Ce que les arcs radio de Jupiter (et bientôt de Saturne ?) nous apprennent sur la magnétosphère

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- Introduction
- Io-controlled decameter arcs and Io-Jupiter interaction [Queinnec & Zarka, JGR, 1998]
- Lead angle of Io-controlled radio emission : Alfvèn wave or slow shock ? [Zarka, Langmayr, Gerbault, MOP, 2002]
- Radio Astronomy Science with JUNO

  [P. Z. & French RAR team]
- Conclusions

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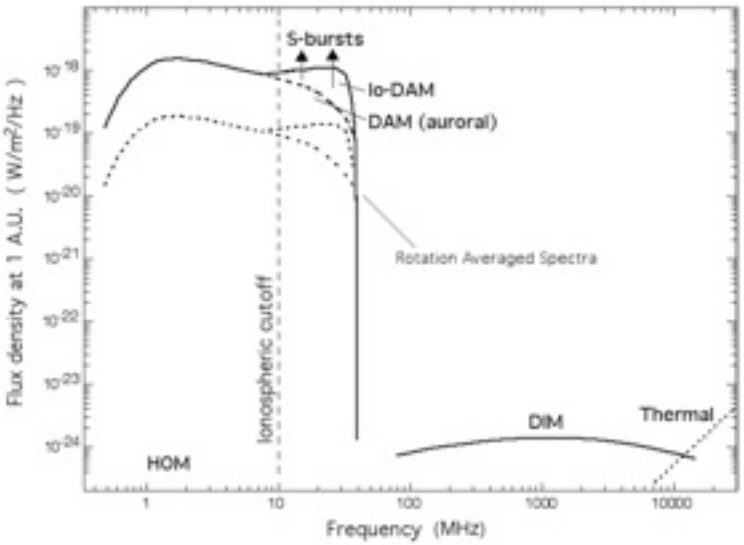
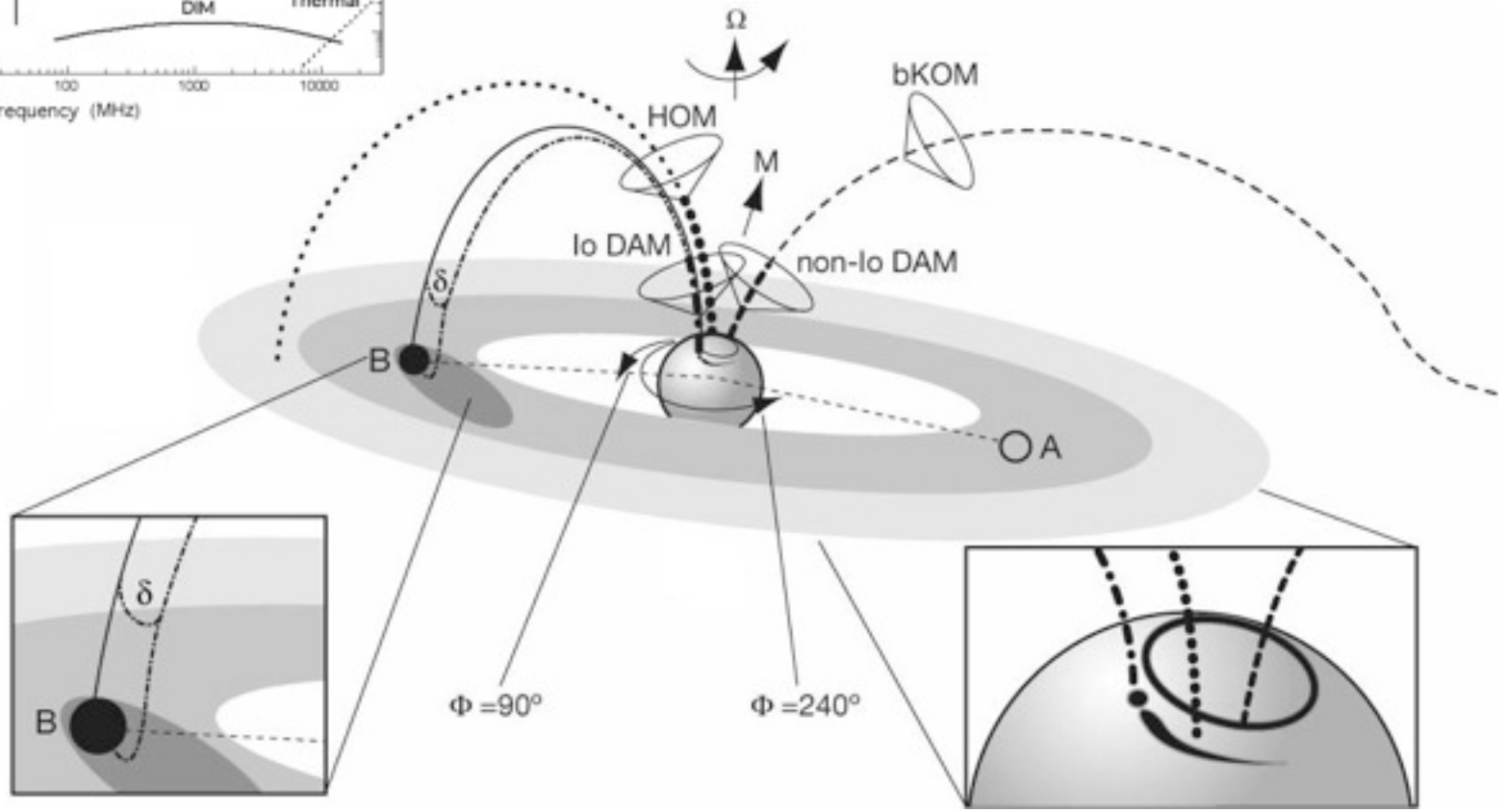
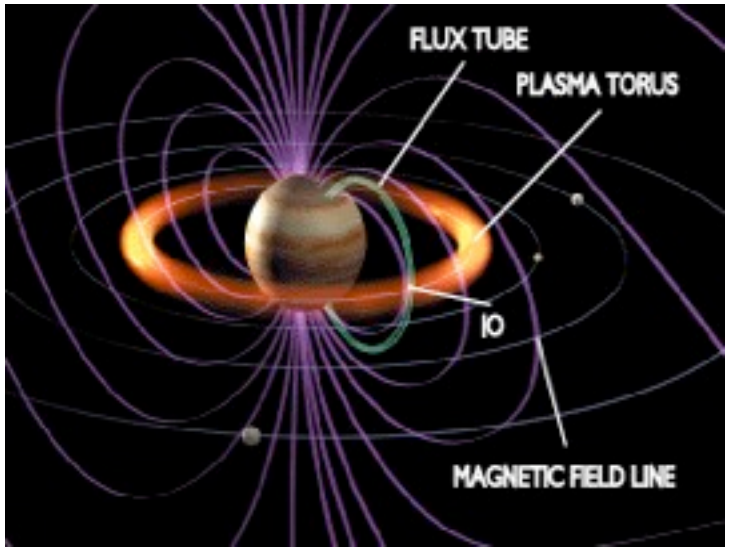
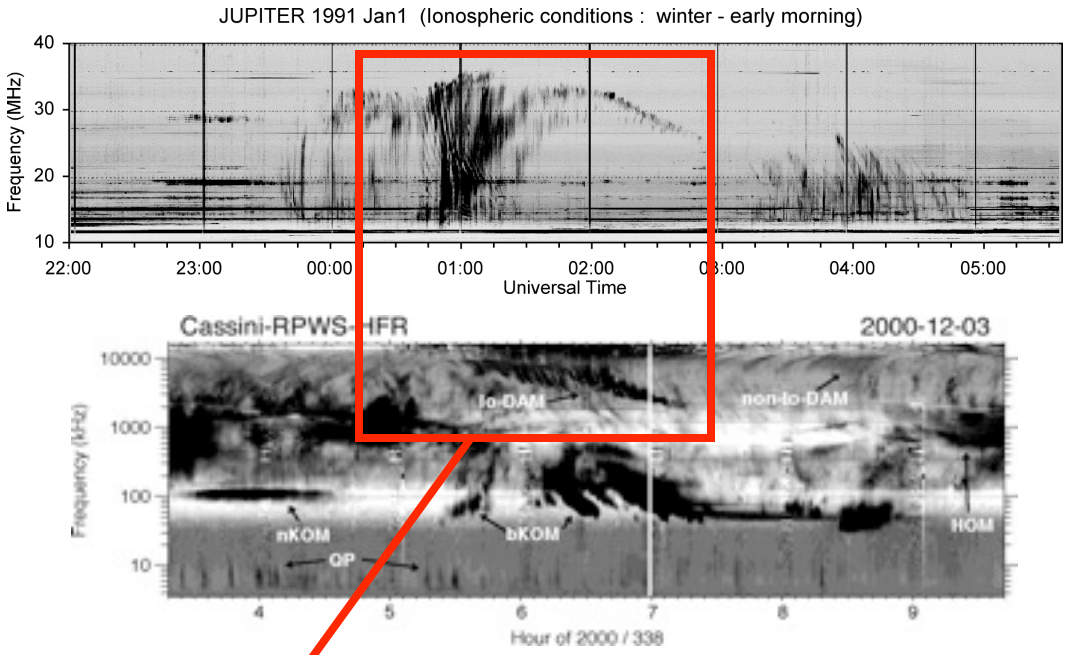
Jovian radiosources



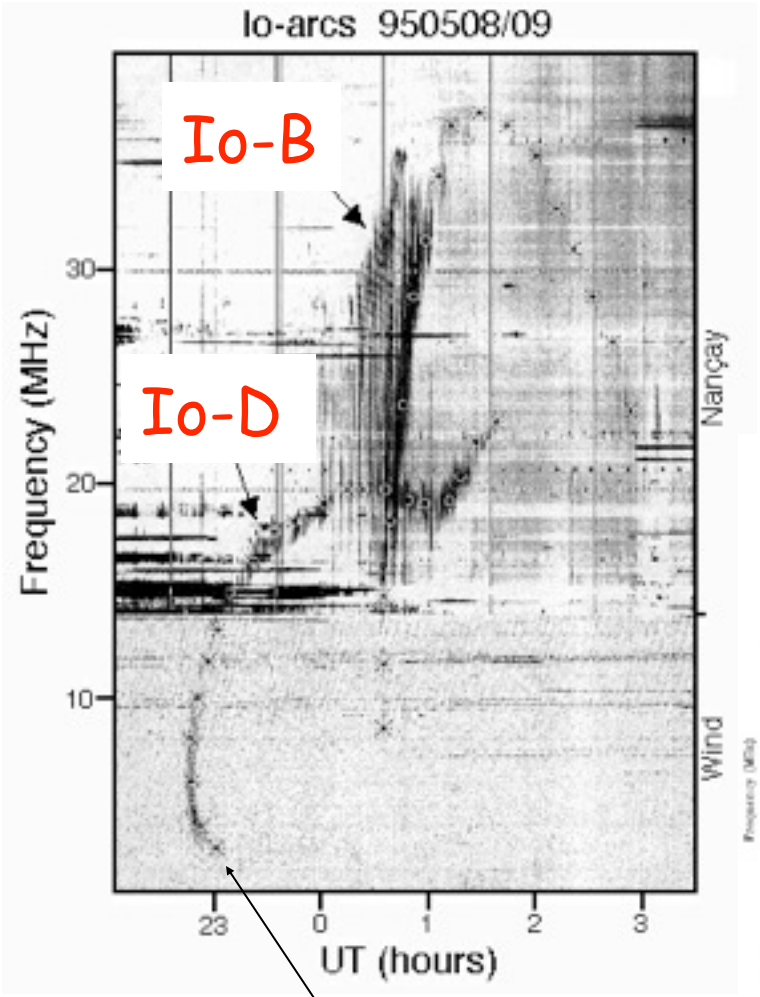


Io-Jupiter emissions

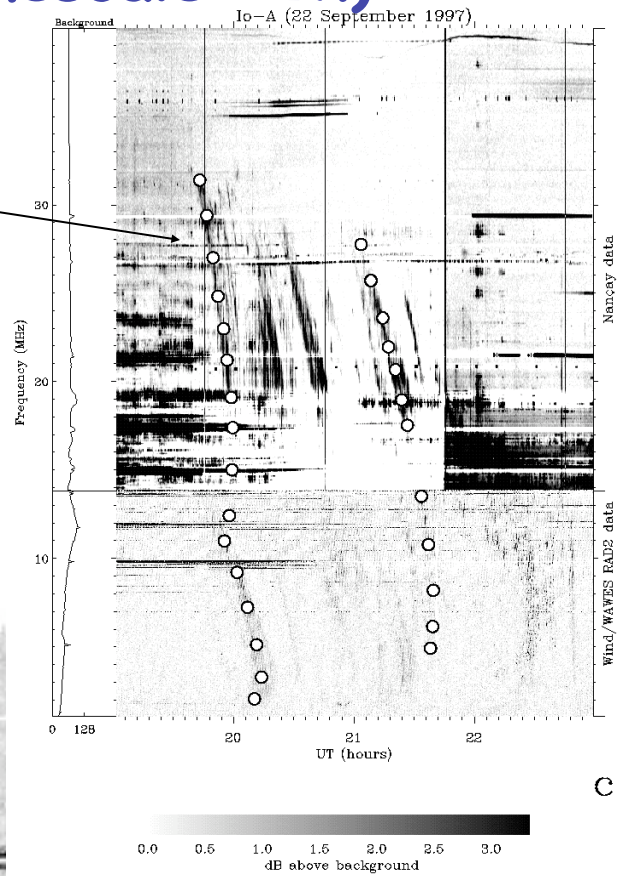


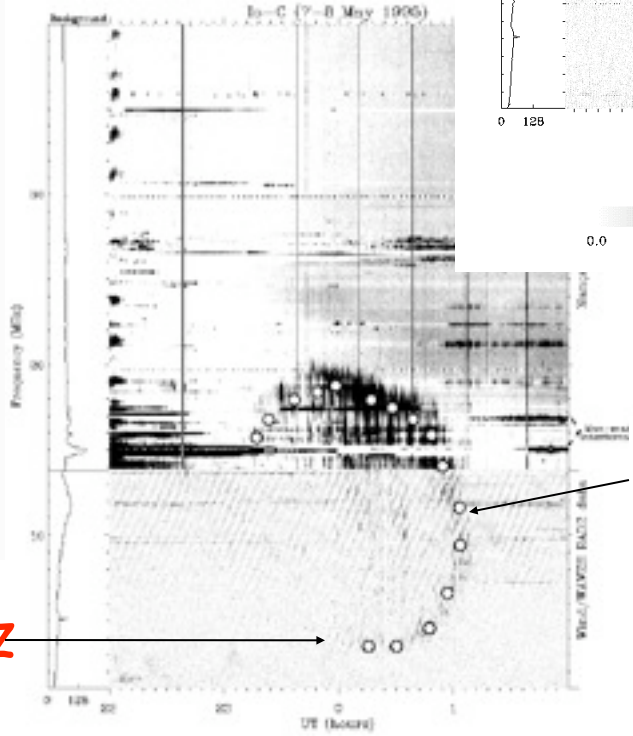


Recurrent radio « arcs » (at timescale ~1h)



Io-A

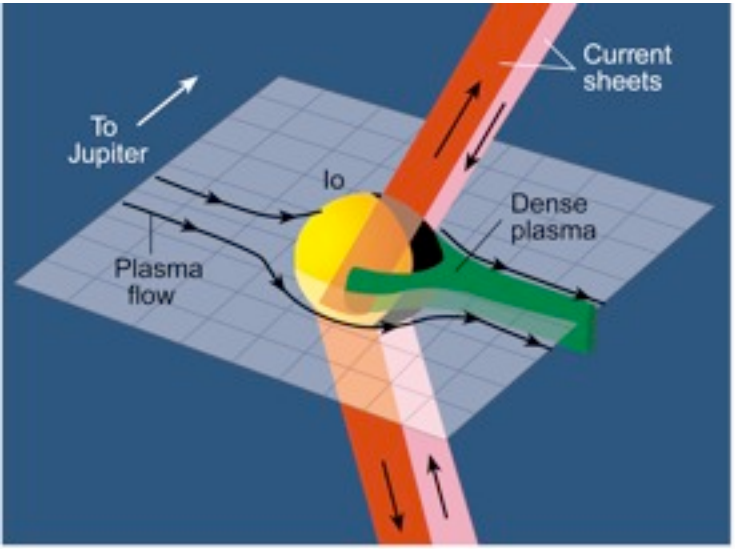


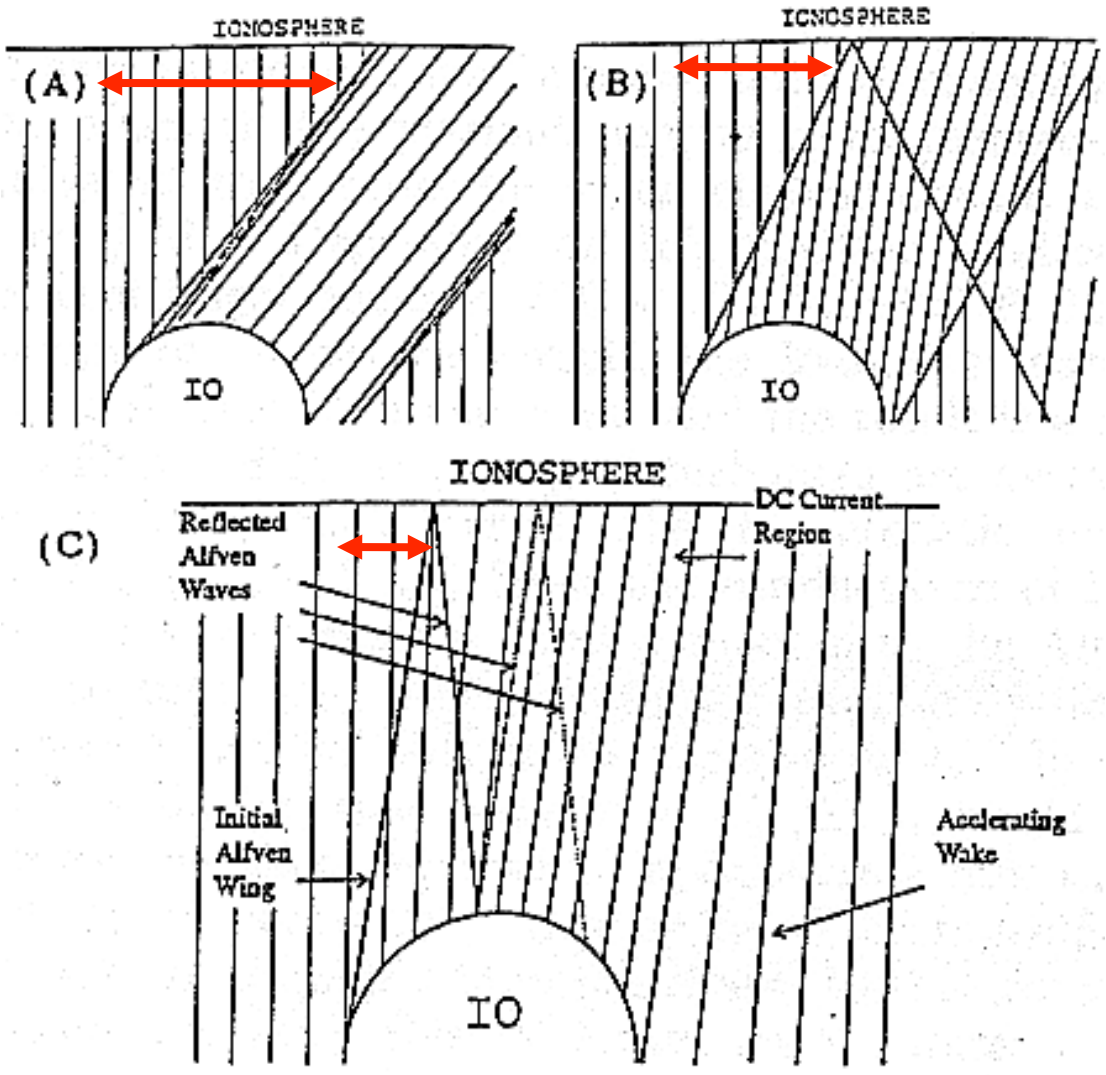


Io-C

f_{min}~1-2 MHz

Io-Jupiter interaction

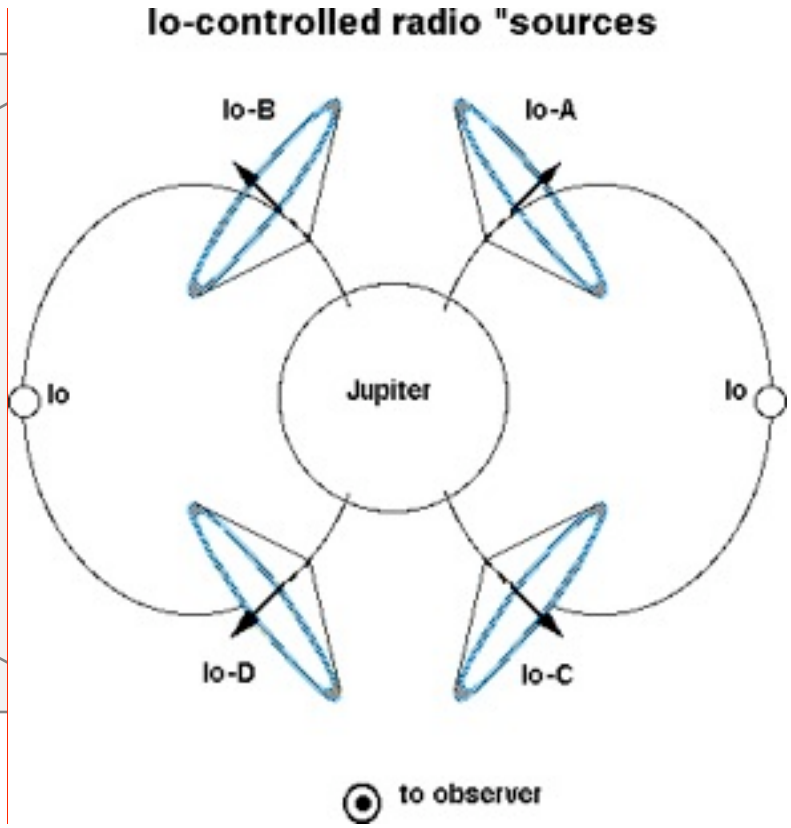




Interaction + Emission scenario

- Alfvén waves produced « at » Io, accelerate e^-
- Cyclotron Maser emission
  ($f \sim f_{ce}$, unstable e^- distribution , $f_{pe} << f_{ce}$, large θ/B)
- Polarisation + Io phase → NS « sources » x EW viewing

?



