Lightning on Jupiter and the implications for its ionosphere

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Supported by

FWF Austrian Science Fund

URSI Austria Meeting,
TU Graz, 12. Mai 2026,
16:00-18:00.

Optical detection of lightning on Jupiter

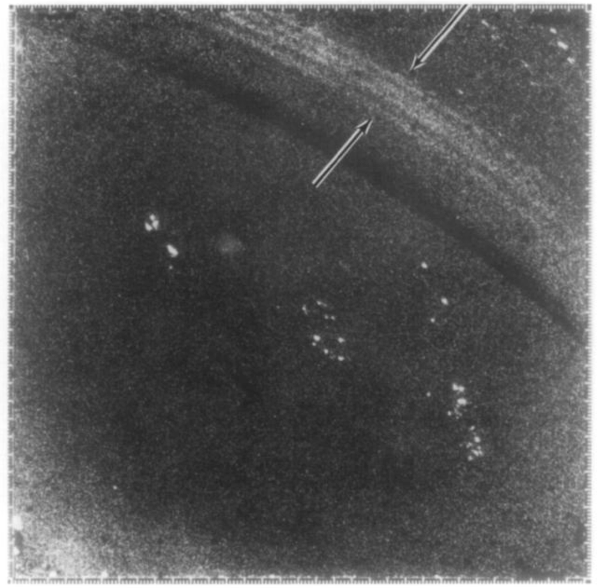
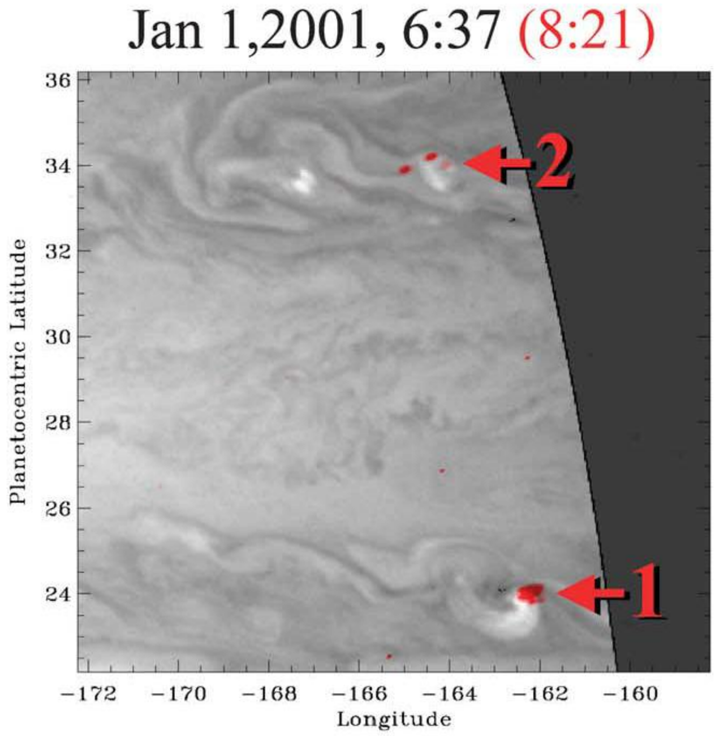
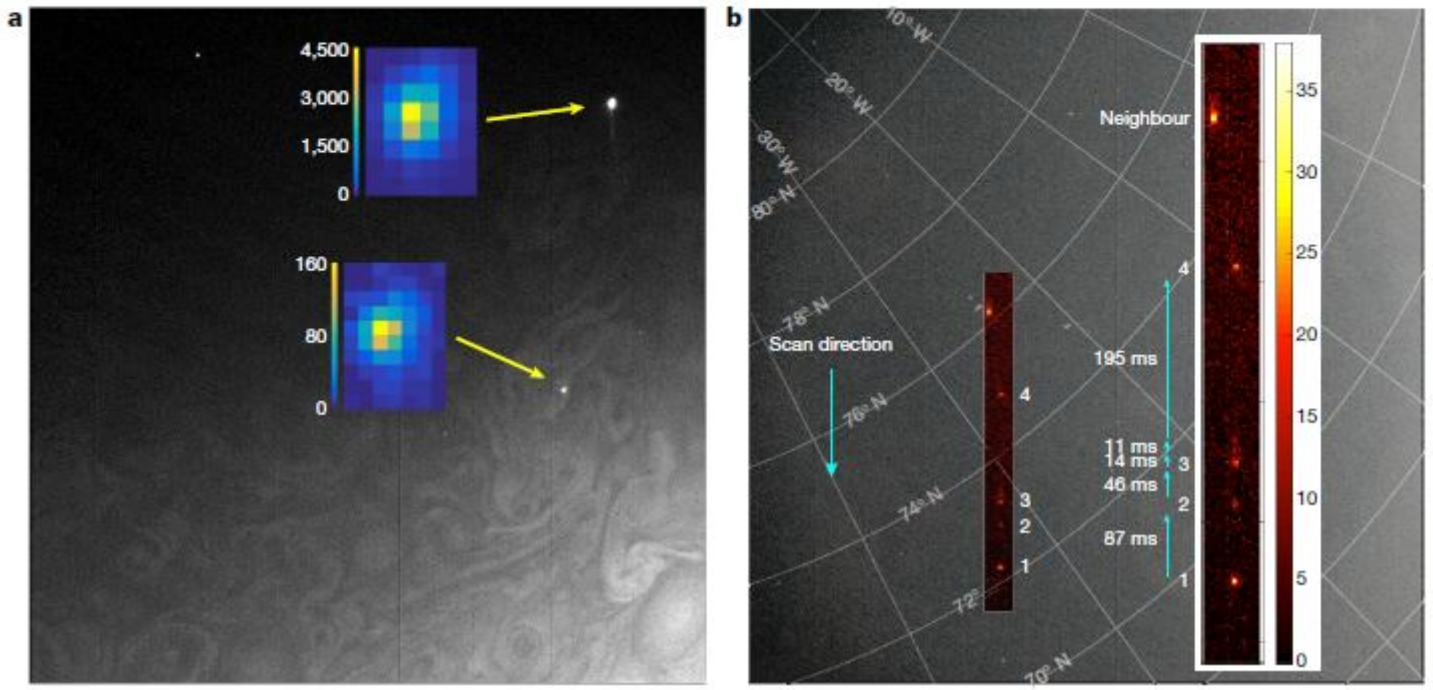


