Jupiter's radiophysics unveiled by 2 decades of decameter observations in Nancay

P. Zarka

LESIA, Observatoire de Paris, Meudon

philippe.zarka@obspm.fr

- Discovery of Jovian Radio emissions (DAM) using Mills cross array at 22 MHz [Burke & Franklin, 1955], circularly polarized [Franklin & Burke, 1956]
  → cyclotron emission
- Synchrotron decimeter emission from radiation belts [Sloanaker, 1959]
  → magnetic field and magnetosphere

VARIABLE RADIO SOURCE ASSOCIATED WITH JUPITER 215

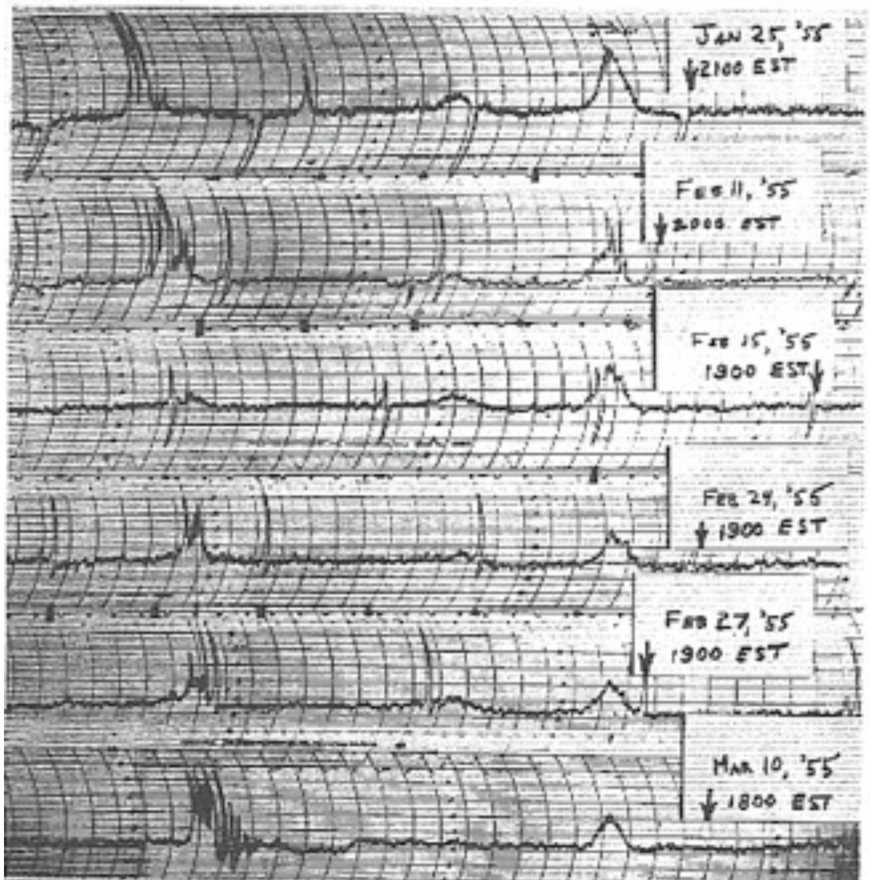
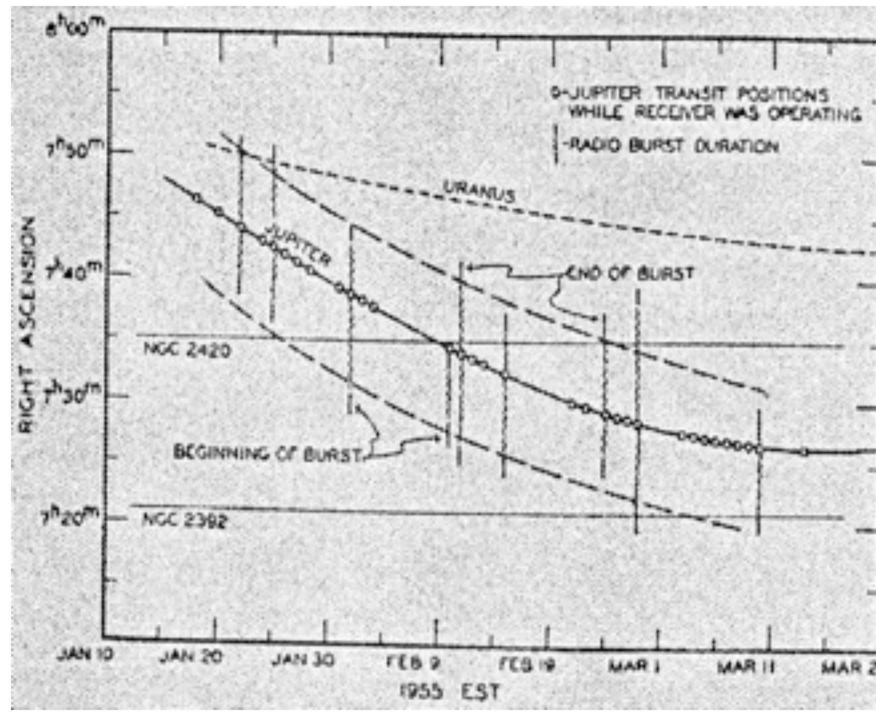
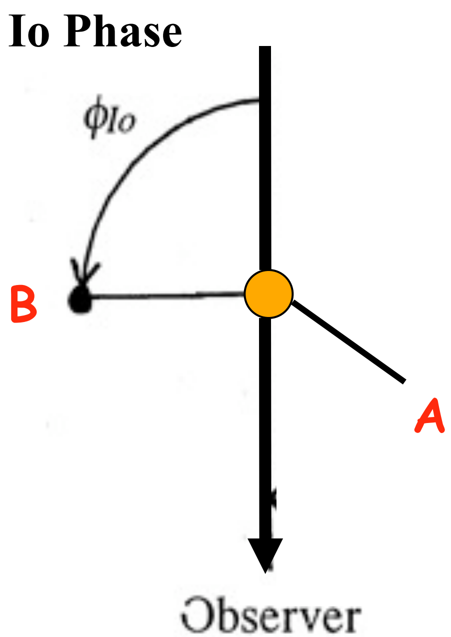


FIG. 2—Phase-switching records showing the appearance of the variable source



- Discovery of Io control [Bigg, 1964]



T_{Io}~42 hours

T_J ~10 hours

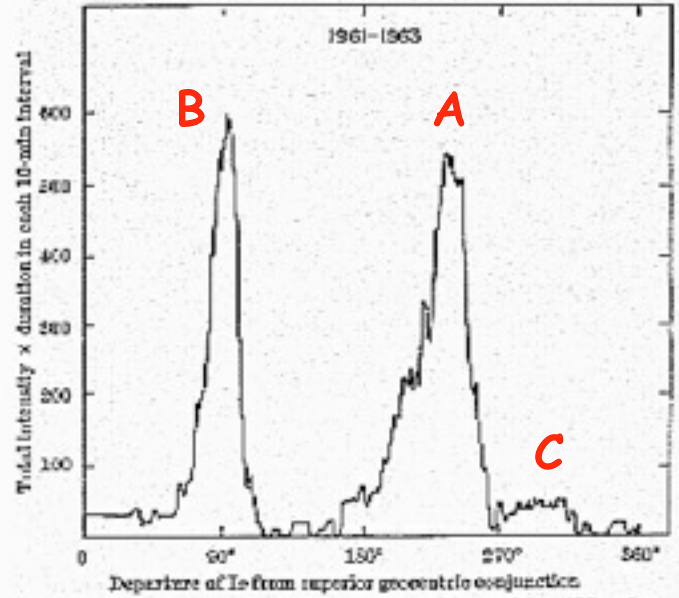


Fig. 4. Dependence of Jupiter's emission on the position of Io when only cases having top frequencies >30 Mc/s are considered

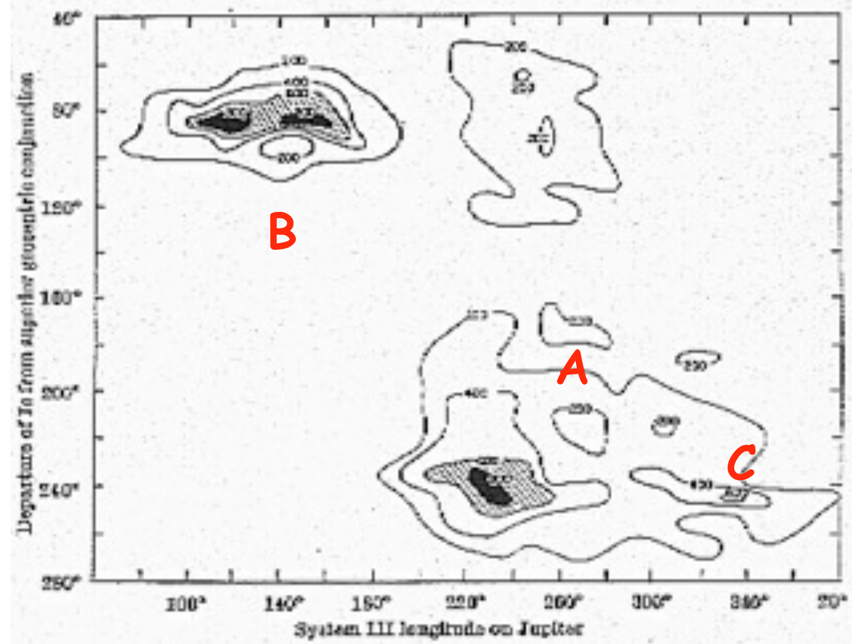
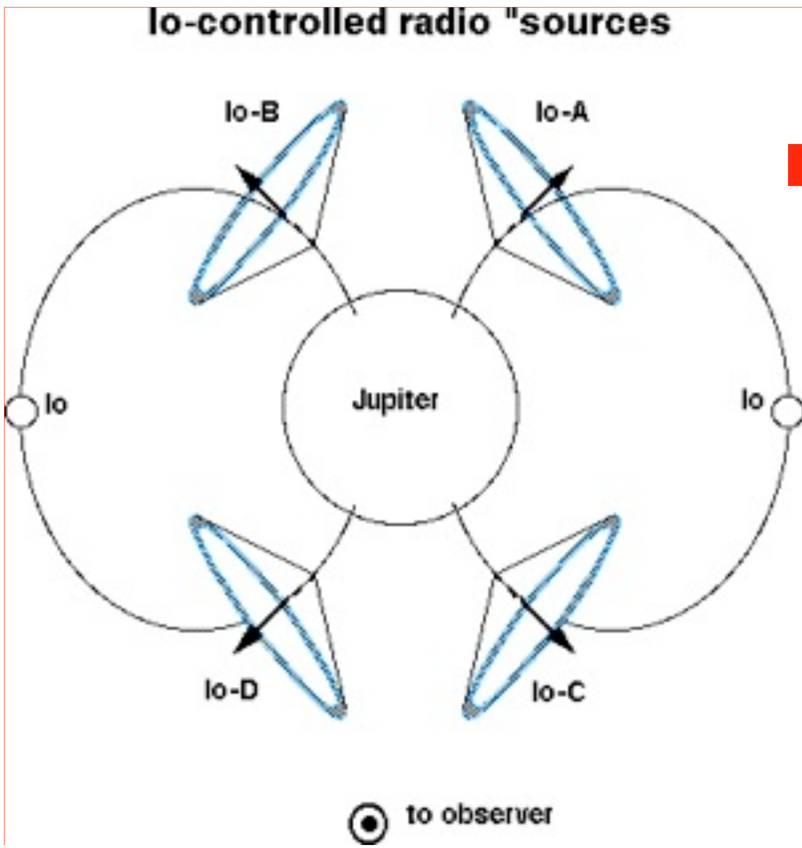
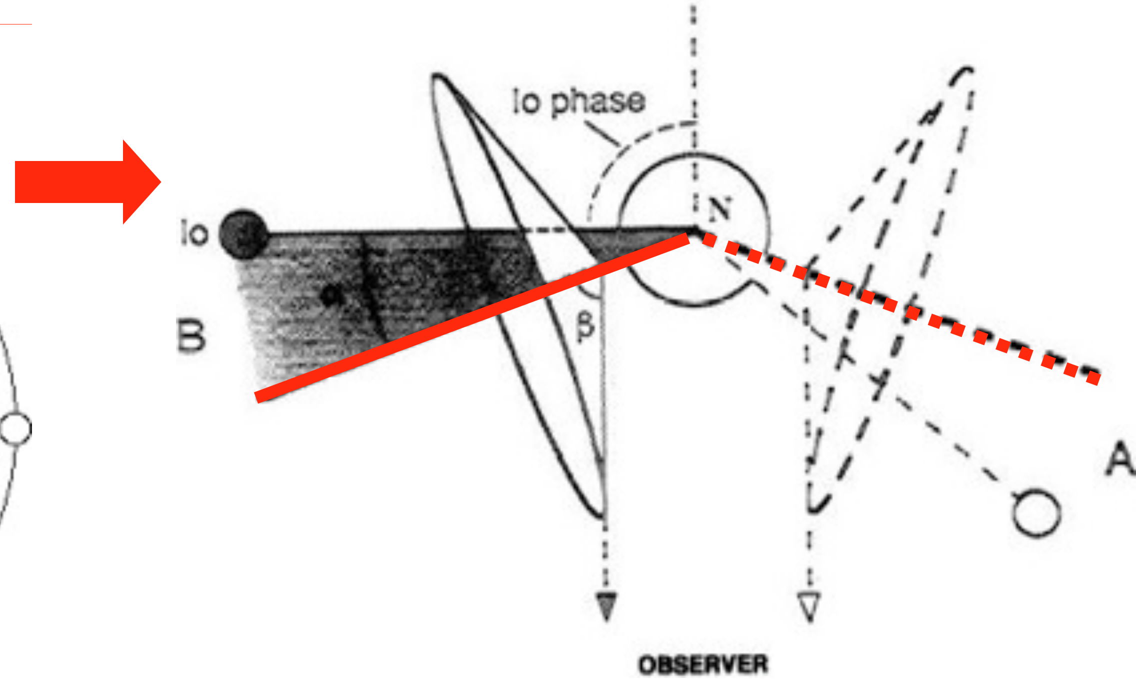


Fig. 5. The relationship between the position of Io and the orientation of Jupiter for the reception of decametric emission at the Earth

- Qualitative interpretation





- We focus here on DAM emission

  (there are also NRT studies of the synchrotron radiation)

- No angular resolution (λ/D)