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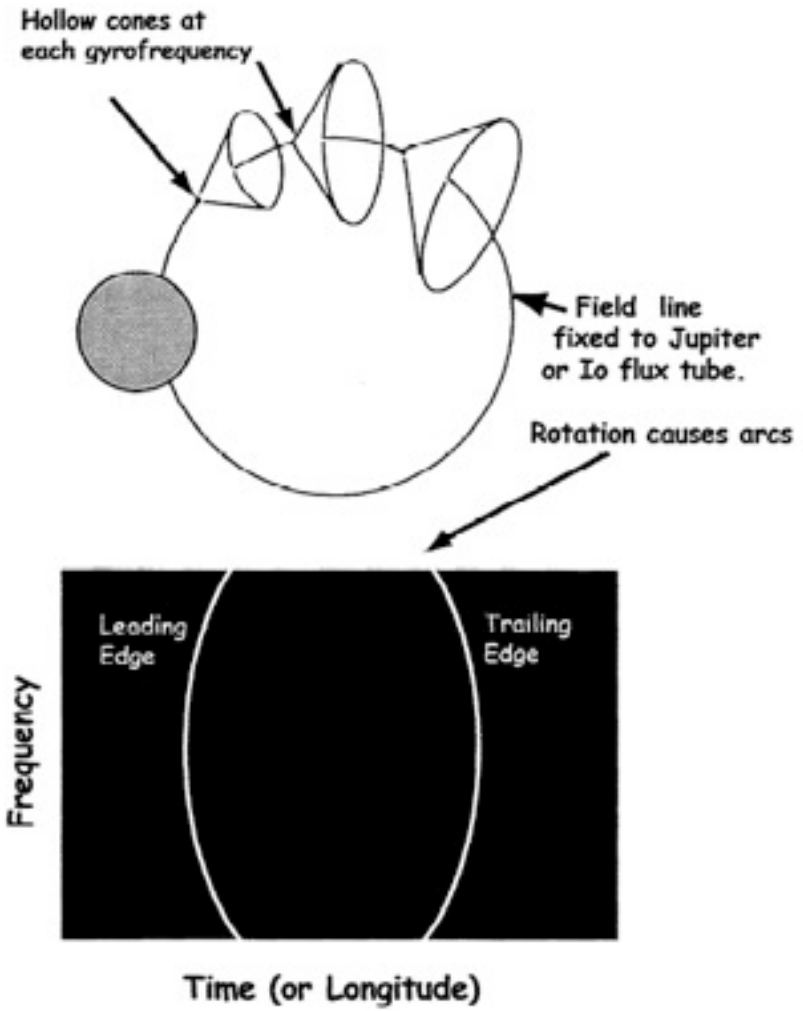
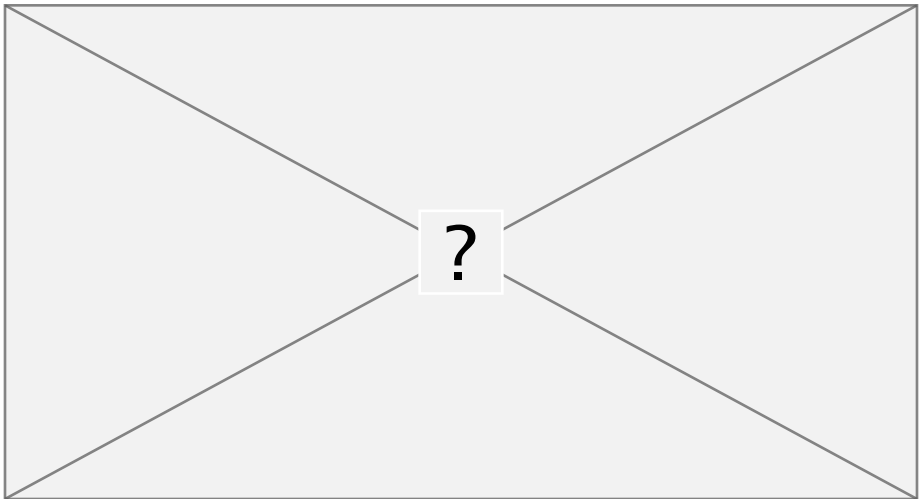
Basic idea for the origin of radio arcs

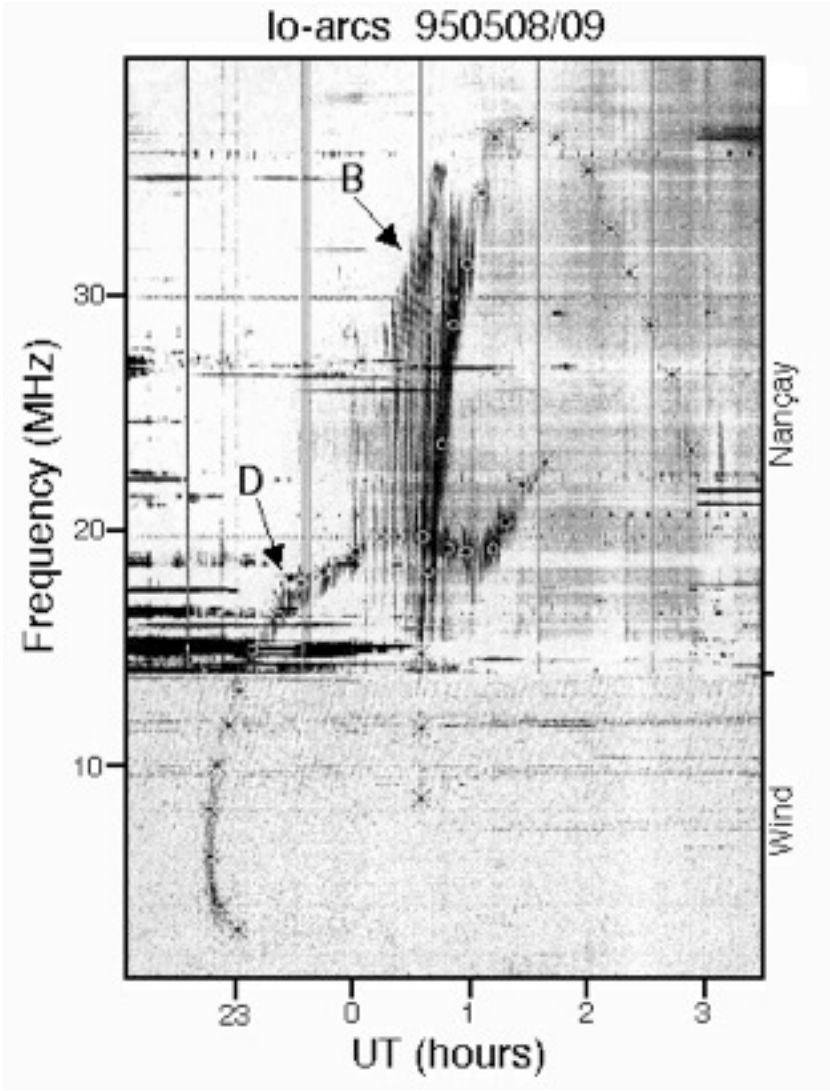


[Kaiser et al., JGR, 2000]

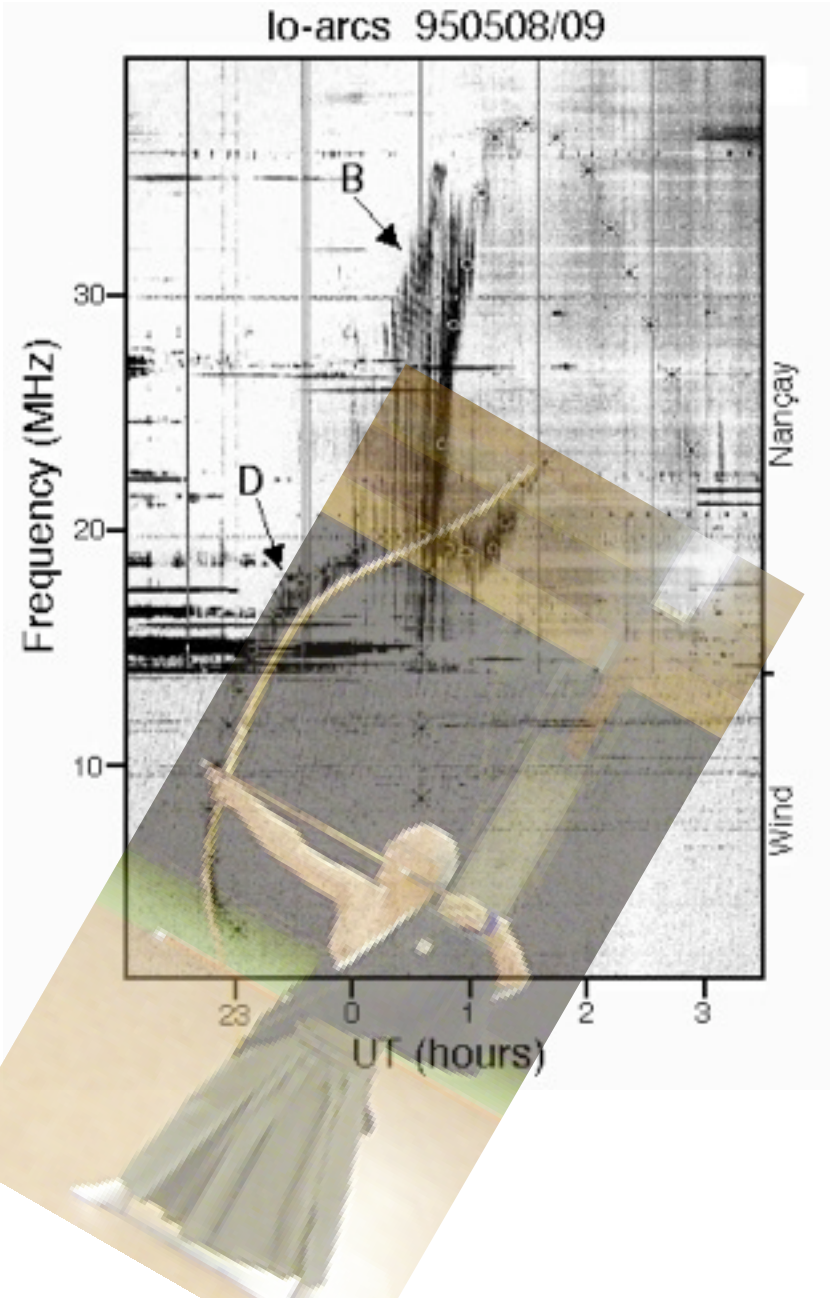
- Morphology function of
  - lead angle δ
  - beaming angle θ
  - longitude of Io Λ
  - hemisphere of source
  - B model: O6, VIP4 … ($f \sim f_{ce}$)



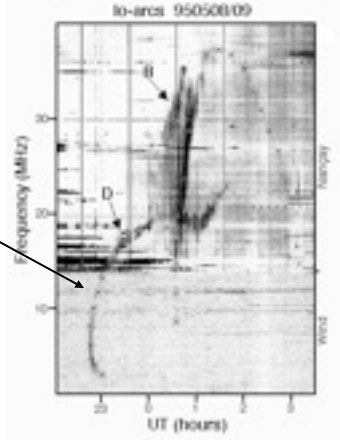
Arcs observed over their whole frequency range



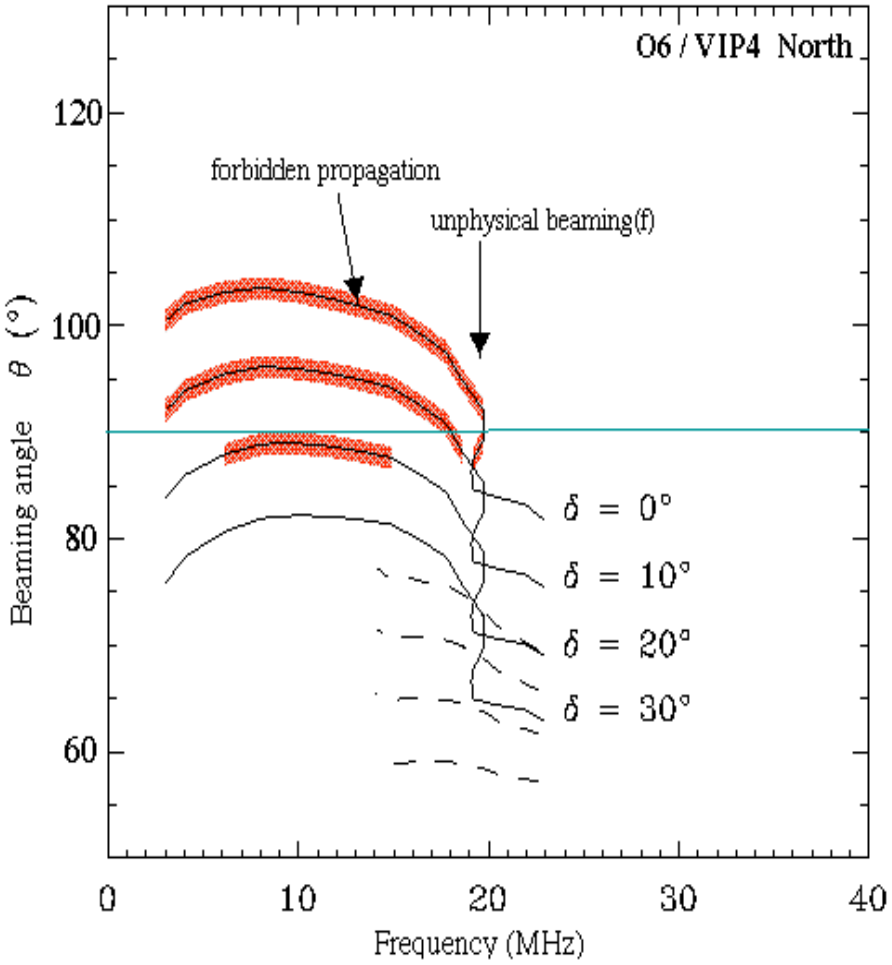
Arc modelling (1st attempt)

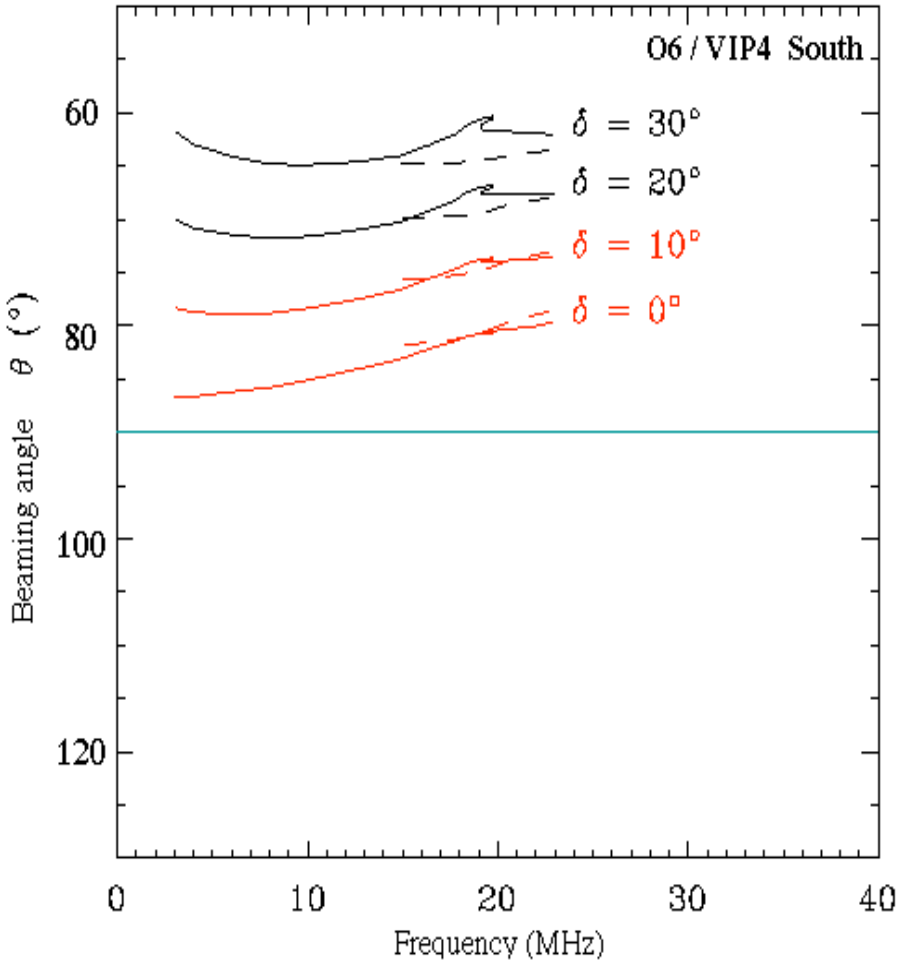


Analysis of Io-D arc



- Source along fixed flux tube / Io





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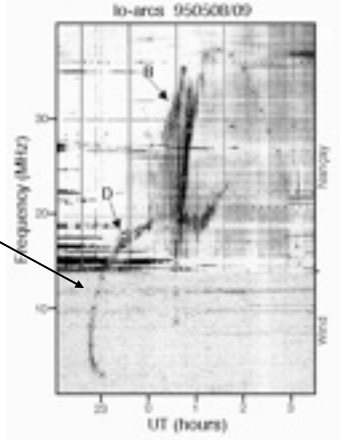
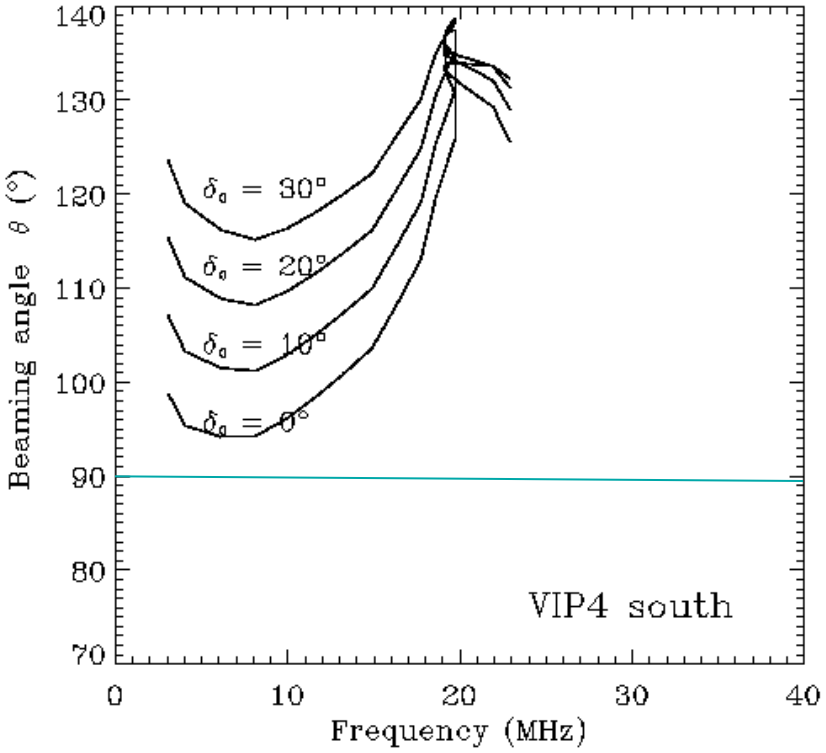


