GROUND-BASED AND SPACE-BASED RADIO OBSERVATIONS OF PLANETARY LIGHTNING

P. Zarka[1], W. Farrell[2], G. Fischer[3], and A. Konovalenko[4]

[1]LESIA, CNRS-Observatoire de Paris, 92190 Meudon, France, philippe.zarka@obspm.fr
[2]Science Exploration Directorate, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA, william.farrell@gsfc.nasa.gov
[3]Dept. of Physics and Astronomy, University of Iowa, 203 Van Allen Hall, Iowa-City, IA 52242, USA, georg-fischer@uiowa.edu
[4]Institute of Radio Astronomy, National Academy of Sciences of Ukraine, 4 Chervonopraporna Str., Kharkiv 61002 SU, Ukraine, akonov@ira.kharkov.ua

- Lightning's radio signature
- Space-based radio observations of planetary lightning
- Lightning and ionospheric probing
- Compared temporal & spectral characteristics
- The case of Mars
- Prospects for ground-based observations
- Prospects for space-based observations

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Lightning basics

- Atmospheric lightning = transient, tortuous high-current electrostatic discharge resulting from macroscopic (a few km) electric charge separation

- Small-scale particle electrification (collisions & charge transfer) + large-scale charge separation (convection & gravitation) ⇒ large-scale E-field

- For $E > E_{critical}$ ⇒ accelerated electrons ionize intervening medium ⇒ cascade ⇒ « lightning stroke »
(a lightning discharge/flash consists of many consecutive strokes)

[e.g. Gibbard et al., 1997]

Interest of planetary lightning studies

- ❑ Role in the atmospheric chemistry
(production of non-equilibrium trace organic constituents, potentially important for biological processes)

- ❑ Signature of atmospheric dynamics and cloud structure
(correlation with optical and IR observations)
$\Rightarrow$ comprehensive picture of storm activity, planetographic and seasonal variations, transient activity, etc.

- ❑ Comparative studies of electrification processes, esp. at Earth
(influence of atmospheric composition)

- ❑ Ionospheric probing

[e.g. Zarka et al., 2004]

Radio (and other e.m.) signatures

Lightning discharges produce various electromagnetic waves :

- Optical emission due to intense heating of lightning channel
- High frequency radio emission up to a few 10's MHz (current channel acting as an antenna)
- Very low-frequency plasma waves (< a few 10's kHz, ducted by magnetic field lines and plasma density gradient, showing characteristic t-f dispersion, = whistlers) [Helliwell, 1965]

Time profile and radio spectrum

- Stroke current time profile may be described by :

  $i = i_o (e^{-\alpha t} - e^{-\beta t})$ [Bruce and Golde, 1941]

- Terrestrial discharge, e.g. : i_o ~ 30 kA, $\alpha \sim 2\times10^4$ s^{-1}, $\beta \sim 2\times10^5$ s^{-1}

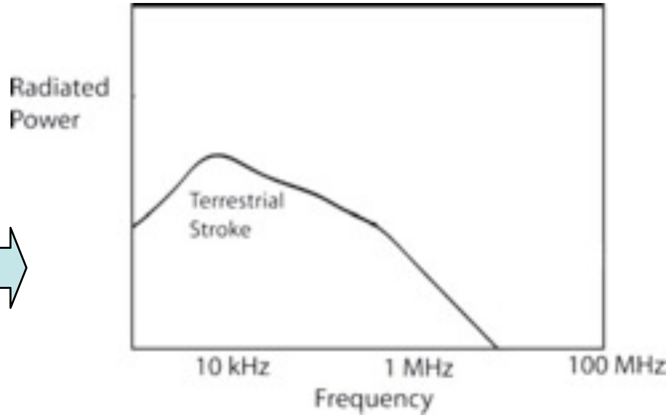
  $\Rightarrow$ stroke duration ≈100 μs [Levine and Meneghini, 1978a,b; Volland, 1984]

- Radiated radio power : $P(f) \propto f^{-4}$ at high frequencies [Farrell et al., 1999]

- At lower frequencies, channel tortuosity

  $\Rightarrow$ radiated radio power : $P(f) \propto f^{-1}$ to f^{-2}

- Low-frequency radio emission produced in a broad spectrum peaking (@ Earth) at ~10 kHz (~1/(100 μs))



- Typical discharge duration @ Earth : a few msec to 100's msec

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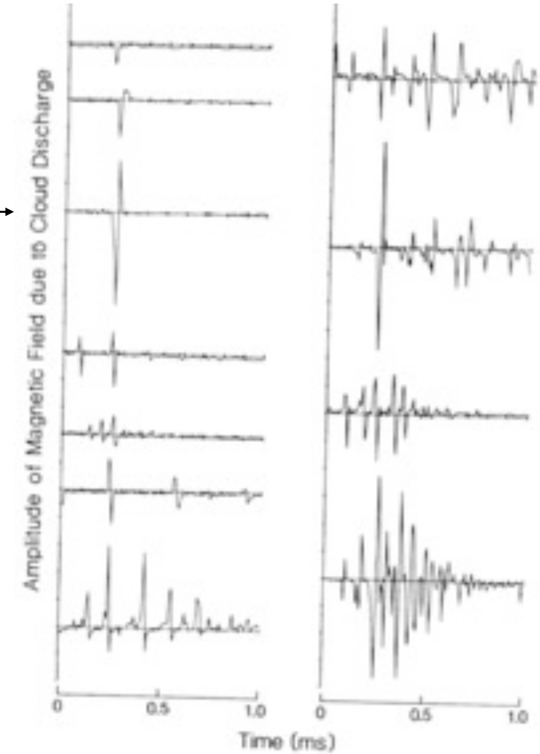
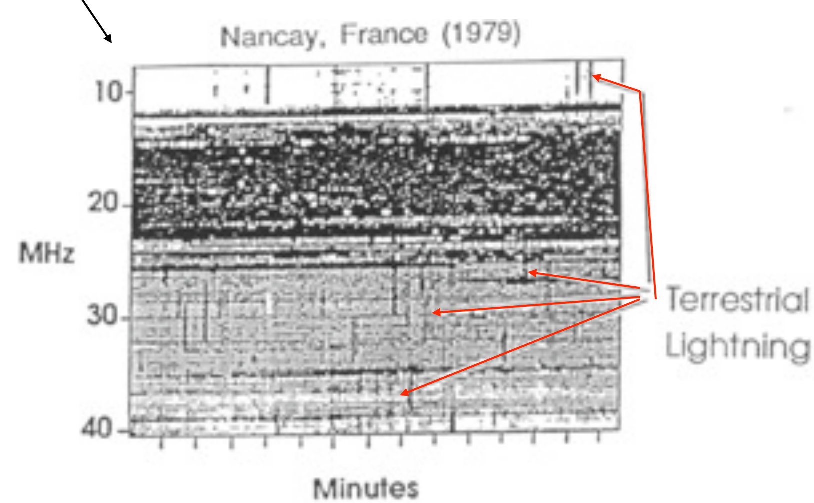
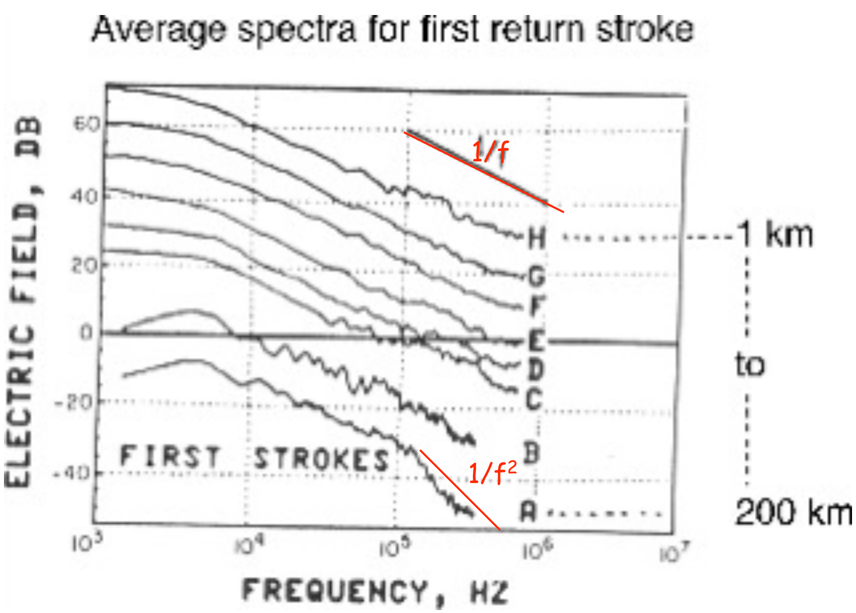
Earth