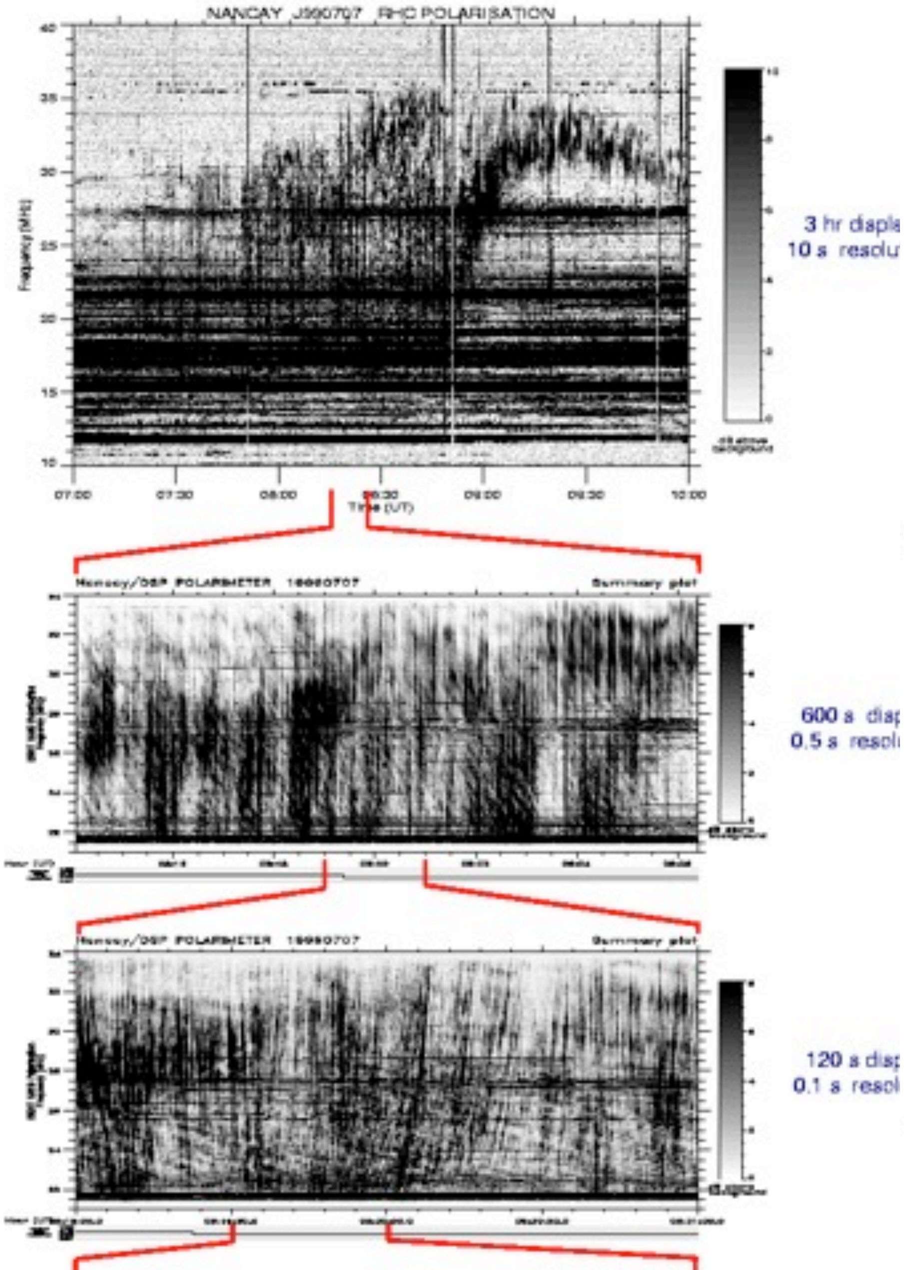
  → spectral studies

- Emission very sporadic, results from many superimposed modulations (seasonal, SW, Io, rotation, short term)

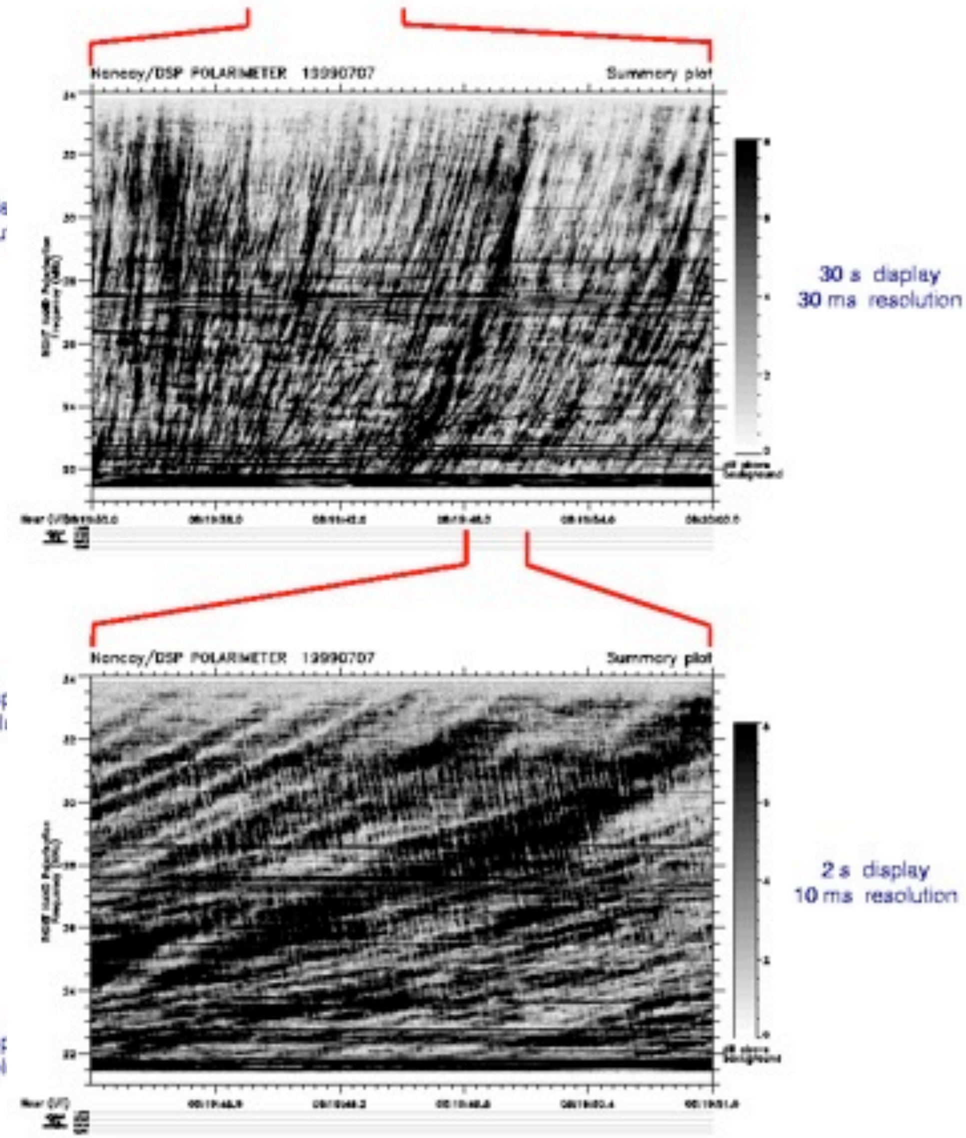
  + propagation effects

  → multi-scale dynamic spectral studies

Nested fringes modulations in Jovian DAM radiation



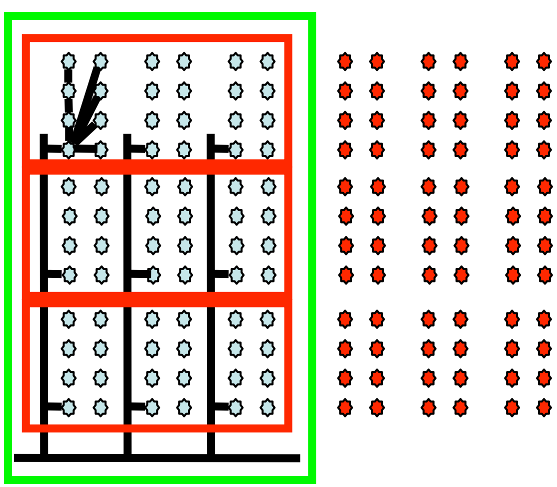
Nested fringes modulations in Jovian DAM radiation (continued)



[Lecacheux, 2004]

- Voyager launch : 1977
- Voyager @ Jupiter : 1978-79
- Nançay Decameter Array : 1977+

[Boischot et al., 1980]

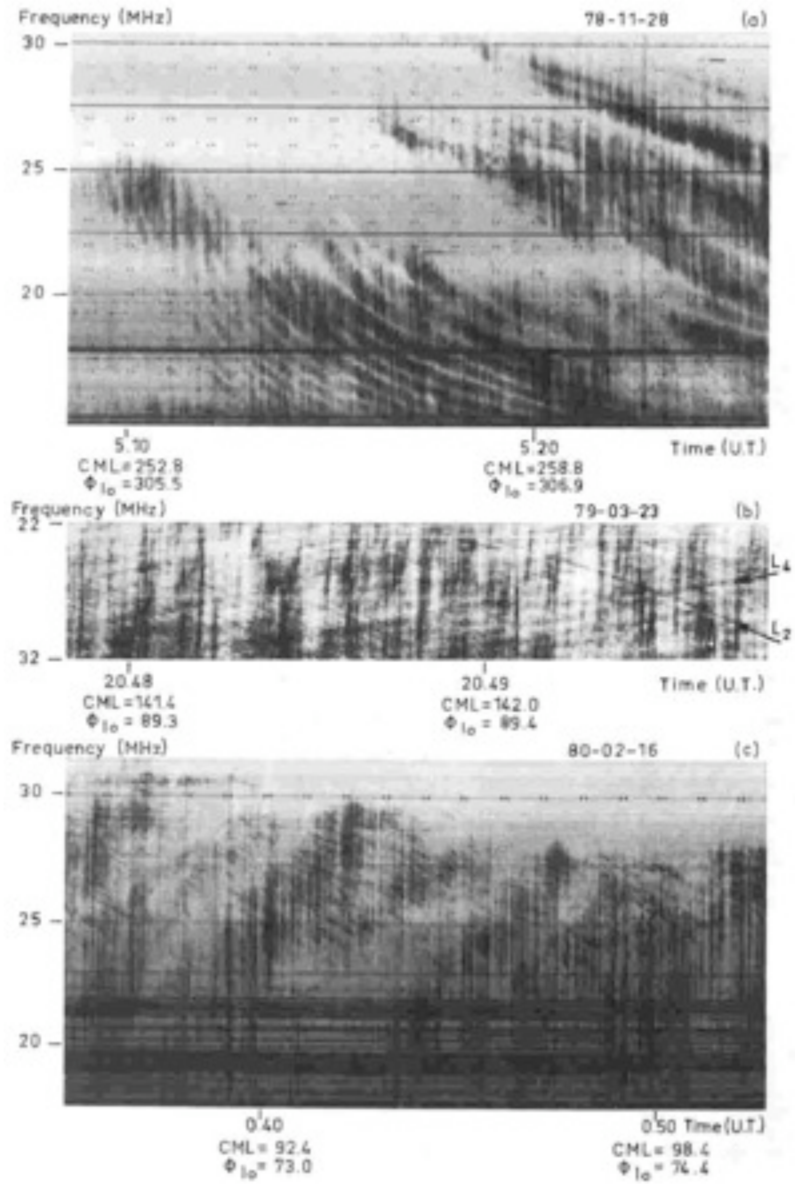


Array specification

- NDA : filled-aperture phased arrays allowing to derive calibrated fluxes
- 144 conical log-spiral antennas (~Clark-Lake)
  72 LHC, 72 RHC, over ~100m×100m field
- 10-120 MHz total band
- Beam of single antenna = 90° half power width
- Phasing scheme : analog beamforming through
  blocks of 8 antennas phased by 45° steps rotation
  + delay lines → Main beam ~6°×10°
  (beamforming optimized over ~1 octave)
- Gain = 25 dB (overall), 15 dB (1 block) , 6 dB (1 antenna)
- $A_e = 24\ \lambda^2 \leq 4000\ m^2$
- Computer-controlled electronic pointing, $-20° \leq \delta \leq +50°$,
  tracking time= meridian transit ±4h

• 4 epochs and corresponding results

(1) Early studies (<1990) : « Routine » on facsimile



→ Catalogs and occurrence rates

[Leblanc & al.]

