Jupiter: Voyager 2 imaging science results, *Science*, **206**, 927, 1979.
- Smith, B. A., L. Soderblom, R. Beebe, J. Boyce, G. Briggs, A. Bunker, S. A. Collins, C. J. Jansen, T. V. Johnson, J. L. Mitchell, R. J. Terrile, M. Carr, A. F. Cook II, J. Cuzzi, J. B. Pollack, G. E. Danielson, A. Ingersoll, M. E. Davies, G. E. Hunt, H. Masursky, E. Shoemaker, D. Morrison, T. Owen, C. Sagan, J. Ververka, R. Strom, and V. E. Suomi, Encounter with Saturn: Voyager 1 imaging science results, *Science*, **212**, 163–191, 1981.
- Smith, B. A., L. Soderblom, R. Batson, P. Bridges, J. Inge, H. Masursky, E. Shoemaker, R. Beebe, J. Boyce, G. Briggs, A. Bunker, S. A. Collins, C. J. Hansen, T. V. Johnson, J. L. Mitchell, R. J. Terrile, A. F. Cook II, J. Cuzzi, J. B. Pollack, G. E. Danielson, A. P. Ingersoll, M. E. Davies, G. E. Hunt, D. Morrison, T. Owen, C. Sagan, J. Ververka, R. Strom, and V. E. Suomi, A new look at the Saturn system: The Voyager 2 images, *Science*, **215**, 504–537, 1982.
- Smith, B. A., L. A. Soderblom, D. Banfield, C. Barnet, A. T. Basilevsky, R. F. Beebe, K. Bollinger, J. M. Boyce, A. Brahic, G. A. Briggs, R. H. Brown, C. Chyba, S. A. Collins, T. Colvin, A. F. Cook II, D. Crisp, S. K. Croft, D. Cruikshank, J. N. Cuzzi, G. E. Danielson, M. E. Davies, E. De Jong, L. Dones, D. Godfrey, J. Goguen, I. Grenier, V. R. Haemmerle, H. Hammel, C. J. Hansen, C. P. Helfenstein, C. Howell, G. E. Hunt, A. P. Ingersoll, T. V. Johnson, J. Kargl, R. Kirk, D. I. Kuehn, S. Limage, H. Masursky, A. McEwen, D. Morrison, T. Owen, W. Owen, J. B. Pollack, C. C. Porco, K. Rages, P. Rogers, D. Rudy, C. Sagan, J. Schwartz, E. M. Shoemaker, M. Showalter, B. Sicardy, D. Simonelli, J. Spencer, L. A. Sromovsky, C. Stoker, R. G. Strom, V. E. Suomi, S. P. Synott, R. J. Terrile, P. Thomas, W. R. Thompson, A. Verbiscer, J. Veverka, Voyager 2 at Neptune: Imaging science results, *Science*, **246**, 1422, 1989.

- Taylor, W. L., Radiation field characteristics of lightning discharges in the band 1 kHz–100 kHz, *J. Res. Nat. Bur. Stand.* **67D**, 539, 1963.
- Tokar, R. L., D. A. Gurnett, F. Bagenal, and R. R. Shaw, Light ion concentrations in Jupiter's inner magnetosphere, *J. Geophys. Res.*, **87**, 2241, 1982.
- Tyler, G. L., V. R. Eshleman, J. D. Anderson, G. S. Levy, G. F. Lindal, G. E. Wood, and T. A. Croft, Radio science with Voyager 2 at Saturn: Atmosphere and ionosphere and the masses of Mimas, Tethys, and Iapetus, *Science*, **215**, 553, 1982.
- Warwick, J. W., J. B. Pearce, R. G. Peltzer, and A. C. Riddle, Planetary radio astronomy experiment for Voyager missions, *Space Sci. Rev.*, **21**, 309, 1977.
- Warwick, J. W., J. B. Pearce, D. R. Evans, T. D. Carr, J. J. Schauble, J. K. Alexander, M. L. Kaiser, M. D. Desch, B. M. Pedersen, A. Lecacheux, G. Daigne, A. Boischot, and C. H. Barrow, Planetary radio astronomy observations from Voyager 1 near Saturn, *Science*, **212**, 239, 1981.
- Warwick, J. W., J. H. Romig, and D. R. Evans, Saturn electrostatic discharges, *IAU Colloquium No. 75, Planetary Rings*, A. Brahic (Ed.), 1982.
- Weidenschilling, S. J. and J. S. Lewis, Atmospheric and cloud structures in the Jovian planets, *Icarus*, **20**, 465, 1973.
- Williams, M. A., On the energy of possible Saturnian lightning, private communication, 1983.
- Williams, M. A., An analysis of the Voyager images of Jovian lightning, *PhD thesis*, Univ. of Arizona, 1986.
- Williams, M. A., E. P. Krider, and D. M. Hunten, Planetary lightning: Earth, Jupiter, and Venus, *Rev. Geophys.*, **21**, 892, 1983.
- Yung, Y. L., M. Allen, and J. P. Pinto, Photochemistry of the atmosphere of Titan: Comparison between model and observation, *Astrophys. J. Suppl. Ser.*, **55**, 465, 1984.
- Zarka, P., On the detection of radio bursts associated with Jovian and Saturnian lightnings, *Astron. and Astrophys.*, **146**, L15, 1985.
- Zarka, P. and B. M. Pedersen, Radio detection of Uranian lightning by Voyager 2, *Nature*, **323**, 605, 1986.