- Lightning detected by :
  - Galileo probe detector
  - Voyager PRA receiver



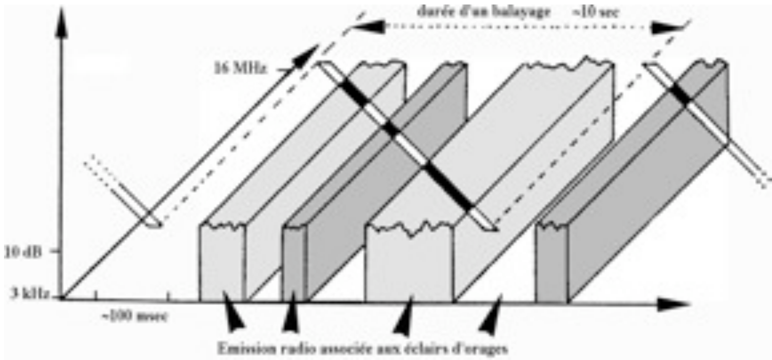


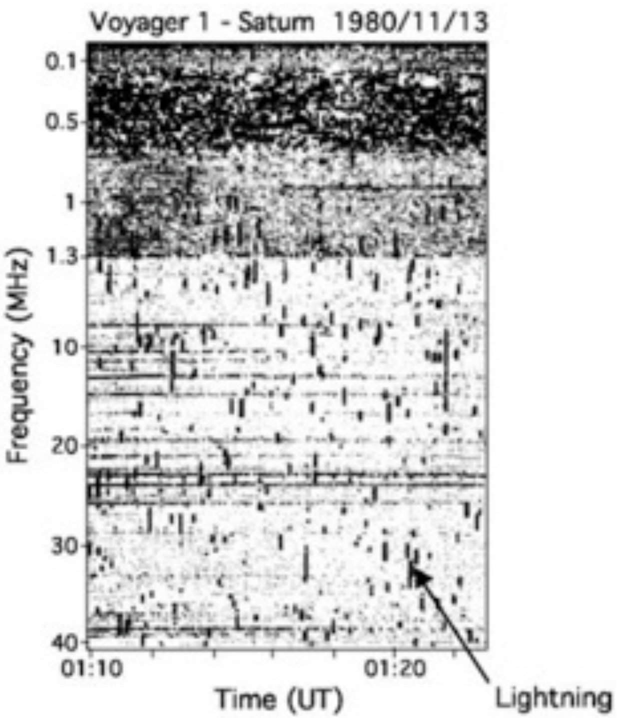
- Stroke spectrum



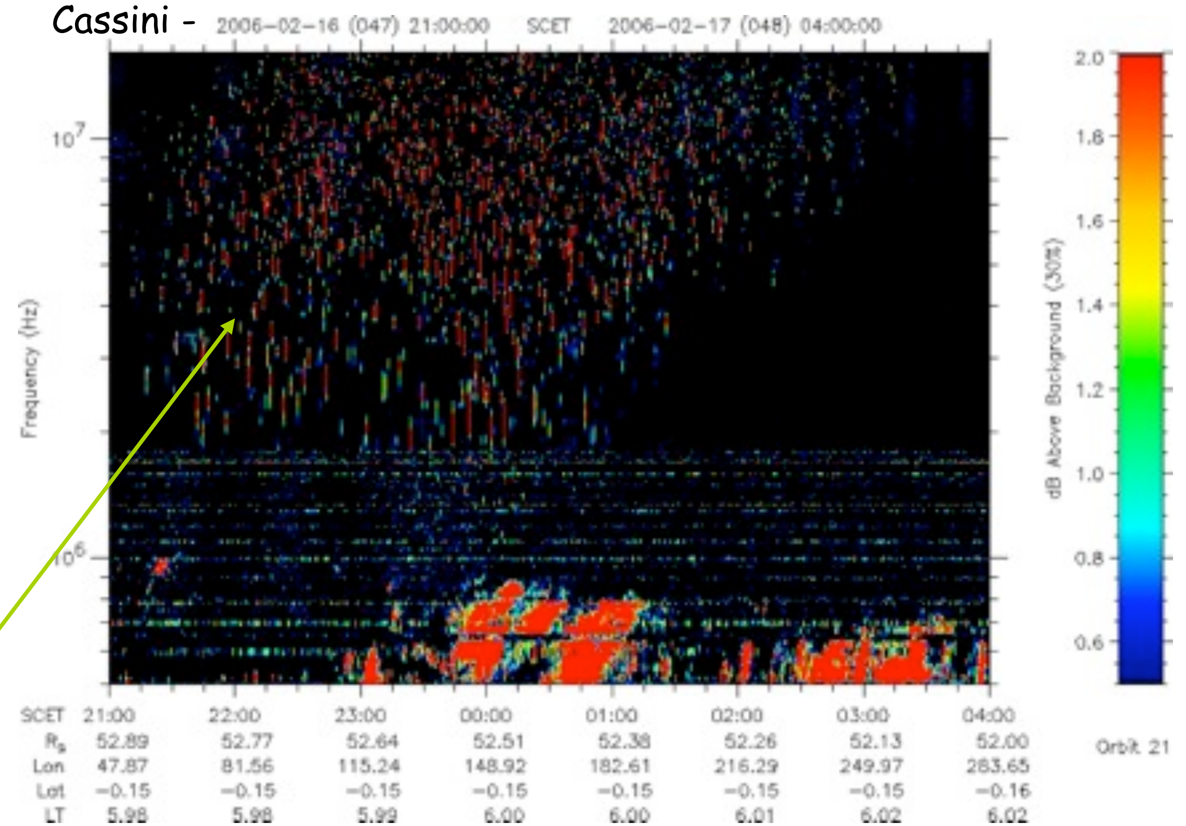
Saturn

- SED for "Saturn Electrostatic Discharges"
  - → discovered by Voyager 1
  - → studied by Voyager 1-2 in 1980-81
    [Warwick et al., 1981, 1982 …]
  - and by Cassini since 2004
    [Gurnett et al., 2005 …]





Cassini -



Saturn

❑ SED characteristics (from Voyager 1) :

- occurrence within ~5 hours « episodes »
- typical duration 30 to 300 msec per flash
- broadband spectrum ~flat from ≲20 kHz to 10-20 MHz, then in $f^{-1/-2}$
- instantaneous spectral power ~0.1 to 300 W/Hz
  - ⇒ flux density ~0.4 to 1000 Jy @ Earth [1 Jy = 10^{-26} $Wm^{-2}Hz^{-1}$]
- > 1 event/min. with flux ≥ 50 Jy @ Earth ; ~10 events/min. with flux ≥ 5 Jy
- isotropic beaming [Evans et al., 1983; Zarka and Pedersen, 1983; Zarka, 1985a …]

❑ SED characteristics (from Voyager 2) :

- flux & occurrence ~2-4x weaker than for Voyager 1

❑ SED characteristics (from Cassini) : similar to Voyager 1

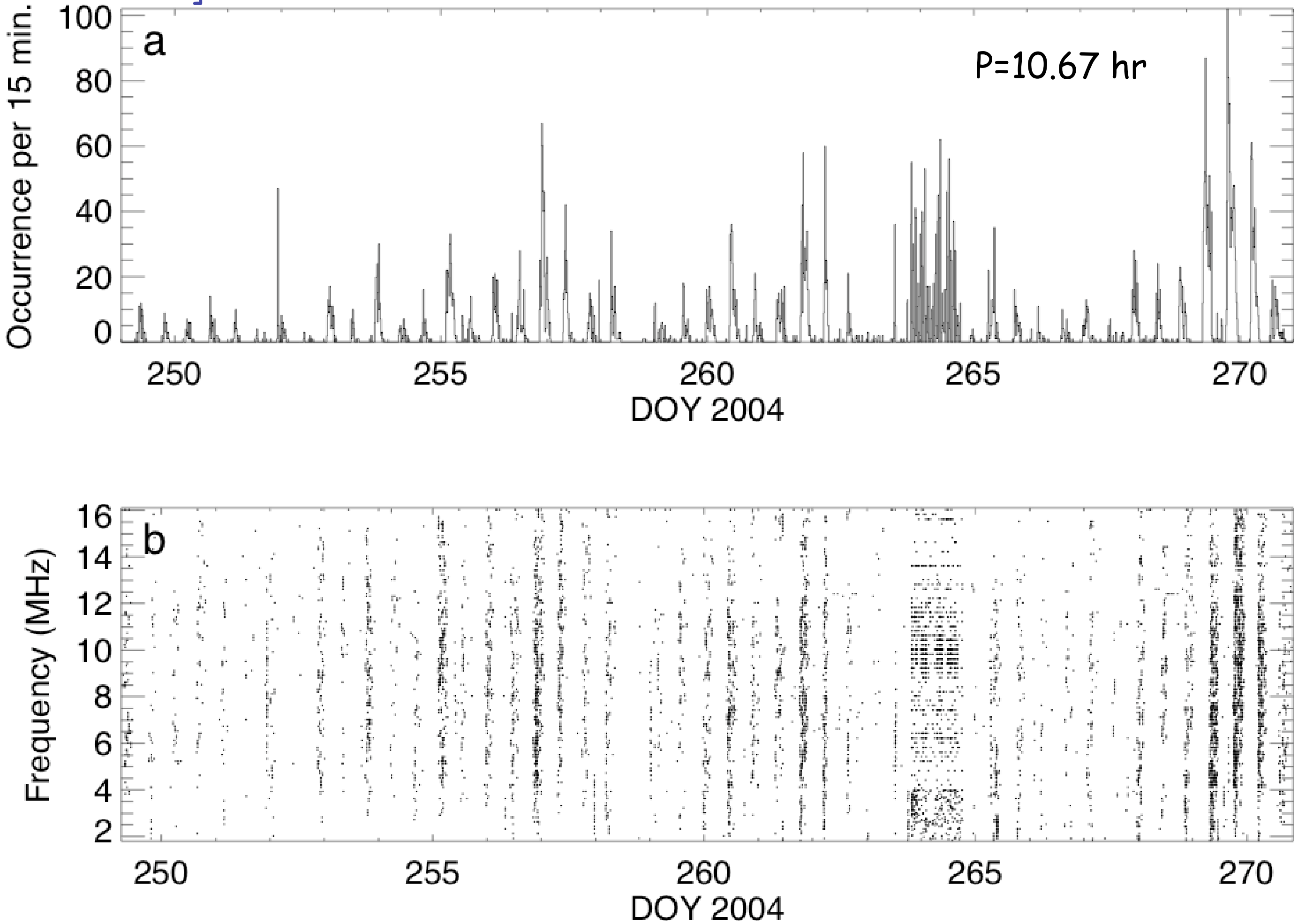
- variable occurrence : storms lasting for days/weeks, separated by weeks/ months of inactivity

[Desch et al., 2006; Fischer et al., 2006; Zarka et al., 2006; …]

Saturn

- Occurrence in september 2004 observed by Cassini/RPWS :
  - peak rate of one SED / 5s (same as Voyager 1)
  - average similar to Voyager 2, ~1/4x Voyager 1

[Fischer et al., 2006; Zarka et al., 2006]

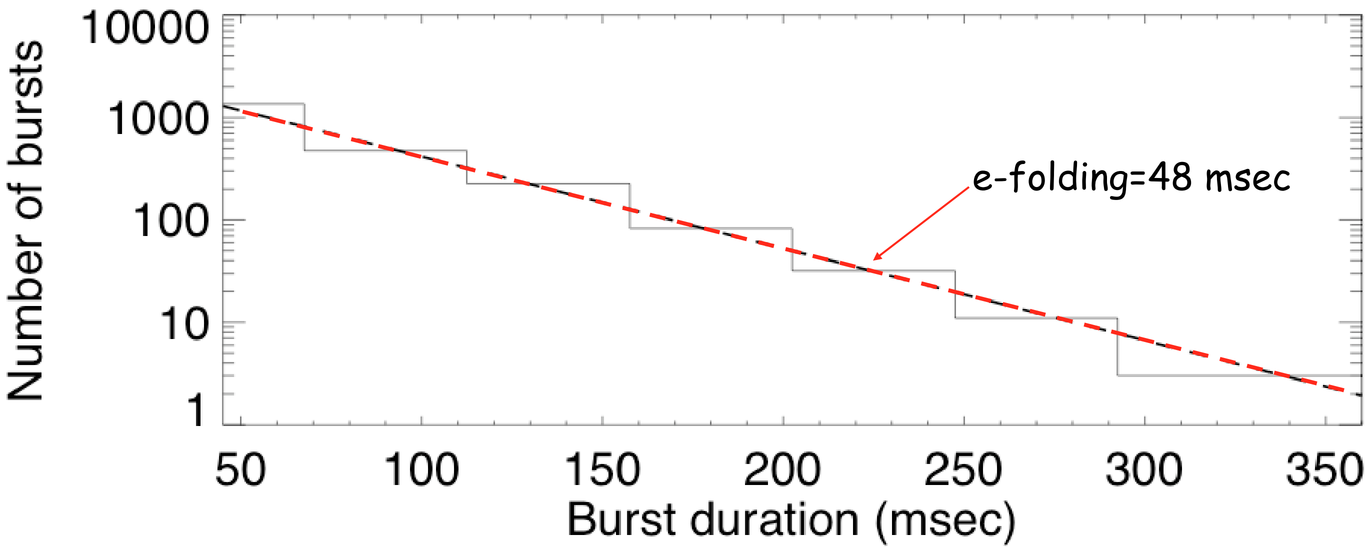


Saturn

- SED duration = 50-350 msec
  (time resolution of Voyager and Cassini measurements ~30 msec)

- e-folding time 48 msec (~40 msec for Voyager)

[Zarka et al., 2006]