Y. Leblanc *et al.*

TABLE I. — *Catalogue.*

DATE YY/MM/DD	DOY JJJ	OBSERVATIONS TIME UT HHMM - HHMM	OBSERVATIONS CML III (1965.Ø)	OBSERVATIONS IO PHASE	OBSERVATIONS WIDTH MHZ	EMISSIONS TIME UT HHMM - HHMM	EMISSIONS CML III (1965.Ø)	EMISSIONS IO PHASE	EMISSIONS WIDTH MHZ
78/ 1/ 3	3	193Ø - 24 Ø	24Ø - 51	119 - 157	1Ø - 5Ø	2Ø54 - 2156	299 - 336	131 - 139	1Ø - 3Ø
78/ 1/ 4	4	Ø Ø - 23Ø	51 - 142	157 - 17Ø	1Ø - 5Ø				
78/ 1/ 4	4	193Ø - 24 Ø	39 - 2Ø2	322 - 1	1Ø - 5Ø				
78/ 1/ 5	5	Ø Ø - 23Ø	2Ø2 - 293	1 - 22	1Ø - 5Ø				
78/ 1/ 5	5	193Ø - 24 Ø	189 - 353	166 - 2Ø4	1Ø - 3Ø	1959 - 232Ø	2Ø7 - 328	17Ø - 19Ø	1Ø - 2Ø
78/ 1/ 6	6	Ø Ø - 145	353 - 57	2Ø4 - 219	1Ø - 3Ø				
78/ 1/ 6	6	19 Ø - 24 Ø	322 - 143	5 - 4Ø	1Ø - 4Ø	22 9 - 24 Ø	76 - 143	32 - 4Ø	1Ø - 2Ø
78/ 1/ 7	7	Ø Ø - 2 Ø	143 - 216	46 - 55	1Ø - 4Ø	Ø Ø - Ø39	143 - 167	4Ø - 53	1Ø - 2Ø
78/ 1/ 7	7	19 Ø - 24 Ø	113 - 294	2Ø9 - 251	1Ø - 4Ø	1941 - 2Ø33	137 - 187	215 - 219	1Ø - 35
						2117 - 24 Ø	195 - 294	22Ø - 251	1Ø - 35
78/ 1/ 8	8	Ø Ø - Ø56	294 - 32Ø	251 - 259	1Ø - 4Ø	Ø Ø - Ø56	294 - 32Ø	251 - 259	1Ø - 35
78/ 1/ 9	9	193Ø - 24 Ø	72 - 235	26Ø - 299	1Ø - 5Ø				
78/ 1/1Ø	1Ø	Ø Ø - 23Ø	235 - 326	299 - 32Ø	1Ø - 5Ø	Ø1Ø - 219	241 - 319	3ØØ - 31Ø	1Ø - 2Ø
78/ 1/1Ø	1Ø	193Ø - 24 Ø	223 - 26	1Ø4 - 142	1Ø - 5Ø	2Ø 5 - 2Ø 8	244 - 246	1Ø9 - 1Ø9	1Ø - 13
						2Ø36 - 2242	262 - 339	113 - 131	1Ø - 2Ø
78/ 1/11	11	Ø Ø - 23Ø	26 - 118	142 - 163	1Ø - 5Ø				
78/ 1/11	11	193Ø - 24 Ø	13 - 176	3ØØ - 346	1Ø - 5Ø	232Ø - 233Ø	152 - 158	34Ø - 341	1Ø - 16
78/ 1/12	12	Ø Ø - 13Ø	176 - 236	346 - Ø	1Ø - 5Ø				
78/ 1/12	12	1545 - 24 Ø	137 - 327	145 - 189	1Ø - 4Ø	2Ø37 - 24 Ø	2Ø4 - 327	161 - 189	1Ø - 25
78/ 1/13	13	Ø Ø - 2 Ø	327 - 4Ø	189 - 2Ø6	1Ø - 4Ø	Ø Ø - Ø36	327 - 345	189 - 194	1Ø - 2Ø
78/ 1/13	13	15 Ø - 24 Ø	296 - 11Ø	351 - 33	1Ø - 4Ø	1933 - 2Ø16	316 - 343	355 - 2	12 - 15
						2248 - 23 5	74 - 87	23 - 28	1Ø - 16
						2325 - 24 Ø	96 - 11Ø	28 - 33	1Ø - 3Ø
78/ 1/14	14	Ø Ø - 1 Ø	11Ø - 154	33 - 41	1Ø - 4Ø	Ø Ø - Ø57	11Ø - 152	33 - 41	1Ø - 3Ø
78/ 1/14	14	1845 - 24 Ø	76 - 26Ø	192 - 237	1Ø - 4Ø				
78/ 1/15	15	Ø Ø - 2 Ø	26Ø - 341	237 - 253	1Ø - 4Ø				
78/ 1/15	15	15 Ø - 24 Ø	237 - 59	36 - 8Ø	1Ø - 4Ø				
78/ 1/16	16	Ø Ø - 1 Ø	59 - 95	8Ø - 89	1Ø - 4Ø				
78/ 1/16	16	15 Ø - 24 Ø	2Ø - 2Ø9	241 - 284	1Ø - 4Ø				
78/ 1/17	17	Ø Ø - 2 Ø	2Ø9 - 292	284 - 3Ø1	1Ø - 4Ø				
78/ 1/17	17	1745 - 2153	133 - 293	74 - 1Ø9	1Ø - 4Ø	193Ø - 2153	197 - 283	89 - 1Ø9	1Ø - 27
78/ 1/18	18	1745 - 24 Ø	284 - 151	27Ø - 331	1Ø - 4Ø	18 6 - 1911	298 - 336	241 - 25Ø	1Ø - 23
78/ 1/19	19	Ø Ø - 2 Ø	151 - 223	331 - 348	1Ø - 4Ø				
78/ 1/19	19	173Ø - 2255	65 - 262	115 - 165	1Ø - 4Ø	1839 - 2Ø28	1Ø7 - 173	129 - 144	1Ø - 22
						22 8 - 2253	234 - 261	159 - 165	1Ø - 27
78/ 1/2Ø	2Ø	173Ø - 24 Ø	216 - 92	323 - 19	1Ø - 4Ø	18 6 - 1945	23Ø - 264	32Ø - 334	15 - 2Ø
						2318 - 24 Ø	66 - 92	12 - 18	1Ø - 25
78/ 1/21	21	Ø Ø - 2 Ø	92 - 164	18 - 35	1Ø - 4Ø	Ø Ø - 152	92 - 16Ø	18 - 34	12 - 25
78/ 1/21	21	173Ø - 24 Ø	7 - 242	166 - 222	1Ø - 4Ø				
78/ 1/22	22	Ø Ø - 2 Ø	242 - 315	222 - 239	1Ø - 4Ø				
78/ 1/22	22	1715 - 24 Ø	14Ø - 33	Ø - 65	1Ø - 4Ø	1859 - 22 Ø	211 - 325	23 - 49	1Ø - 3Ø
78/ 1/23	23	Ø Ø - 2 Ø	33 - 1Ø5	65 - 82	1Ø - 4Ø	1 5 - 157	72 - 1Ø4	71 - 82	15 - 25
78/ 1/23	23	17 Ø - 24 Ø	29Ø - 1Ø4	2Ø5 - 269	1Ø - 3Ø	2129 - 213Ø	92 - 93	247 - 248	17 - 2Ø
78/ 1/24	24	Ø Ø - 2 Ø	1Ø4 - 255	269 - 288	1Ø - 3Ø	135 - 145	242 - 25Ø	282 - 284	1Ø - 25
78/ 1/24	24	17 Ø - 191Ø	8Ø - 159	53 - 71	2Ø - 4Ø				
78/ 1/24	24	191Ø - 24 Ø	159 - 334	71 - 112	13 - 33				
78/ 1/25	25	Ø Ø - 2 Ø	334 - 47	112 - 129	13 - 33				
78/ 1/25	25	17 Ø - 24 Ø	231 - 125	256 - 316	1Ø - 4Ø	17 1 - 175Ø	231 - 261	257 - 264	2Ø - 24
78/ 1/26	26	Ø Ø - 2 Ø	125 - 197	316 - 333	1Ø - 4Ø				
78/ 1/26	26	17 Ø - 24 Ø	21 - 275	1ØØ - 159	1Ø - 4Ø	1935 - 1948	115 - 123	122 - 124	15 - 3Ø
						2Ø59 - 211Ø	15Ø - 173	134 - 135	1Ø - 2Ø
						233Ø - 2335	262 - 263	156 - 155	14 - 17
78/ 1/27	27	Ø Ø - 2 Ø	275 - 348	159 - 176	1Ø - 4Ø				
78/ 1/27	27	17 Ø - 24 Ø	172 - 66	3Ø4 - 3	1Ø - 4Ø	1827 - 2Ø Ø	225 - 286	316 - 33Ø	15 - 25
						2119 - 2135	329 - 33Ø	34Ø - 342	1Ø - 15
78/ 1/28	28	Ø Ø - 2 Ø	66 - 138	3 - 2Ø	1Ø - 4Ø	ØØ29 - ØØ35	43 - 87	7 - 8	15 - 25
78/ 1/28	28	17 Ø - 24 Ø	323 - 216	147 - 2Ø7	1Ø - 4Ø	2Ø48 - 21 5	1ØØ - 111	179 - 182	15 - 25

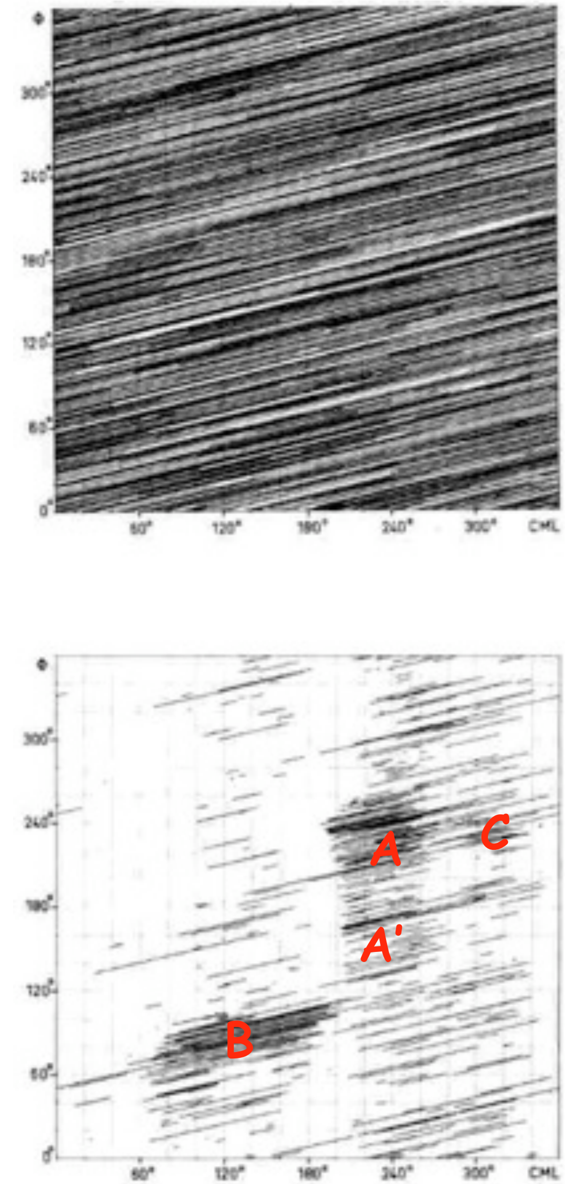
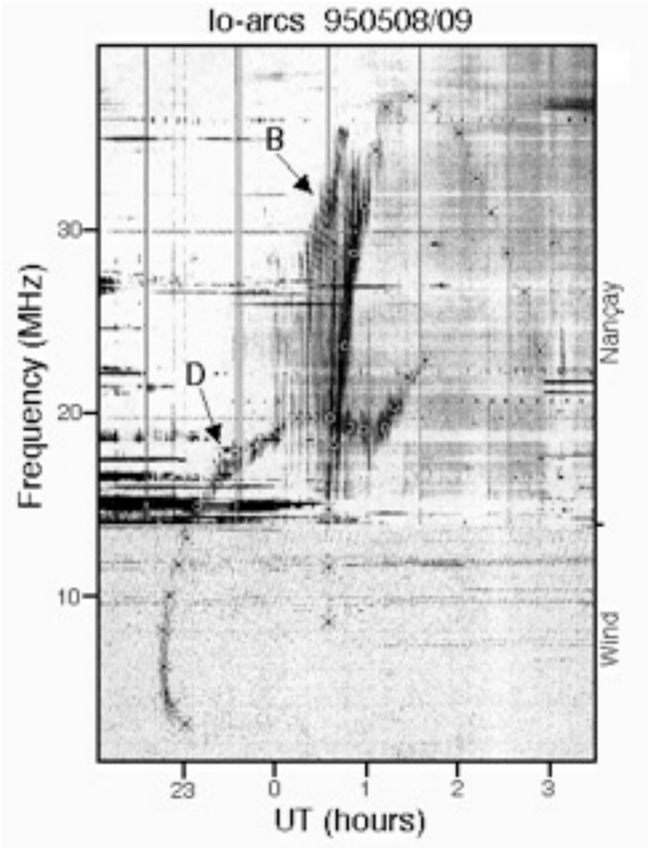
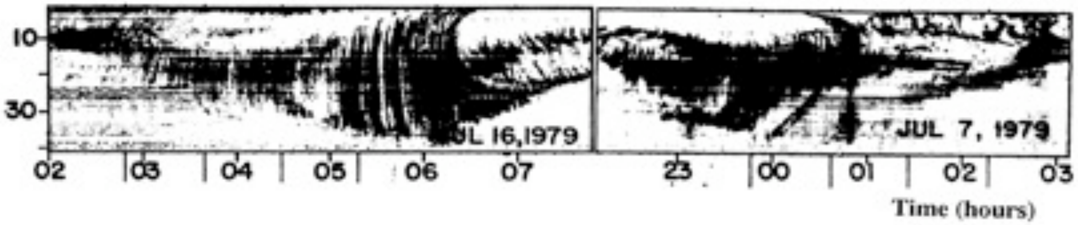


FIGURE 6. — The CML and Io-phase diagram for the period of January 1978 to December 1979. a) the observation tracks ; b) the emission tracks.

→ Radio « arcs » phenomenology :

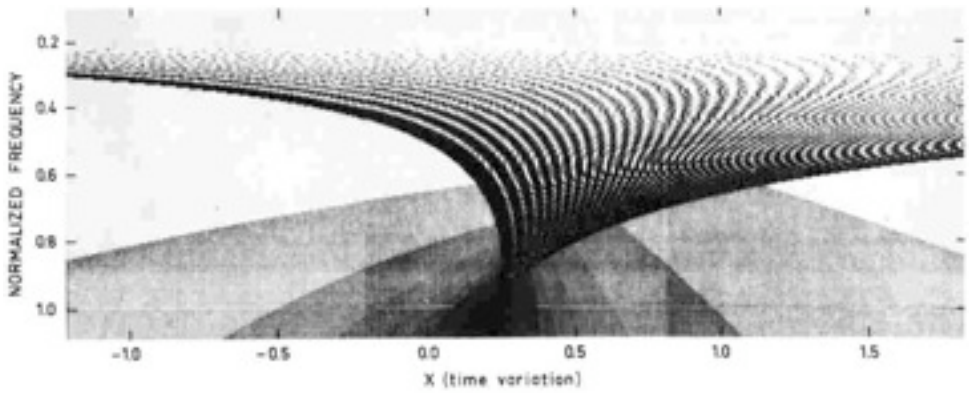


Voyager PRA *Warwick et al. (1979)*

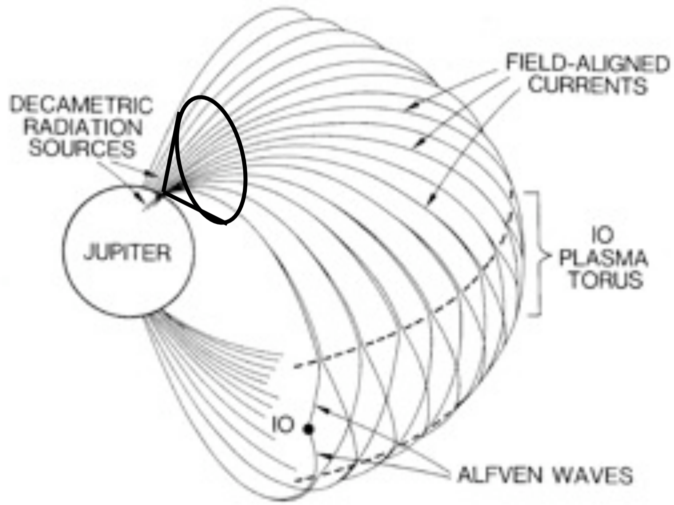


→ Radio « arcs » phenomenology :

Diffraction caustics ? [Lecacheux & al., 1981]



Alfvèn waves ? [Gurnett & Goertz, 1982]



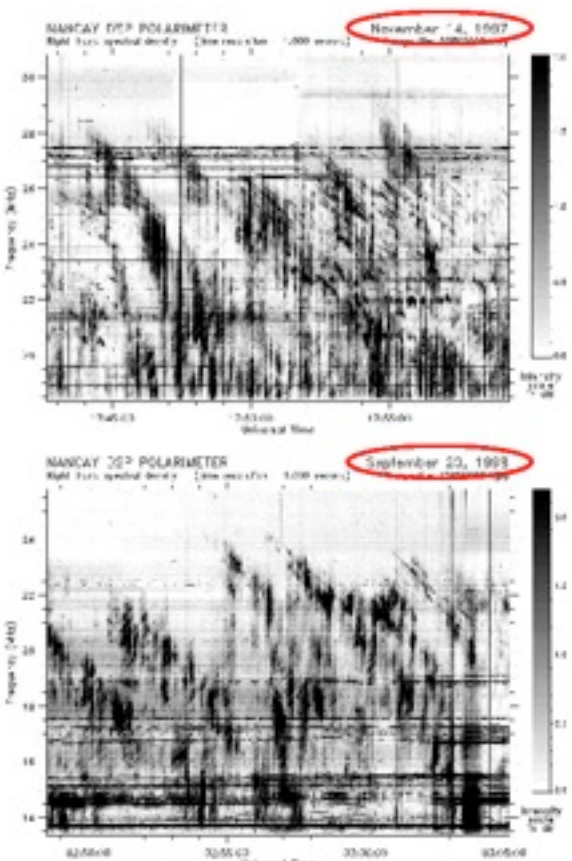
→ Interplanetary scintillation studies :

Source locations, distributed / f

[Genova & Boischot 1981]