Fig. 2. Voyager photo No. 16396.31: Lightning on the nightside of Jupiter. This multiple exposure is composed of three exposures of 53 sec duration. The camera slewed nearly perpendicular to the limb of Jupiter between exposures.

[Borucki et al., 1982]



[Dyudina et al., 2007]



[Becker et al., 2020]

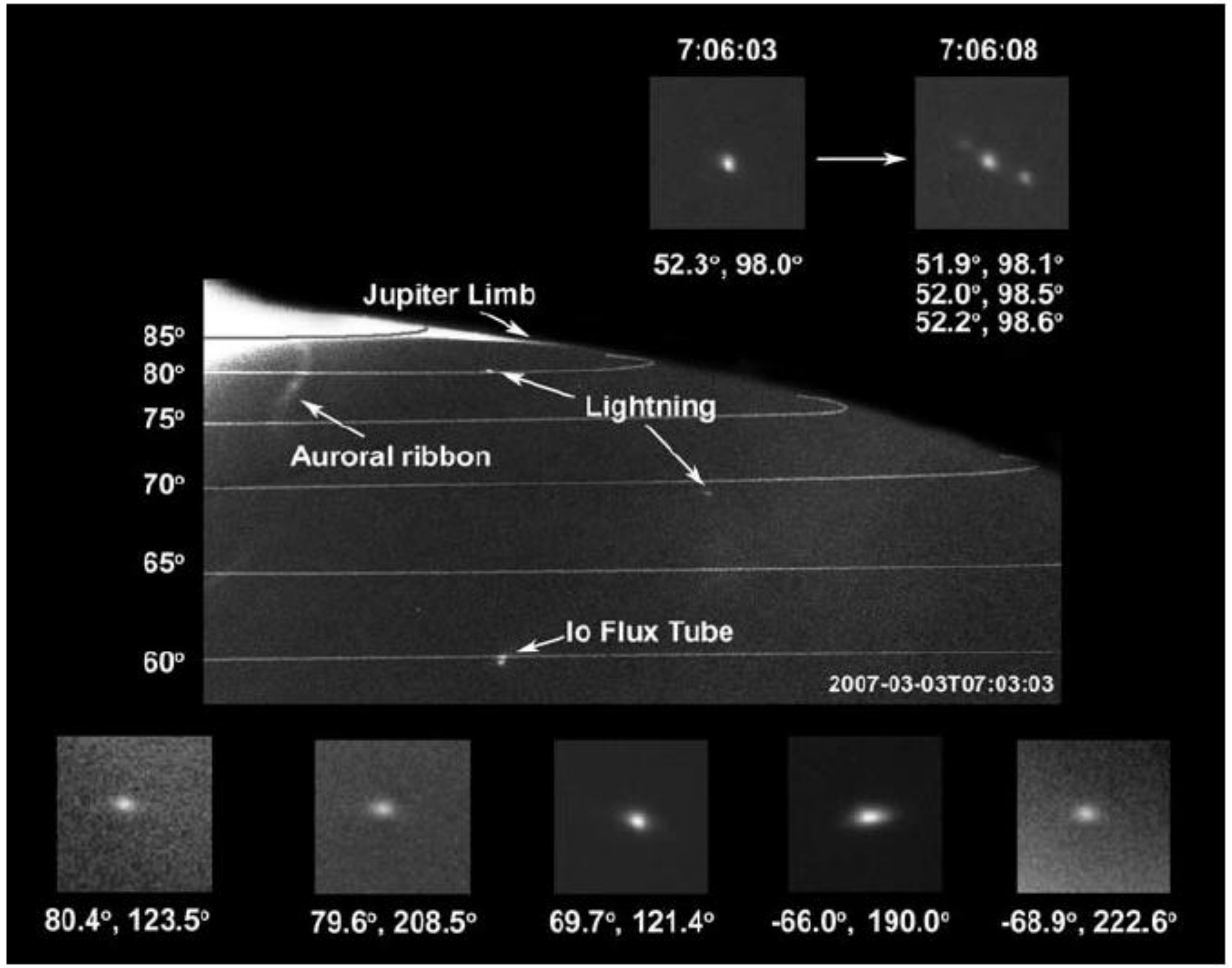


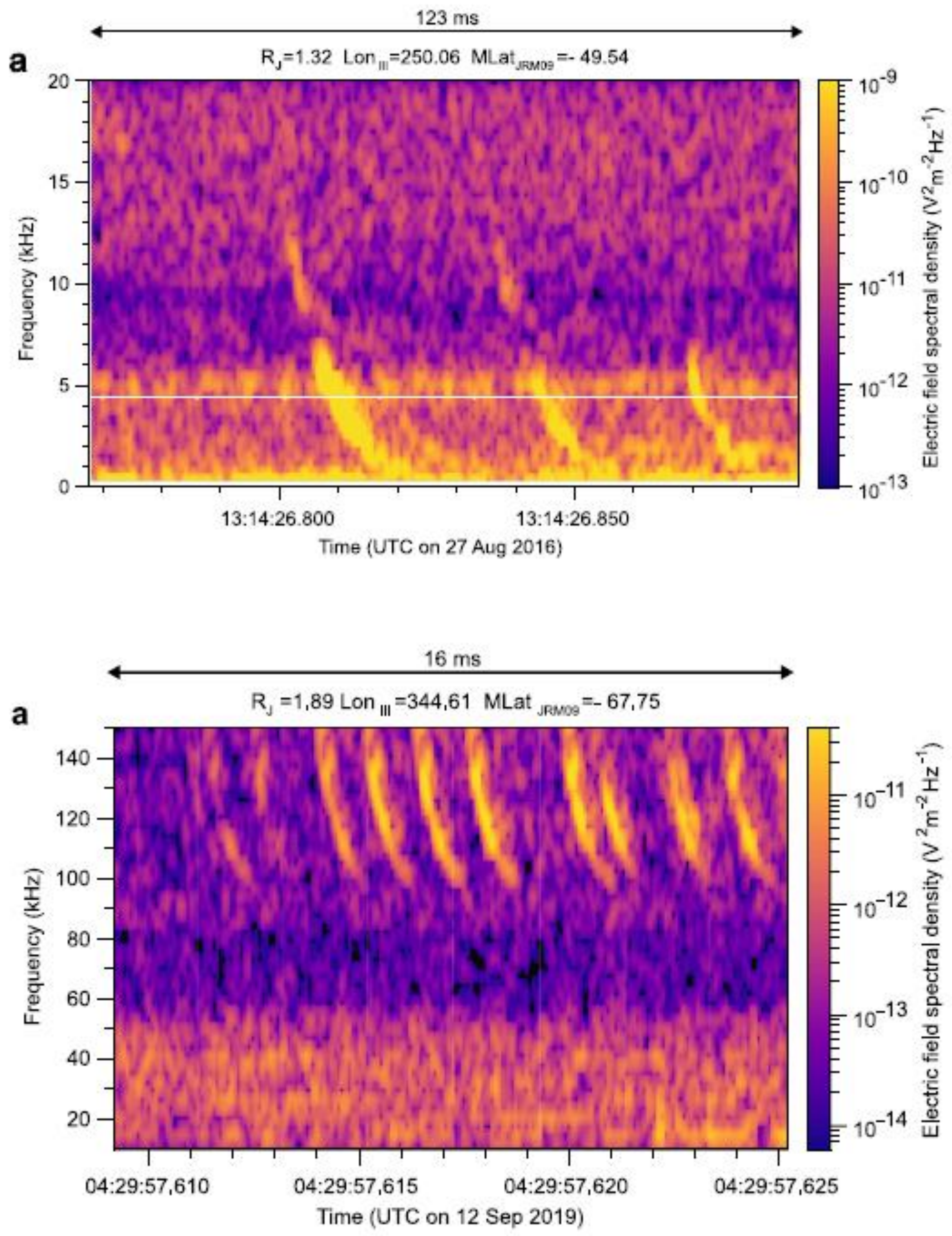
Fig. 1. Representative lightning flashes imaged by LORRI (*14*). (**Top row**) Multiple flashes are observed in consecutive 5-s exposures near 52°N. latitude (planetographic). (**Middle**) Two north polar flashes observed simultaneously in a single 5-s exposure. (**Bottom row**) Flashes in both the north and south polar regions show substantial spatial extension, which is indicative of diffusive aerosol scattering of upwelling emission from near the 5-bar water condensation level.

[Baines et al., 2007]

Optical lightning detection done by:
Voyagers [Cook et al., 1979]
Galileo
Cassini
New Horizons
Juno