- Source along fixed Jovian field line

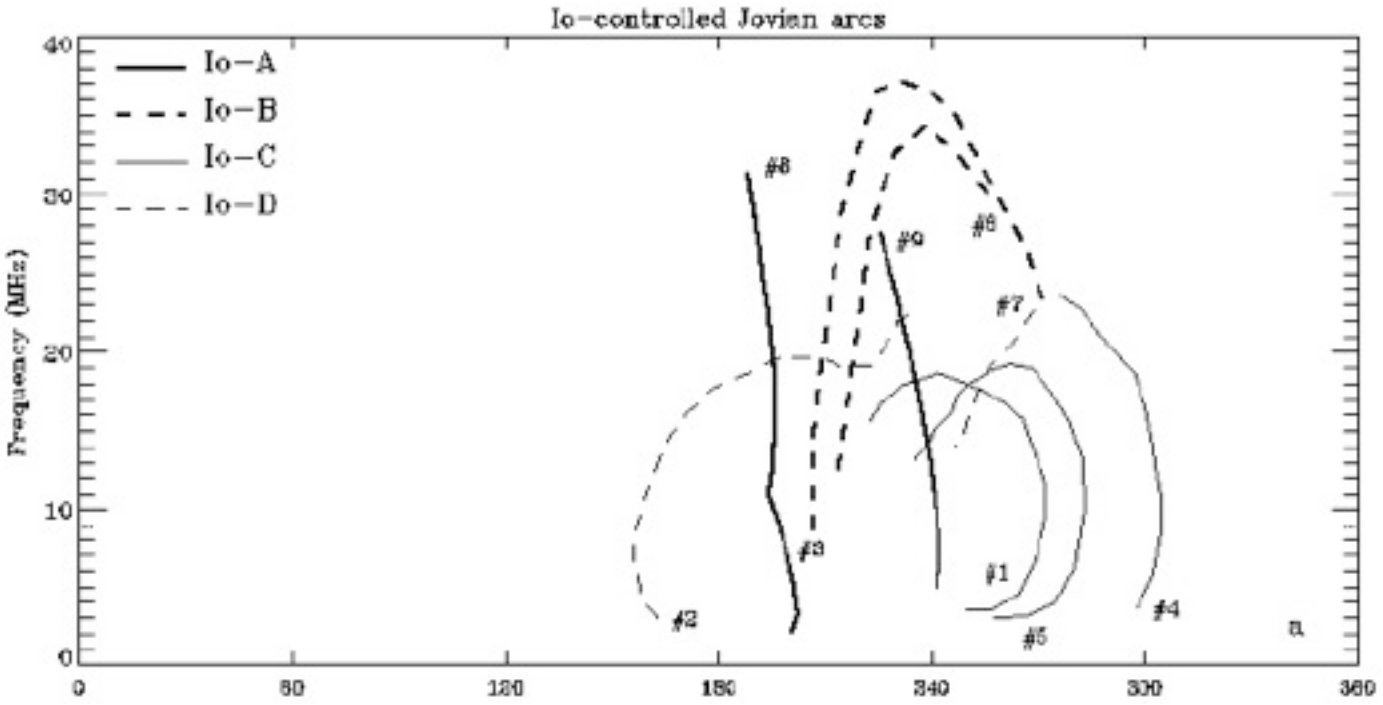


→ Radio arc formed by emission of several field lines in fixed flux tube at $\delta \sim c^{\dagger}$ / Io

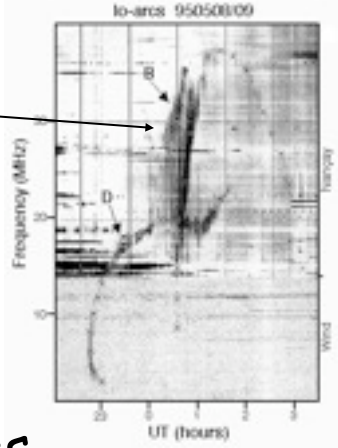
Summary of arc analyses

- Same for Io-*A* & -*C* arcs
- *A* & B from North, *C* & D from South
- δ=10°-30° ~c† along arc
- $\theta(f)$ ~70-75° [$\theta(f_{max})$ generally < $\theta(f_{min})$] , $\delta\theta$ ~1°

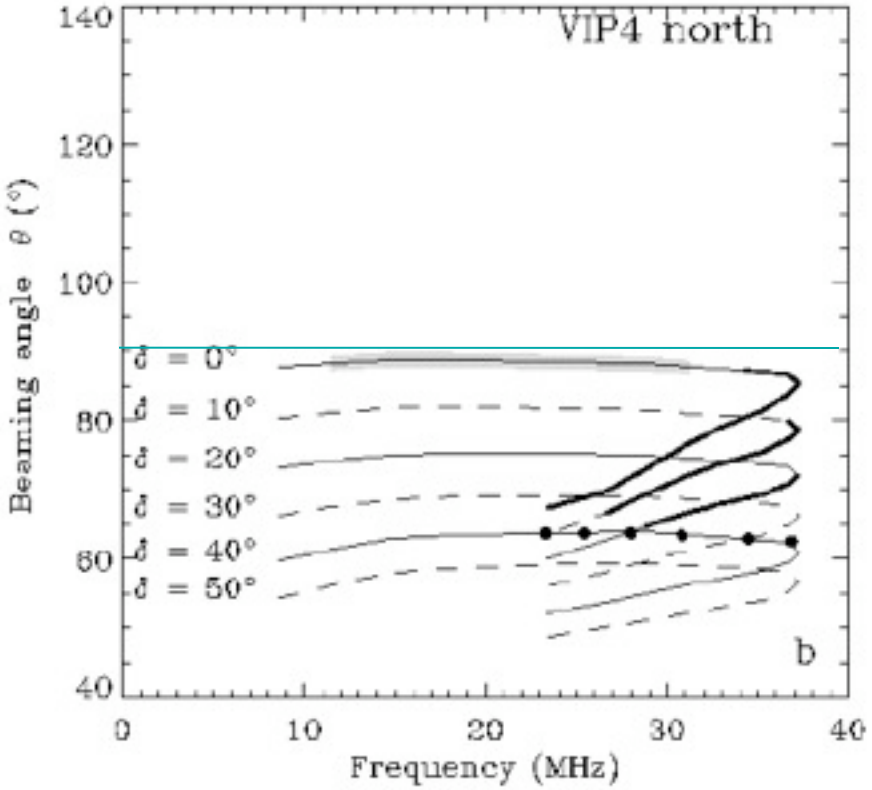
  [confirmed by Kaiser et al., 2000 with stereo Wind-Cassini]
- Better fit with VIP4

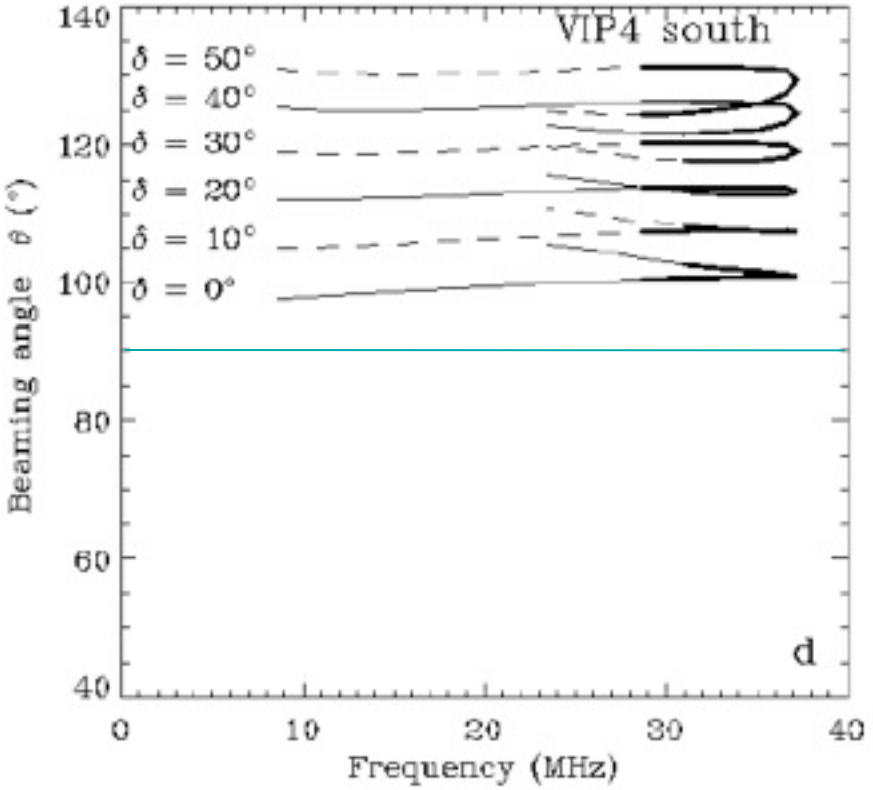


The Io-B case



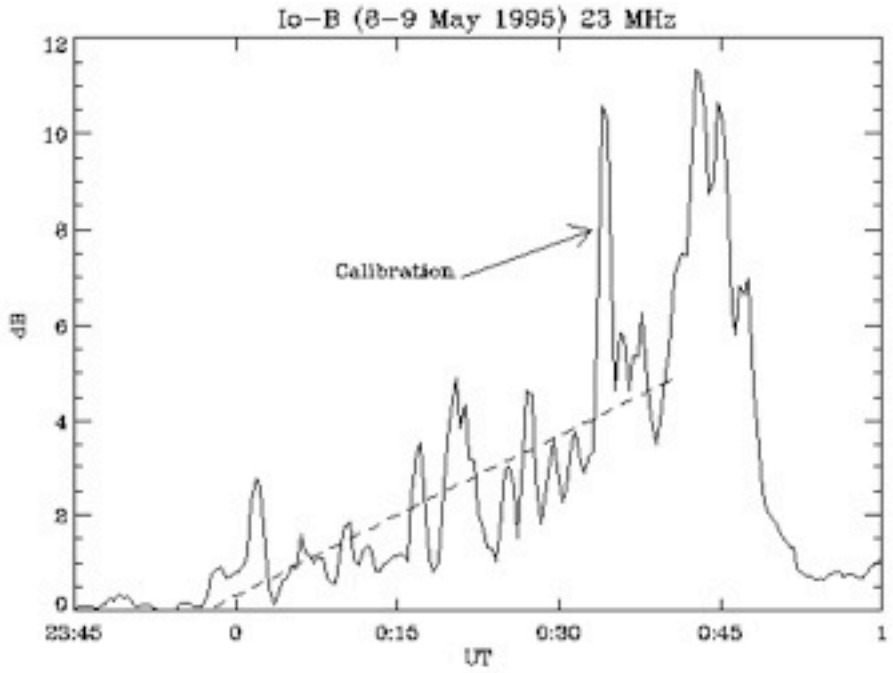
- weak tail, $\delta \geq 30°$, $\theta \leq 70°$
- $\theta(f)$ and δ cannot be BOTH constant
  - $\delta \geq 30°$ c† & double beaming (55-60° & 70-80°) due to 2 refraction indices or 2 free energy sources in radiosources
  - $\theta(f)$=c† & δ variable ~10-40°, with δ(main arc) > δ(tail)



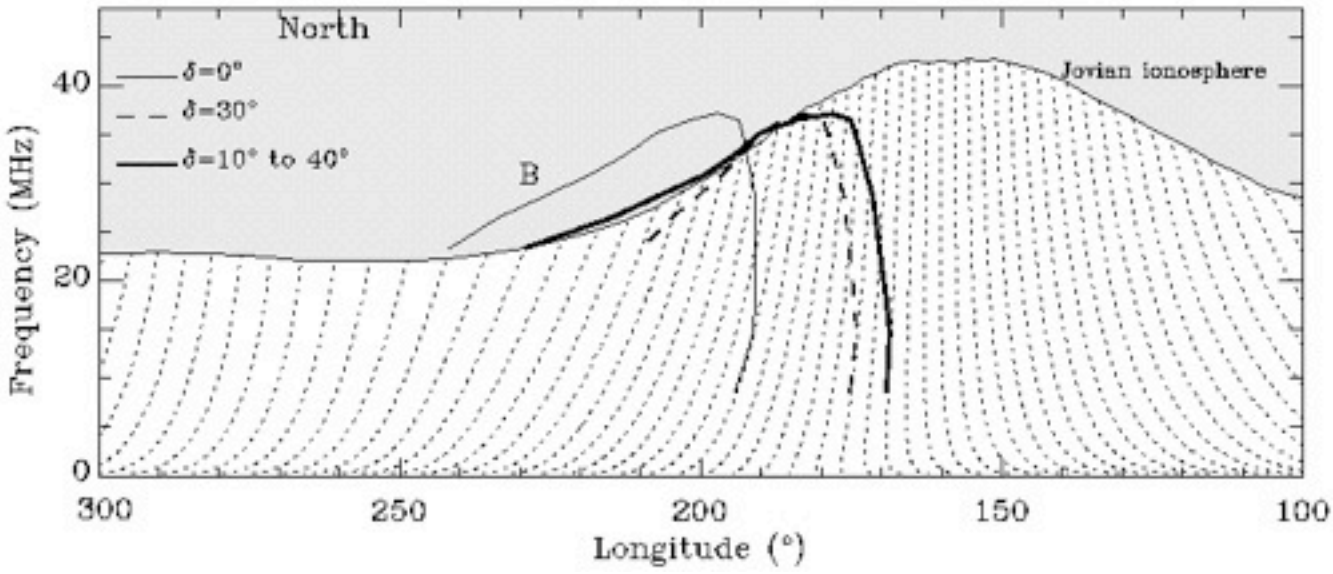


The Io-B case

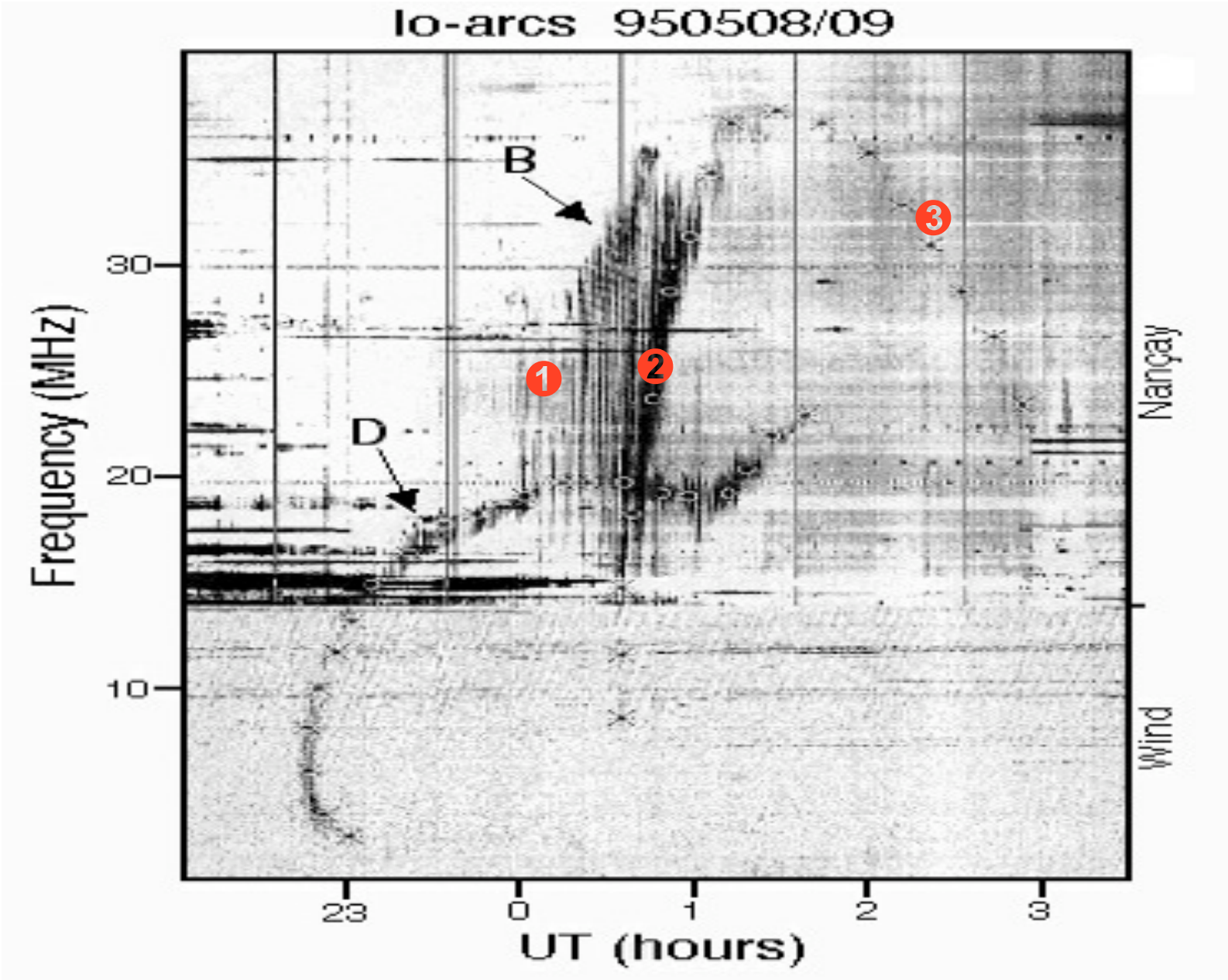
- Periodic fringes prior to main arc



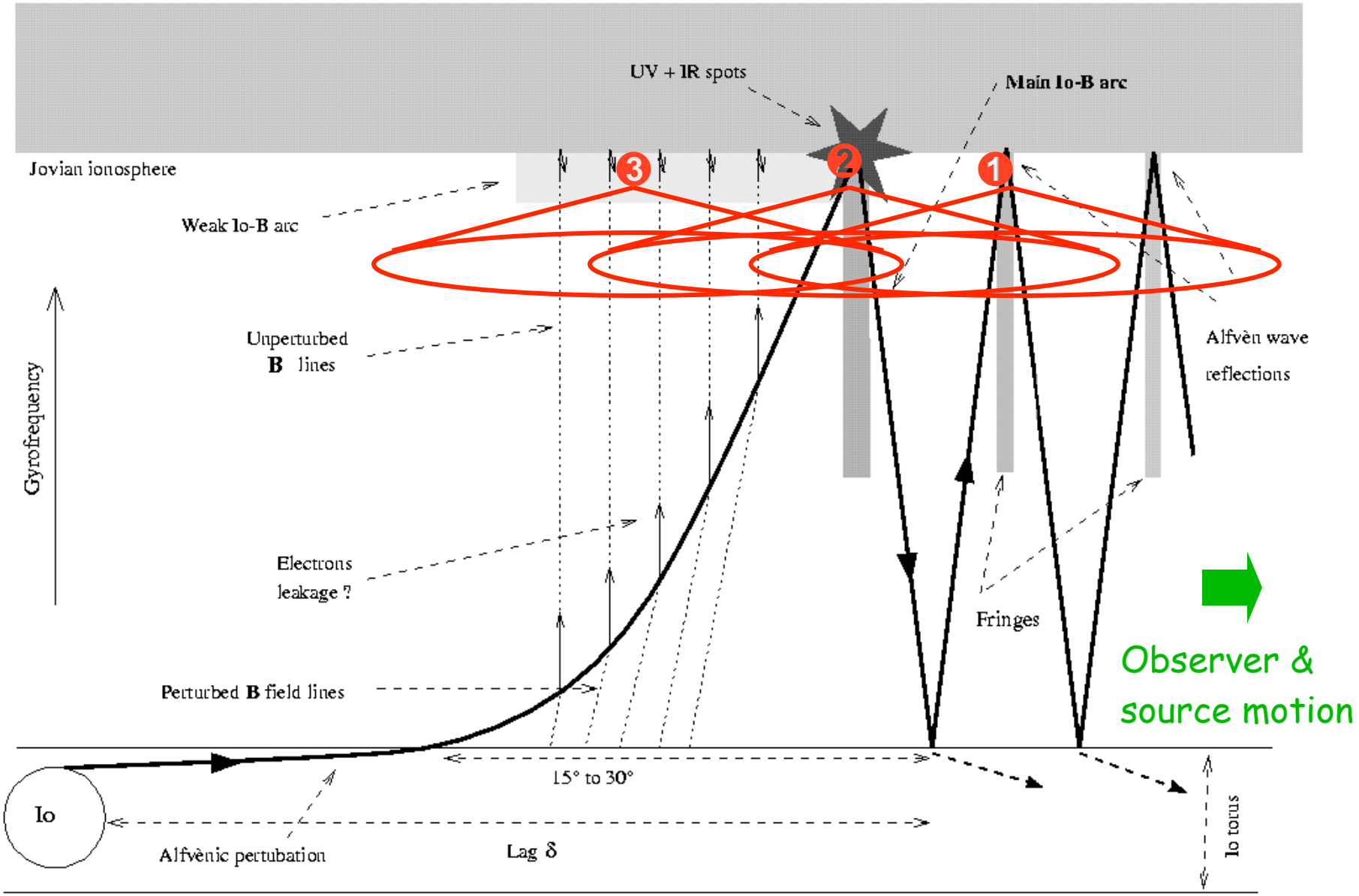
- Tail frequency matches $f_{ce\text{-}max}$ at ionosphere



The Io-B case


Io-arcs 950508/09
B
D
1
2
3
30
20
10
Frequency (MHz)
Nancay
Wind
23
0
1
2
3
UT (hours)

The Io-B scenario #1



- What about Io-A ?