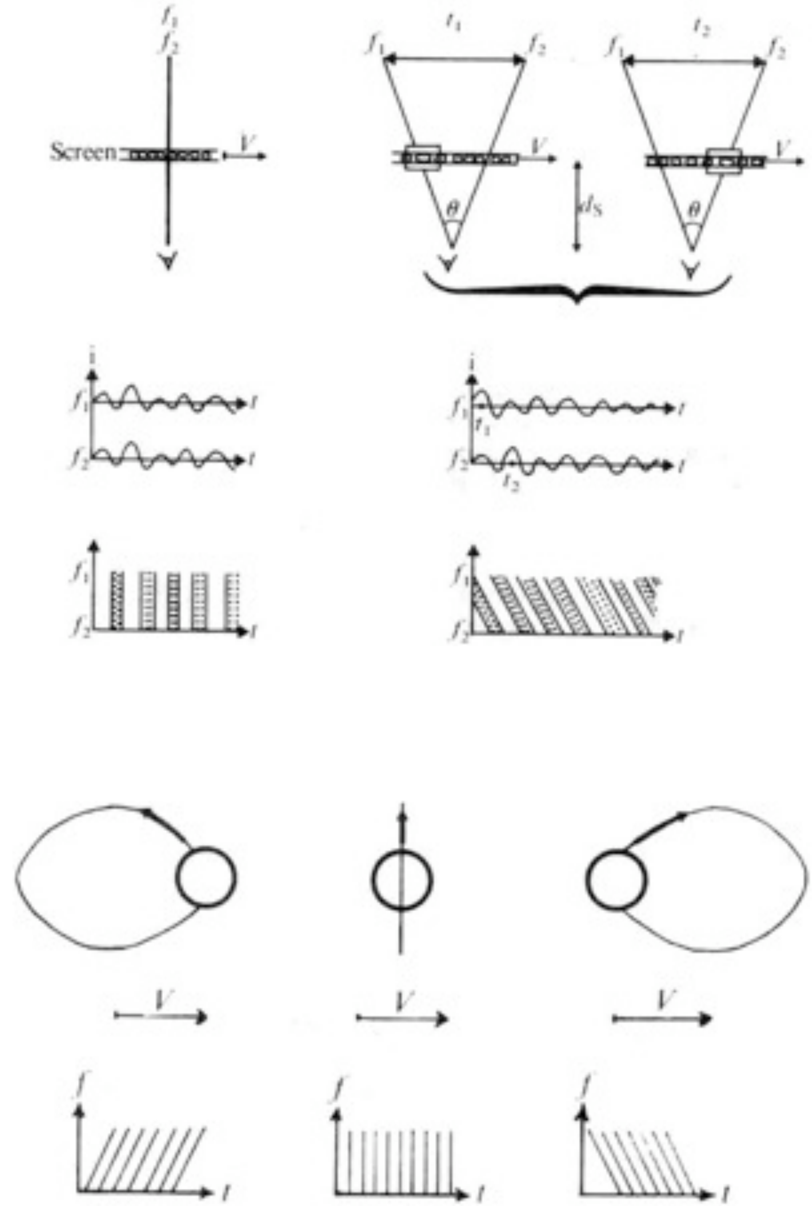
Interplanetary scintillations (IPS) of Jovian DAM radiation

[Douglas and Smith (1967)
Slee and Higgins (1968)
Warwick (1967)
Genova and Leblanc (1981)]



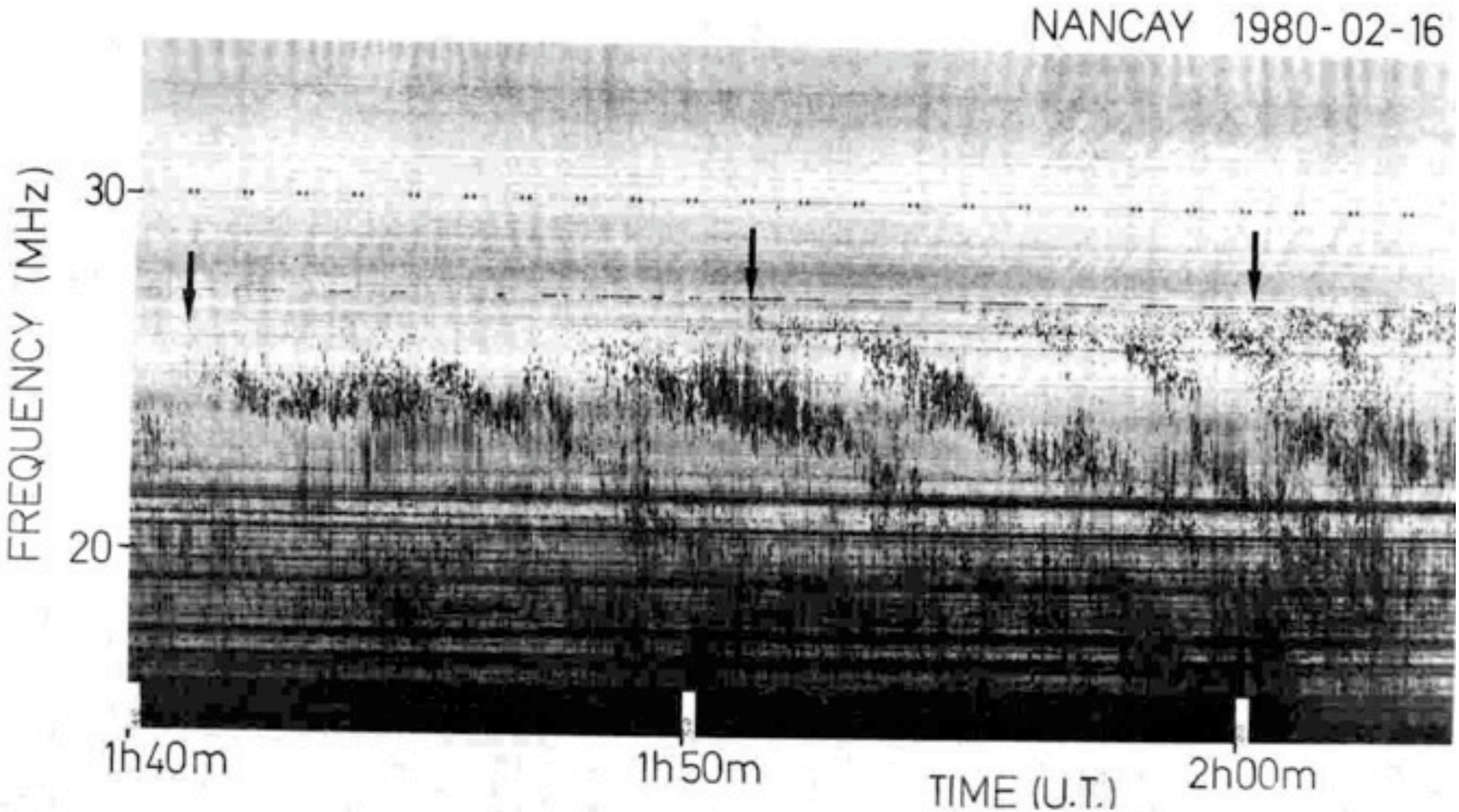
Jupiter **far** from opposition

Jupiter **near** opposition

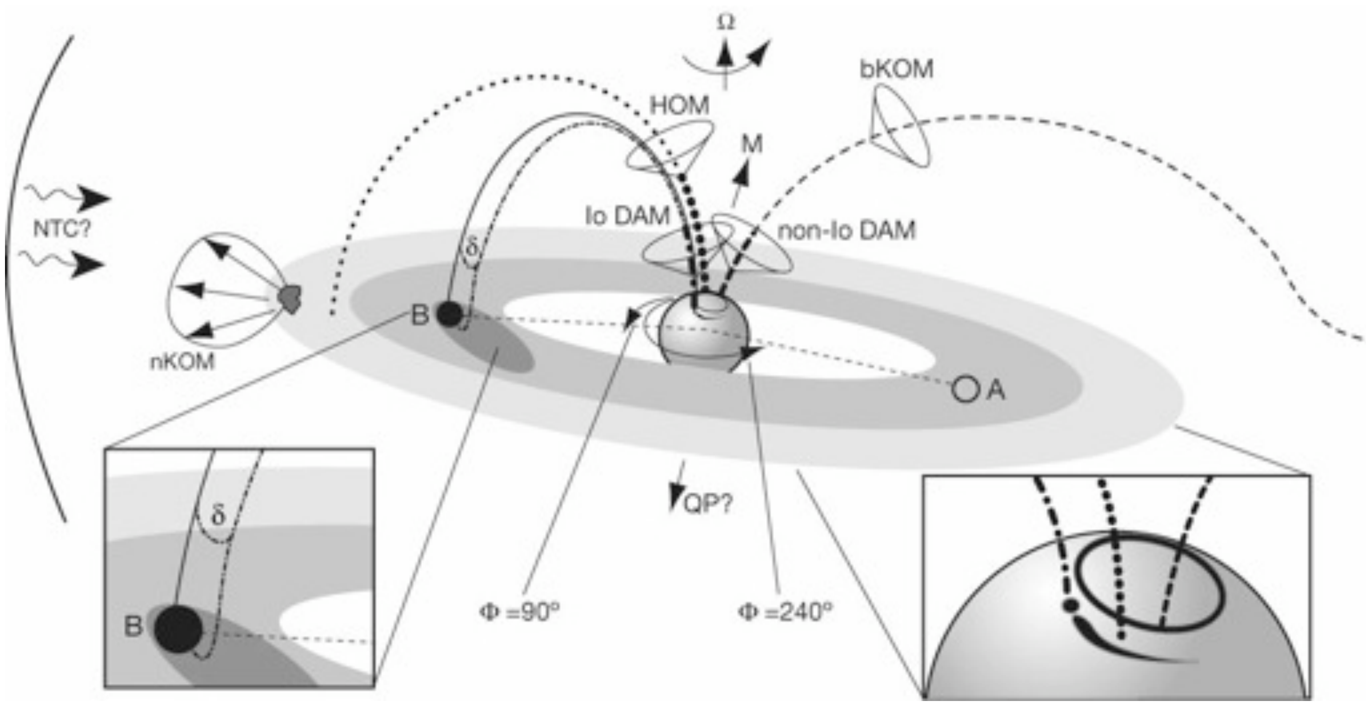


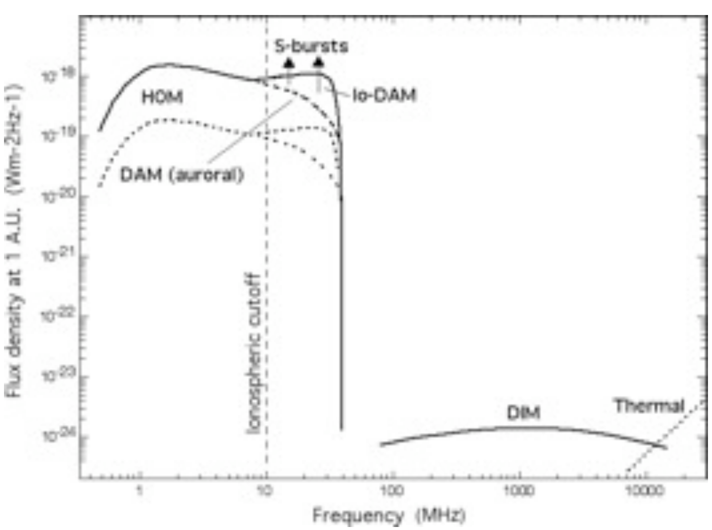
→ Short (« S ») bursts :

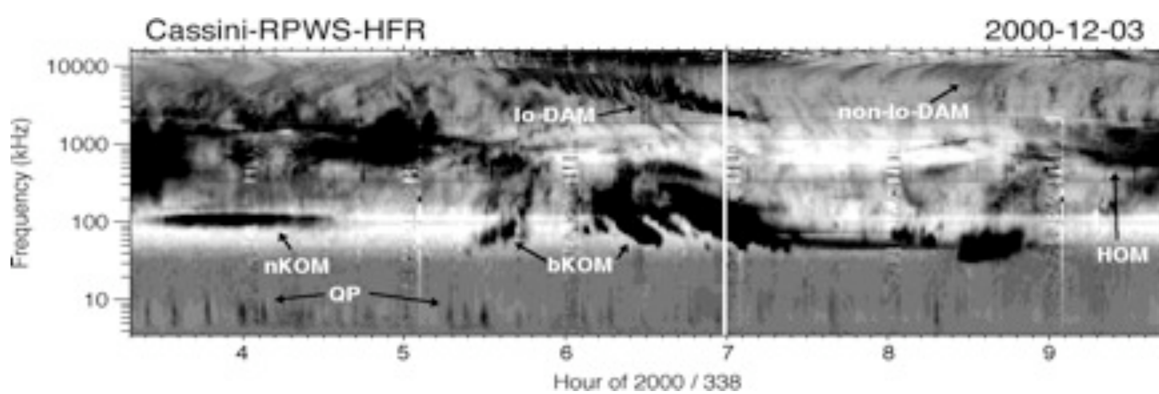
Energetic electron bunches ? [Genova, Leblanc & al.]



→ Radiosources spectra locations and beaming :

