Lightning at Saturn and Jupiter radiation belts emissions seen by LOFAR

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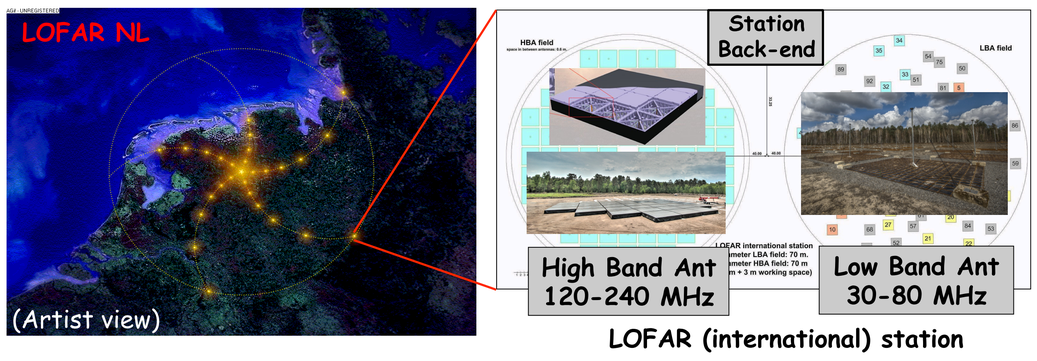
LOFAR the "Low Frequency ARray"

- **New generation radio phased array interferometer and SKA pathfinder.**
- **Operating at low frequencies:** [30-80] & [120-240] MHz.
- **Constituted of ~48 (NL and International) « stations »** in Europe.



LOFAR (international) station

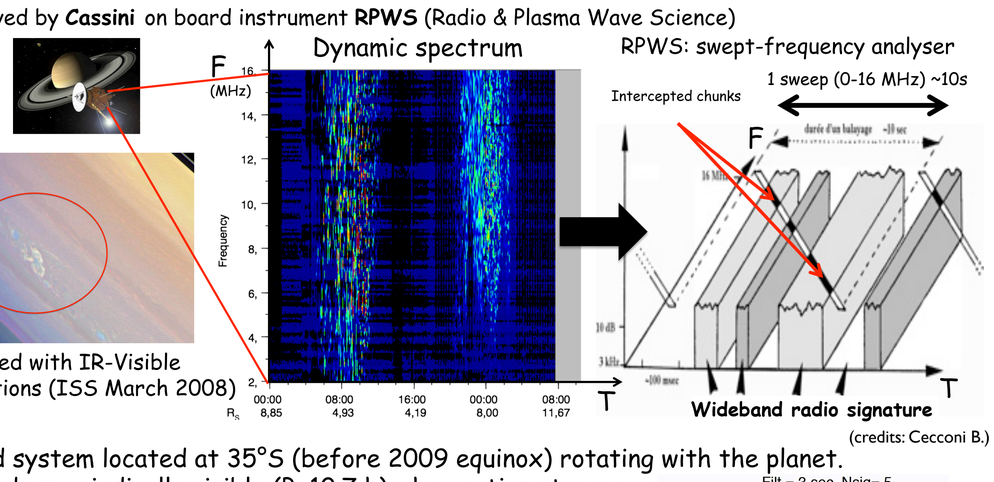
- One station = 2 arrays of digitized and phased (omnidirectional) antennas.
- Signal of stations are processed in BlueGene/P supercomputer in Gronigen Univ.
- LOFAR digital and distributed telescope

operating as a large interferometer (from 100 m to 1500 km baselines in Europe)
as a huge and highly sensitive single dish antenna (« Tied Array Beam »)

with high time (~ns) and spectral (~kHz over 48MHz bandwidth) resolution

Ligthning at Saturn ("SED" - Saturn "Electrostatic" Discharges)

First discovered in radio by **Voyager** (Warwick et al., 1981)
Observed by **Cassini** on board instrument **RPWS** (Radio & Plasma Wave Science)



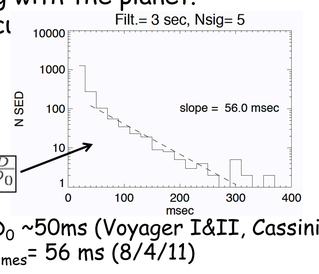
Correlated with IR-Visible observations (ISS March 2008)

(credits: Cecconi B.)