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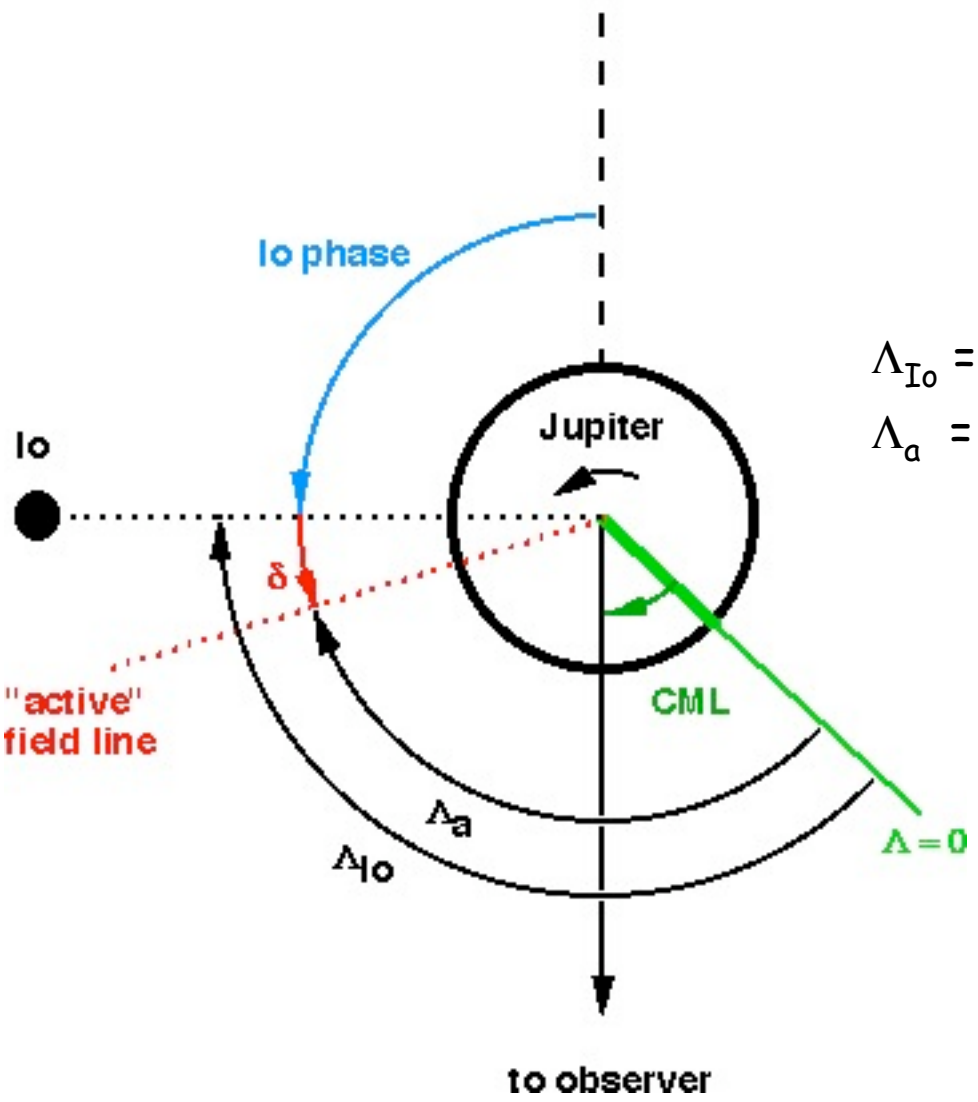
Statistical study of arc maximum frequency

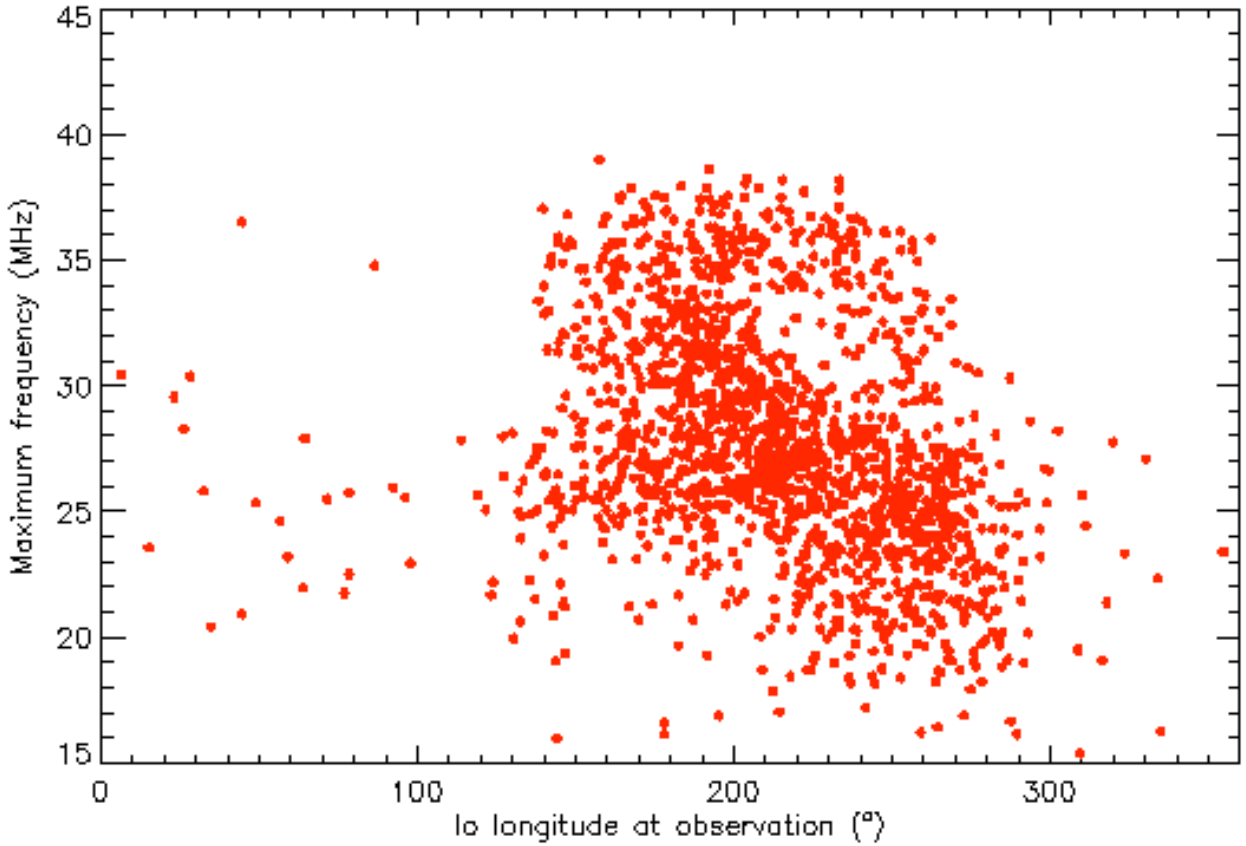
- $f \sim f_{ce} \rightarrow f_{max}(\Lambda_{Io}) \leq f_{ce}(\Lambda_a, \text{surface})$



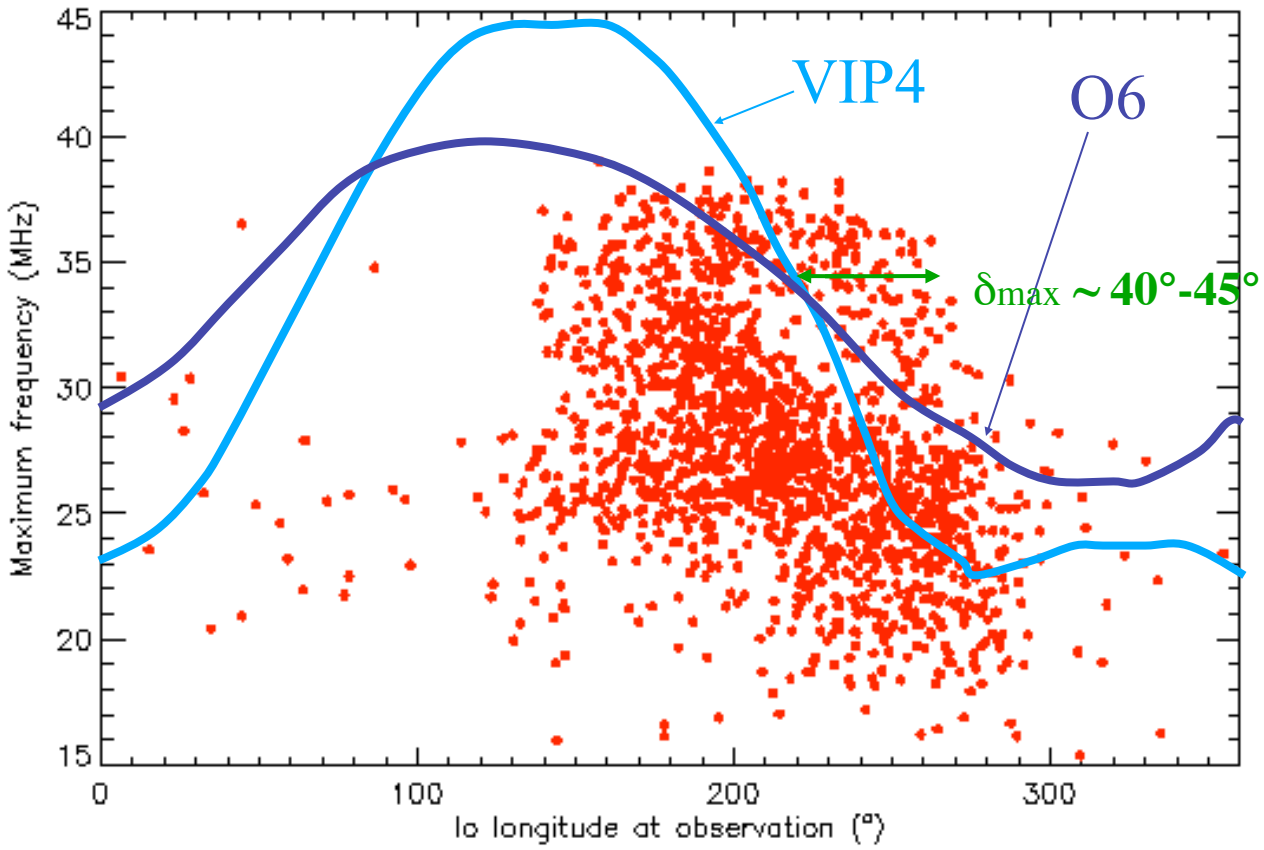
$\Lambda_{Io} = CML + 180° - \Phi_{Io}$

$\Lambda_a = CML + 180° - \Phi_{Io} - \delta$

- Analysis of 7+ years (1995-2002) of Nançay Decameter Array observations of Io A & B emissions → distribution of observed $f_{max}(\Lambda_{Io})$

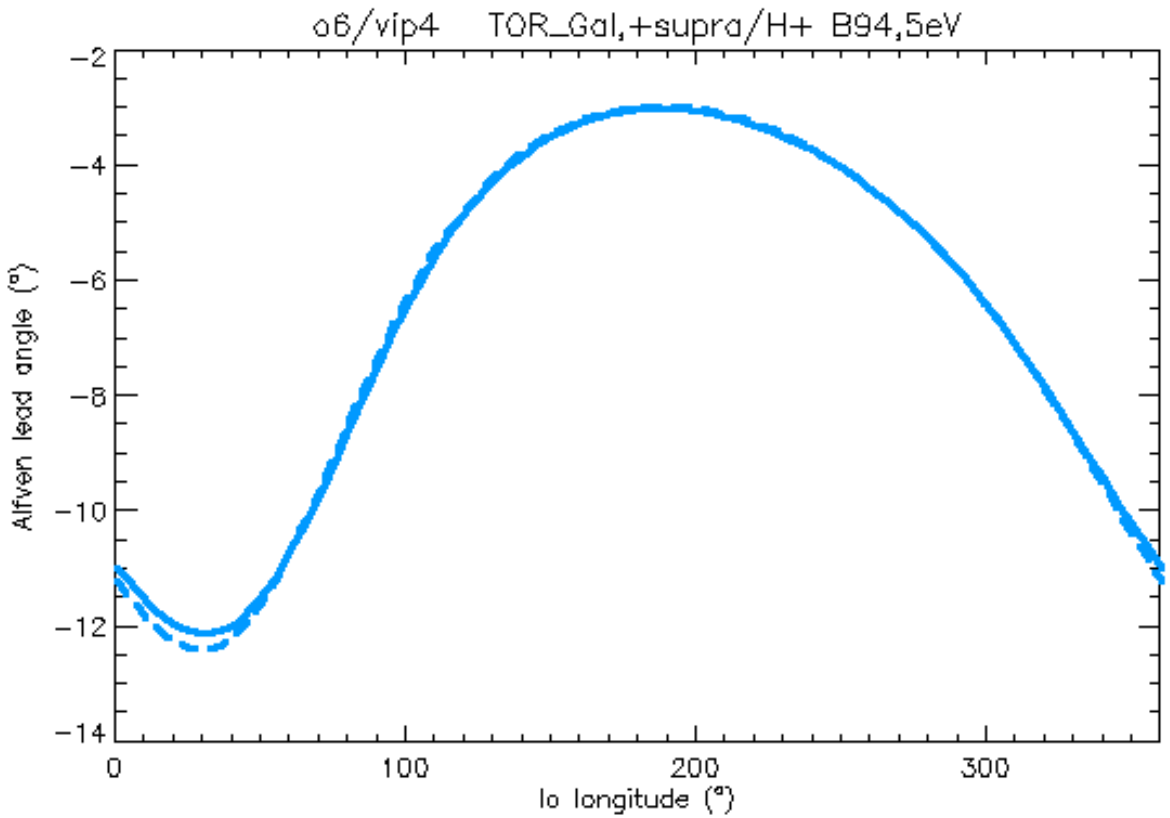


→ Compared to modelled $f_{max}(\Lambda_{Io})$



→ Comparison to modelled $f_{max}(\Lambda_a)=f_{ce}(\Lambda_a,\text{surface})$
for an Alfvén Wave perturbation

• Alfvèn propagation time → lead angle $3° \leq \delta \leq 12°$



Questions :

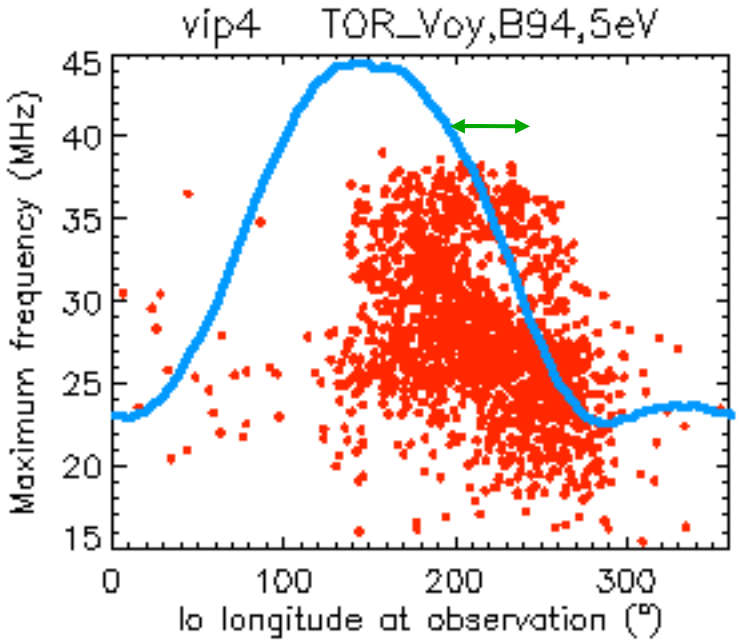
→ How to explain large radio lead angles ?

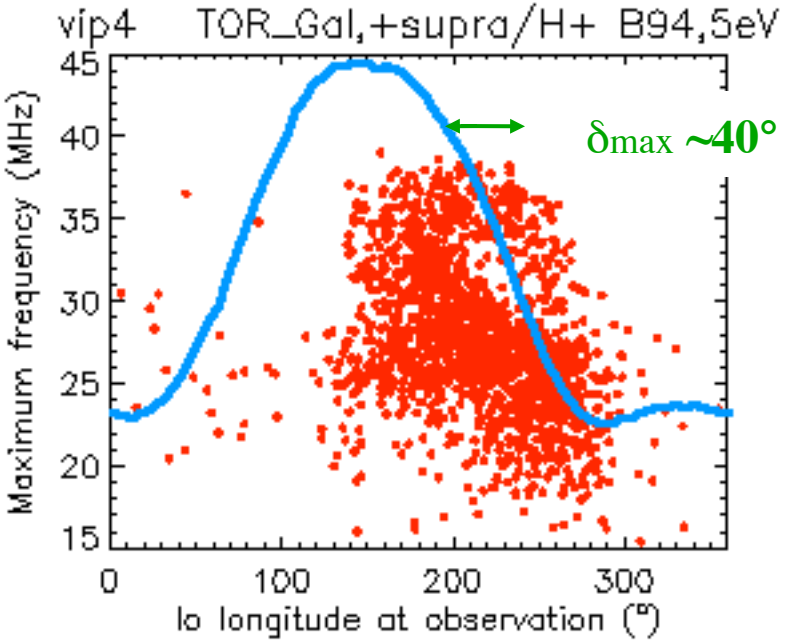
~~→ magnetic field model ?~~

~~→ much denser torus ?~~

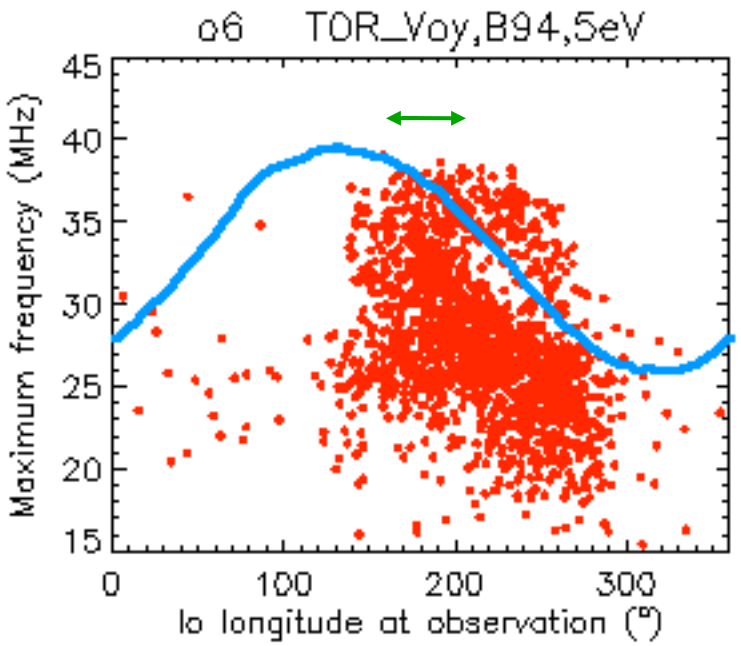
→ Why larger than for UV & IR emissions (0° to 15-20°) ?