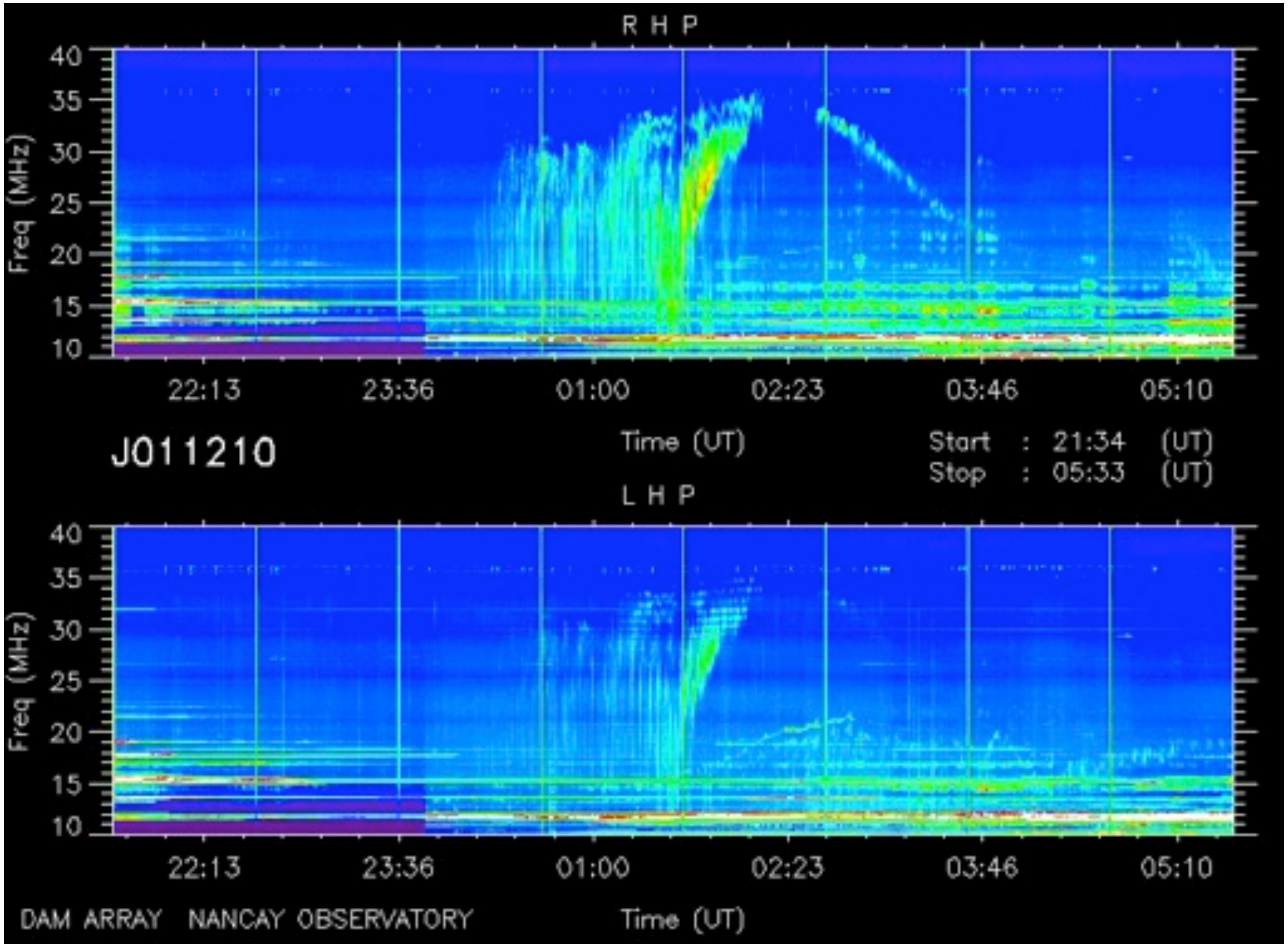




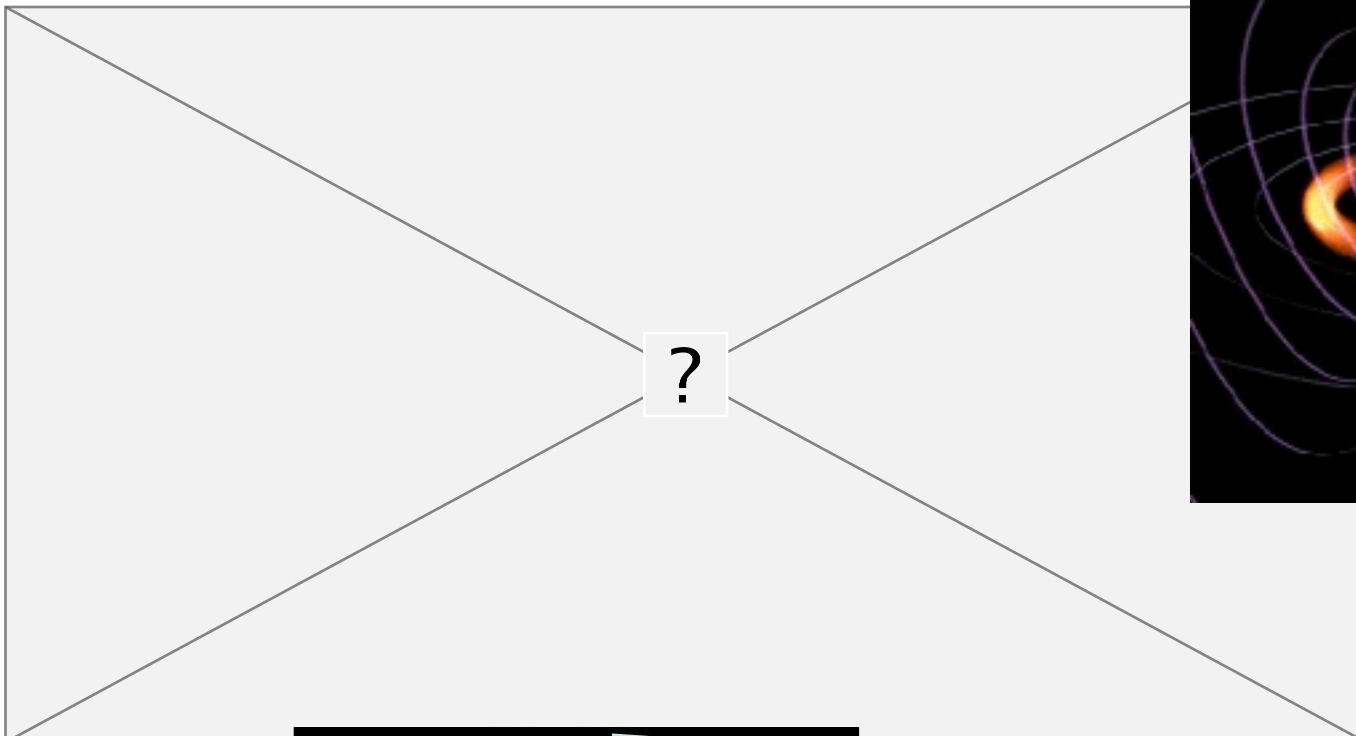


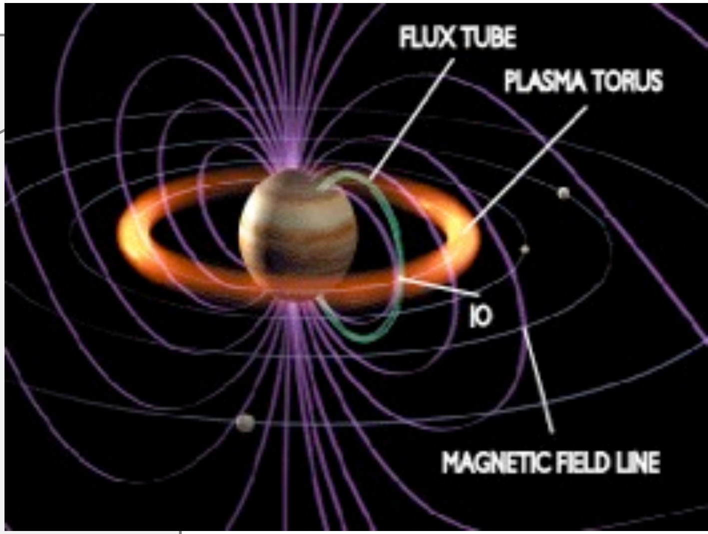
(2) Recent past (1990 - 1998+) :

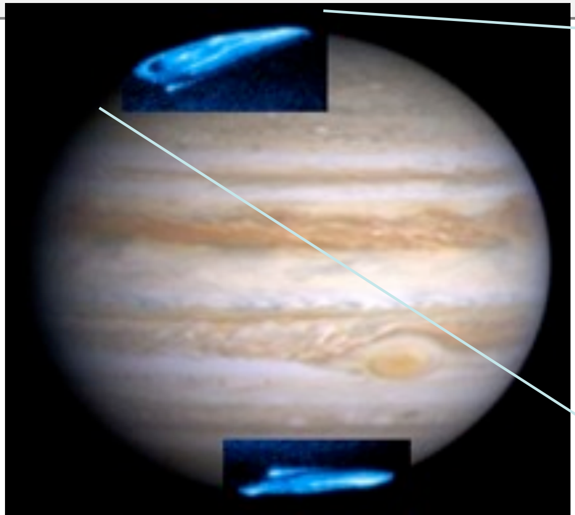
- Digital « Routine » (www.obs-nancay.fr → decameter array)
- Digital swept-frequency polarimeter
- Acousto-Optical spectrograph [Rosolen, Denis…]



→ Io-Jupiter studies using multi-λ & ground-space complementarity :





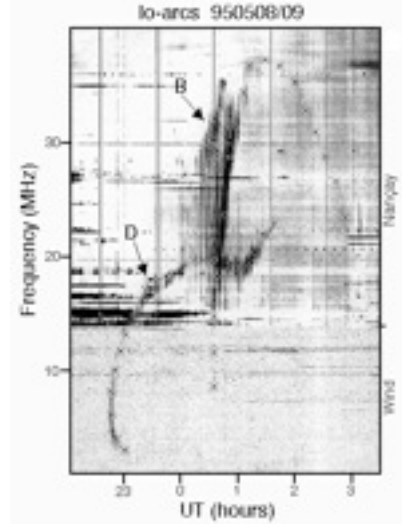


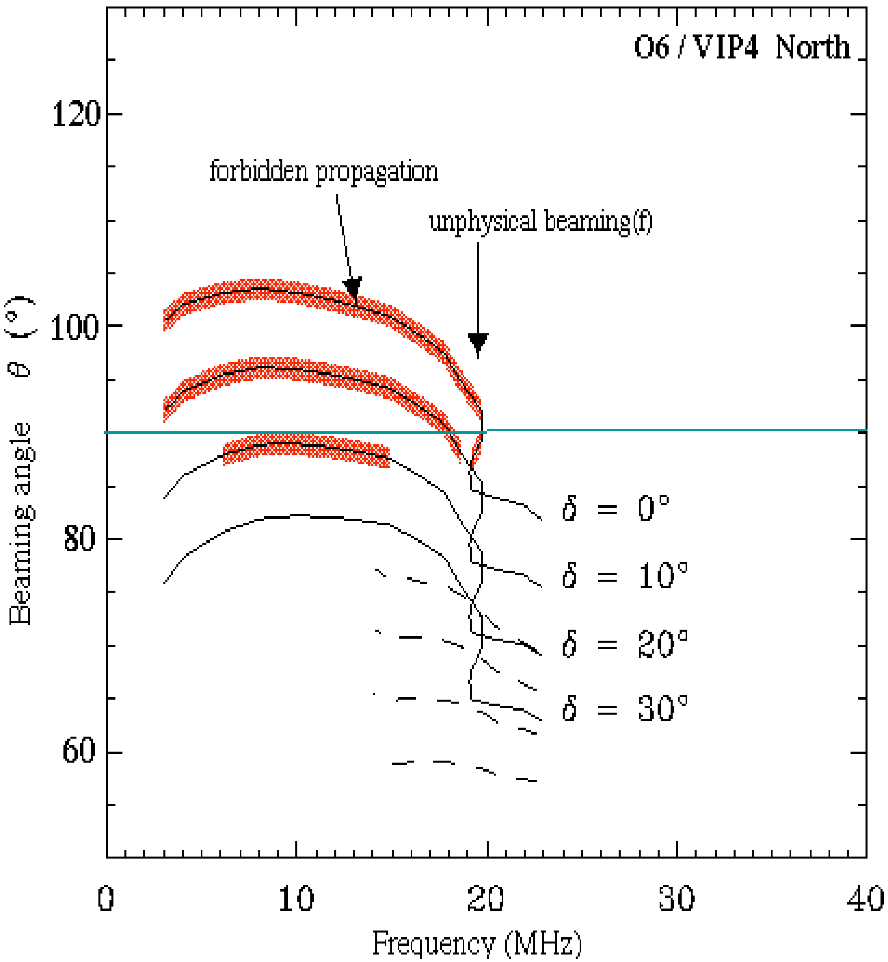
[Prangé & al.]

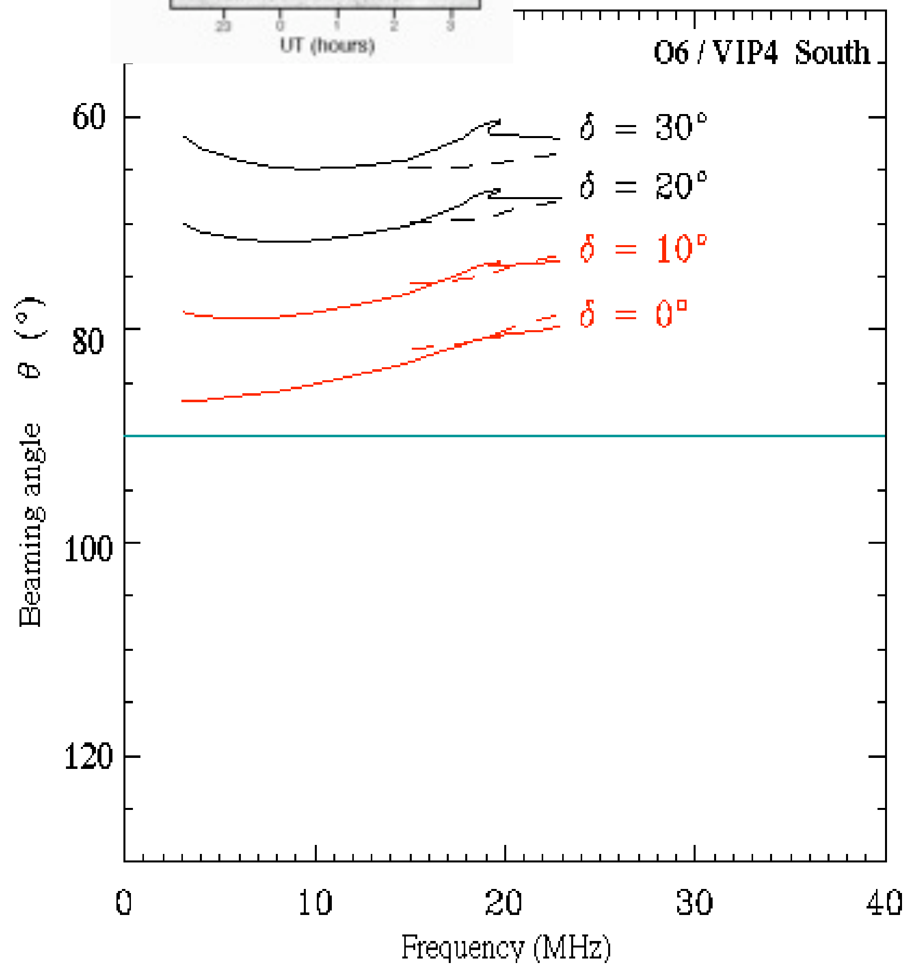
→ Radio Arcs shape :

Magnetic field topology + beaming

[Queinnec & Zarka, 1998]

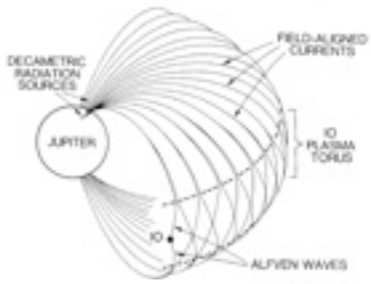


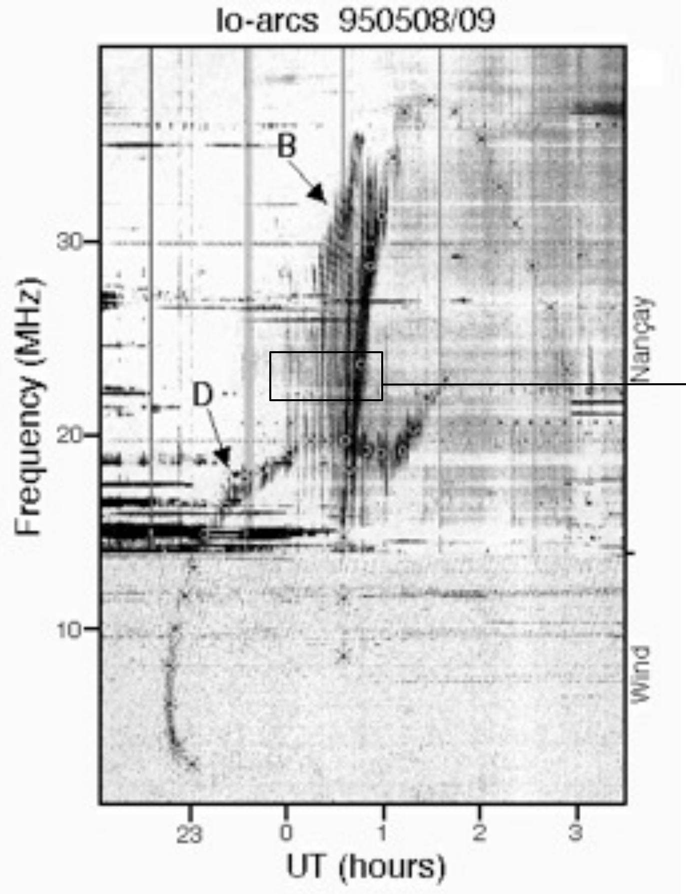


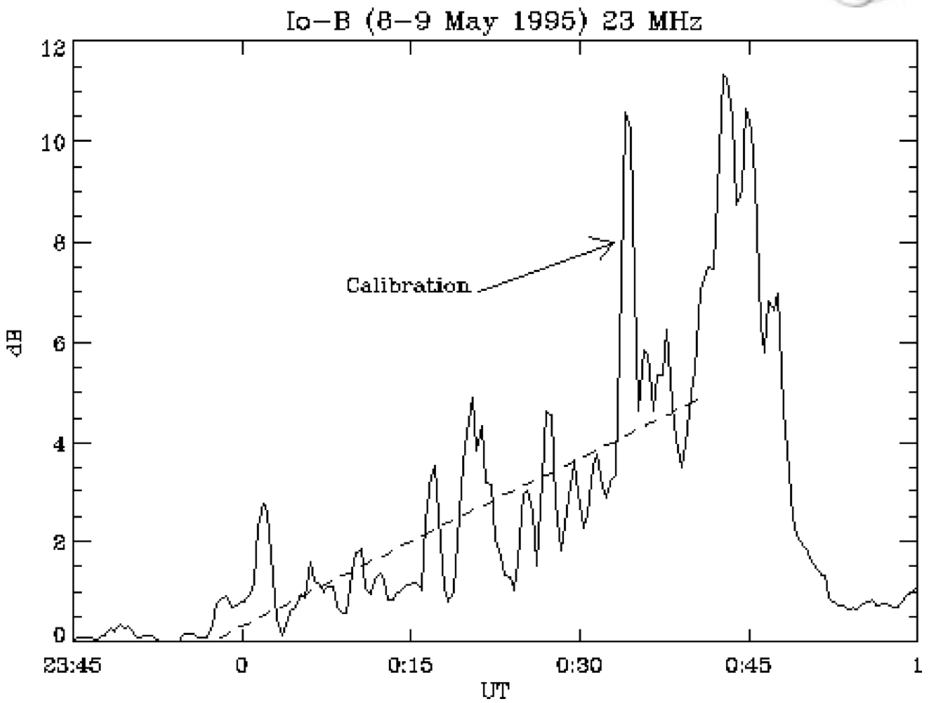


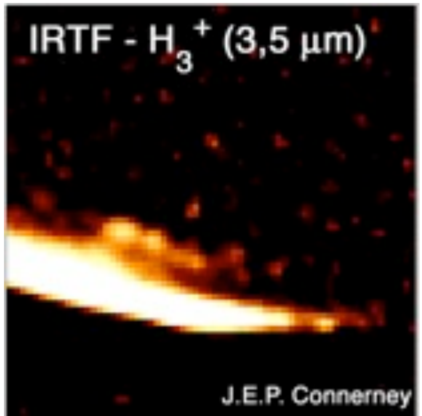
→ Arcs fringes :