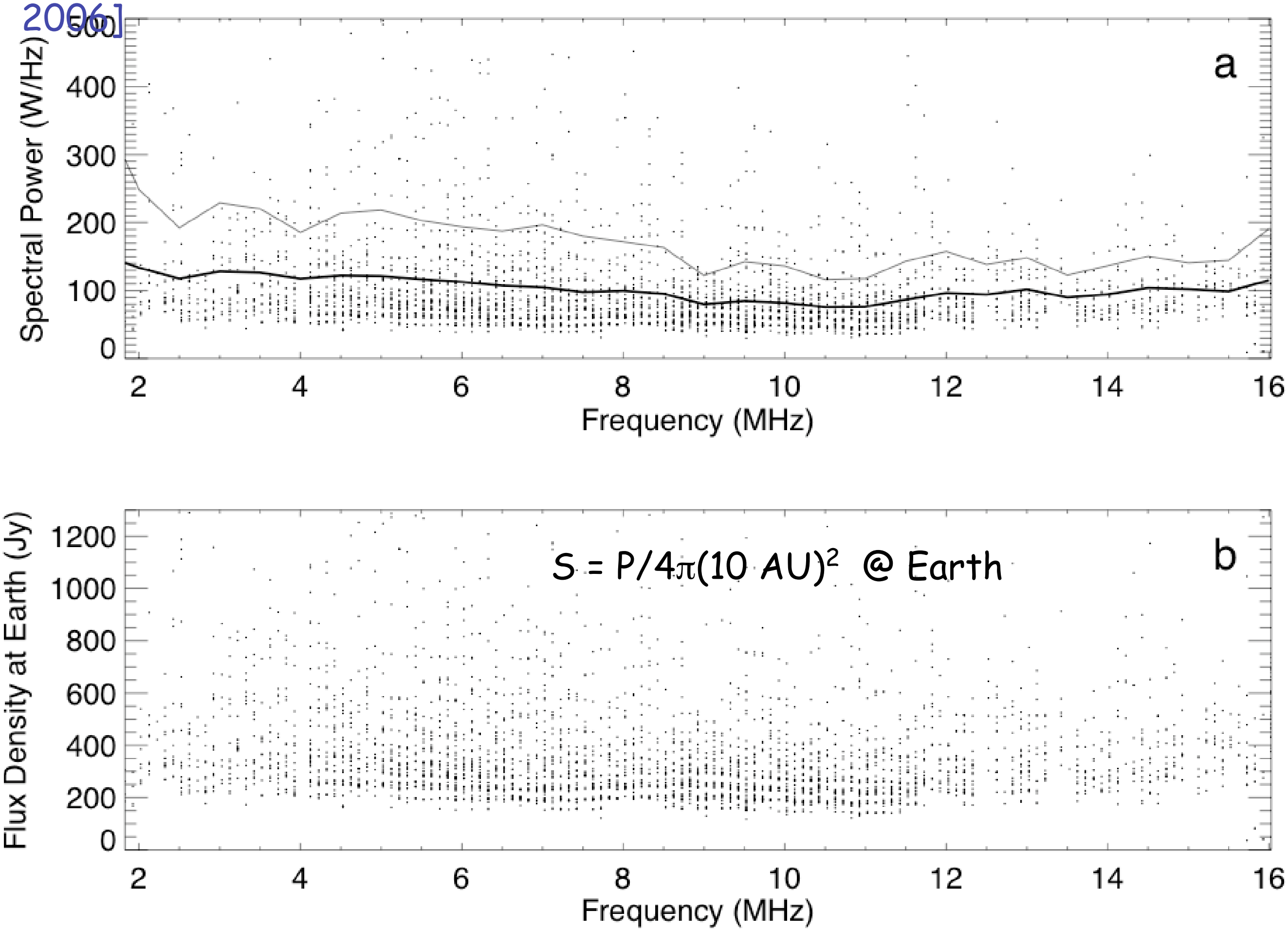
Saturn

❑ Calibrated spectral power :

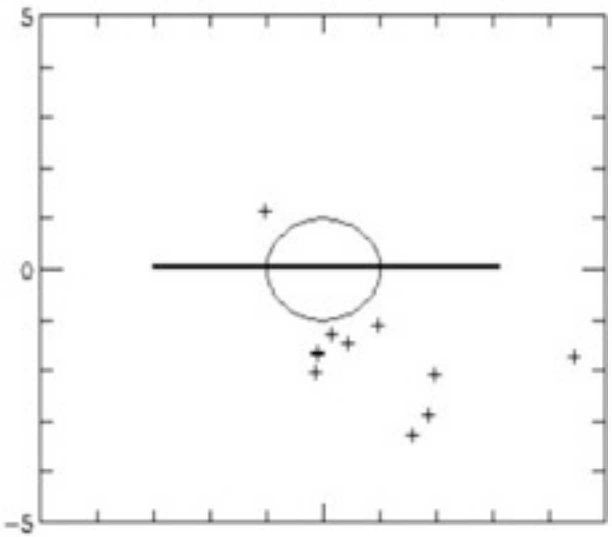
- < P > ~100 W/Hz
- nearly flat up to 16 MHz (same as Voyager 1)

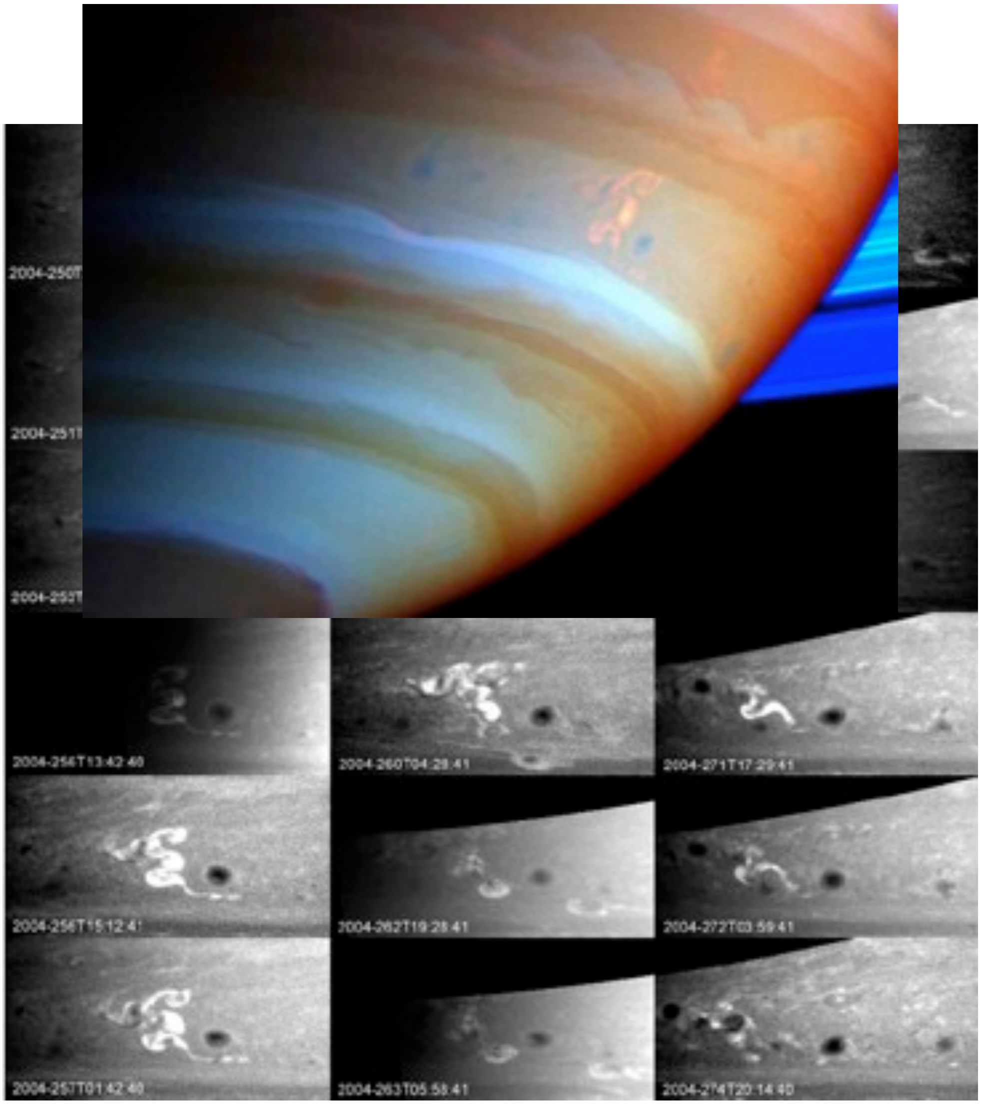
⇒ flux density @ Earth up to a few 100's Jy

[Zarka et al., 2006]



Saturn





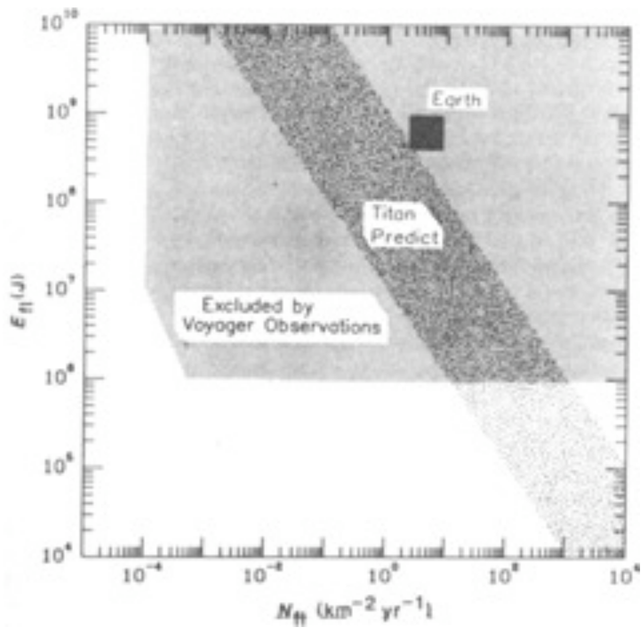
❑ Radio-goniometry confirms Saturnian origin, but low accuracy (weak S/N)

❑ Correlation with optical observations (« Dragon storm » in september 2004)

Titan

- No lightning from Titan detected with Voyager and Cassini

[Desch and Kaiser, 1990; Fischer et al., 2007]



⇒ Very low flux density ? (<2×10^{-5} Jy @ 500 kHz @ Earth)

⇒ Very low flash rate (<1 flash/h) ?

⇒ Low flash duration (0.25 msec) ?

⇒ Episodic activity ? From dayside only ?