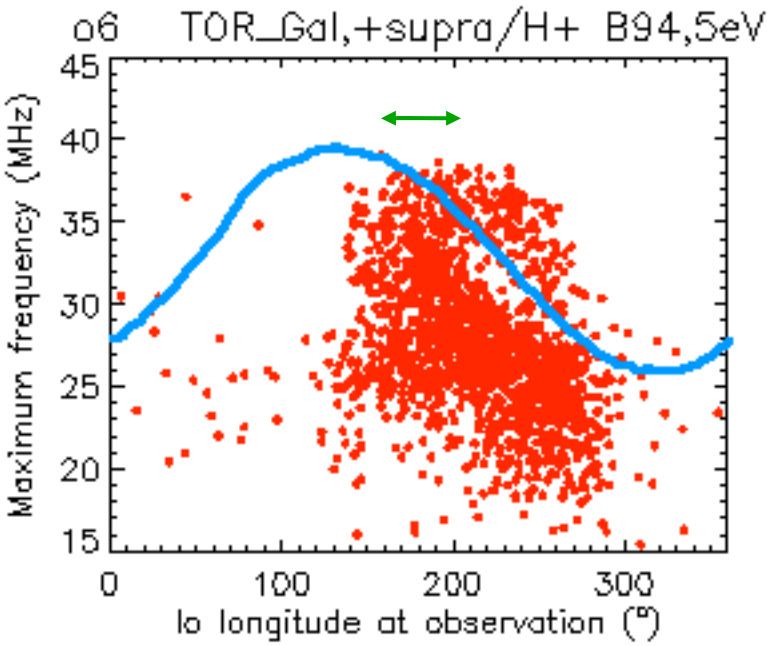
[Connerney, Prangé/Clarke]





VIP4





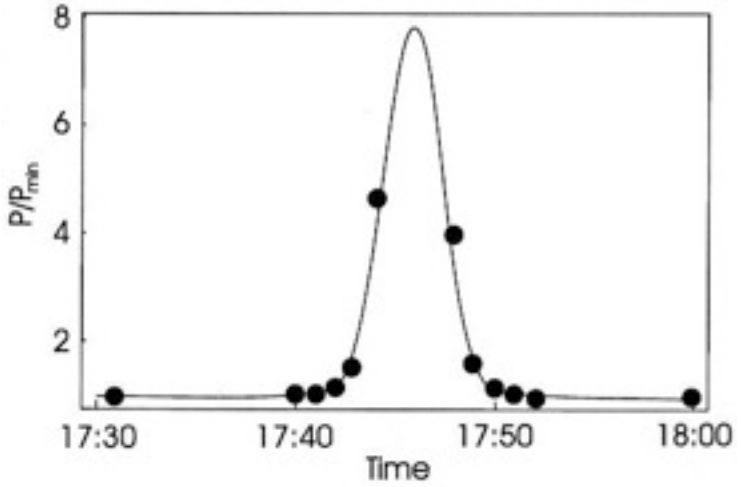
O6

Voyager *[Bagenal, 1994]*

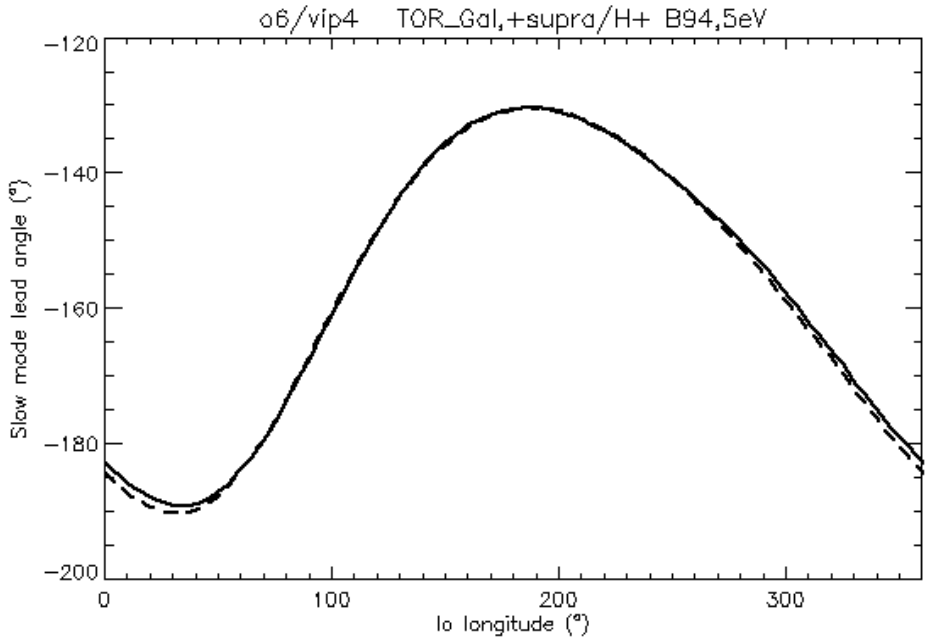
Galileo *[Bagenal et al., 1997, Crary et al., 1998]*

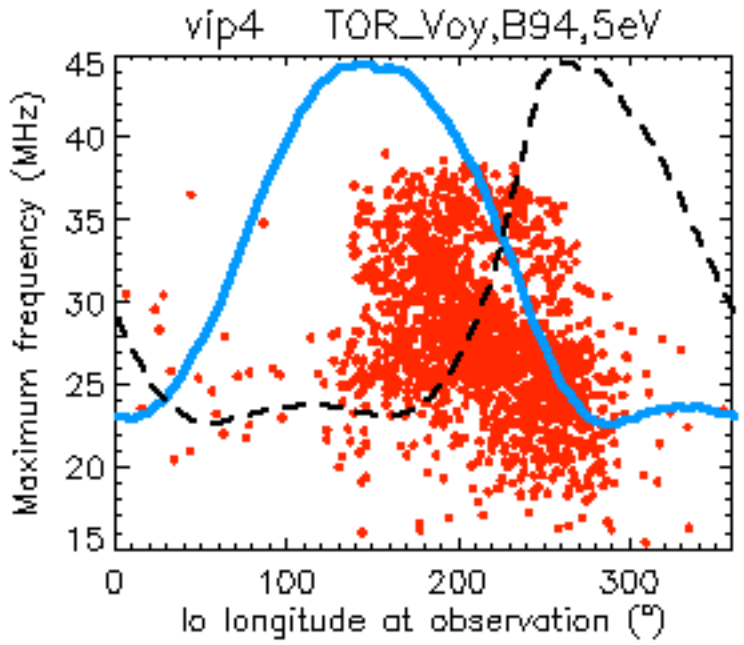
- Alternative perturbation : slow mode wave excited by a plasma pressure pulse *[Kopp, 1996, Linker et al., 1991, + earlier works]*

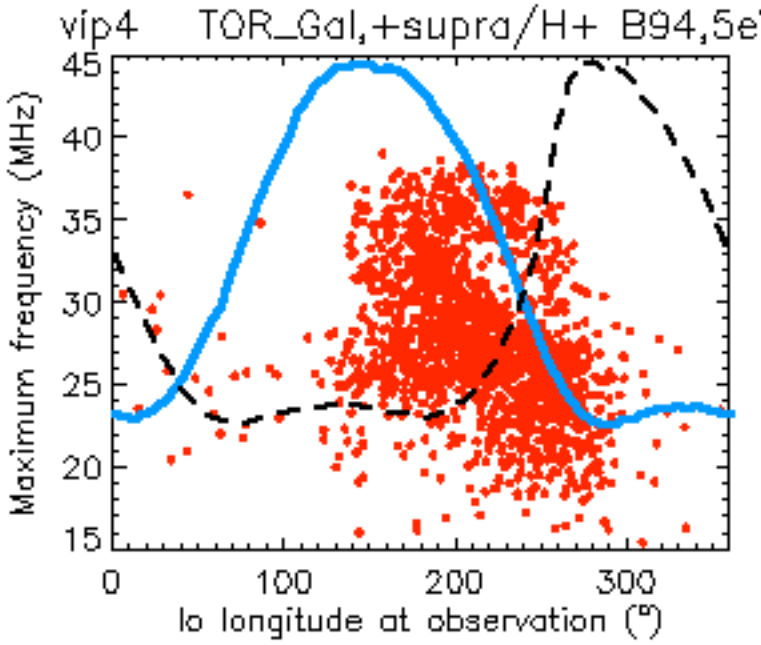
→ observation by *Frank et al. [1996]*
900 km from Io
& gaussian adjustment
[Erkaev et al., 2000]



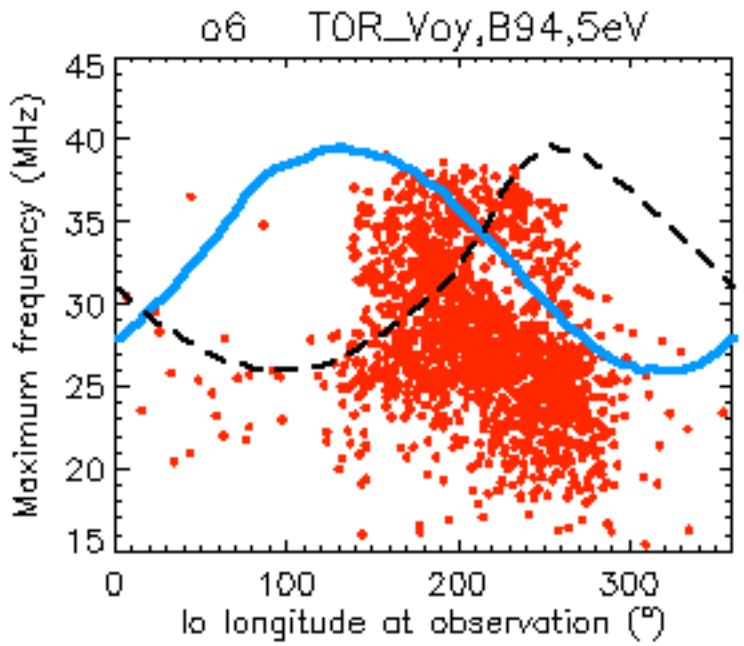
→ modelled
$f_{ce}(\Lambda_a, \text{surface})$

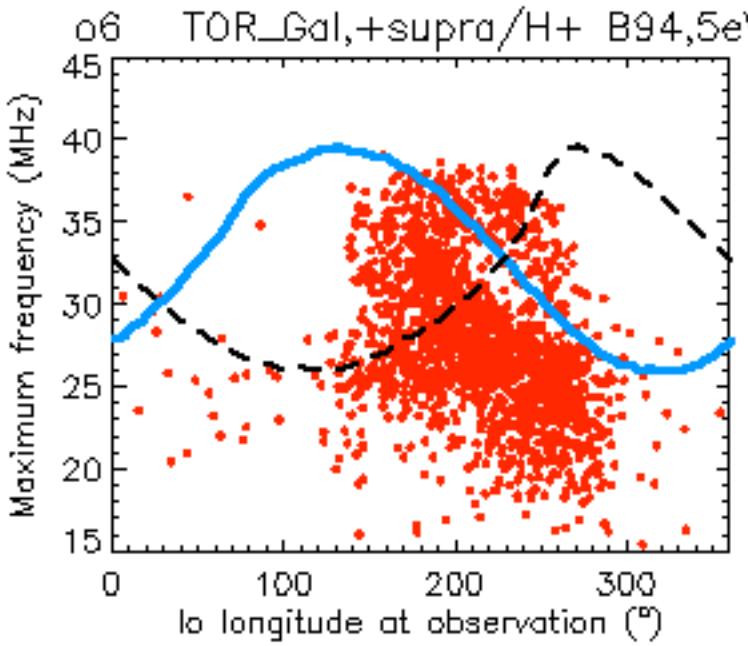






VIP4



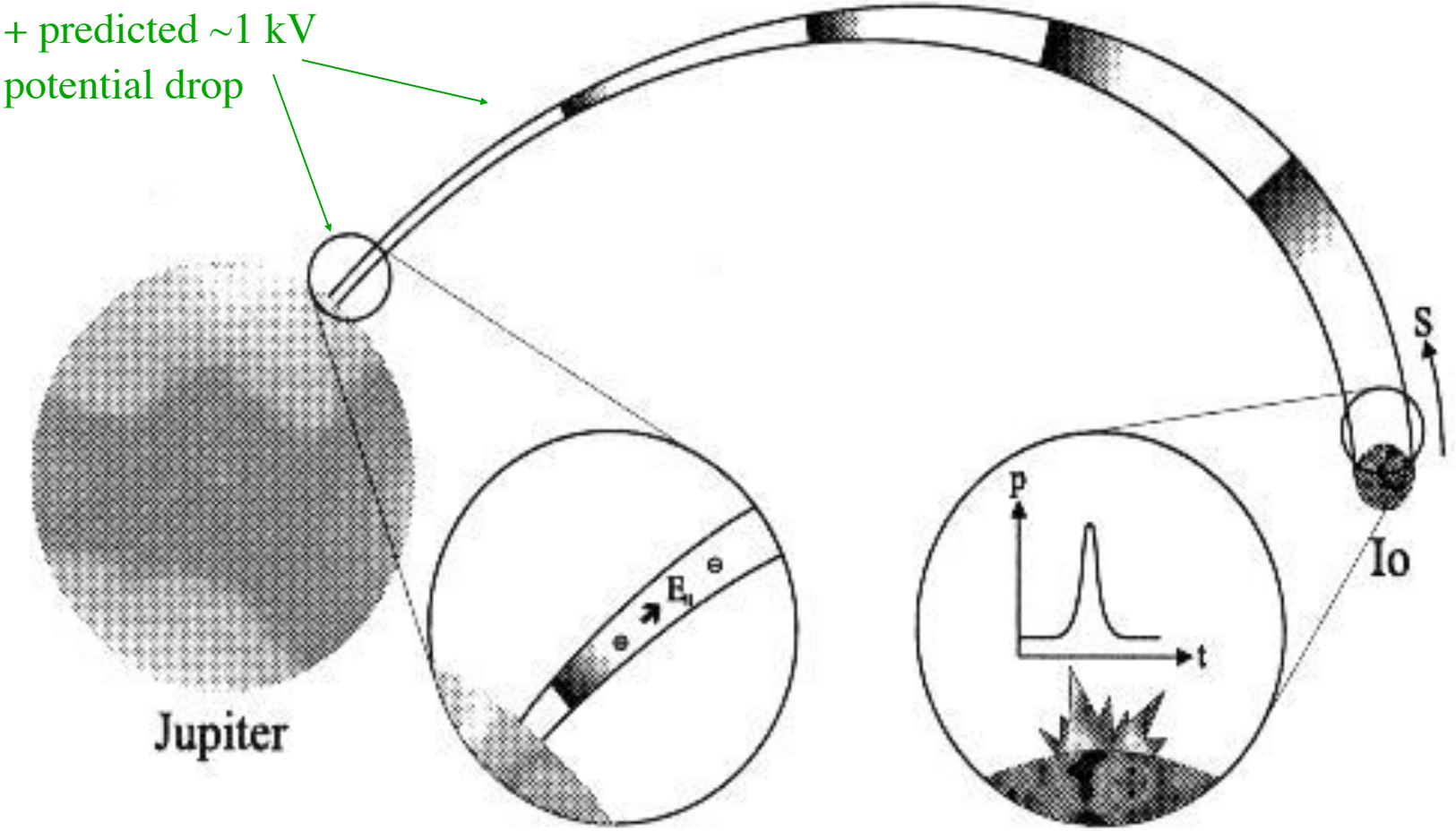


O6

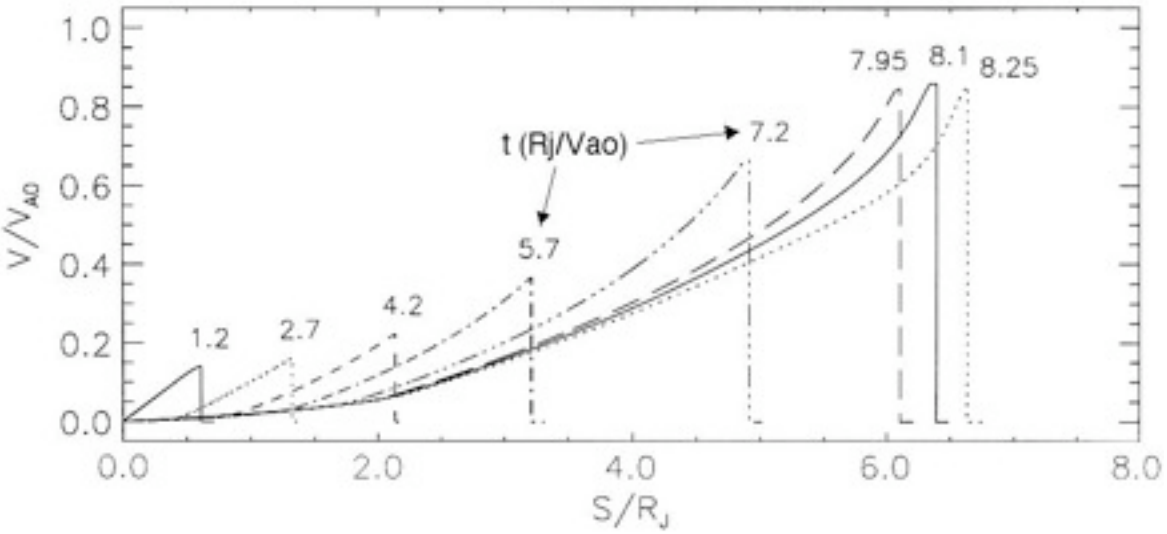
"Voyager"

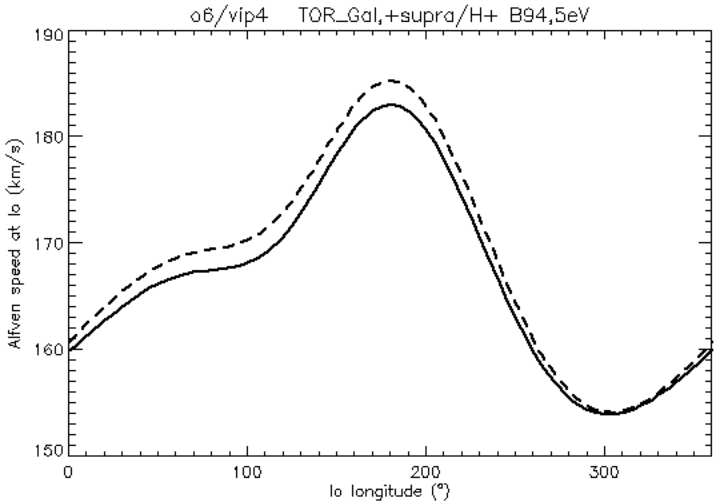
"Galileo"

- *[Erkaev et al., 2000]* → evolution of a slow mode wave in a converging (~dipolar) field geometry
  → slow shock

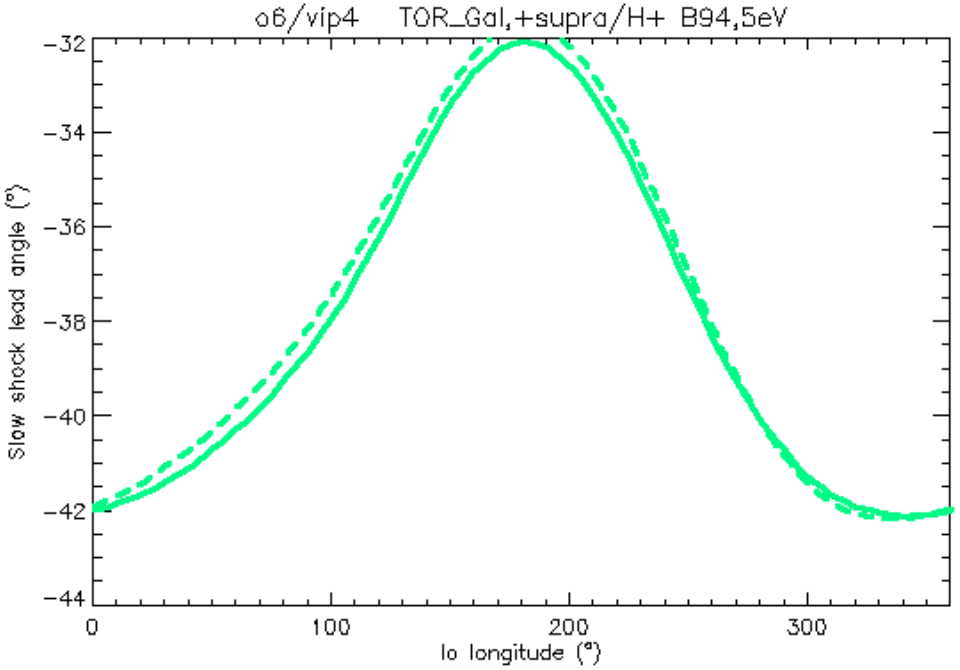


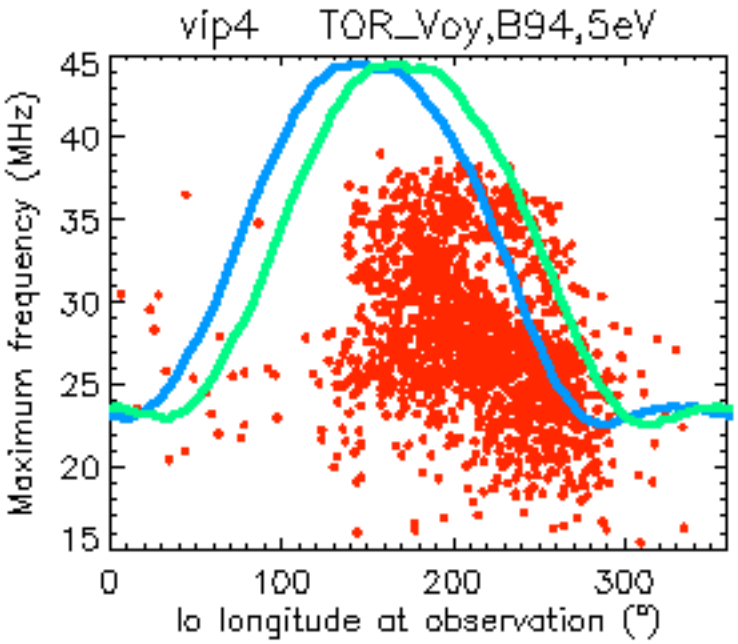
→ propagation velocity : $V_{slow} < V_{slow\_shock} < V_a$