- Cloud system located at 35°S (before 2009 equinox) rotating with the planet.
- Episodes periodically visible (P~10.7 h) when active storm occu

Properties of SED

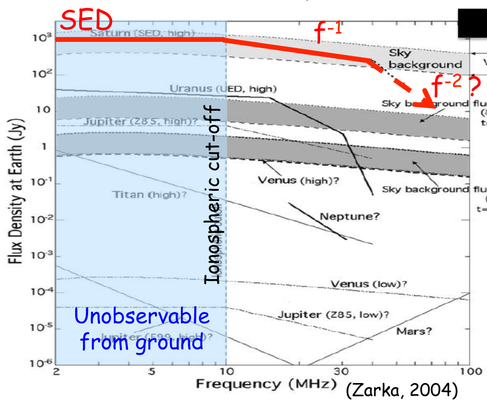
- Wideband & unpolarized energetic bursts
- Bursts duration: few ms to 100s ms
- Spectrum: up to ≥40 MHz
  decreases as f^{-1}, f^{-2}(?)



$N = N_0 e^{-\frac{D}{D_0}}$

e-folding duration D_0 ~50ms (Voyager I&II, Cassini)
$D_{0\ mes}$= 56 ms (8/4/11)

LOFAR Detectability of SED



(Zarka, 2004)

SED flux densities at earth

SEDs @ Earth ~ 10-1000 Jy

$T_{sky} \approx \frac{1,15.10^8}{f^{2.5}}$ (van Haarlem, 2001)

$\sigma_{sky} = \frac{2k_b T_{sky}}{A\sqrt{b\tau}}$

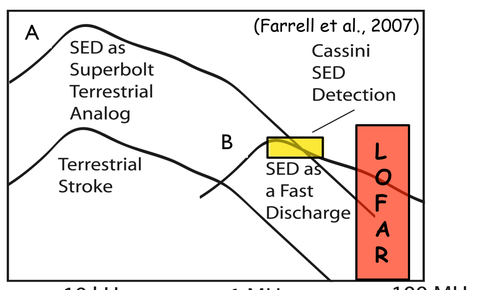
$A_{1\ Core\ LBA\ Station} \sim 48\lambda^2/3$

$N_{stations}$	f	b	τ	σ_{sky}	exp. SNR
1 station	30 MHz	195 kHz	82µs	10^4 Jy	≤1
10 stations incoh sum	30 MHz	6 MHz	20ms	37 Jy	0.3-30
5 stations coh sum	20 MHz 67 MHz	195 kHz	9.1ms	233 Jy 126 Jy	~4.3 ~0.1

Expected SNR for different t-f integrations

Why LOFAR is interesting for SED studies

Radiated Power



Cassini data can't distinguish between two scenarii (Farrell et al. 2007)

→ **scenario A**: SED are « superbolts » with the same spectral content but with much higher energetic strokes.

→ **scenario B**: SED are fast discharges with the same energetic content but with much shorter strokes.

➡ LOFAR detection (and non detection) of SED in the LBA range distinguish between scenarii.

Data processing

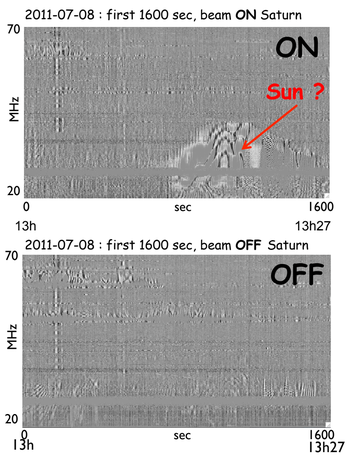
Cassini Data

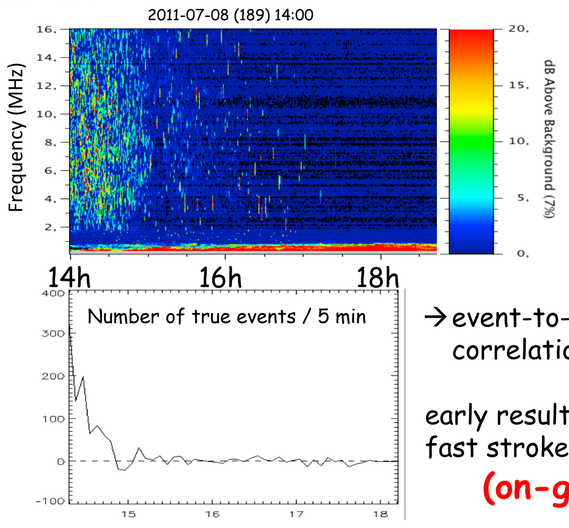
➔ List of detected events within frequency sweeps tagged at only ~10s resolution
➔ Increased time resolution by knowing duty cycle durations in each channel ➔ event tagged at **~10 ms**

LOFAR Data (Tide array beam mode ON & OFF beam)

➔ Cleaning RFI from high-res t-f (dt=82µs, df=195kHz) and time rebinning to 9ms on clean bands
➔ Detecting events > 3σ in both ON & OFF beam
➔ Rate of « true » events $\Delta N_{true} = N_{ON} - N_{OFF}$ per 5 min.