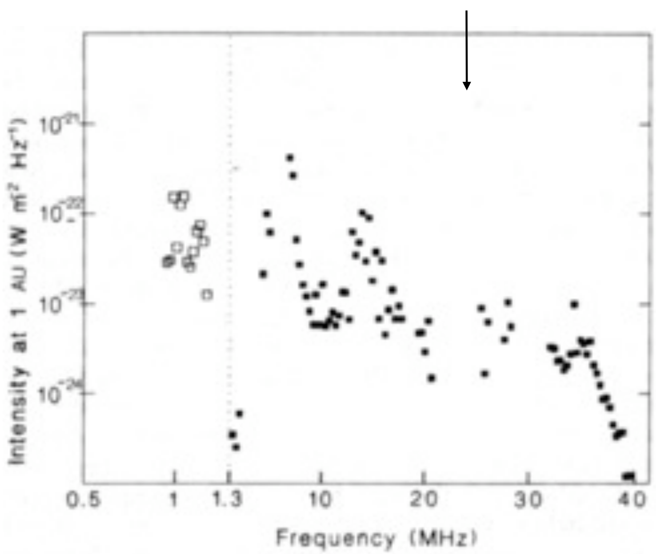
[Lammer et al., 2001; Zarka et al., 2004]

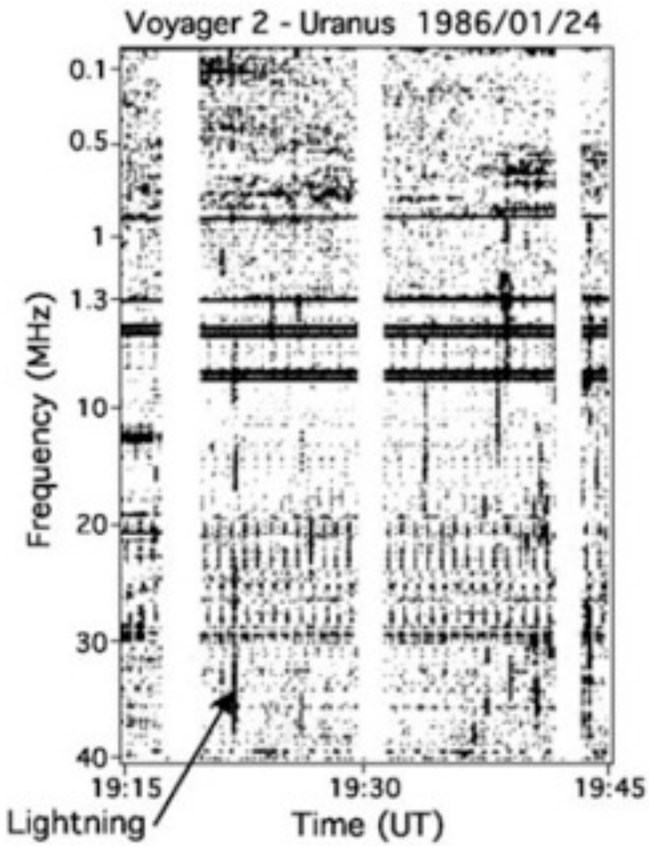
Uranus

- « Uranus electrostatic discharges » detected by Voyager 2 in 1986

[Zarka and Pedersen, 1986]

  - weaker intensity than SED, a few W/Hz ⇒ ~0.4 to 40 Jy @ Earth (≲2.5 Jy above 10 MHz)
  - flash duration 30-240 msec
  - steeper spectrum than SED, in ~f^{-2} (flatter below 20 MHz, steeper above 35 MHz)





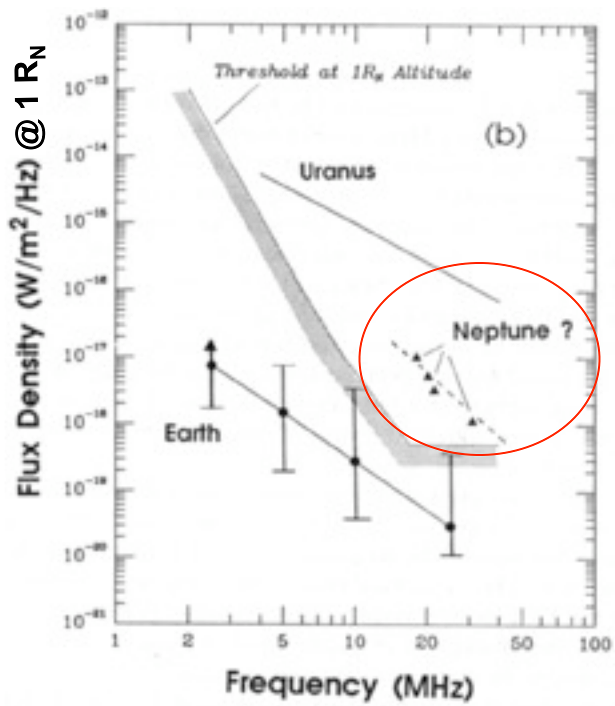
Neptune

- 4 weak events detected by Voyager 2 during flyby

[Kaiser et al., 1991]

(+ a few VLF whistlers detected)

- duration 30-90 msec
- spectrum in ~f^{-4}
- 0.03 - 0.003 Jy @ Earth ?



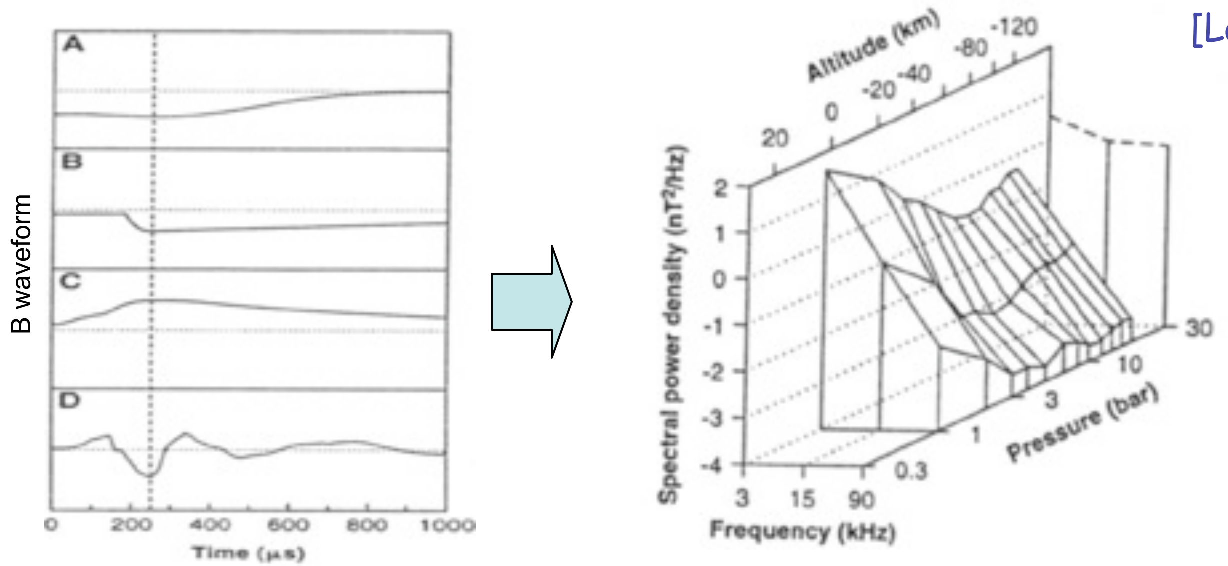
Jupiter

❑ No radio signature of lightning detected by Voyager [Zarka, 1985b]
(but whistlers and optical flashes detected)

❑ No radio detection by Cassini
(but strong magnetospheric decameter noise environment)

❑ Signals with rise time ~msec detected by search coil ≲90 kHz on Galileo descent probe ⇒ tentatively attributed to lightning

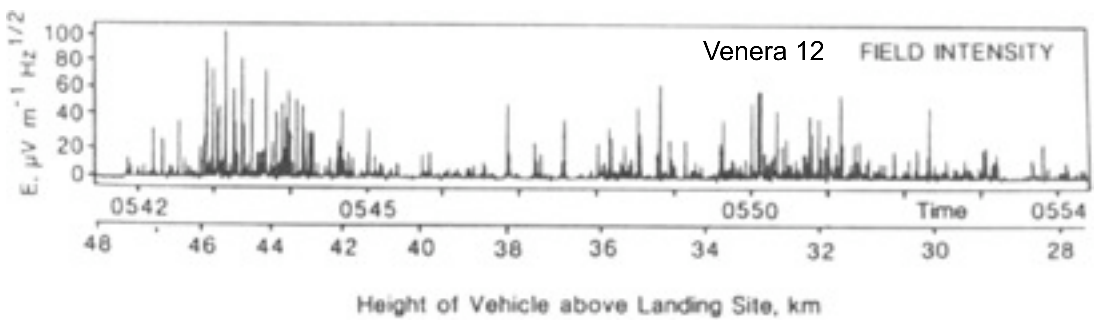
[Lanzerotti et al., 1996]



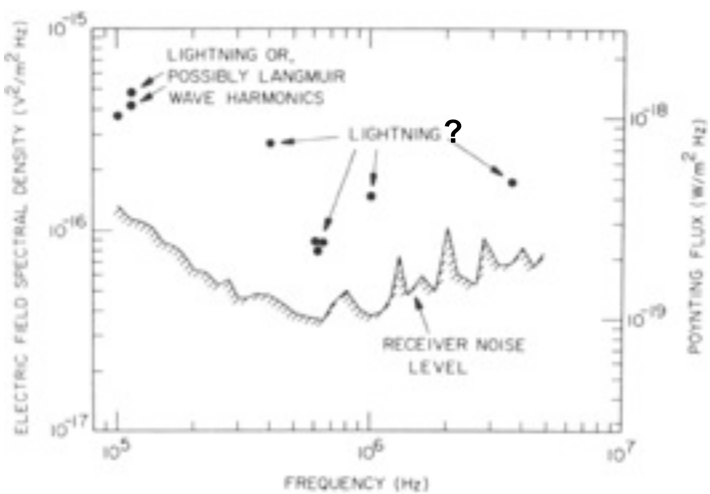
Venus

❑ Controversial optical and radio detections (spurious ?) since 1978-79 (Venera, Pioneer-Venus Orbiter) [cf. Russell, 1991, 1993]

⇒ existence of lightning controversial in the 1990's



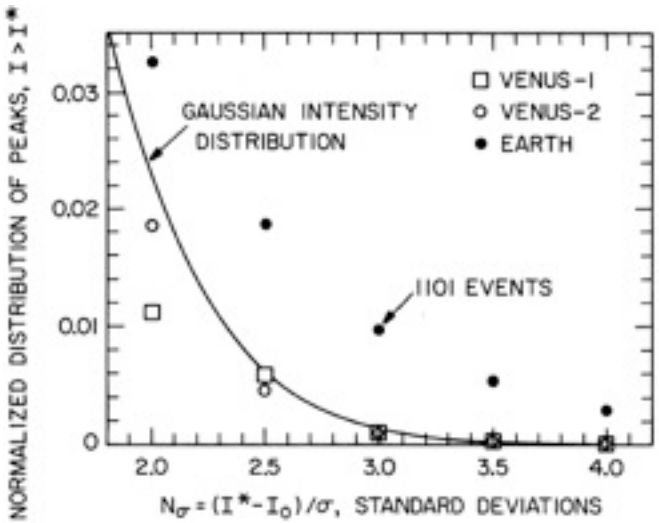
❑ A few isolated spikes observed by Galileo [Gurnett et al., 1990]

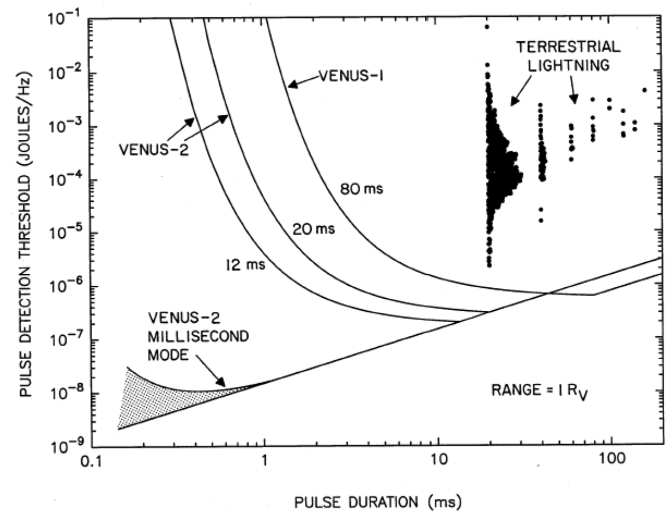


Venus

❑ Cassini Venus flybys in 1998 and 1999 ⇒ no lightning detected by RPWS

❑ Cassini Earth flyby in 1999 ⇒ >1000 flashes detected by RPWS, up to 40 dB >detection threshold





[Gurnett et al., 2001]

⇒ Venus lightning :

- rare (<< 1 flash / hour), or
- very weak (<$10^{-2/-3}$× terrestrial ones), or
- have a very steep spectrum at high frequencies

⇒ Possibly due to very low vertical convection, inhibited by the strong horizontal atmospheric circulation at this planet ?