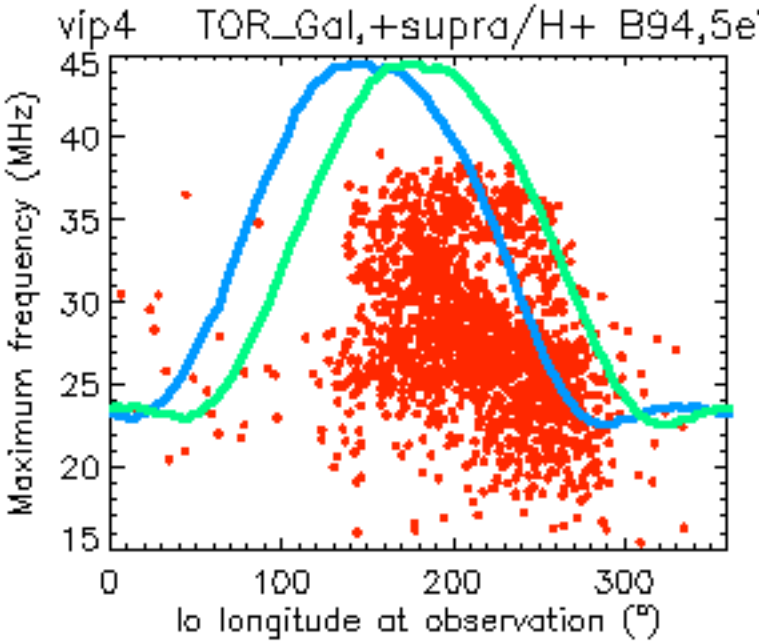




→ modelled
$f_{ce}(\Lambda_a, surface)$







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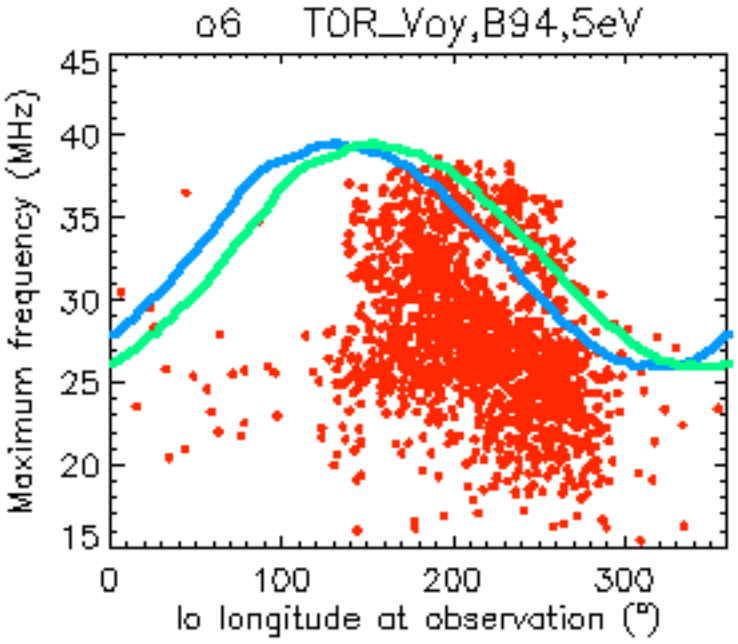
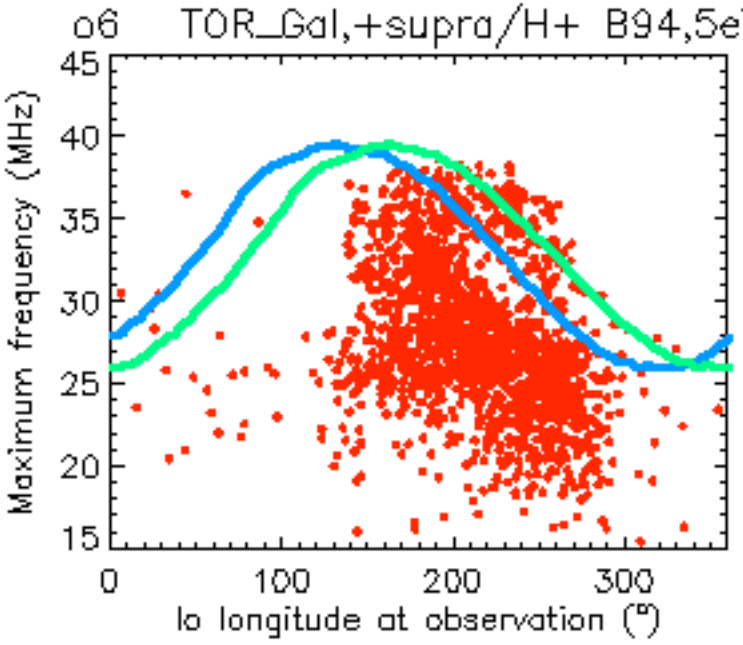


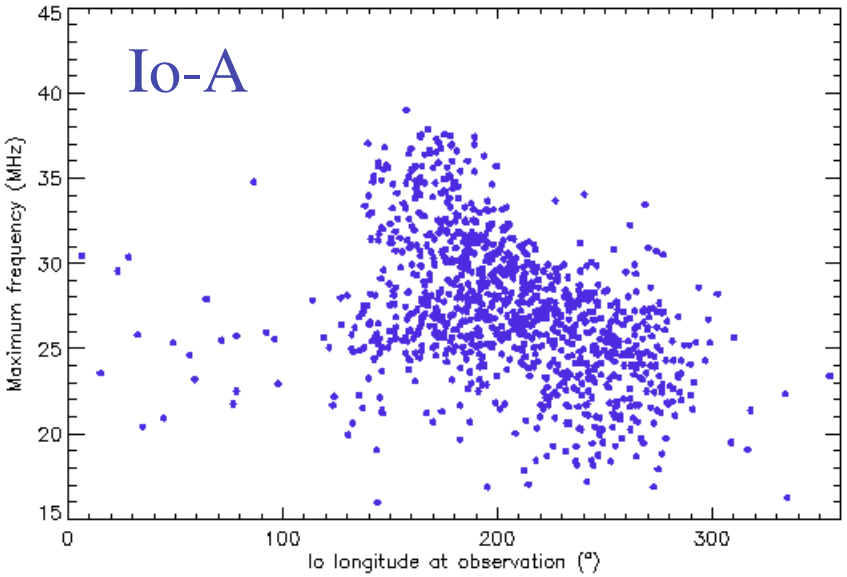


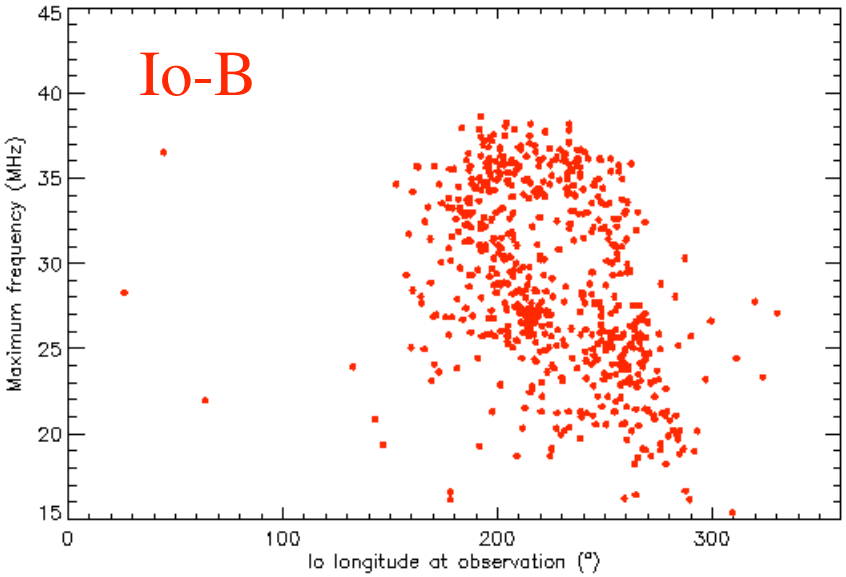
O6

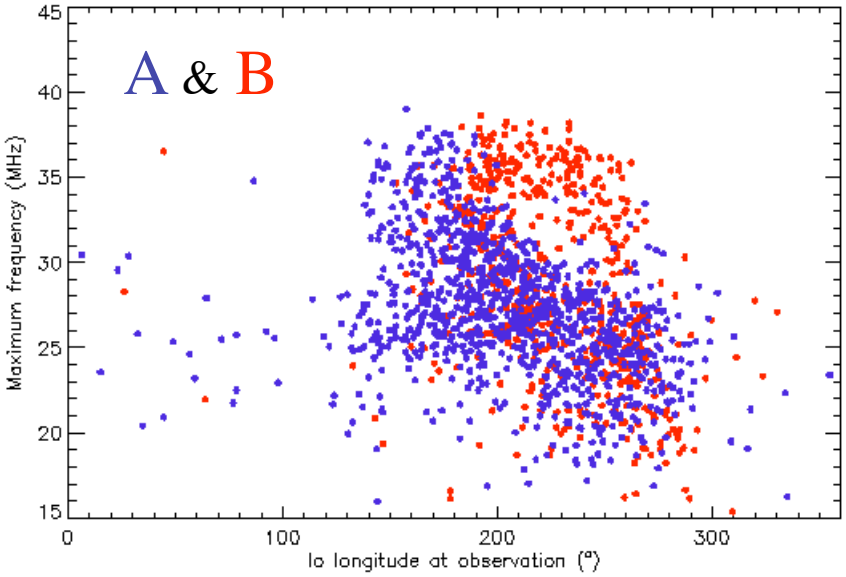
"Voyager"

"Galileo"

- back to observed $f_{max}(\Lambda_{Io})$



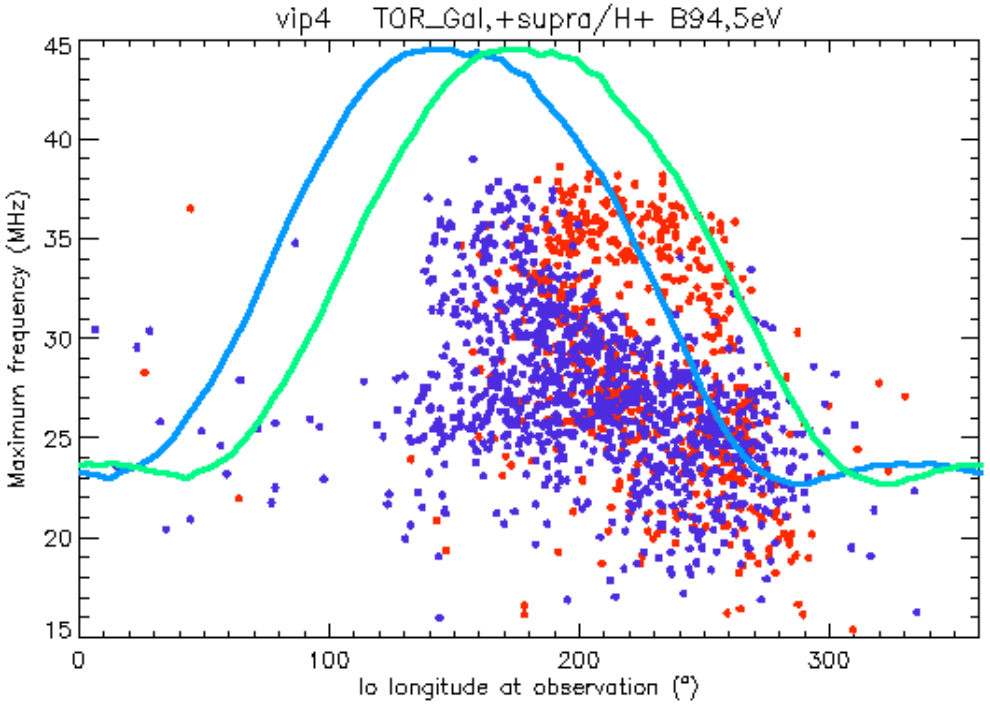


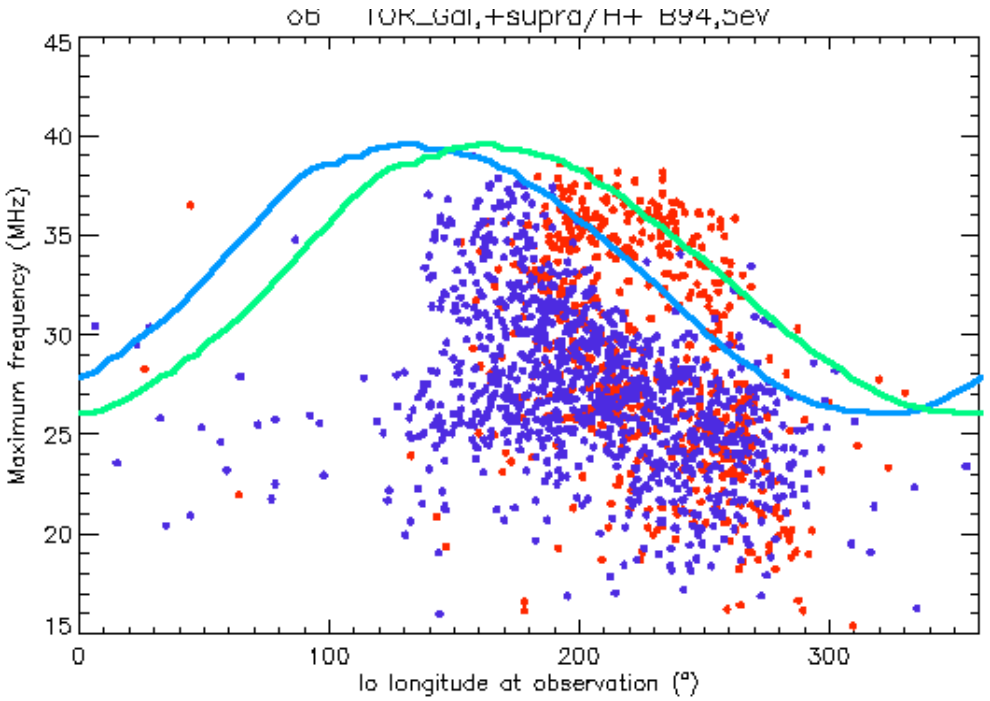


→ modelled

$f_{ce}(\Lambda_a, \text{surface})$

2 populations ?



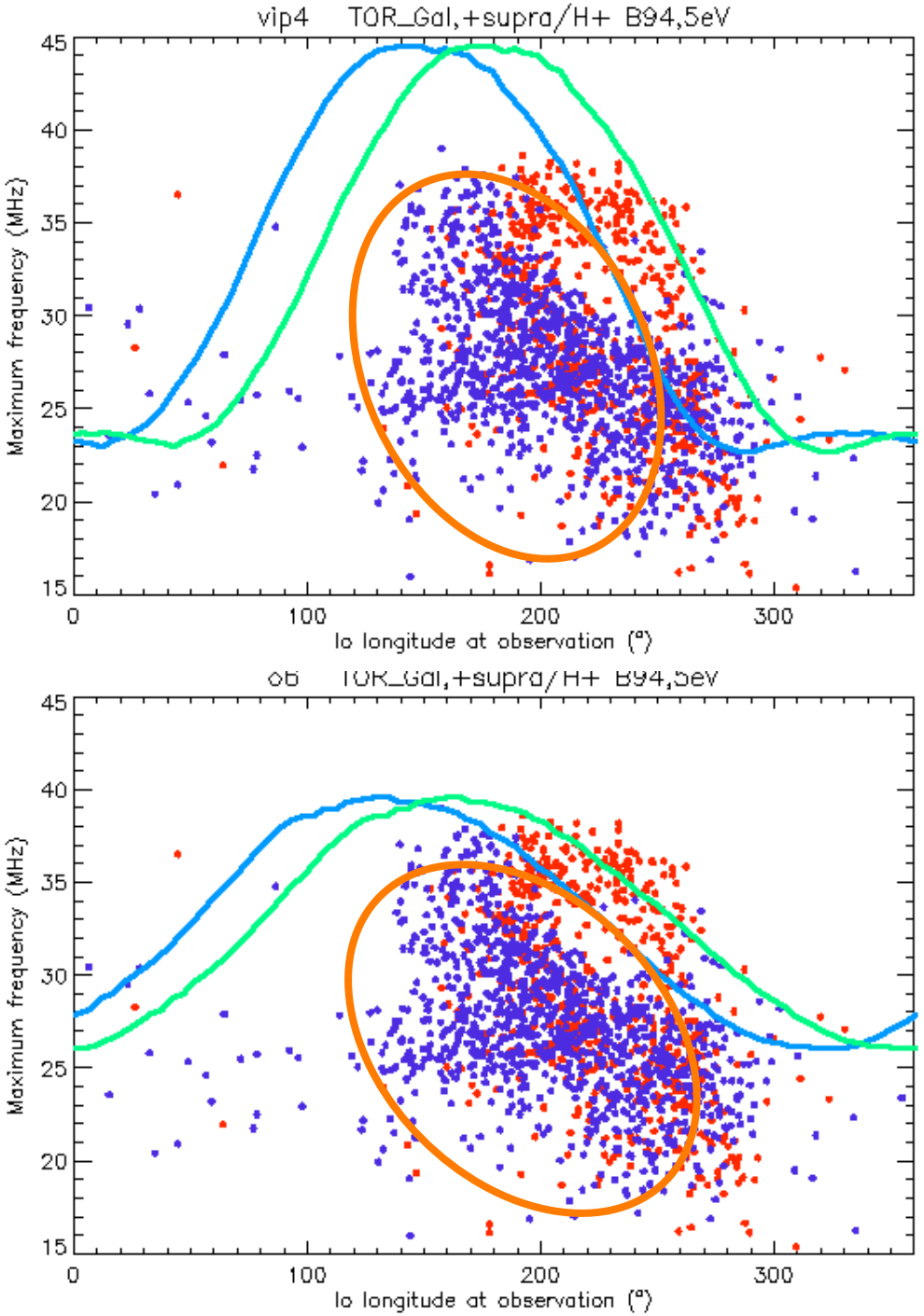


→ modelled

$f_{ce}(\Lambda_a, \text{surface})$

2 populations ?