Lightning detection with Juno mission

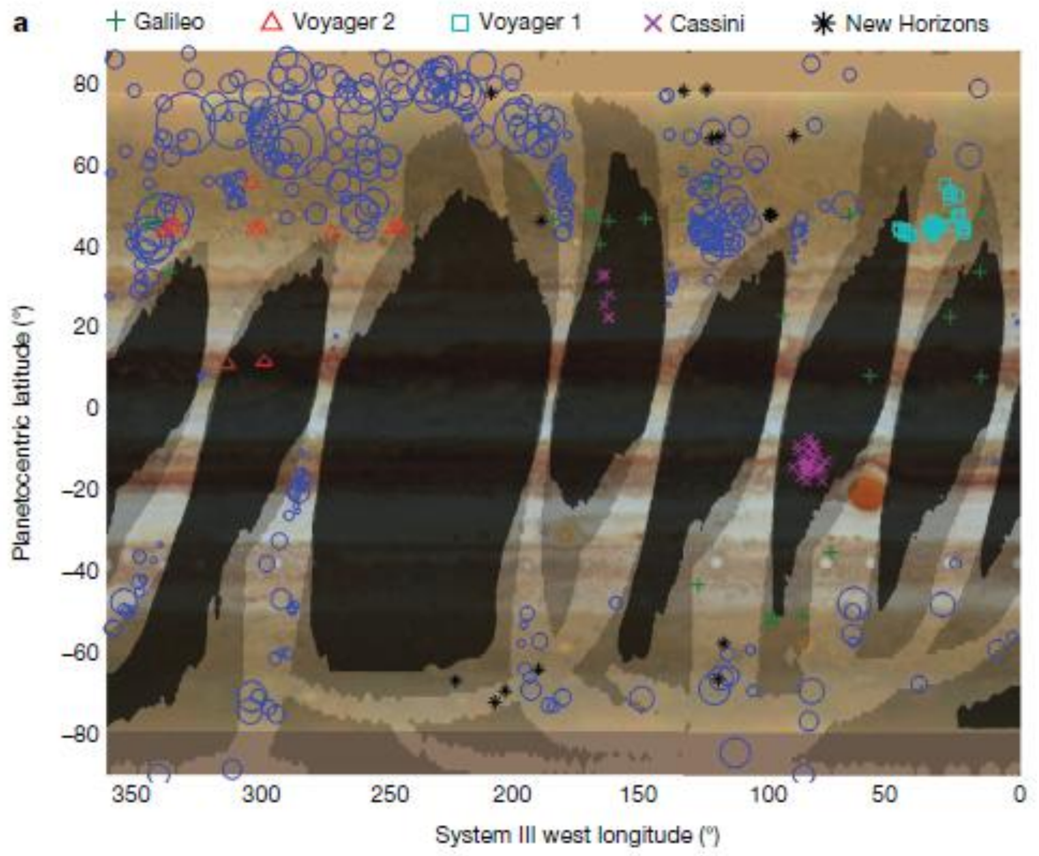
- “Rapid whistlers”: dispersed pulses <20 kHz in whistler mode with dispersion proportional to electron density along ray path. Detected by Kolmasova et al. (2018) in LF receiver of Juno Waves. Dispersion is small (~10 ms) compared to whistlers propagation along Io plasma torus (~seconds) as detected by Gurnett et al. (1979), because Juno is close
- Jupiter Dispersed Pulses (JDP): are even faster, duration around 1 ms, and are thought to be sferics propagated in O-mode through ionospheric holes (Imai et al., 2019), at frequencies 20-150 kHz, mostly observed at distance <3 R_J in high band of LF receiver of Juno Waves
- Microwave bursts: detected in 600 and 1260 MHz channels of Juno Microwave RadioMeter (MWR) by Brown et al. (2018). Most found at higher latitudes in northern hemisphere.



[Kolmasova et al., 2022]