Data after cleaning





→ event-to-event correlation…

early results suggest fast strokes…

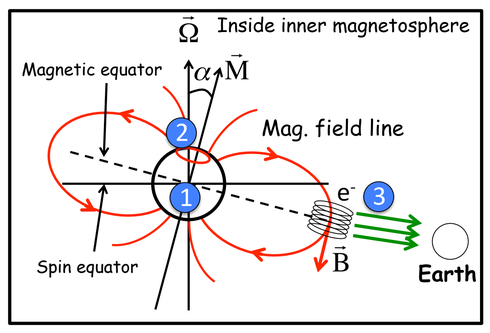
(on-going !)

Jupiter radio emissions

$\vec{\Omega}$ Rotation vector • rotation period= 9h55m27s

$\vec{M}$ Magnetic dipole • tilted from rotation axis α≈9.4°
• toward longitude λ_{III}≈210°

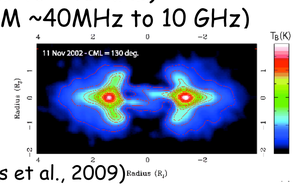
$\vec{B}$ Magnetic field
4.29 G (>>B_{earth} = 0.312 G)



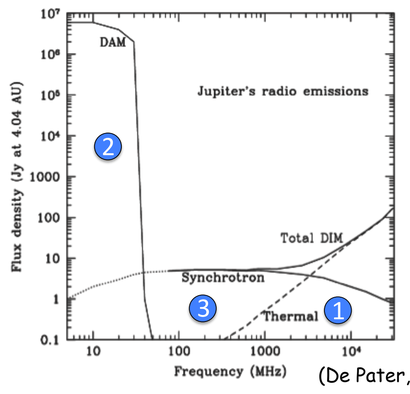
Main radio emissions at Jupiter

1) Planet: thermal emission in the mm-cm range.
2) Auroral : Cyclotron emission in the decameter range (DAM ~5MHz to ~40MHz)
3) Radiation belts: synchrotron emission in the decimeter range (DIM ~40MHz to 10 GHz)

→ from high energy particles (100s of keV → MeV)
→ essentially equatorial emission with high latitudes components
→ optically thin
→ strechted out to ~10 Rj

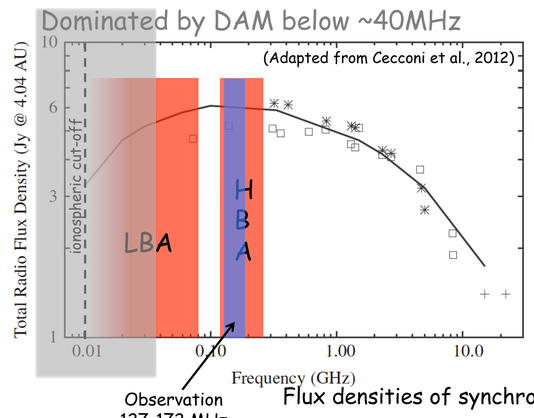


(Santos-Costas et al., 2009)



(De Pater, 2004)

Why LOFAR is interesting for Jupiter



- **model** Santos-Costa et al., 2008
+ Mar 91
✳ Jun94
☐ Sep 98
} De Pater et al., 2003

Fig. 4. Radio spectrum of Jupiter's synchrotron radiation in the [0.01–15] GHz frequency range. The simulated spectrum (solid line) was computed by combining a synchrotron simulation code with a particle diffusion transport model (e.g., Santos-Costa and Bolton, 2008). The cross symbols represent data taken in March 1991, star symbols for data collected in June 1994, and observations in September 1998 were plotted using the square symbols (e.g., de Pater and Dunn, 2003).

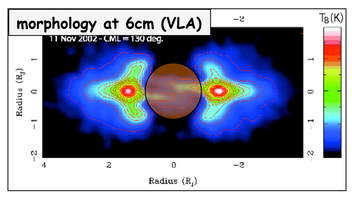
Note: during our observation (10-11 Nov 2011),
$D_{Jupiter-Earth}$ = 3.99 AU
→ expected fluxes have to be increased by ~2%.