- **AW-driven**

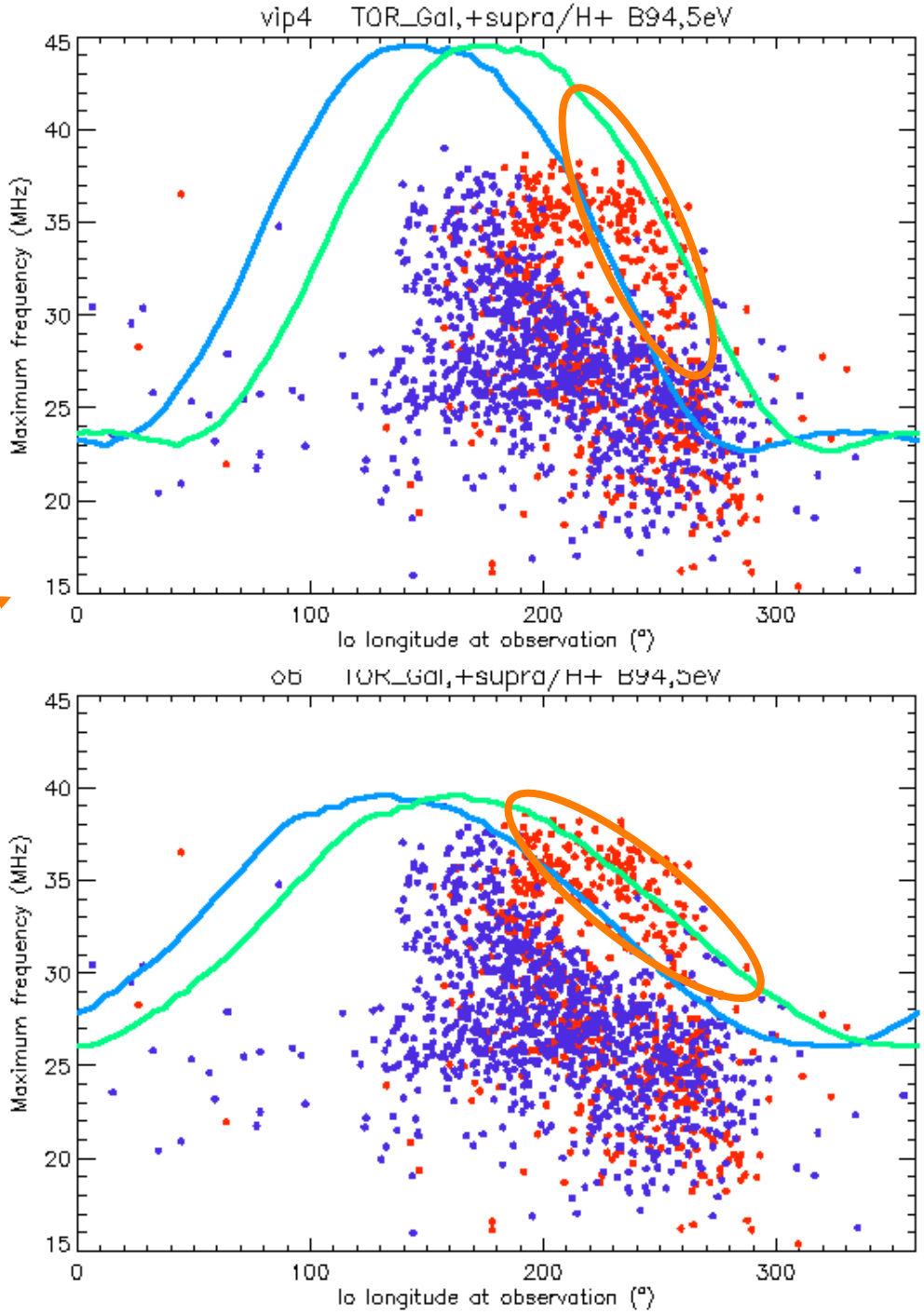


→ modelled

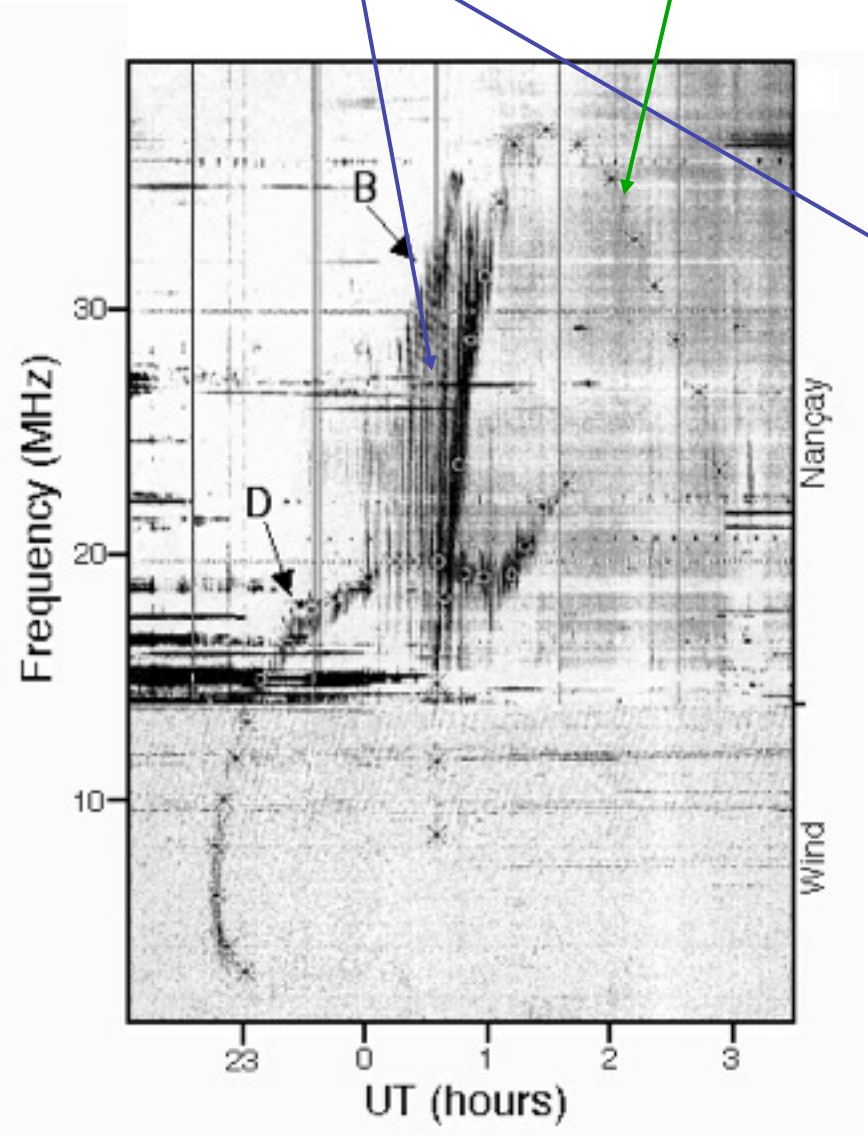
$f_{ce}(\Lambda_a, \text{surface})$

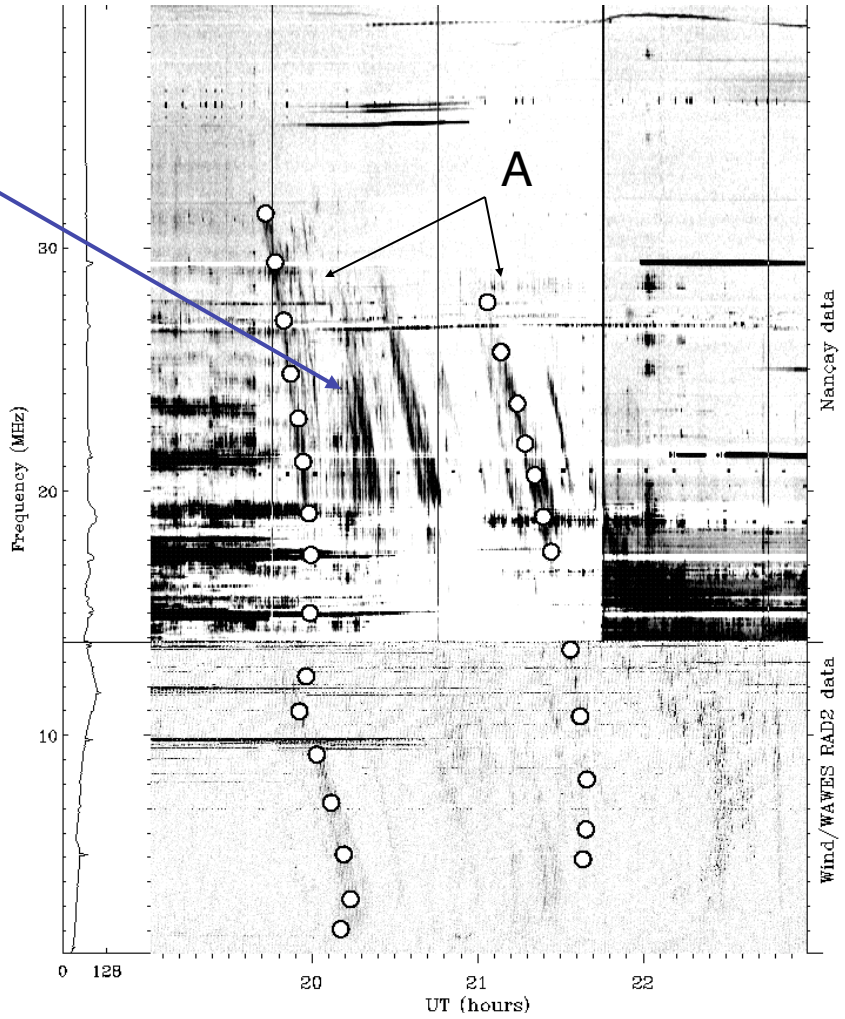
2 populations ?

- **AW-driven**
- **Shock-driven**



• Nature of AW- versus shock- driven radio emissions ?





[Queinnec & Zarka, 1998]

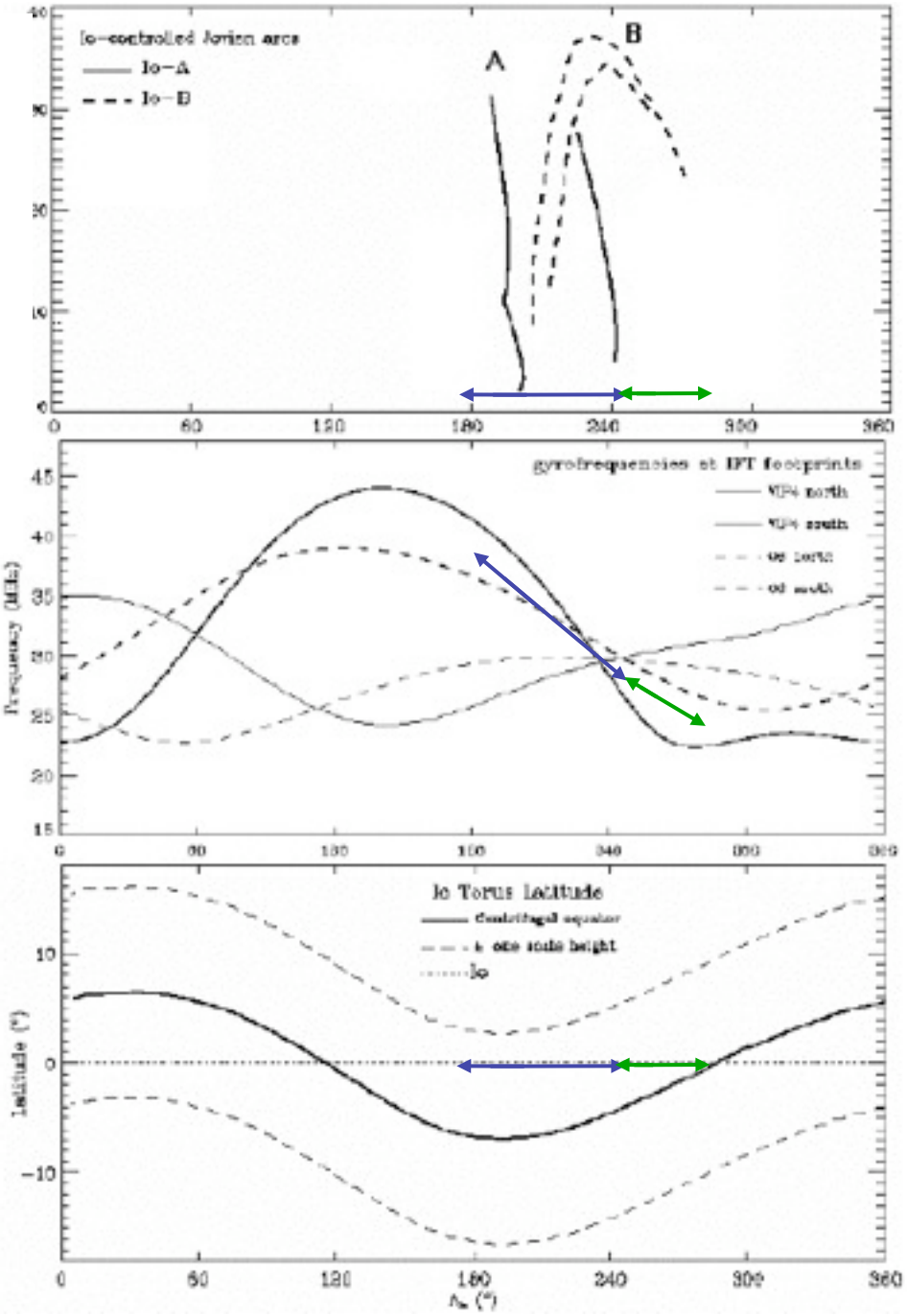
- Origin of AW- versus shock-driven radio emissions ?

- Radiosources on $dB/d\Lambda_{Io} < 0$

  [Galopeau et al., 2004]

→ AW-driven when Io near torus northern edge

→ shock-driven when Io closer to torus center

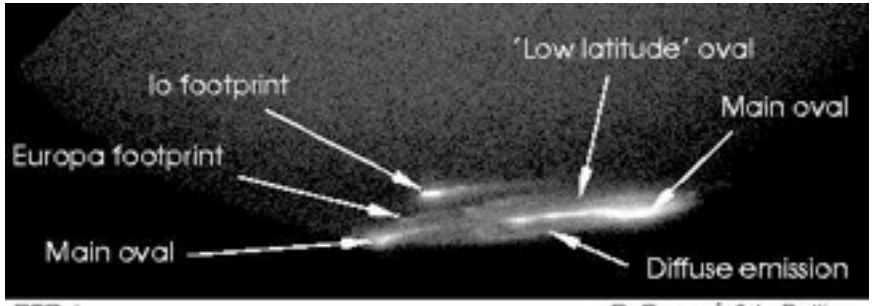


Statistical study of arc maximum frequency : Conclusions

- δ(main arc) $\leq$15°-20°
  - → consistent with Alfvèn wave perturbation & UV / IR lead angles
  - → several keV e^- ?
  - ⇒ intense Radio arcs + UV/IR spots ?

- δ(Io-B tail) ~20°-40° > δ(main arc)
  - → evidence for slow shock-acceleration
  - → ~1 keV e^- ?
  - ⇒ weak emission close to $f_{ce}(\Lambda_a$, surface) + Io's UV/IR trail ?

  ⇒ « double beaming » (≤60° for tail & ≥75° for main arc)



Statistical study of arc maximum frequency : Conclusions

• AW-driven radio emissions produced when Io near torus Northern edge → lower plasma density ⇒ B perturbation dominant/only ?

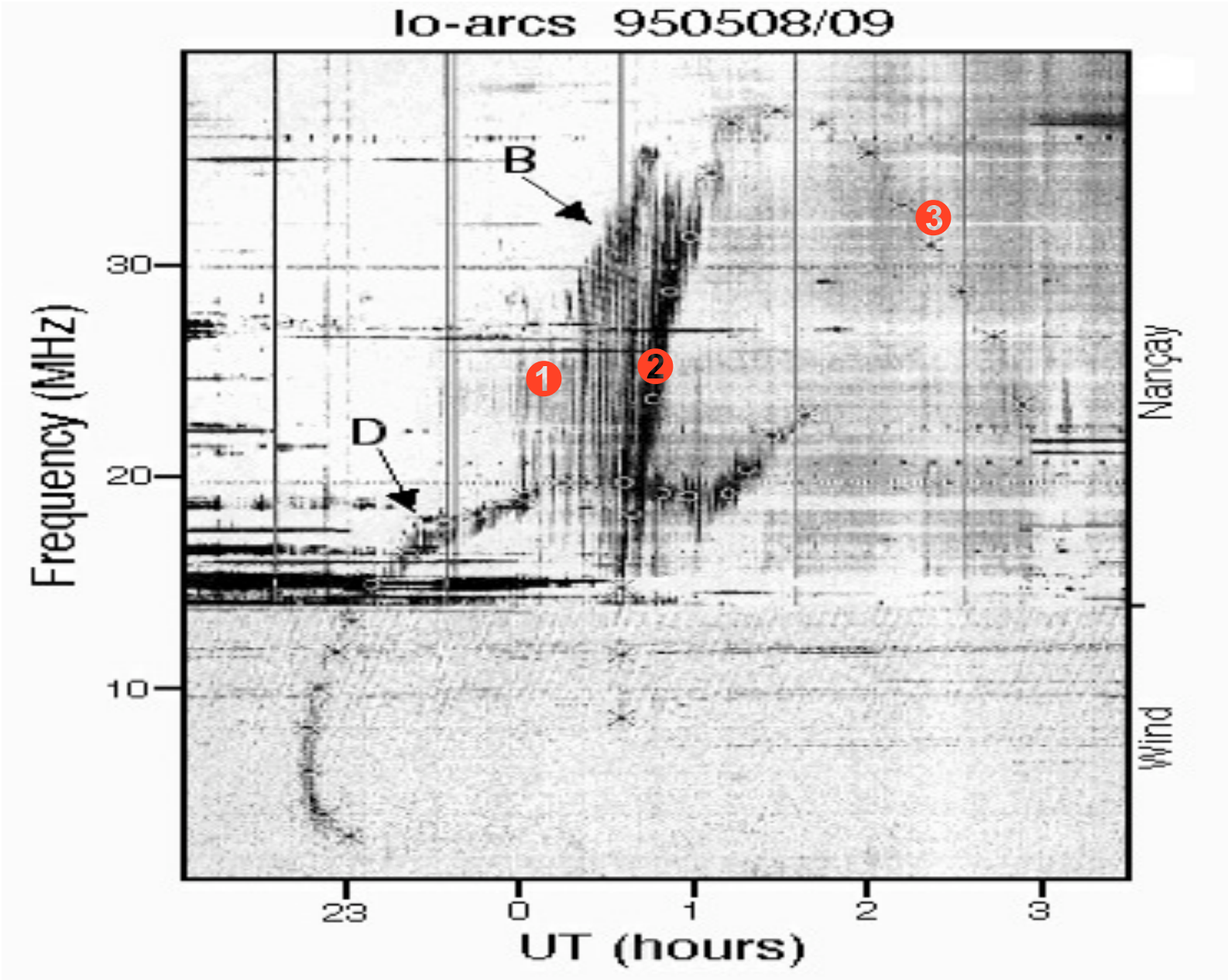
• Slow shock-driven radio emissions produced when Io near torus center → higher plasma density ⇒ strong pressure pulse ?