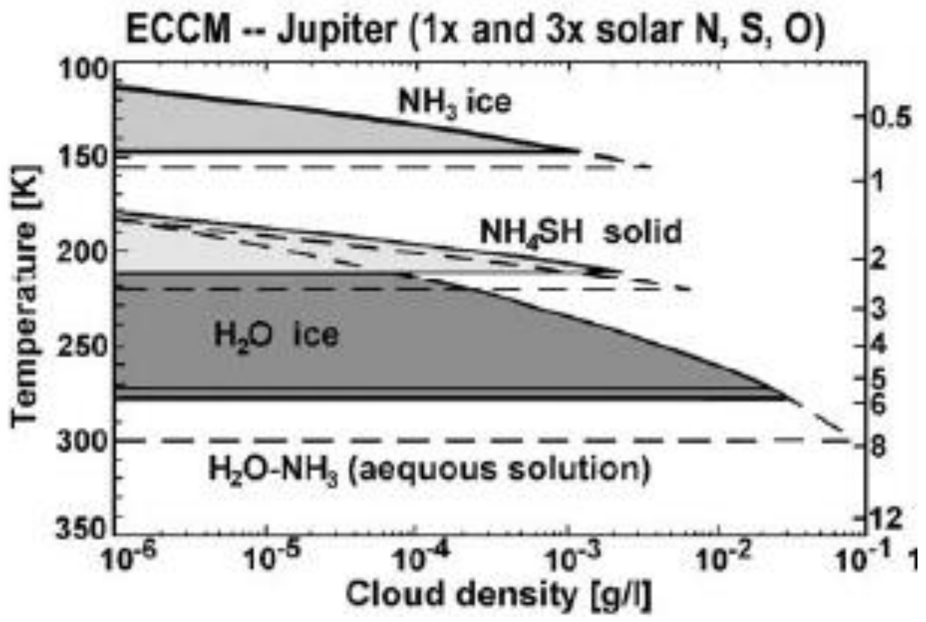
Lightning detection on Jupiter & Saturn

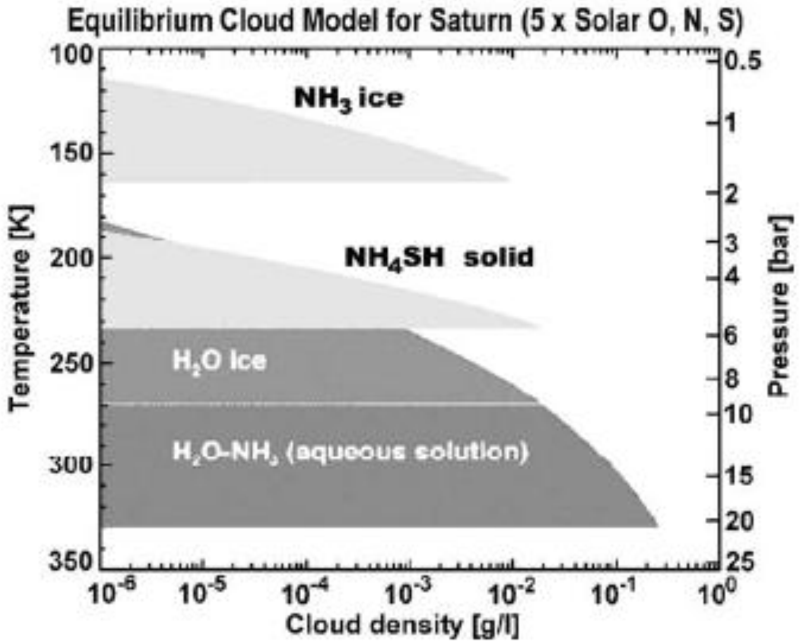
Way of detection		Jupiter	Saturn
optical	storm clouds	yes, look through a telescope	yes, imaged by Cassini and ground-based
	light of flashes	yes, Voyager 1, 2 (Cook et al., 1979); Galileo, Cassini, New Horizons, Juno	yes, Dyudina et al. (2010) nightside and later dayside observations (Dyudina et al., 2013)
radio waves	whistlers	yes, Gurnett et al. (1979)	maybe, Akalin et al. (2006), single event; no thunderstorm during proximal orbits
	HF sferics (few MHz)	No, but why?	yes, SEDs=Saturn Electrostatic Discharges
	kHz sferics below ionosphere	yes, by Galileo probe Lanzerotti et al. (1998)	no Saturn atmospheric probe
	„rapid whistlers"	Juno Waves, Kolmasova et al. (2018), 1-tens of ms, <20 kHz	no detection reported
	JDP (Jupiter Dispersed Pulses)	Juno Waves, Imai et al. (2019), <5 ms, 40-140 kHz	no detection reported
	Microwaves, 600 & 1200 MHz	Juno Microwave Radiometer, Brown et al. (2018)	no adequate instrument on Cassini

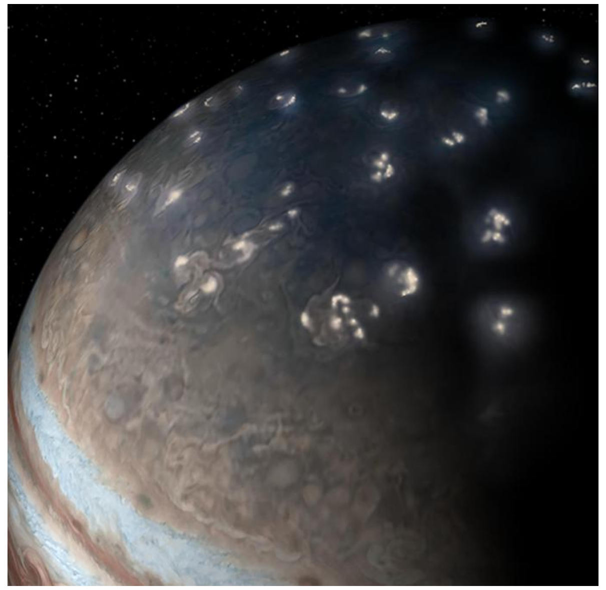


[Brown et al., 2018]

Atmospheres of Jupiter & Saturn





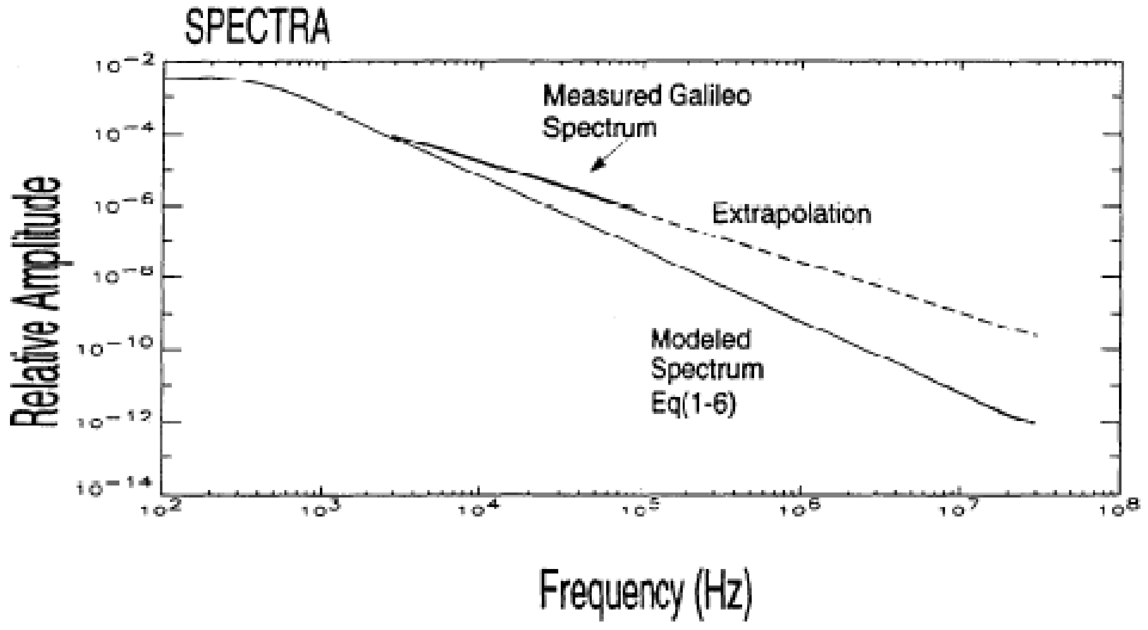


Artist impression!