Alfvèn bouncing torus-ionosphere [Queinnec & Zarka, 1998]

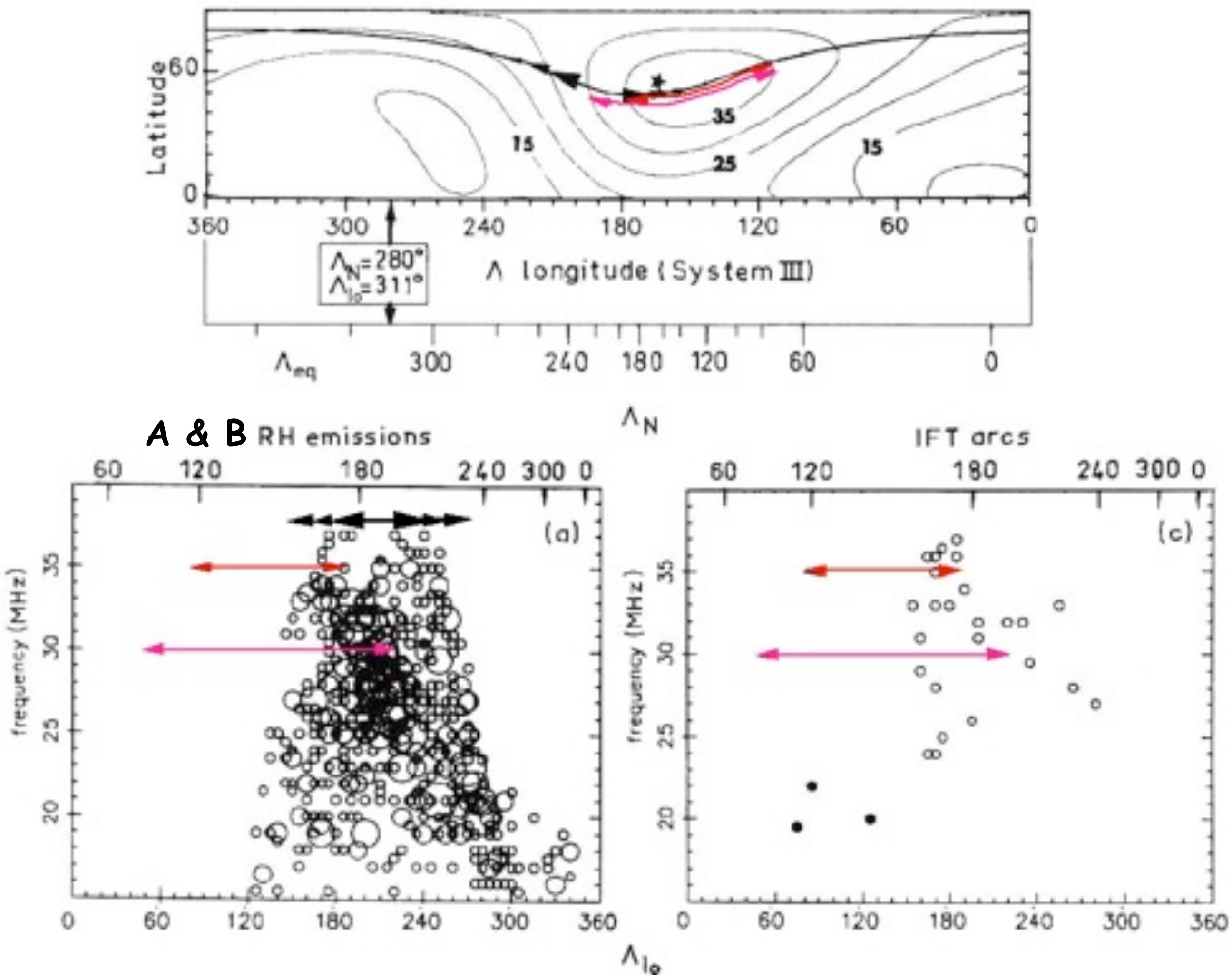






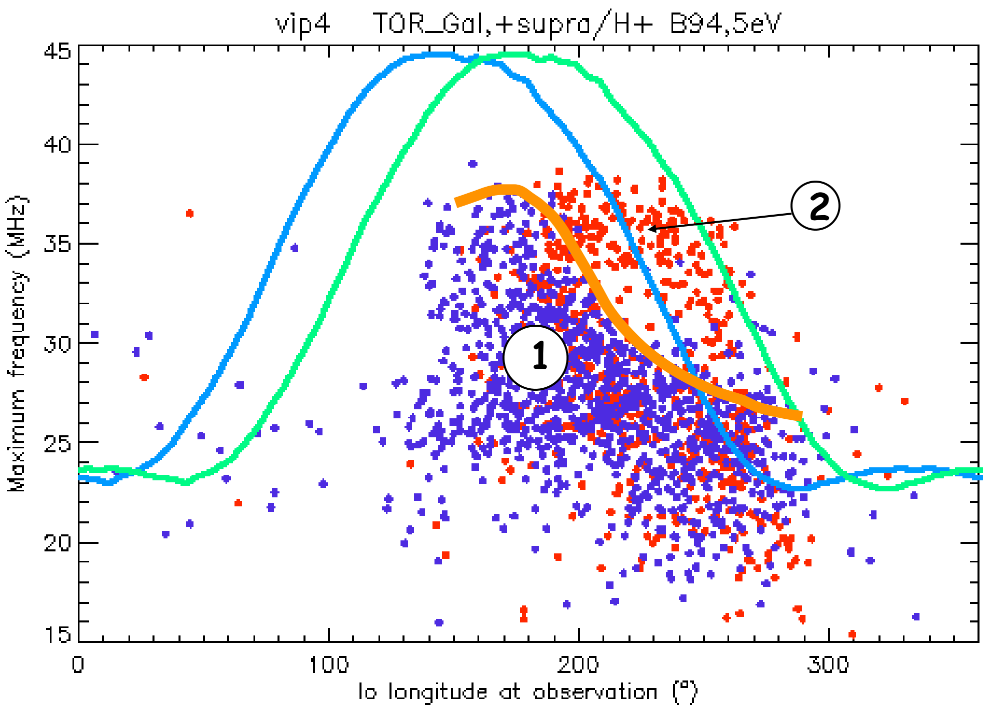


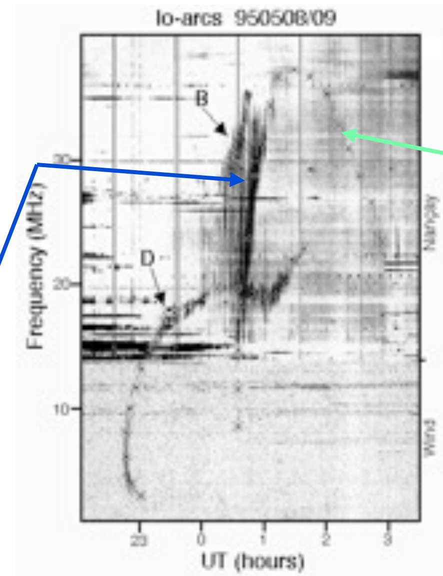
→ Inconsistency f_{max}(DAM) - magnetic field models [Genova & Aubier, 1985]

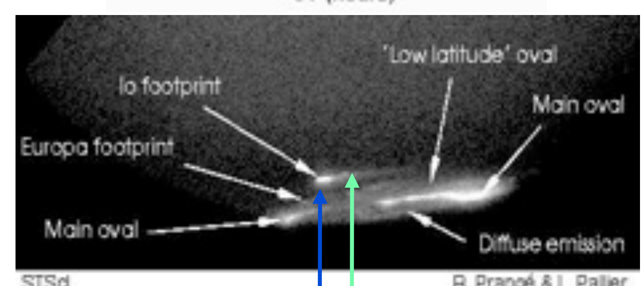


→ Inconsistency f_{max}(DAM) - magnetic field models [Genova & Aubier, 1985]

solved as 2 radio emission populations, excited by Alfvén waves and slow shock / wake reacceleration currents [Zarka, Gerbault & al., 2002]







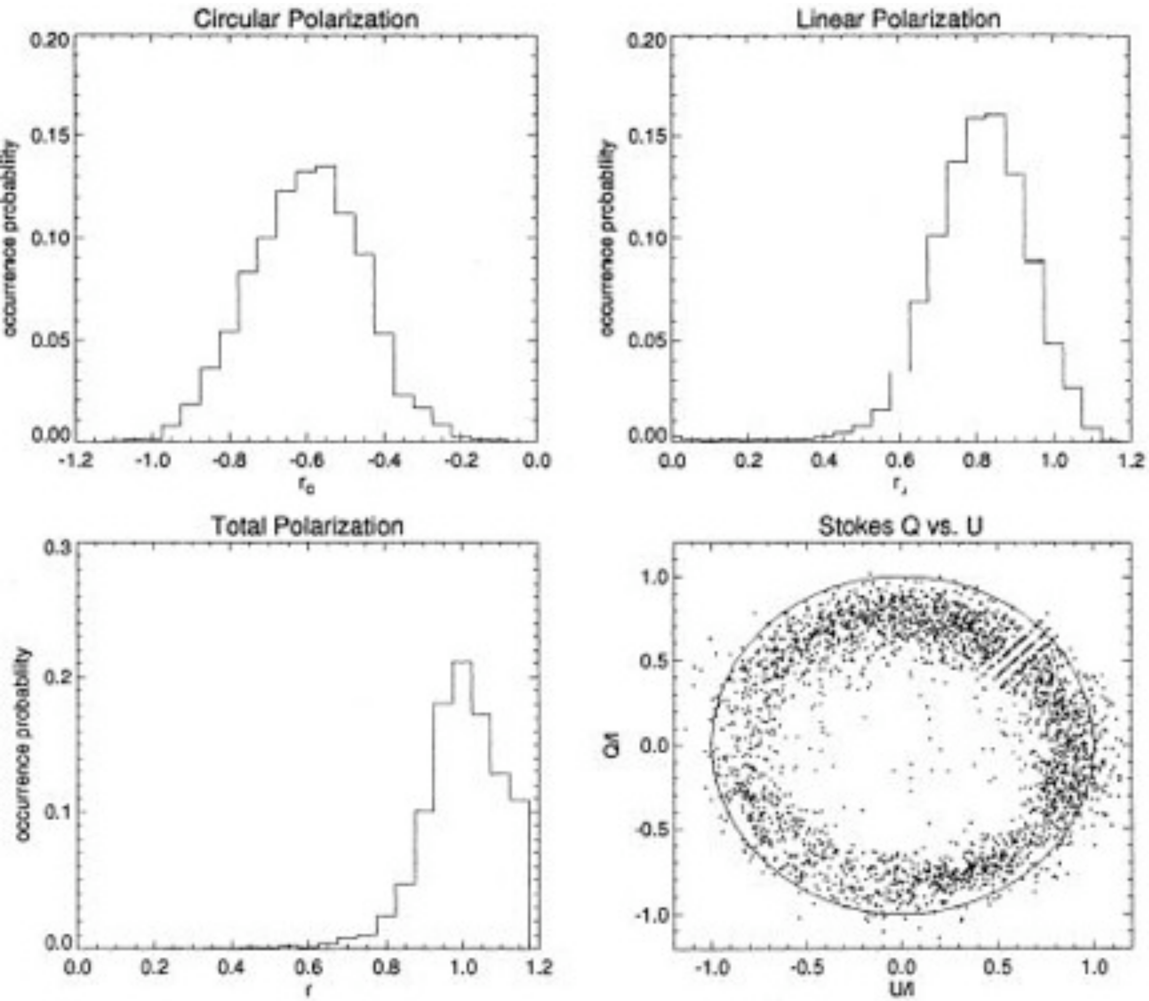
(1) Alfvèn waves → several keV electrons → intense radio arcs + UV/IR spot

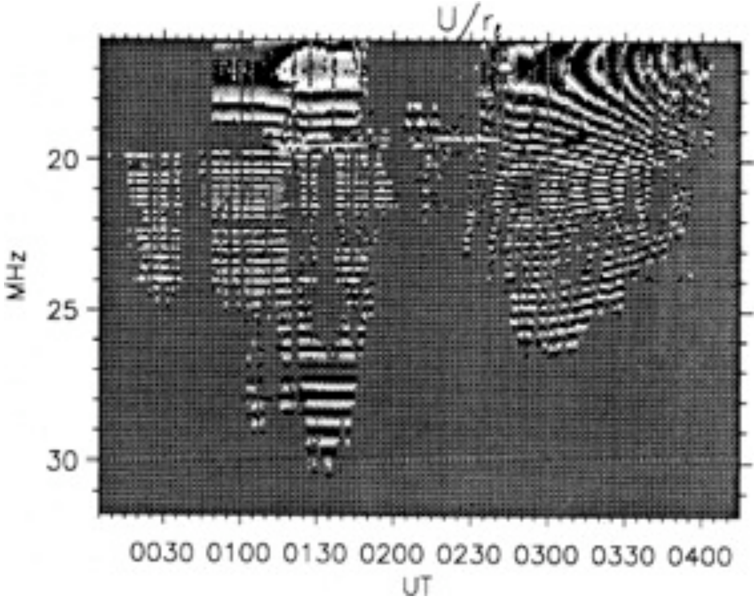
(2) slow shock / wake reacc. J → ~1 keV electrons → radio & UV/IR "trails"