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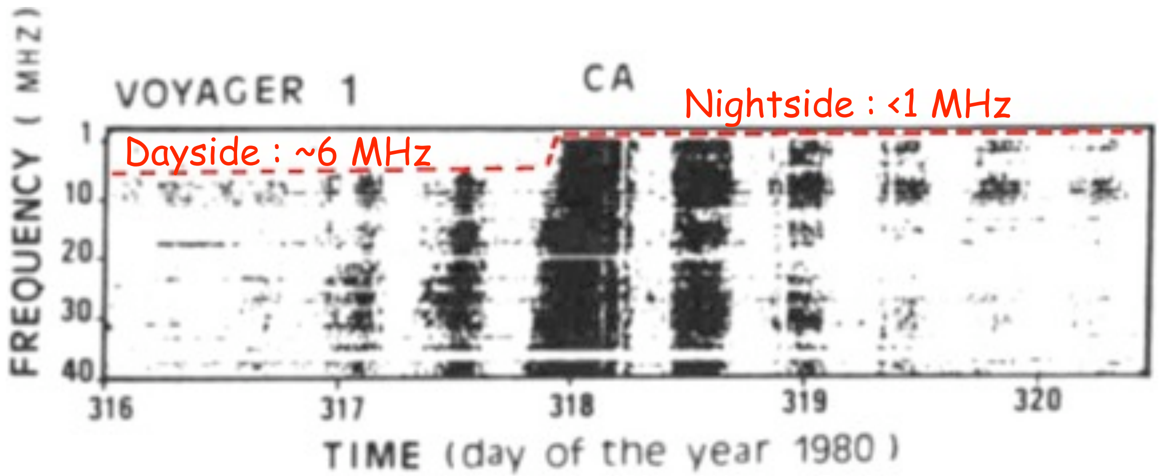
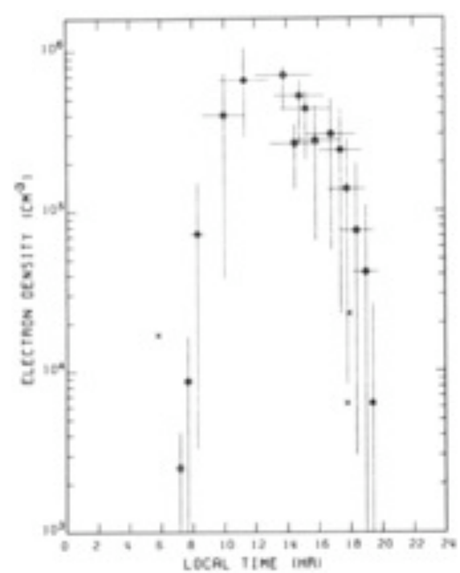
Saturn

- LF ionospheric cutoff day/night [Kaiser et al., 1983; Zarka et al., 1983]



⇒ Ionospheric peak N_e diurnal profile

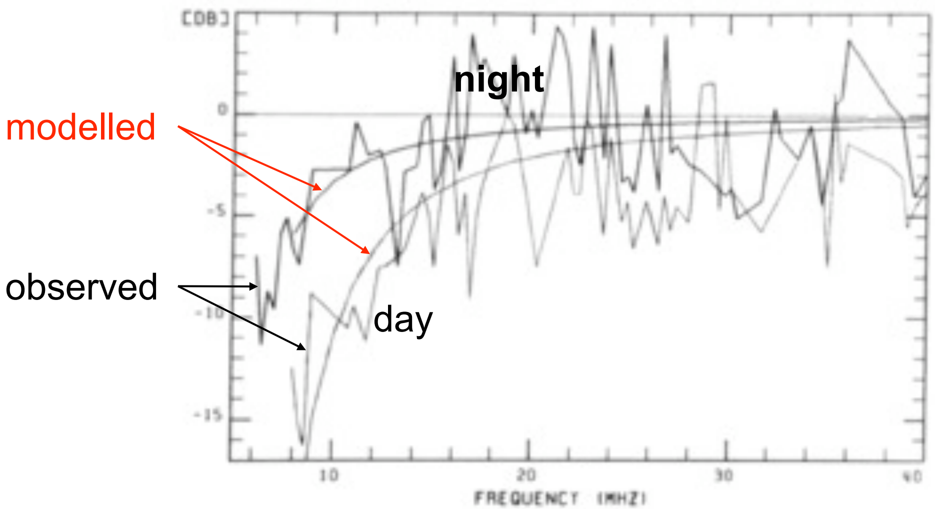
[Zarka, 1985]

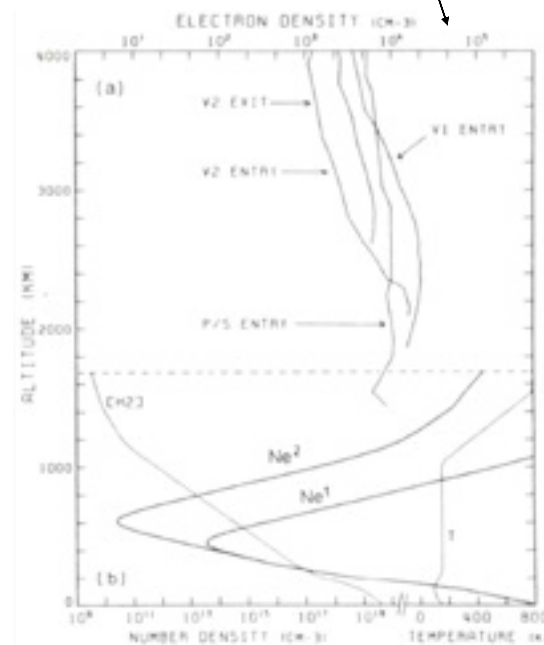


Saturn

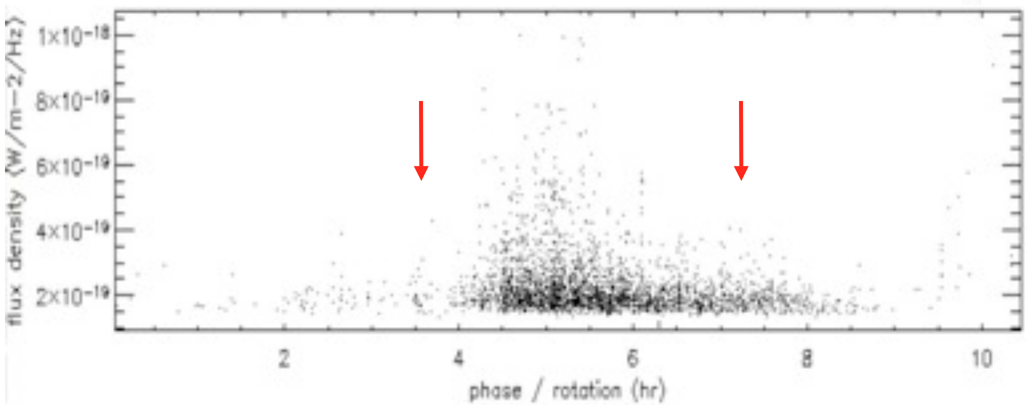
- ❑ Ionospheric absorption ⇒ upper limit on vertical Ne profile

[Zarka, 1985a, 1985b]



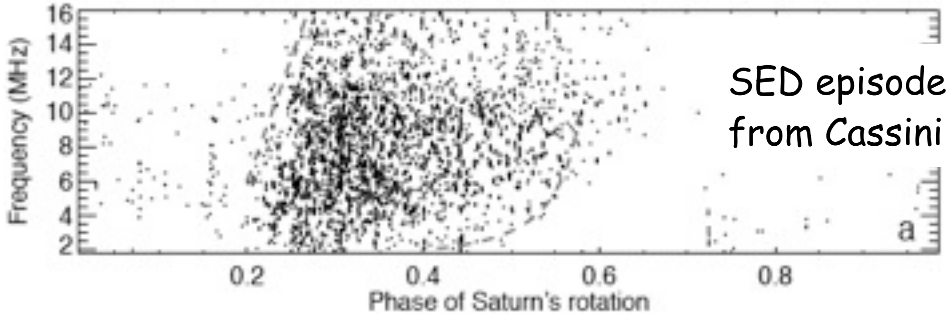


- ❑ Attenuation at episode edges :



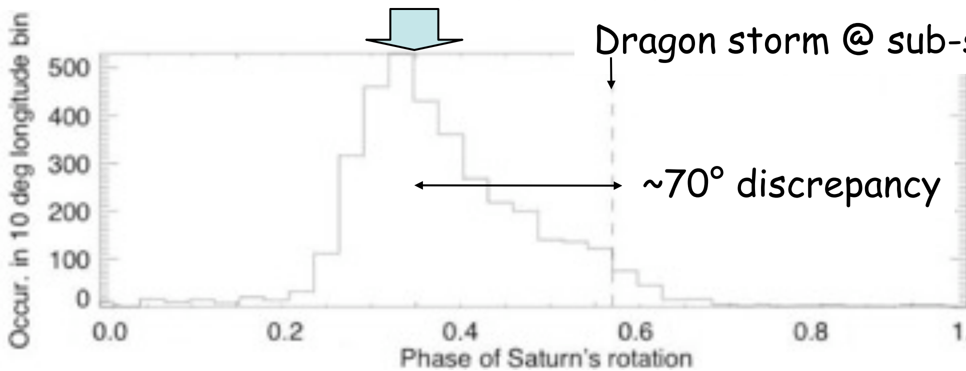
Saturn

- Discrepancy between radio (SED) and optical (Dragon storm) obs.