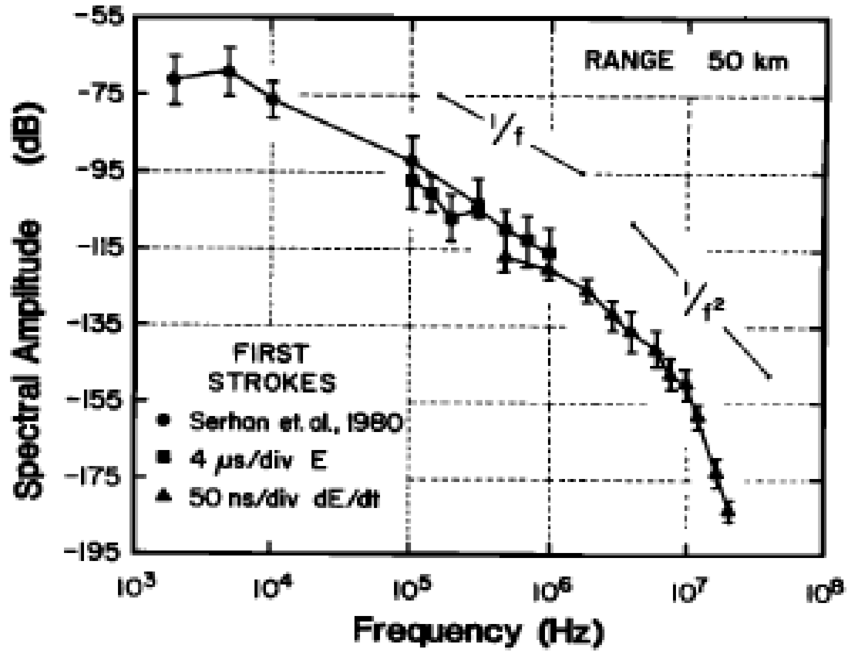
[Atreya and Wong, 2005]

- Similar 3 cloud-layered structure for Jupiter & Saturn, Saturn‘s atmosphere is more extended due to lower gravity (ammonia ice cloud, ammonia hydrosulfide cloud, water cloud)
- Lightning source region most likely at bottom of water ice cloud: 5 bar level for Jupiter, 8-10 bar level at Saturn (50 km below 1-bar level at Jupiter, 200 km at Saturn)
- Charging of cloud particles at Earth most effective at -25°C to -10°C
- Unclear why Jupiter is permanently flashing, whereas Saturn shows large gaps in activity and a smaller number of storms (1-3), Jupiter storms last days, Saturn storms weeks to months

Why are there no HF sferics at Jupiter?



[Farrell et al., 1999]