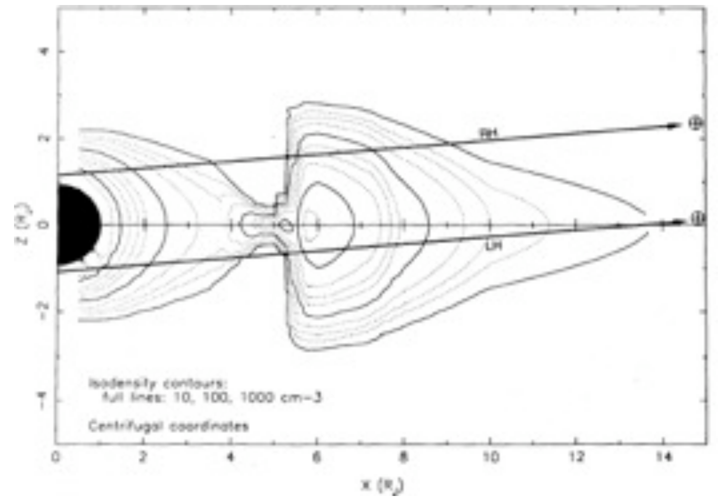
→ Strong constraints on Jovian magnetic field model

→ 100% elliptical polarization of DAM [Dulk & al., 1992, 1994]

implies plasma depleted ($N_e \leq 5$ cm^{-3}) source regions [Lecacheux, 1988]



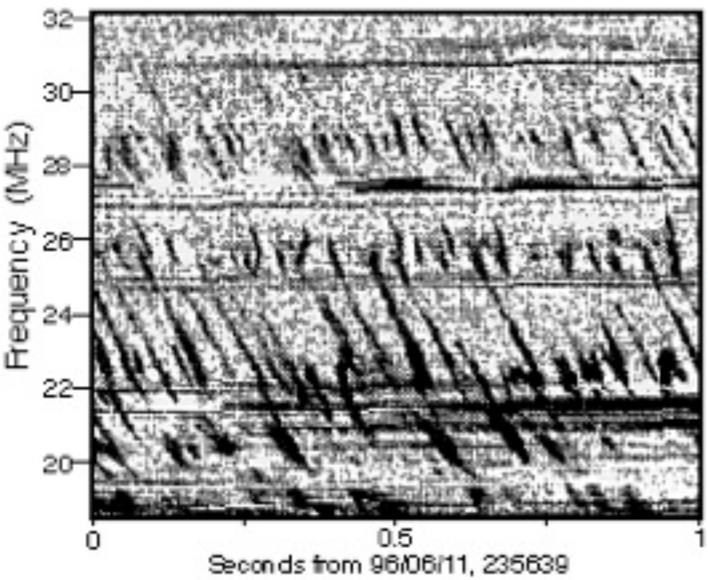


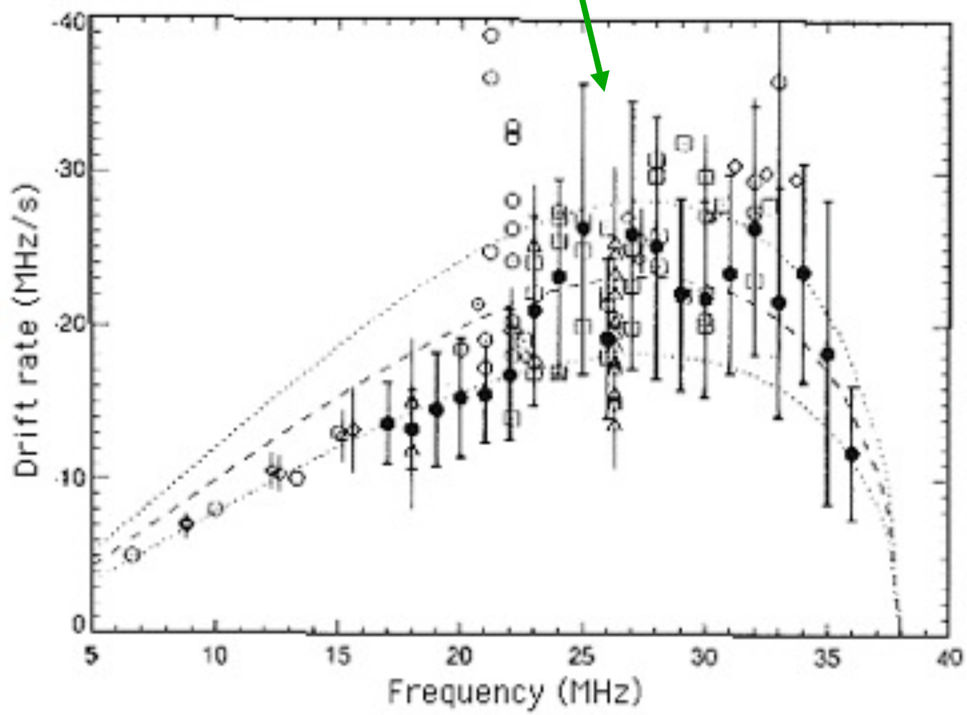


→ Massive measurements of S-bursts drift rates df/df(f)

5±2 keV electron bunches in adiabatic motion

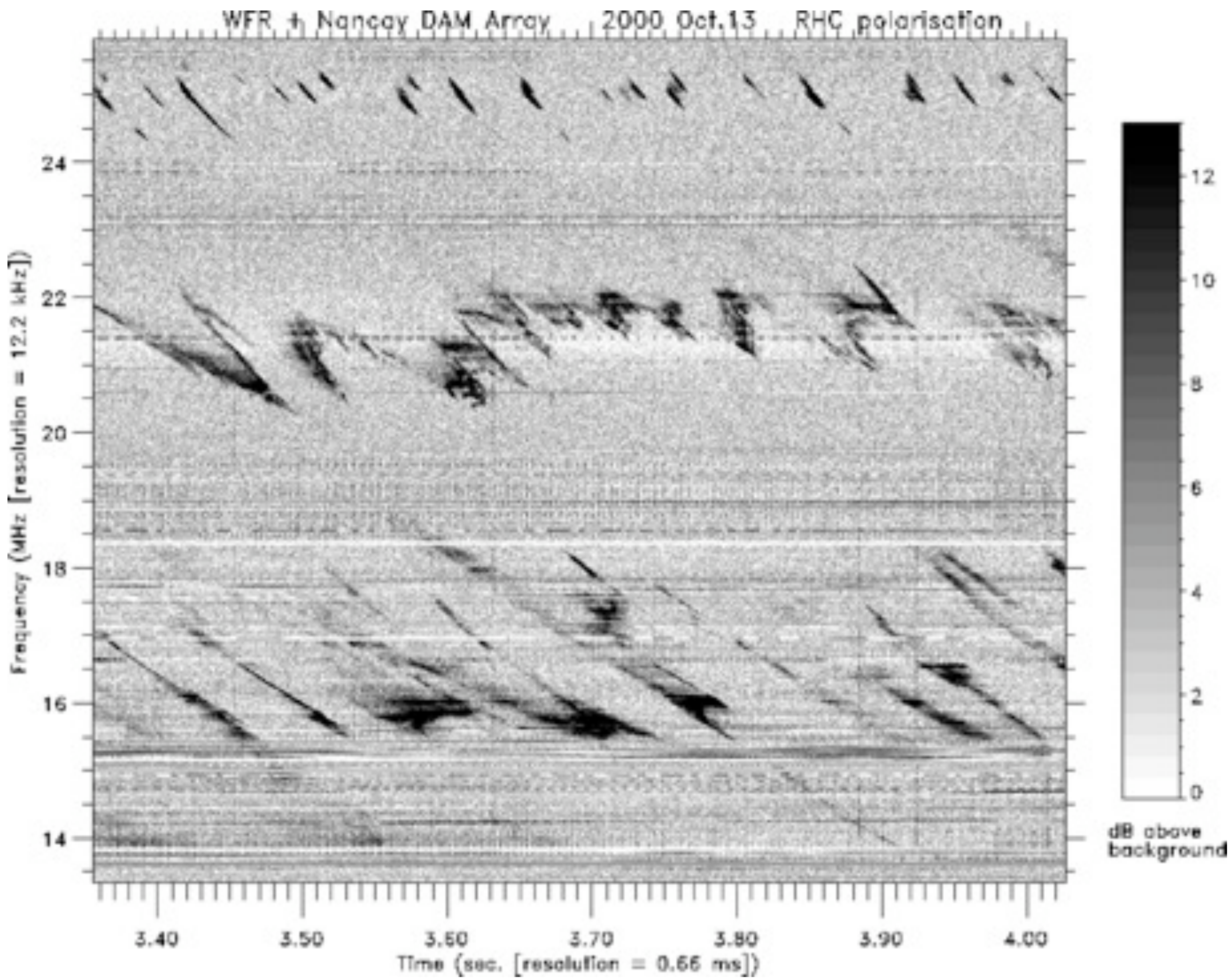
[Zarka & al., 1996]



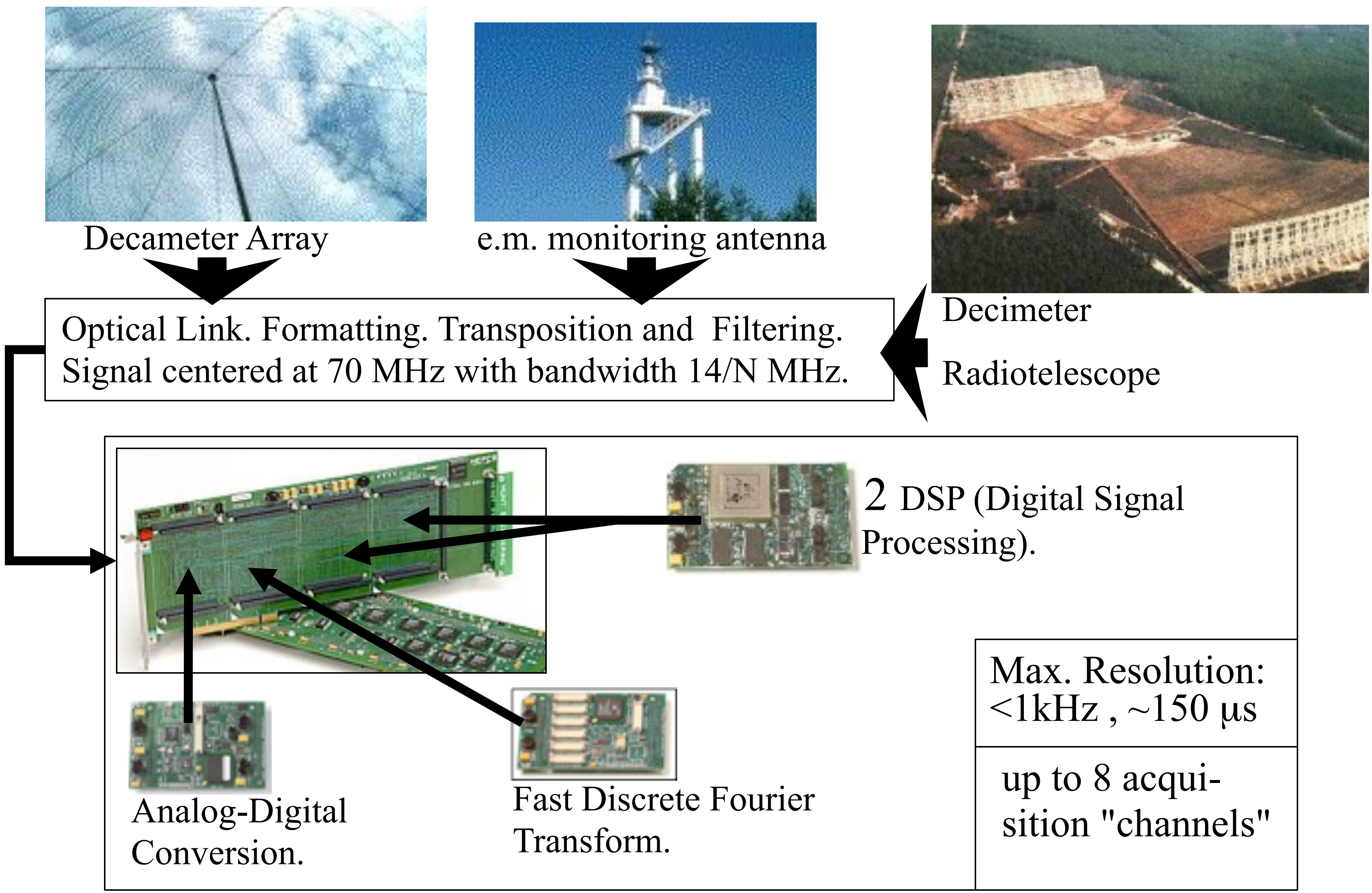


(3) Present :

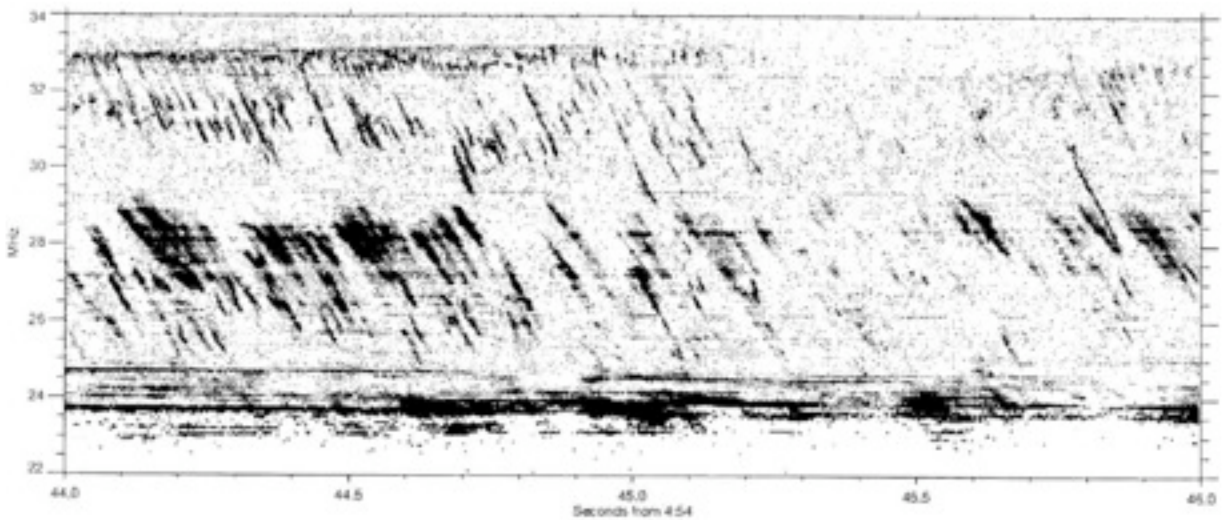
- Digital DSP/FFT spectrograph (I) [Rosolen, Lecacheux…]
- Waveform capture (ROBIN)
- Digital DSP/FFT spectrograph (II) = « Reconquête » [Denis…]