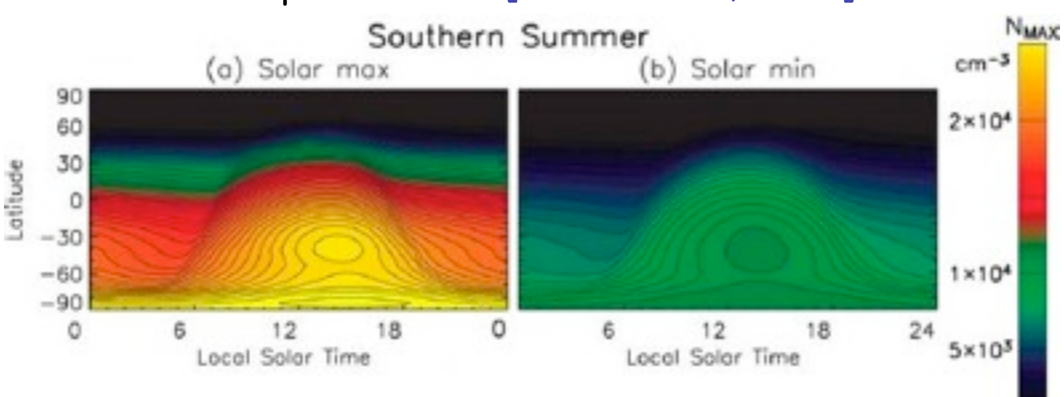
SED episode shape (stacked from Sep. 2004 obs.)
from Cassini @ 06 LT

Dragon storm @ sub-s/c meridian

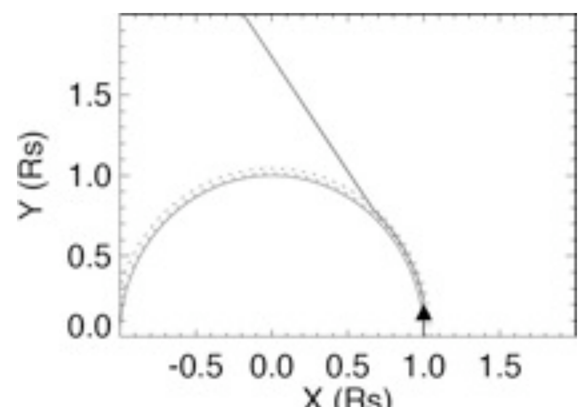


~70° discrepancy

Ionosphere model [Moore et al., 2004]



Radio propagation over the horizon
[Zarka et al., 2006]



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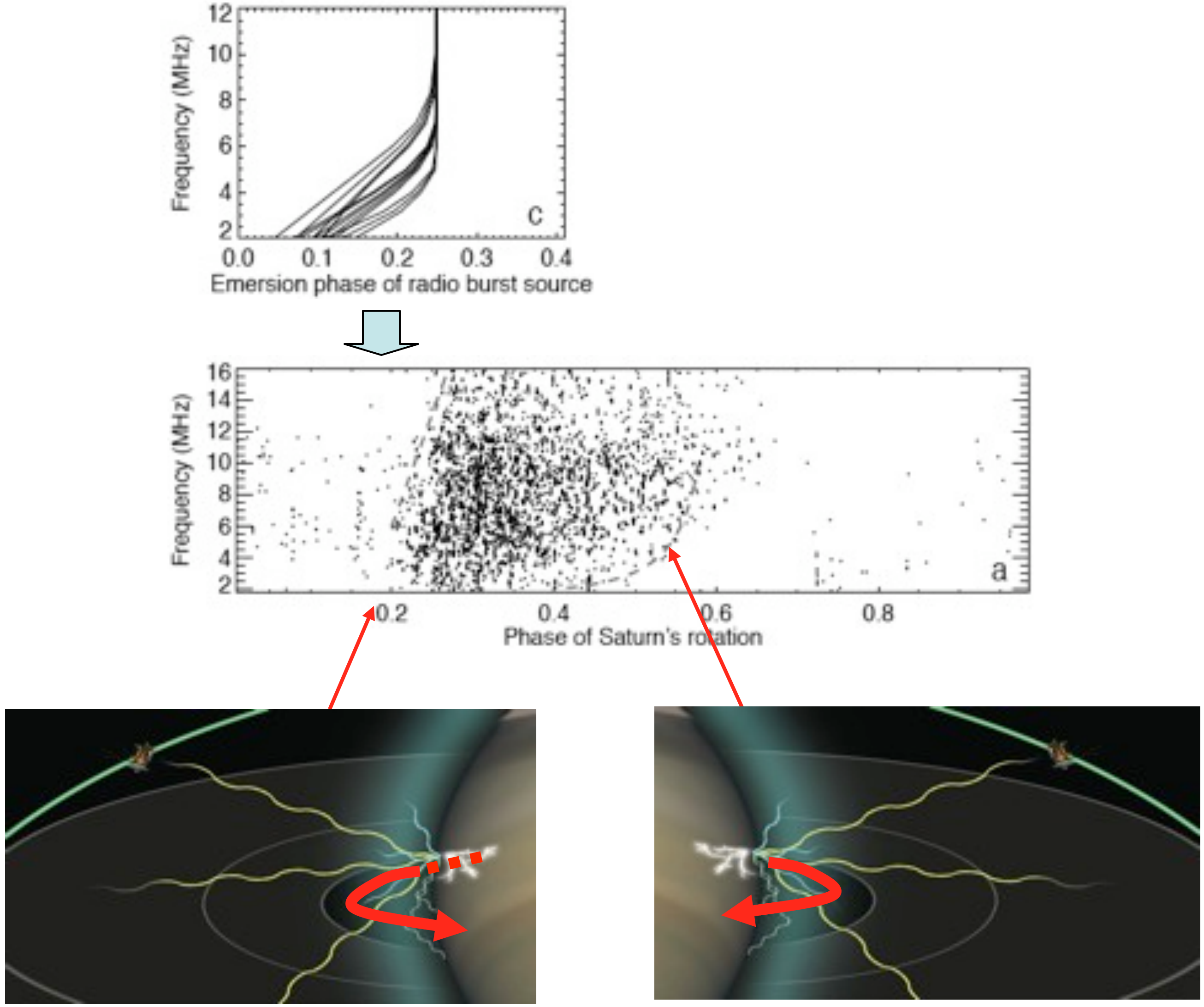


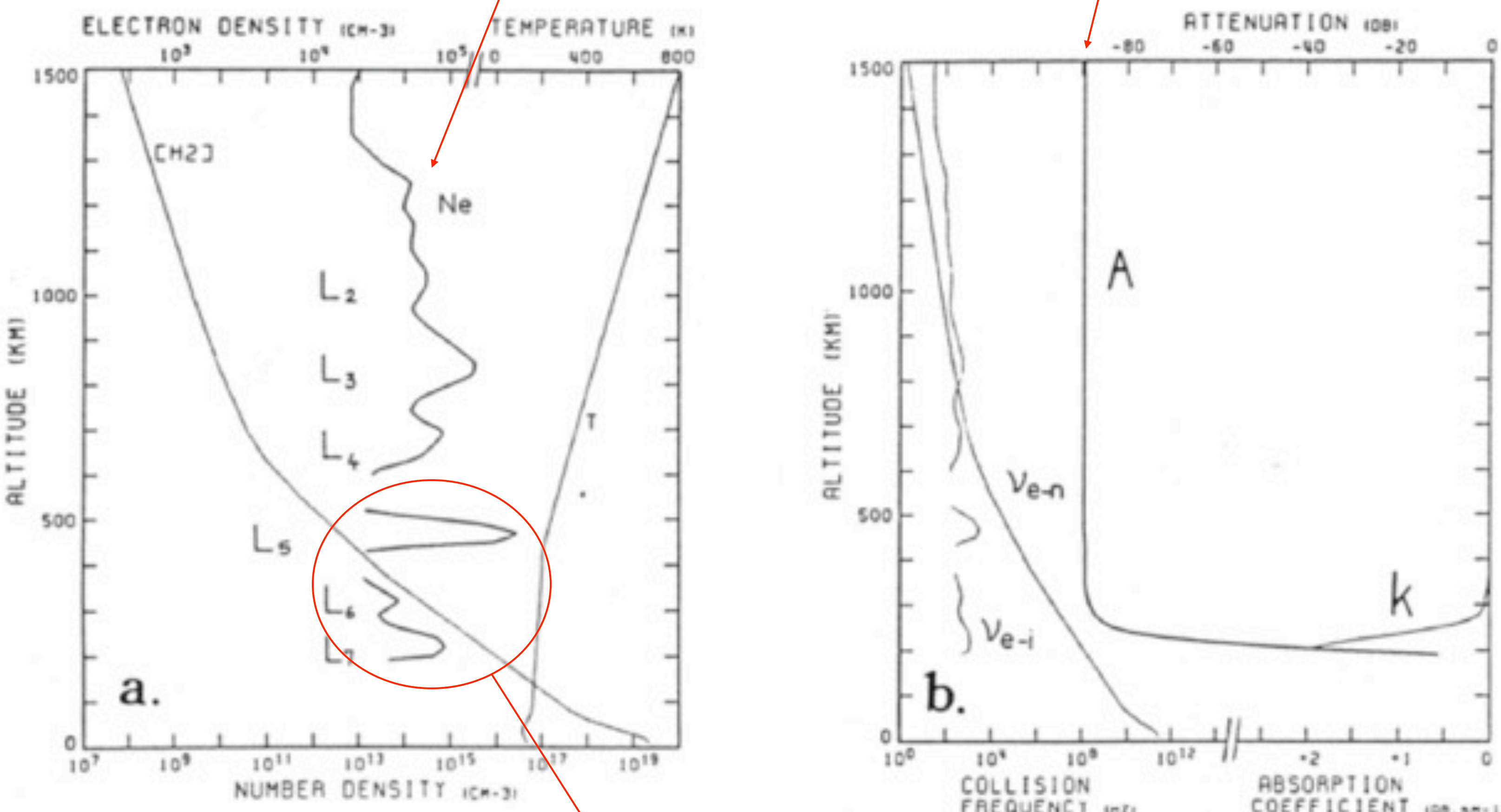
Refraction + propag. over horizon (nightside)

Ionospheric cutoff (dayside)

Jupiter

❑ Low altitude, high Ne ionospheric layers ⇒ large radio attenuation

[Zarka, 1985b]



Meteoritic origin ? (non-permanent ?)