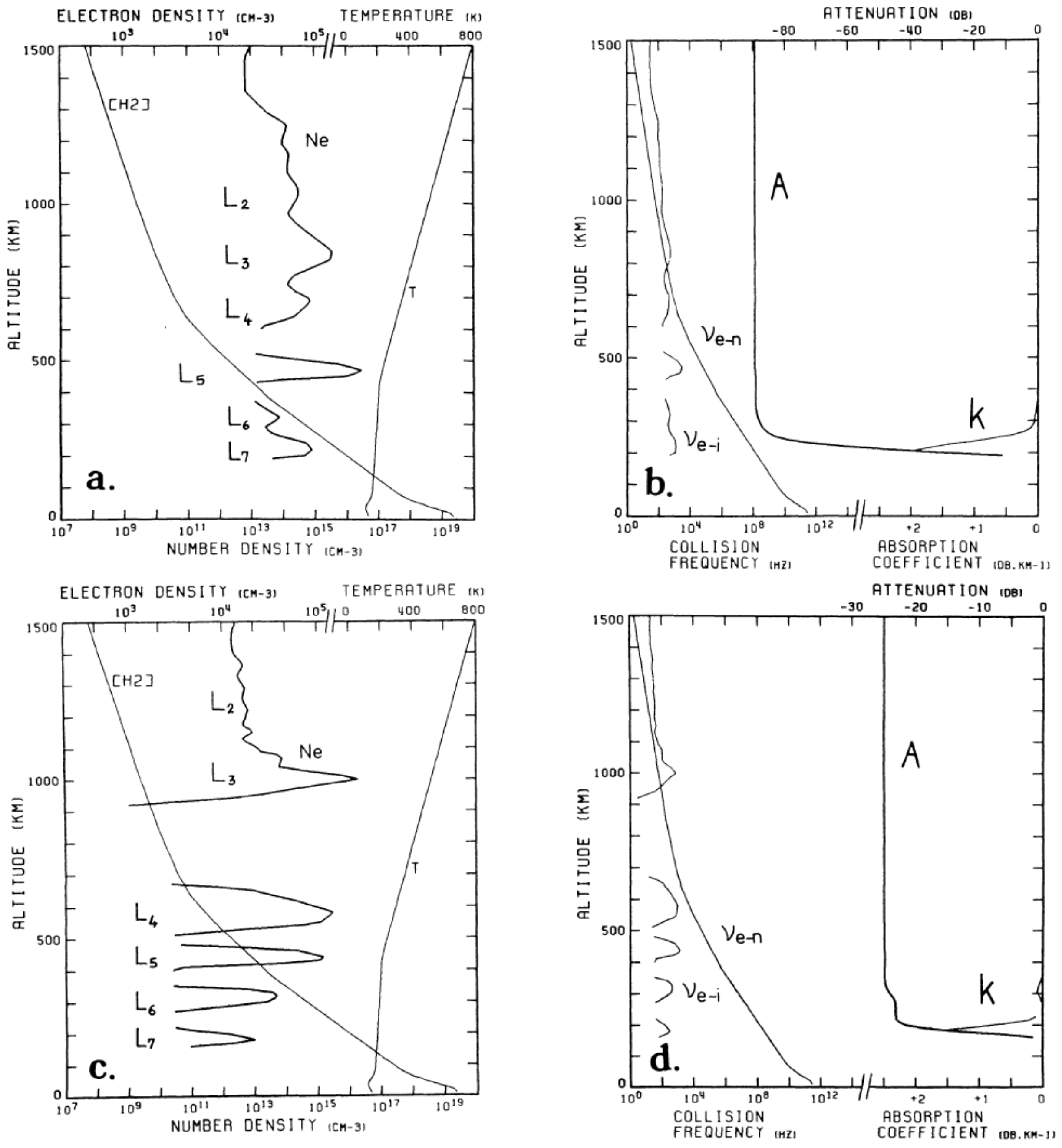


[Weidman et al., 1981]

- Model of Farrell et al. (1999): slow discharge shows maximum of radiation at a few 100 Hz
- Terrestrial lightning: max. wave intensity at 10 kHz, fall off with $1/f$ to 1 MHz and $1/f^2$ for >1 MHz
- $1/f$ decrease means decrease of 10 dB in intensity and 20 dB in amplitude per decade in frequency (decrease even larger >1 MHz)
- HF signal of Jovian lightning might be too weak
- Detection of lightning at 600 MHz rather suggests this theory is not right

Radio wave absorption in ionosphere

- Model of Zarka (1985): radio wave absorption by low-altitude layers of ionosphere
- Radio wave detection depends on signal strength, galactic and receiver noise level and distance R to source (~1/R²)
- Radio wave absorption due to collisions of electrons with neutrals and ions, absorption coefficient after Ratcliffe (1962), see below
- Attenuation is given by integrating K along ray path
- Zarka (1985): attenuation of 90 dB (dayside), 25 dB (nightside), most attenuation occurs at altitude of ~200 km (L7 ionospheric layer), electron-neutral collisions are relevant as $\upsilon_{e-n} >> \upsilon_{e-i}$



Zarka [1985]

$$K = \frac{e^2 . Ne . \nu}{2.c.\mu.\epsilon_o.m.[4\pi^2.(f \pm f_c)^2 + \nu^2]}$$