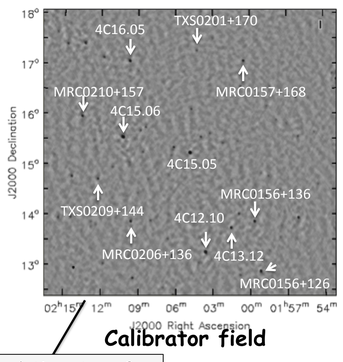
Flux densities of synchrotron emission between 10MHz-10GHz

- Radiation belts observations at VLA, GMRT → unresolved image of Jupiter at 74 MHz.
  → resolved at 6cm, 21 cm
- Now resolved with LOFAR HBA → DIM (& LBA → DAM)
- Negligible thermal contribution at ~100 MHz
- Unveils the morphology of radio emissions at low frequencies
  → Tracking the variation of spatial & energy distribution of particles (ions, e^-)
  → 3D Mapping of radiation belts and magnetic field
  → Monitoring of total flux variability in time-freq (short-term & long-term)
- Improving current models of Jupiter synchrotron emission (Salammbô-3D Santos-Costas, 2008)

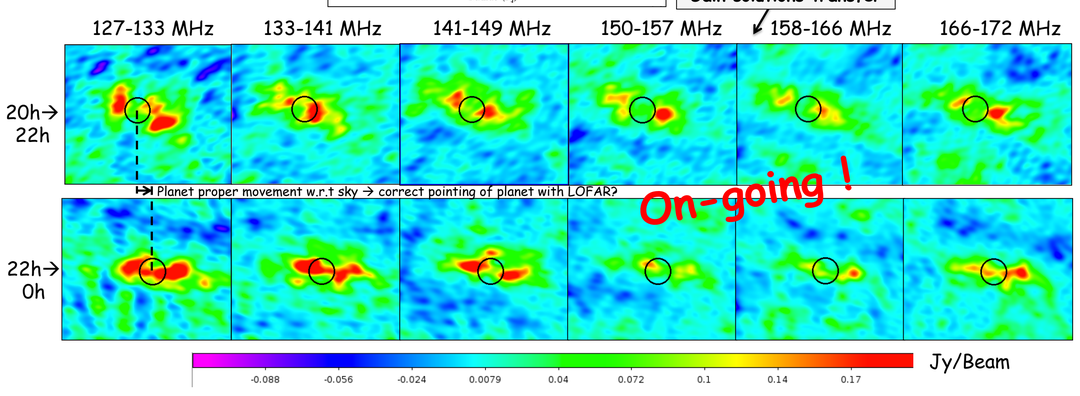
Early results of observation

LOFAR HBA **T_{obs}= 10h (10/11/2011 → 11/11/2011)**
F= 127MHz – 172 MHz
UV-range= 0.2-15 kλ (max = 56kλ not yet included)
Jupiter angular diameter ~49" (black circle = Jupiter position by JPL Horizons)
Beam: 12"x25"
20x195kHz per image





Gain solutions transfer



→ Similar morphology but need some more processing and analysis (variation of mag. equator, residual planet movement, T[0h→6h], …)

Conclusion and future plans

Saturn Lightning

☞ Need of efficient detection of RFI-like signals (event to event correlations with Cassini)
☞ Large statistical study of SED properties over past three LOFAR observations
☞ More observations with coherent summation of more stations when storm resumes.

Jupiter Synchrotron emissions

☞ Instrumental & data processing challenges in planetary imaging
- Variables and moving sources
- Calibration (self-cal, time & direction dependent effects, …)
- Long and very long baseline observations (// to joint obs at higher freq)

☞ High resolution mapping (~arcsec) of radiation belts emissions
- Short scale variability of emission

☞ Imaging with LBA of (low DIM) + High DAM sporadic emissions (Io, non-Io, S-Bursts, …)

References

Zarka P., *Study of solar system planetary lightning with LOFAR*, PSS, 2004

Farrell W. M. et al., *Are Saturn electrostatic discharges really superbolts? A temporal dilemma*, GRL, 2007

De Pater I., *LOFAR and Jupiter's radio (synchrotron) emissions*, PSS, 2004

Santos-Costas D. et al., *Evidence for short-term variability of Jupiter 's decimetric emission from VLA observations*, A&A, 2009