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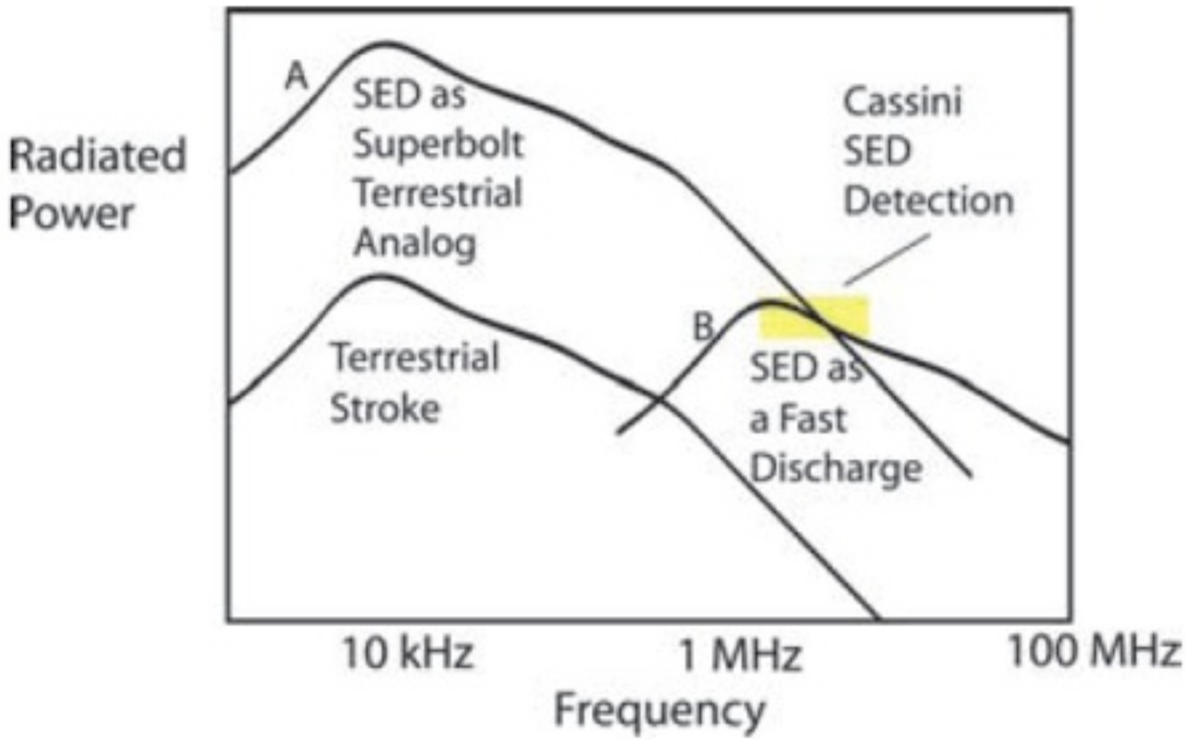
Saturn

- ❑ SED = superbolts (>10^{13} J) if stroke duration ~ terrestrial (~100 μs)
- ❑ SED = weak energy ($10^{3\text{-}6}$ J) if fast discharge (≤1 μs)

[Farrell et al., 2007]

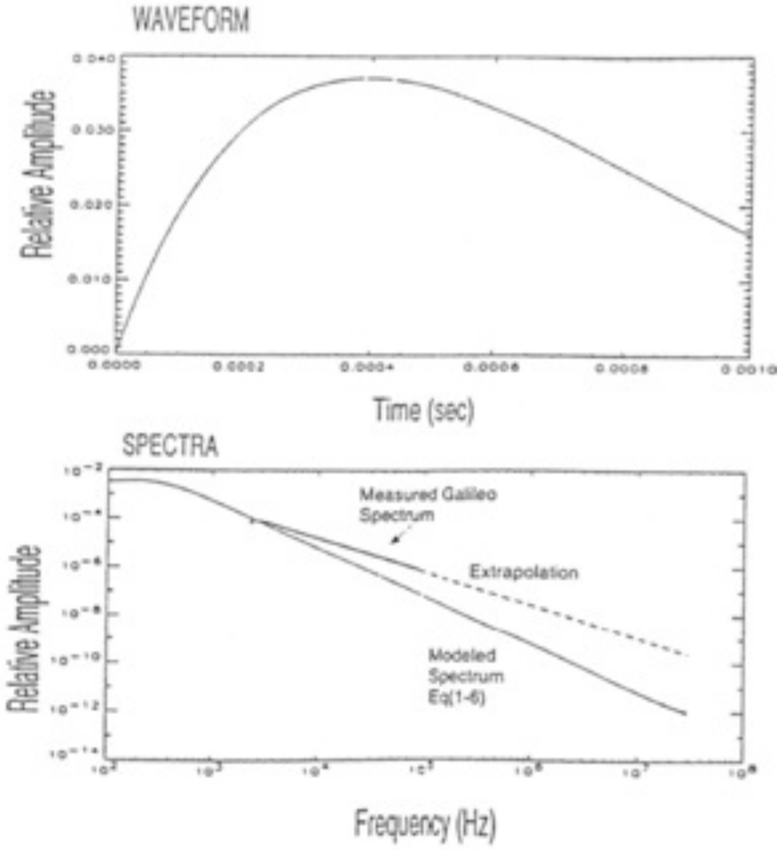


- ❑ same for Uranus ?

Jupiter

❑ If slow discharge (~a few msec, cf. Galileo probe) ⇒ possibly no HF emission, explains absence of Jovian radio lightning

[Farrell et al., 1999; Farrell, 2000]



❑ same for Venus ?

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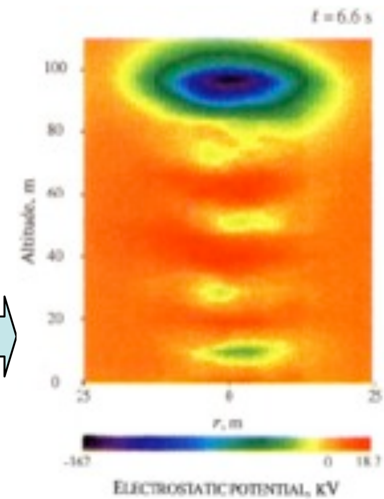
Electrostatic fields in dust devil/storms

- No lightning ever detected on Mars (little searched for)

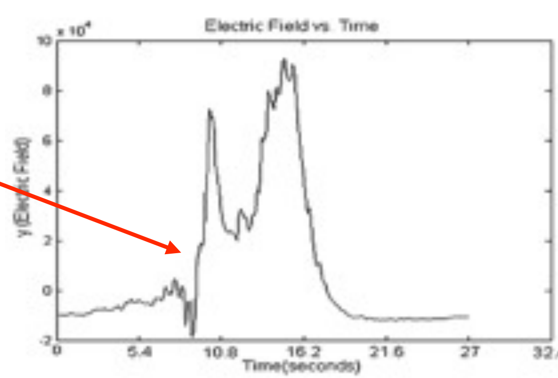
- Existence of dust storms ⇒ Dust charging and substantial electric field build-up not excluded [Farrell et al., 1999]

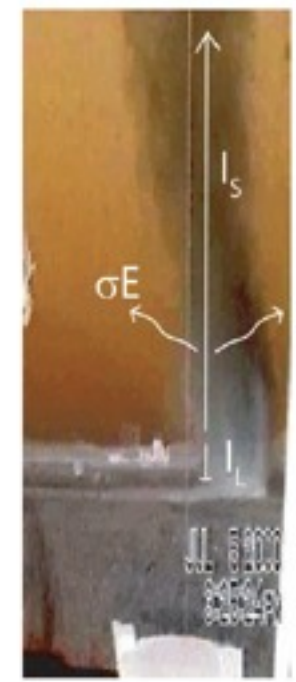
- PIC-codes modeling show that large charge centers and potentials develop due to mass/charge vertical stratification in dust devils [Melnik and Parrot, 1998]



- Dust devils on Earth have coherent E-fields exceeding 100 kV/m

[Freier, 1960; Crozier, 1964; Delory et al. 2002; Farrell et al., 2004; Jackson and Farrell, 2006]





igure 1. False color picture of a dust devil in Nevada, ith small-grain, large-grain, and atmospheric dissipation urrents superposed.

Nature of Martian discharge ?

❑ Laboratory experiments : tribo-electrified dust in low pressure Martian-like CO_2 atmosphere found to create a plasma glow discharge + filamentary discharges to the wall [Eden and Vonnegut, 1973; Mills, 1977]

- Glow discharge: from electron impact excitation of CO_2 in collisional plasma ⇒ sprite-like
- Filamentary discharge: Full breakdown analogous to terrestrial C-G lightning (breakdown requires secondary electrons to be present : on Mars, possibly cosmic ray sources)

⇒ filament "fast" discharge may be possible (5-50 ns ?)

(corona-like glow discharge may dissipate or bleed off charge centers, reducing amplitude of discharge)

[Farrell et al., 2006]