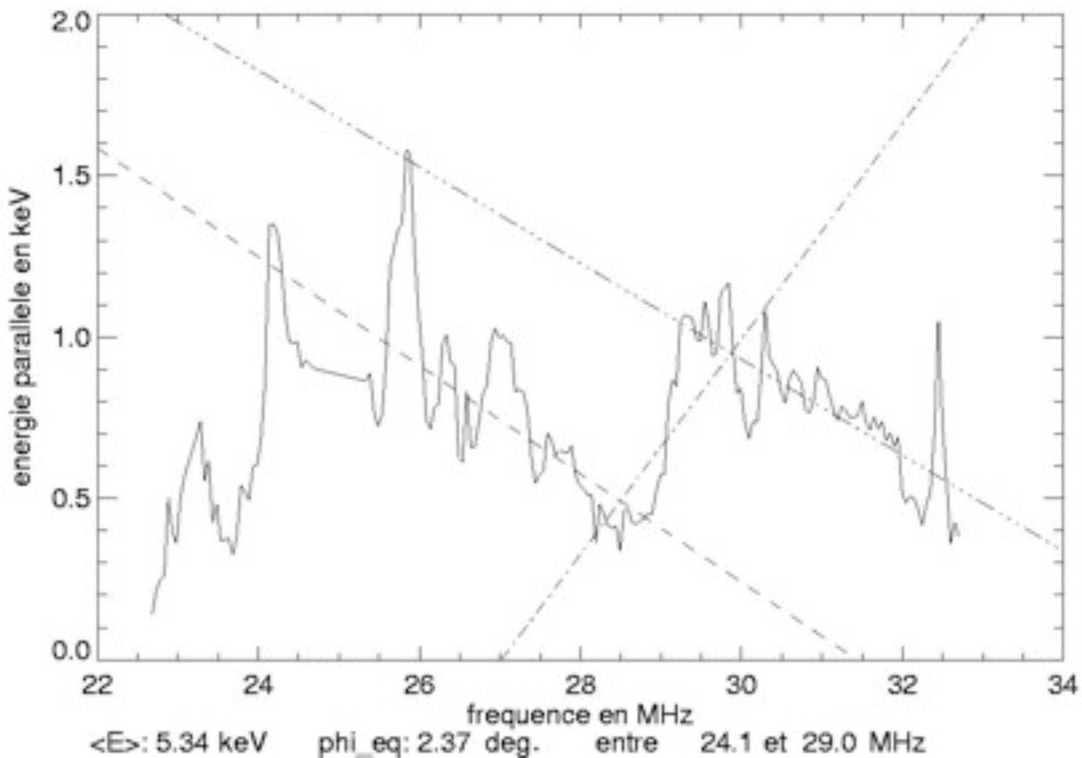


"Reconquête" system: one acquisition channnel



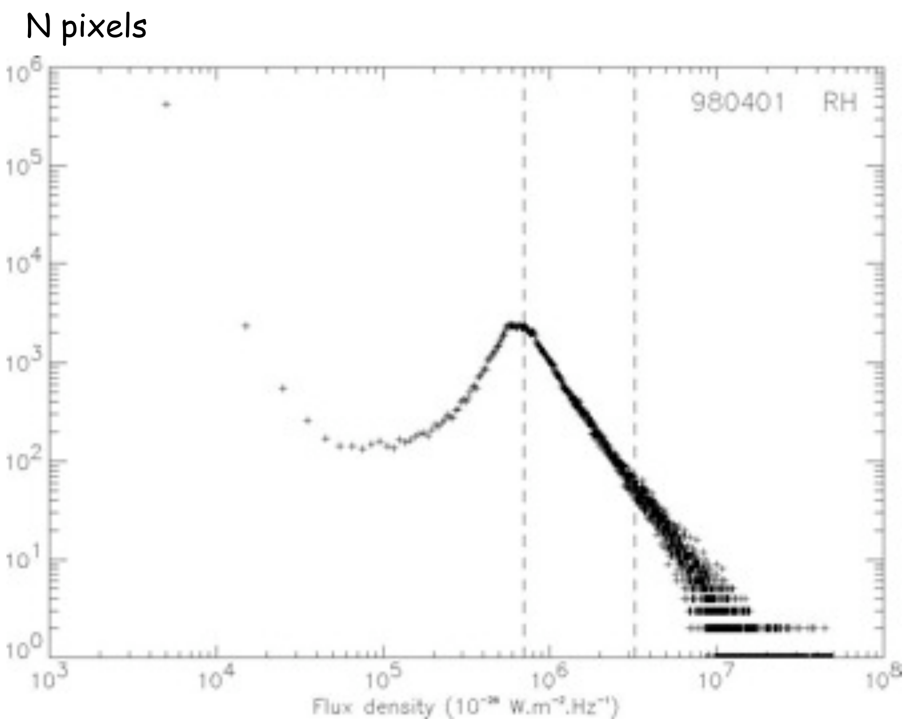
→ Potential drops & accelerations along Io flux tube ? [Hess & al., in progress]

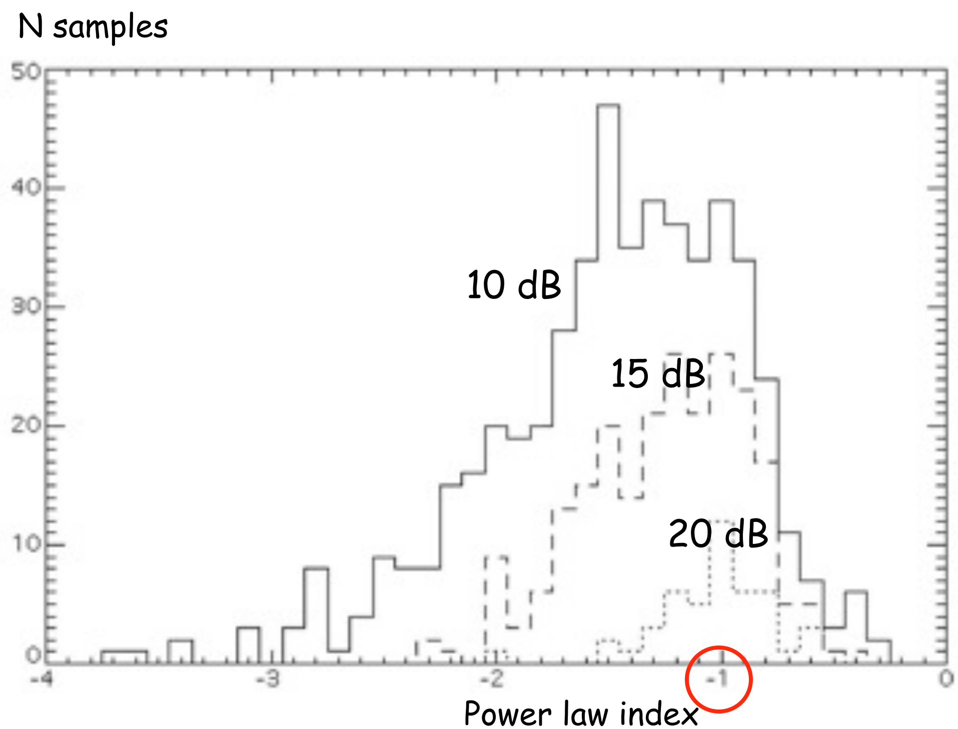




→ Power law distributions for S-burst intensities :

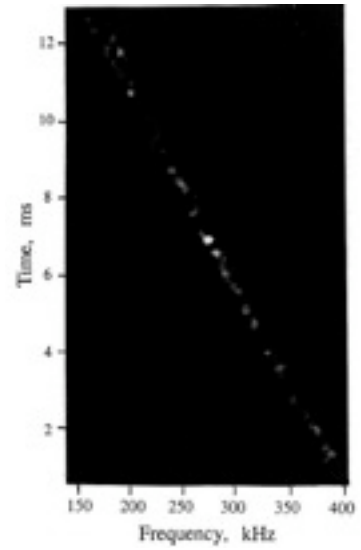
SOC ? [Queinnec & Zarka, 2001; Cohier, 2003]

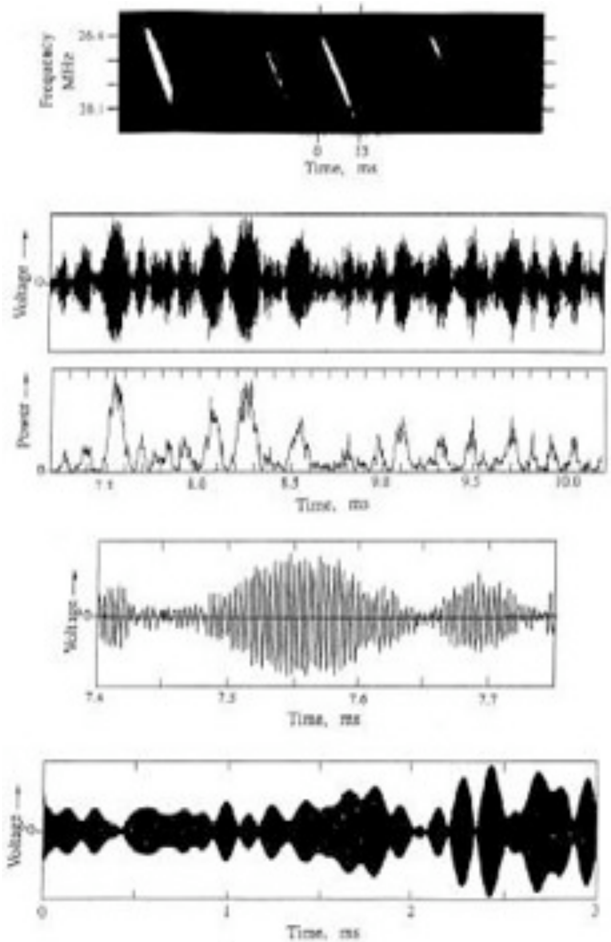


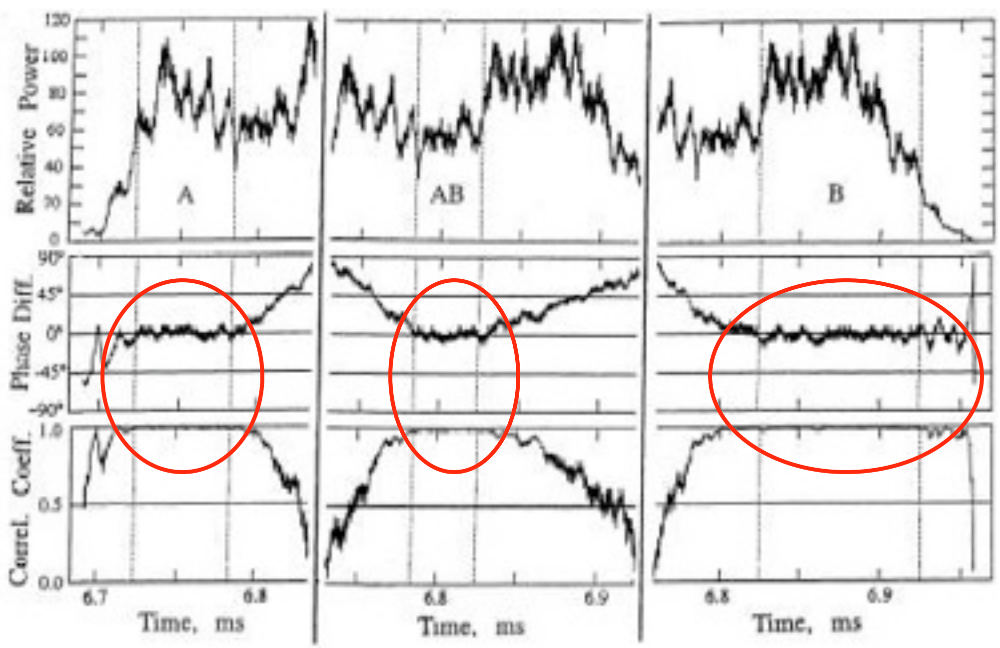


→ Waveform analysis on S-burst emission :

monochromatic time segments ? [Carr & Reyes, 1999]

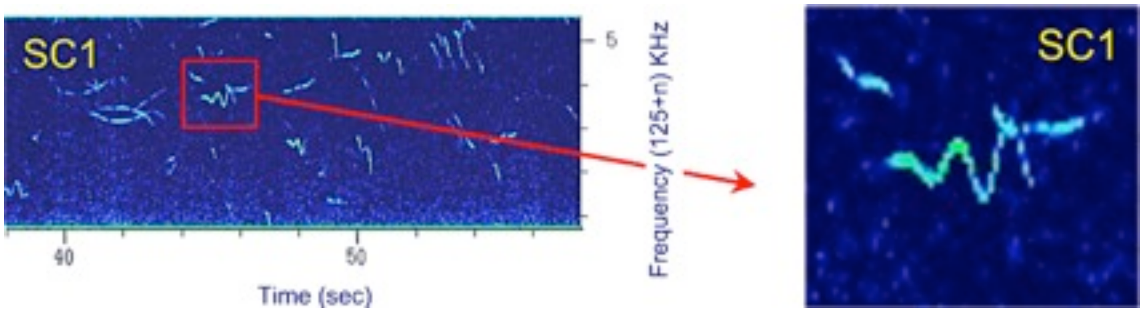




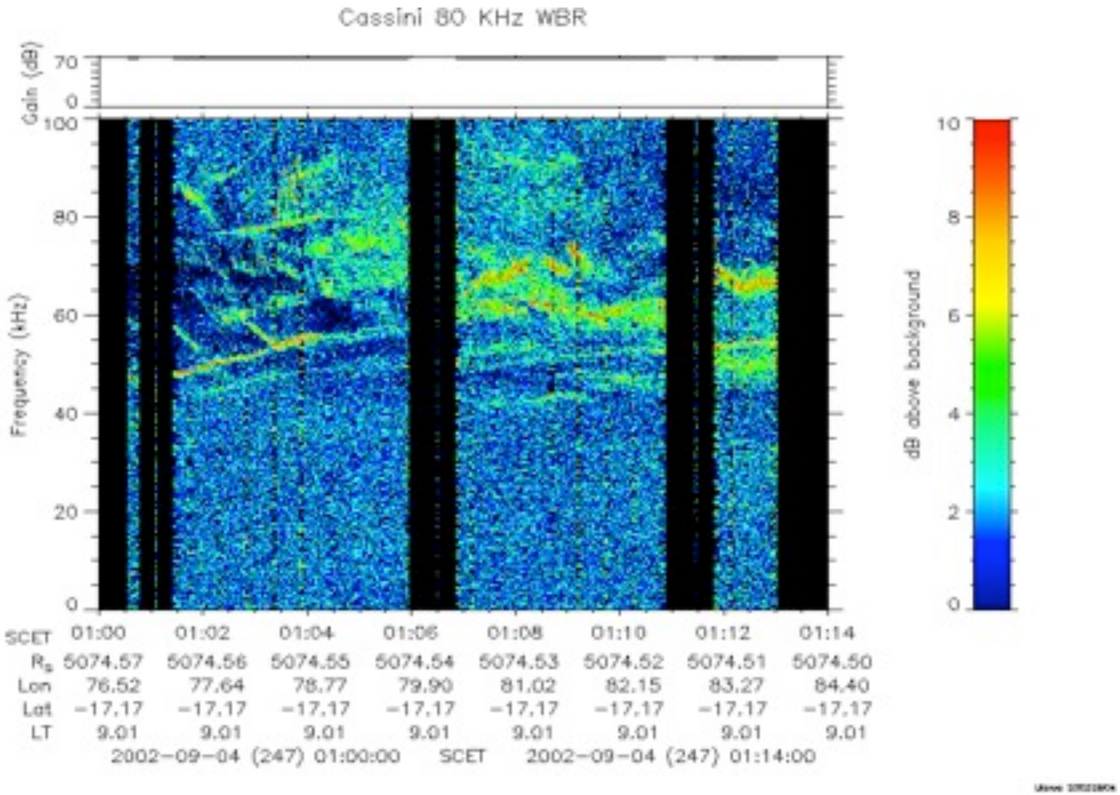


→ Fine structures of other planetary radio emissions

Earth: Cluster [Mutel & al.]



Saturn : Cassini [Kurth & al.]



(4) Future : fast spectro-imagery with LOFAR [Zarka, 2004]

- Cartography of $B_{jupiter}$
- Parameters of Io-Jupiter interaction
- Direct observation of S-bursts electrons
- Io torus sounding (Faraday effect)

= REMOTE MAGNETOSPHERIC PHYSICS → EXOPLANETARY PHYSICS ?

Requires 1" - 2" resolution at 40 MHz → ~1000 km bases

→ Correlation tests on Jupiter between LOFAR-ITS and NDA

[Falcke, Nigl, Zarka, Denis…]