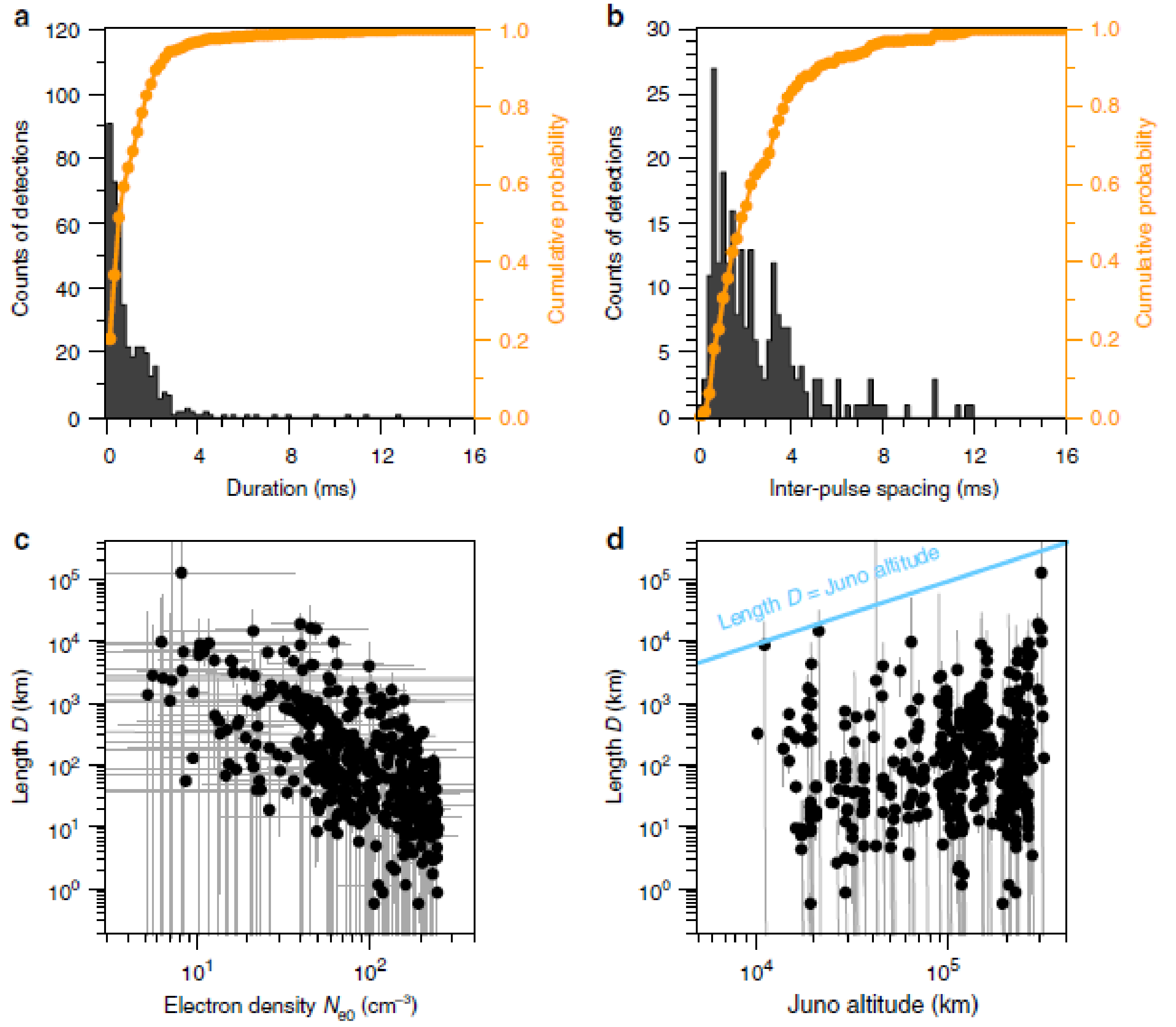
with $\nu = \nu_{e-i} + \nu_{e-n}$

$\nu_{e-i} = 6.1 \; 10^{-9} \; (T/300)^{-3/2} \; Ni$

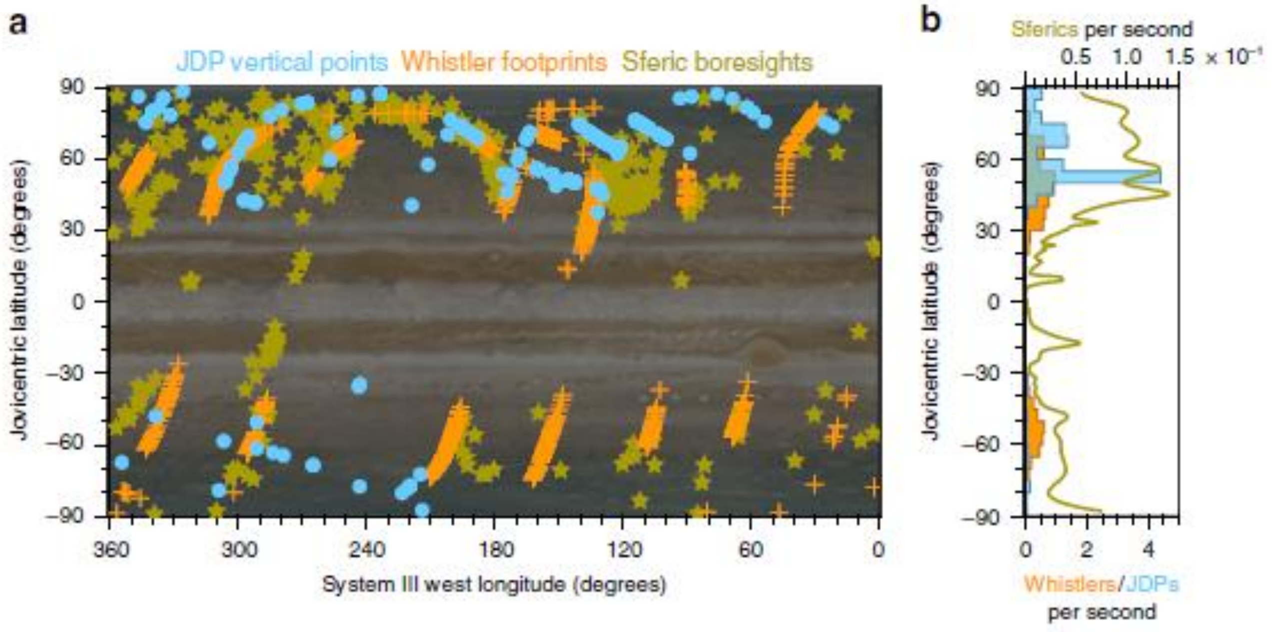
and $\nu_{e-n} = 1.8 \; 10^{-14} \; (T/300)^{1/2} \; Nn$

Holes in Jupiter‘s ionosphere

- Jupiter dispersed pulses (JDPs) found in freq. range from 20-150 kHz (upper limit of LF receiver high band)
- Typical duration of a few milliseconds
- Thought to be O-mode emissions which freely propagate above the plasma frequency (some are above f_{ce} and f_{uh})
- Lower cutoff frequency is nearly identical to peak electron density in Jupiter‘s ionosphere
- Must be low density holes in nightside ionosphere with < 250 cm^{-3} and down to a few e^{-} per cm^{-3} (normal ionosphere has plasma frequency peak of 1-5 MHz, $1{,}2 \cdot 10^{4}$ to $3{,}1 \cdot 10^{5}$ cm^{-3})
- Show small dispersion at low freq. edge which can be modelled with O-mode model (Imai et al., 2019)
- JDPs, whistler (footpoints), and microwave burst originate from lightning storms at medium to very high latitudes



[Imai et al., 2019]



Summary

- Jovian lightning storms are different to Saturnian ones, despite the similar atmospheres
- Optical detection of lightning for both planets (more difficult for Saturn because of larger depth)
- Saturn Electrostatic Discharges are HF sferics in frequency range of a few MHz, practically the only kind of radio wave from lightning (unfortunately no clear detection of whistlers)
- From Jupiter lightning the following radio waves were detected: whistlers, rapid whistlers, Jovian Dispersed Pulses (JDPs), microwave bursts and sferics in kHz range (below ionosphere)
- The absence of sferics of a few MHz for Jupiter is puzzling, most likely there are absorbing layers in the ionosphere caused by electron-neutral collisions
- The presence of JDPs in the O-mode suggests ionospheric holes with e^- density of $<250\ cm^{-3}$ and down to a few e^- per cm^3