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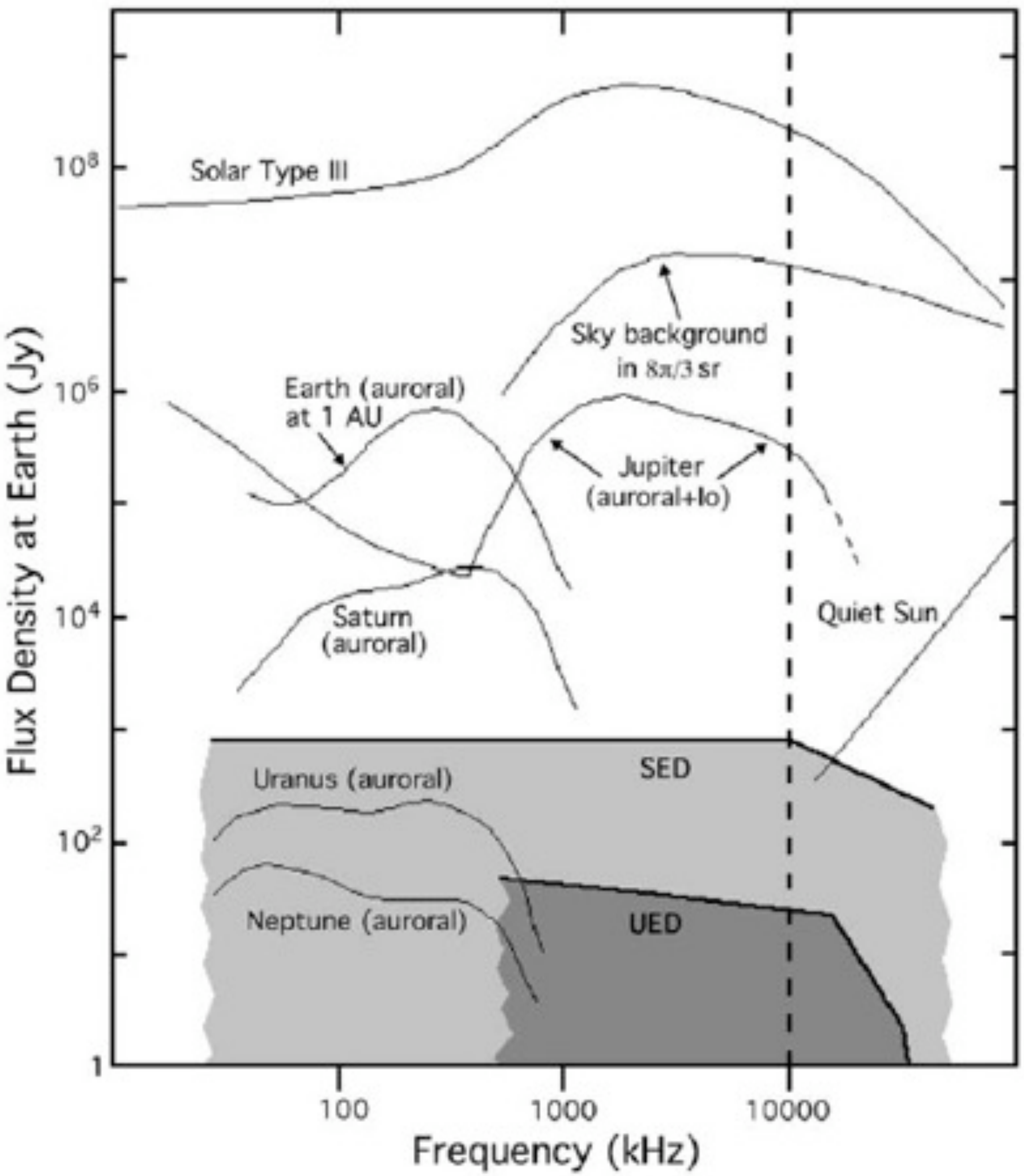
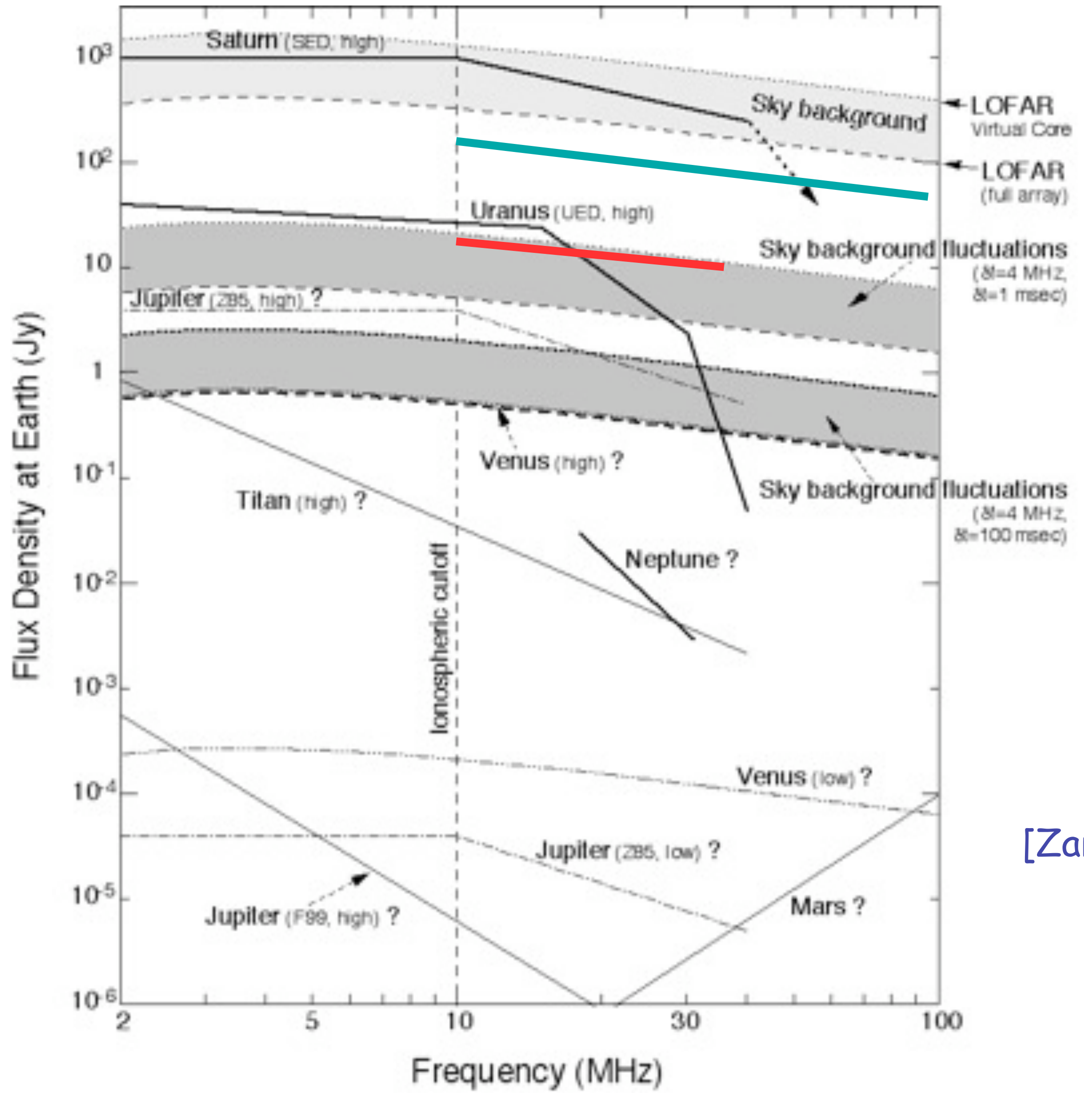
Spectra of Saturn' and Uranus' lightning compared to other natural radio emissions



Summary of radio detectability of all planetary lightning



Nançay DAM array + RDH, 12 MHz, 20 msec

UTR-2, N/S array, 10 MHz, 20 msec

[Zarka et al., 2004]

- Saturn' & Uranus' lightning should be detectable above sky background fluctuations, with a large instrument (as LOFAR)

Previous attempts to detect SED : Nançay

- at 21 Centimeters (Nançay RT) → <u>Negative</u>

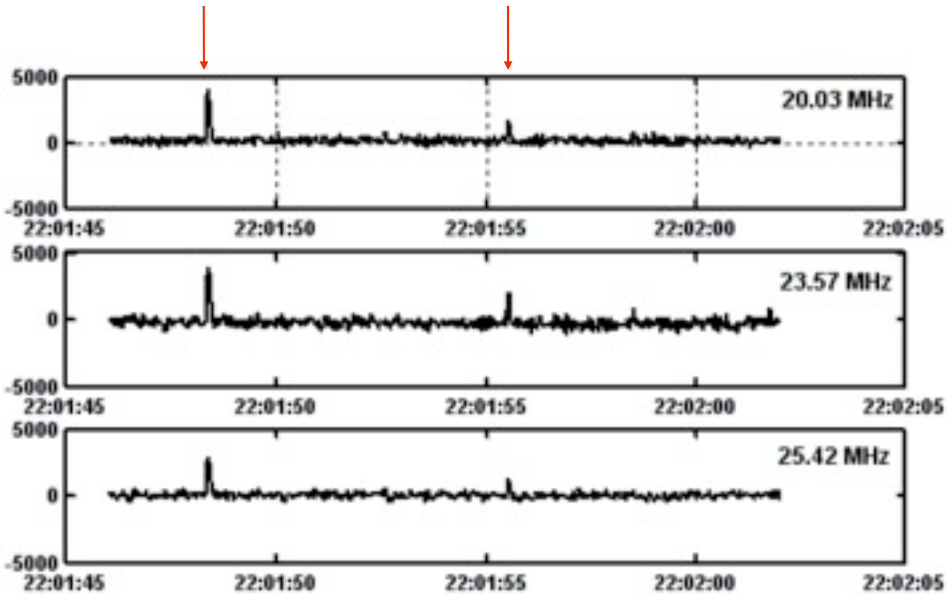
[Lecacheux and Biraud, 1984]

- in the range 14-28 MHz (Nançay decameter array) → <u>Negative/Marginal</u>

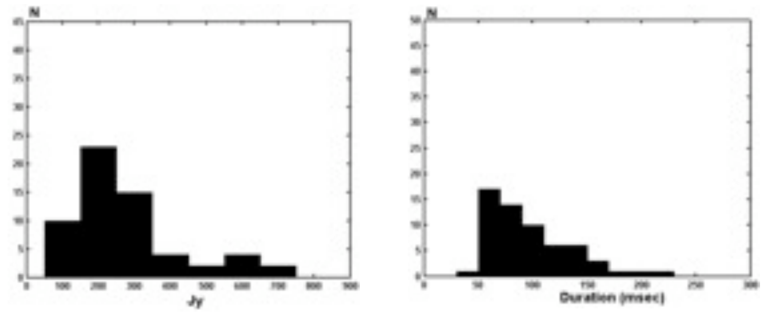
[Zarka et al., 2006]

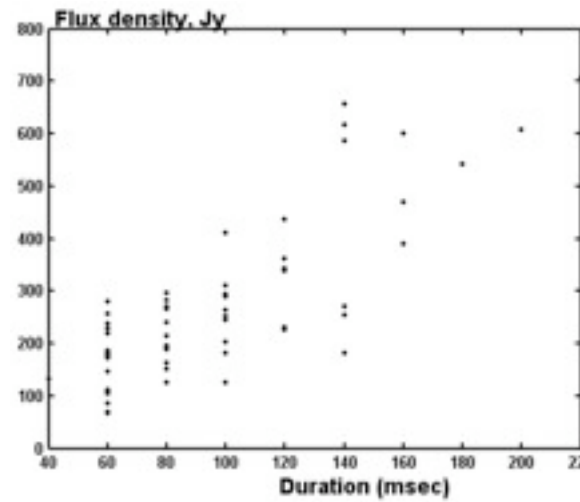
Instrument Name & Location	Description	Frequency range (MHz)	Effective area (m^2)	Beam	Polarisation	Maximum effective sensitivity (Jy)
NDA (Nançay Decameter Array), France	2×72 helix-spiral antennas (rectangular arrays)	10 - 100	~2 × 4000	~ 6° × 10°	2 circular → 4 Stokes	~10^2
NRT (Nançay Radio Telescope), France	« single dish » spherical mirror with rectangular diaphragm	1400 - 3100	~8000	~ 1.5′ x 7′	2 circular → 4 Stokes	< 1

Successful detection at UTR-2



[Konovalenko et al., 2007]





Instrument Name & Location	Description	Frequency range (MHz)	Effective area (m^2)	Beam	Polarisation	Maximum effective sensitivity (Jy)
UTR-2, Kharkov, Ukraine	2040 dipoles (T-shape array)	7 - 35	~140000 (NS: 1800×60, EW: 900×60)	~30' × 10°	1 linear polar. (EW)	10^{0-1}

Future imaging with LOFAR ?

Planet	$Ø_{eq}$ (km)	a (ua)	$Ø_{eq-max}$ ('')
Venus	12140	0.72	60.5
Mars	6790	1.52	17.9
Jupiter	142600	5.20	46.8
Saturne	120200	9.54	19.4
Titan	5150	9.54	0.8
Uranus	49000	19.18	3.7
Neptune	50200	30.06	2.4

Instrument Name & Location	Description	Frequency range (MHz)	Effective area (m^2)	Beam	Polarisation	Maximum effective sensitivity (Jy)
LOFAR (Low Frequency Array), The Netherlands + Europe	Interferometer / Phased arrays of dipoles (core + stations up to 100-1000 km)	10 - 240	$\sim 2\times10^5 \times (15/\nu)^2$	1.5'' $\times(100/\nu)$ [ν in MHz]	4 Stokes	$\leq 10^{-2}$

Prospects for ground-based observations

- Saturn, Uranus: accessible targets for radio lightning search and detection and monitoring with LOFAR, UTR-2, NDA?
- Venus, Titan : existence of lightning ? physical properties ?
- Mars : existence of discharges (dust devils), physical properties ?
- Neptune : transient activity ?
- Jupiter : non permanent low z high N_e layers ? (if fast discharge)

- ❑ Lightning's radio signature
- ❑ Space-based radio observations of planetary lightning
- ❑ Lightning and ionospheric probing
- ❑ Compared temporal & spectral characteristics
- ❑ The case of Mars
- ❑ Prospects for ground-based observations
- ❑ Prospects for space-based observations

Prospects for space-based observations

- Juno : Jupiter's polar atmosphere ?
- Bepi-Colombo : Mercury ?
- New Horizons : Pluto ?
- Kronos (Cosmic Vision proposal) : Titan, Saturn
- Laplace (Cosmic Vision proposal) : Jupiter-Europa orbiter