•Absence of Io-A shock-driven radio tail ? [acknowledgement to A. J. Dessler]

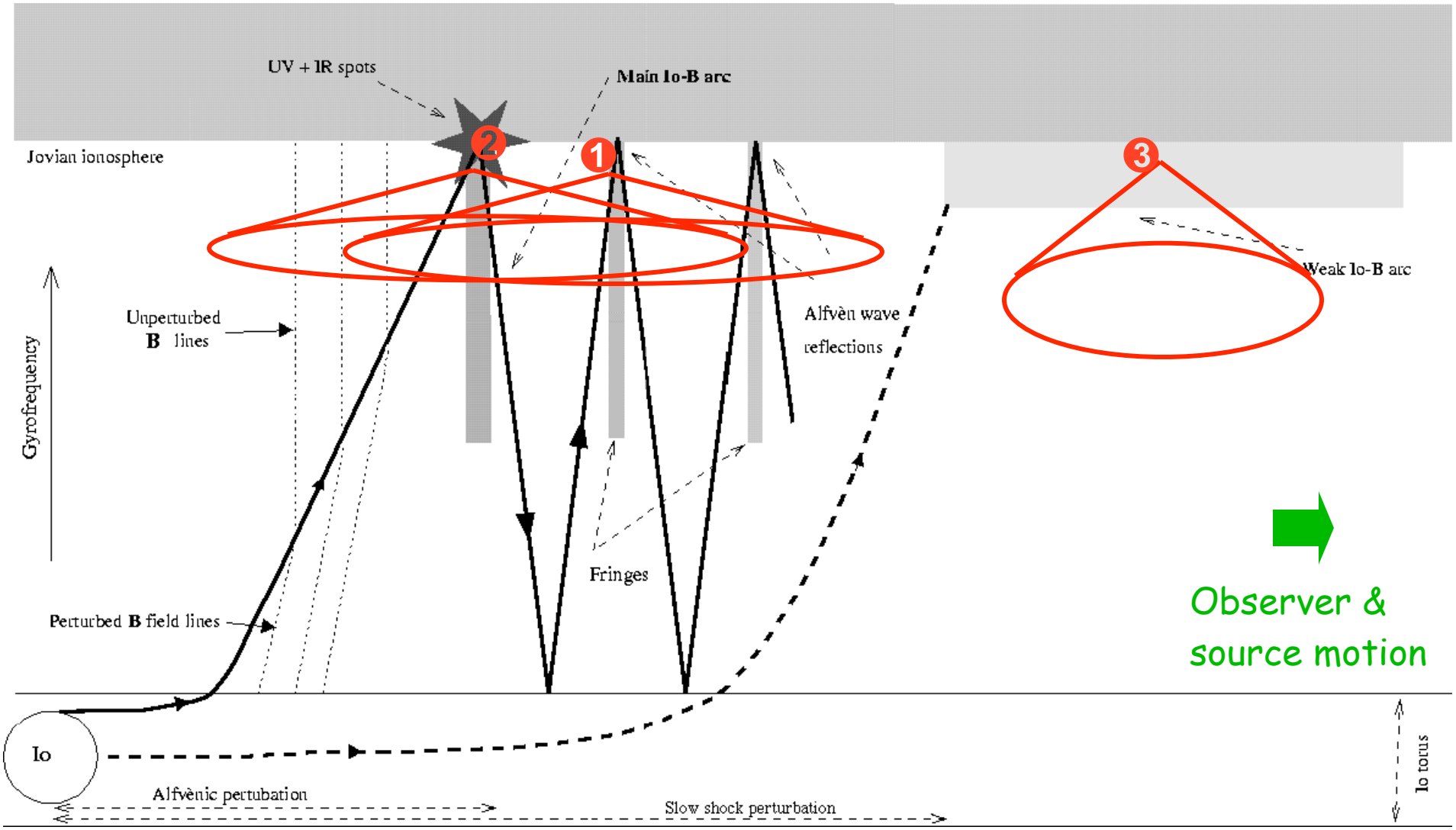
→ torus east-west asymmetry

⇒ Io always in torus on dawn side (B) but near torus edge on dusk side (A)

The Io-B case


Io-arcs 950508/09
B
D
1
2
3
30
20
10
Frequency (MHz)
Nancay
Wind
23
0
1
2
3
UT (hours)

The Io-B scenario #2



- Introduction
- Io-controlled decameter arcs and Io-Jupiter interaction [Queinnec & Zarka, JGR, 1998]
- Lead angle of Io-controlled radio emission : Alfvèn wave or slow shock ? [Zarka, Langmayr, Gerbault, MOP, 2002]
- **Radio Astronomy Science with JUNO**

  [P. Z. & French RAR team]
- Conclusions

Simulation of Radio arcs

- Parameters : B model, δ, $\theta(f)$, $\delta\theta$, observing geometry (CML, Λ_{Io} …)

- Radio beaming $\theta(f)$:

  Cyclotron Maser Instability : $\gamma \propto \iint \partial f/\partial v_\perp \, \delta(R.C.) \, dv_{//} dv_\perp$

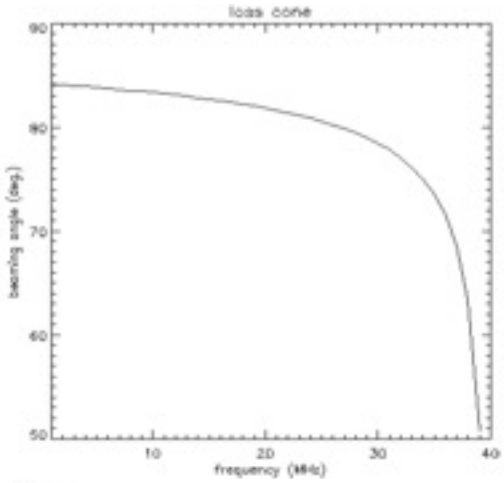
  Energy source : e^- distribution with $\partial f/\partial v_\perp > 0$

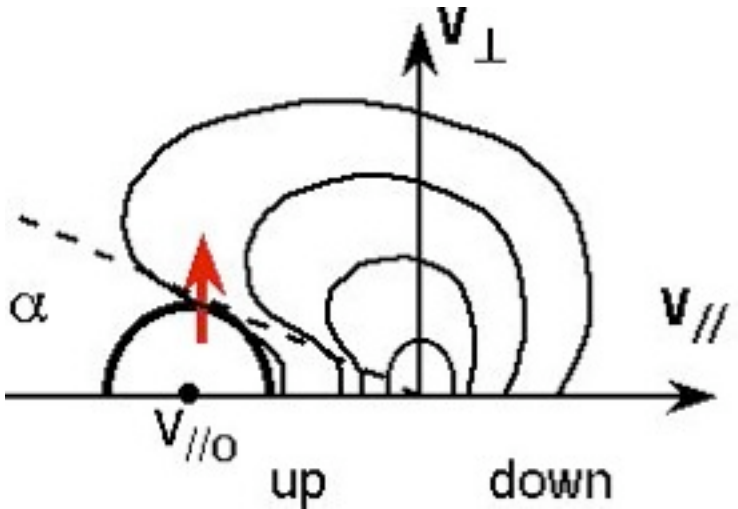
  - loss-cone (α) / e^- conics : $V_{//o} = c.\cos\theta = V/\cos\alpha$

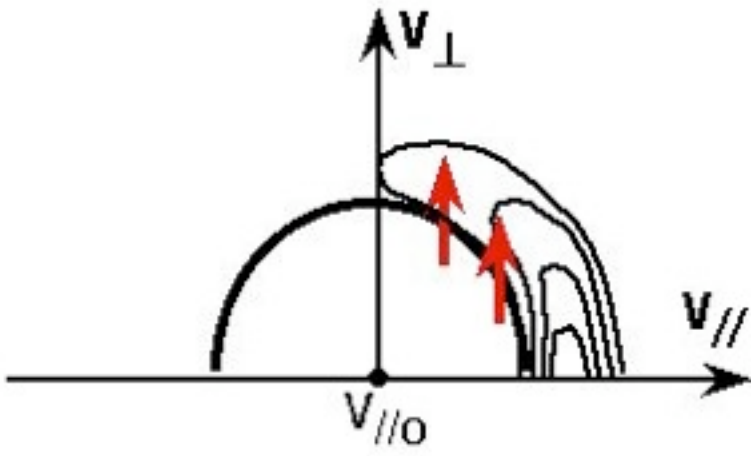
    $\Rightarrow \theta_{LC} = \cos^{-1}(V/c.\cos\alpha) < 90°$ ($\theta\downarrow$ for $V\uparrow$ or $f\uparrow$)

  - horseshoe/shell ($E_{//}$) : $V_{//o} = c.\cos\theta \sim 0$

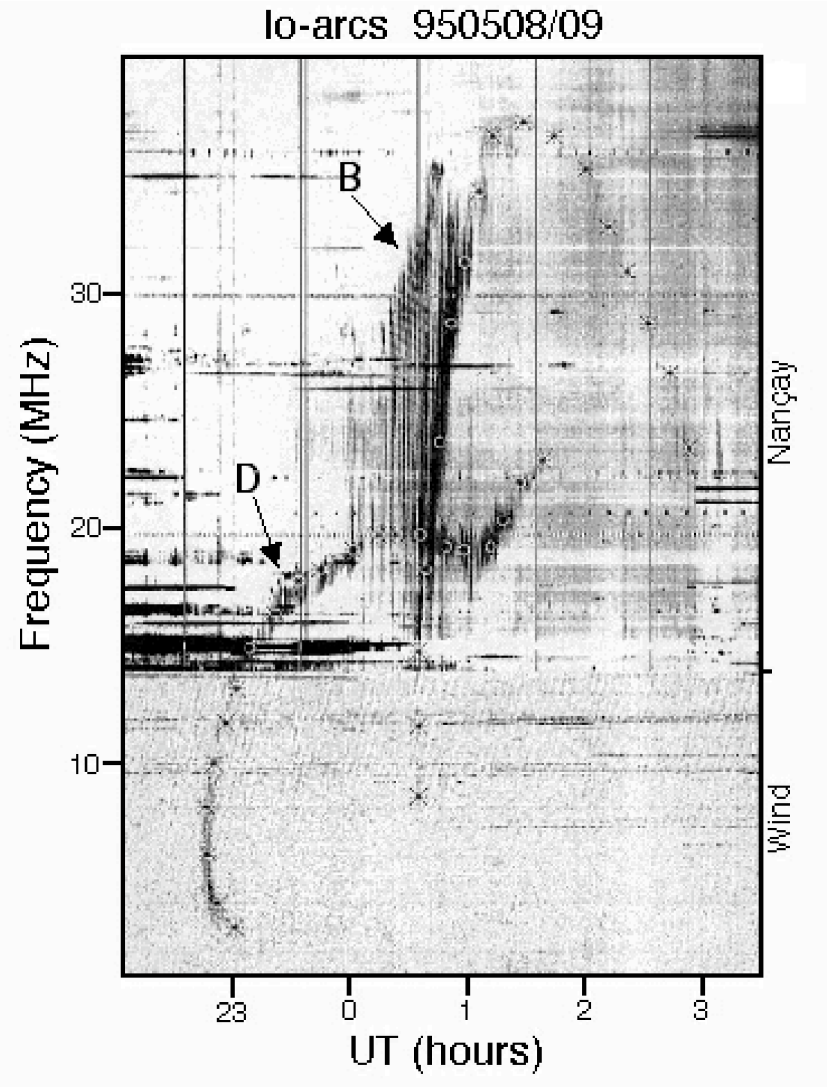
    $\Rightarrow \theta_{Shell} \sim 90°$ ($\forall f$) intensity $\uparrow$ with V



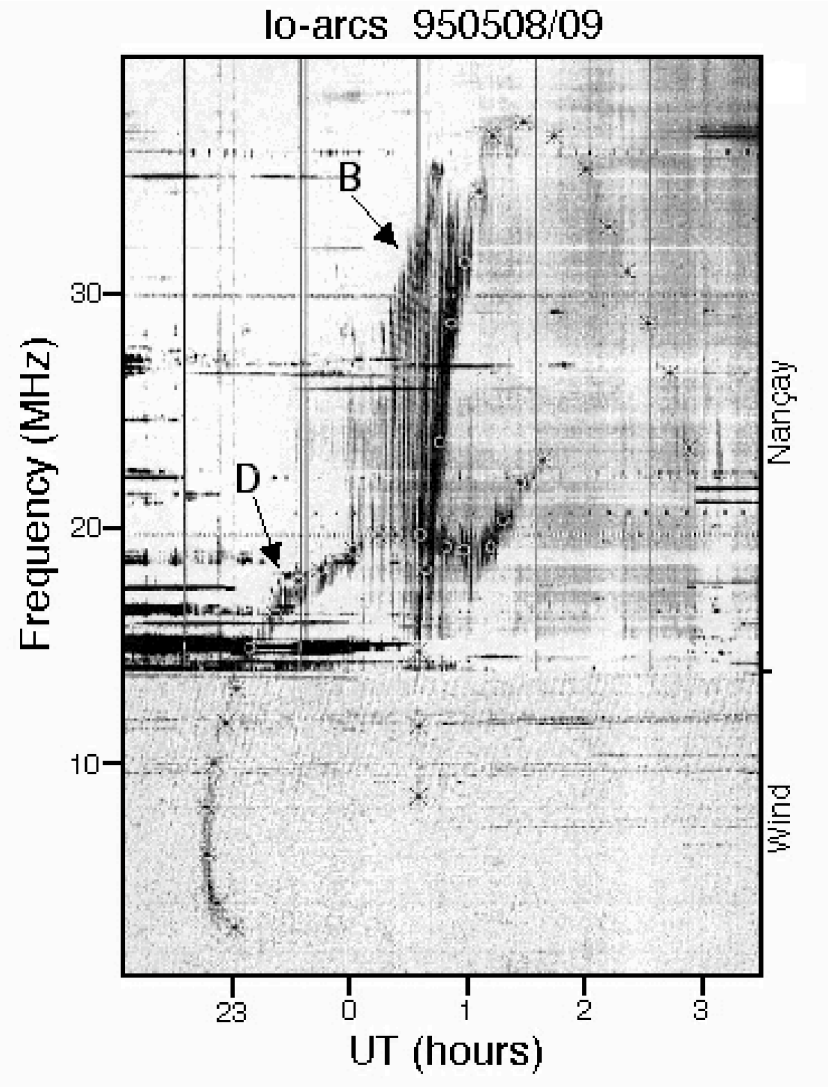


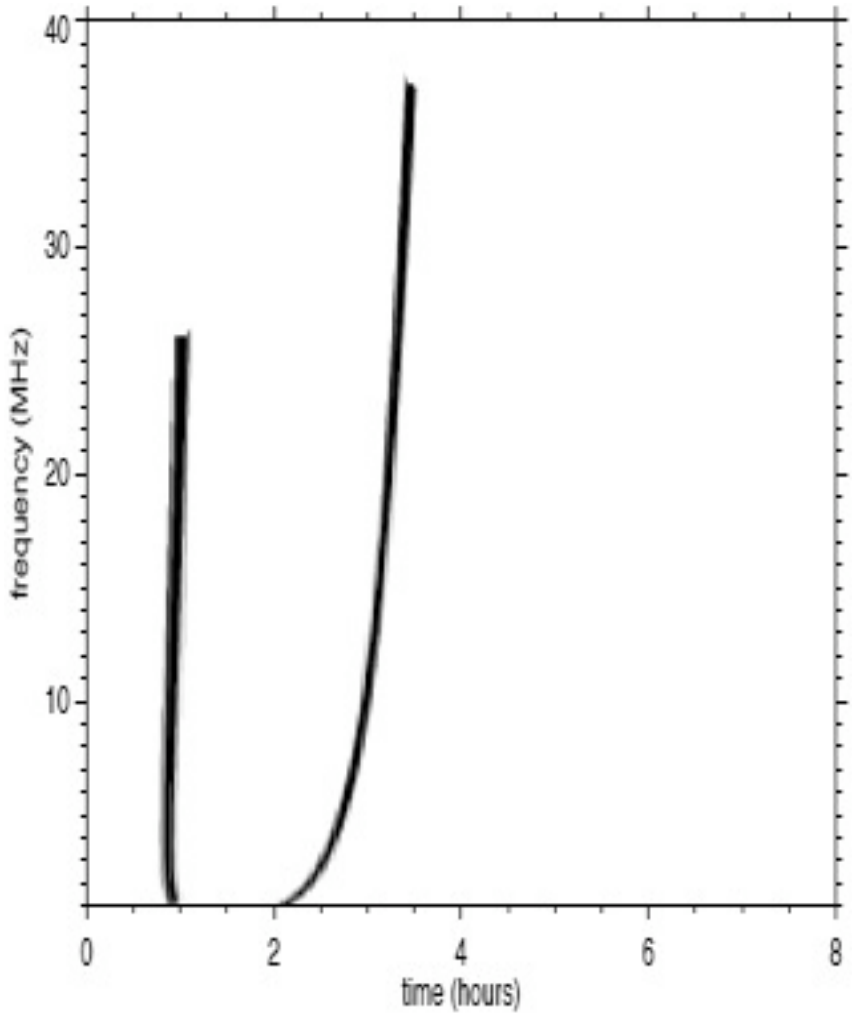


Simulation of Radio arcs



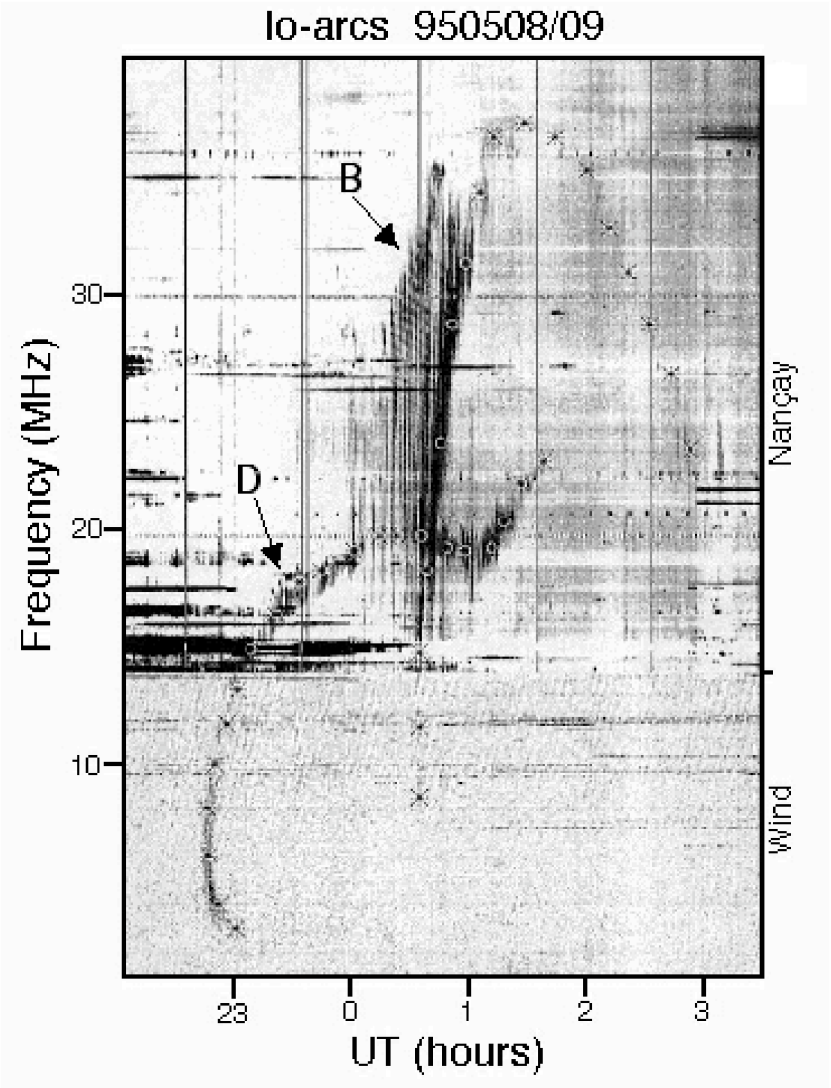
Simulation of Radio arcs

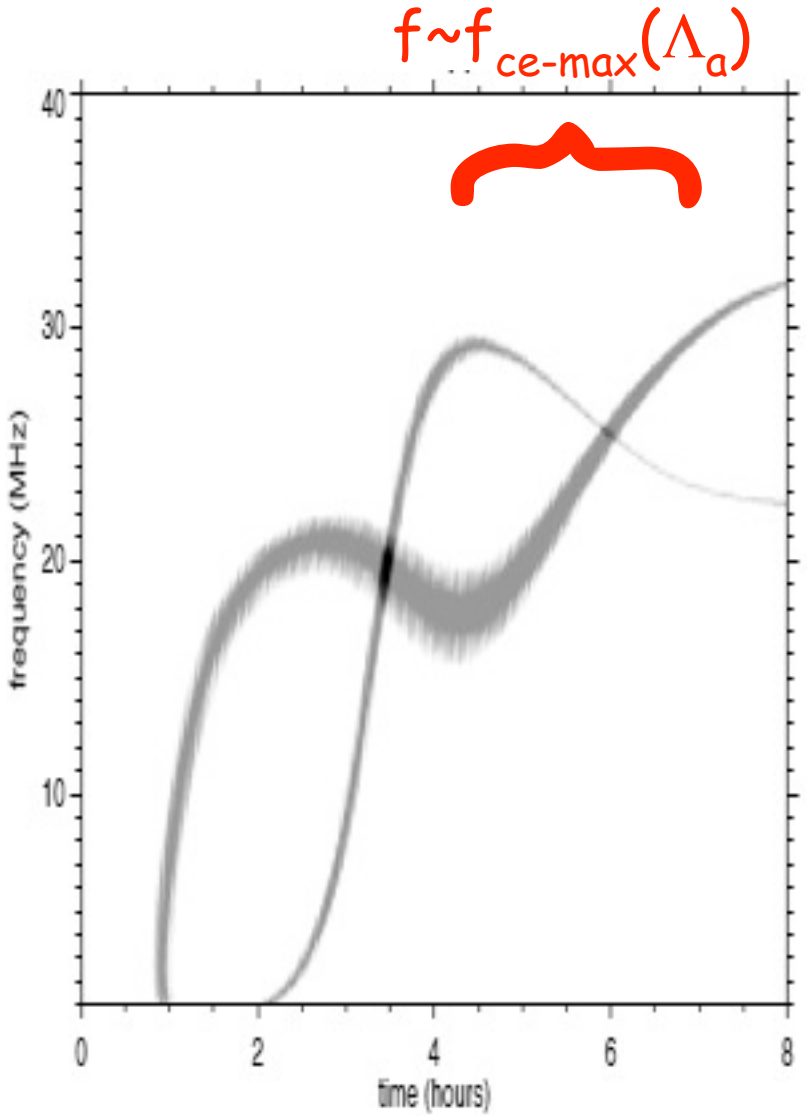




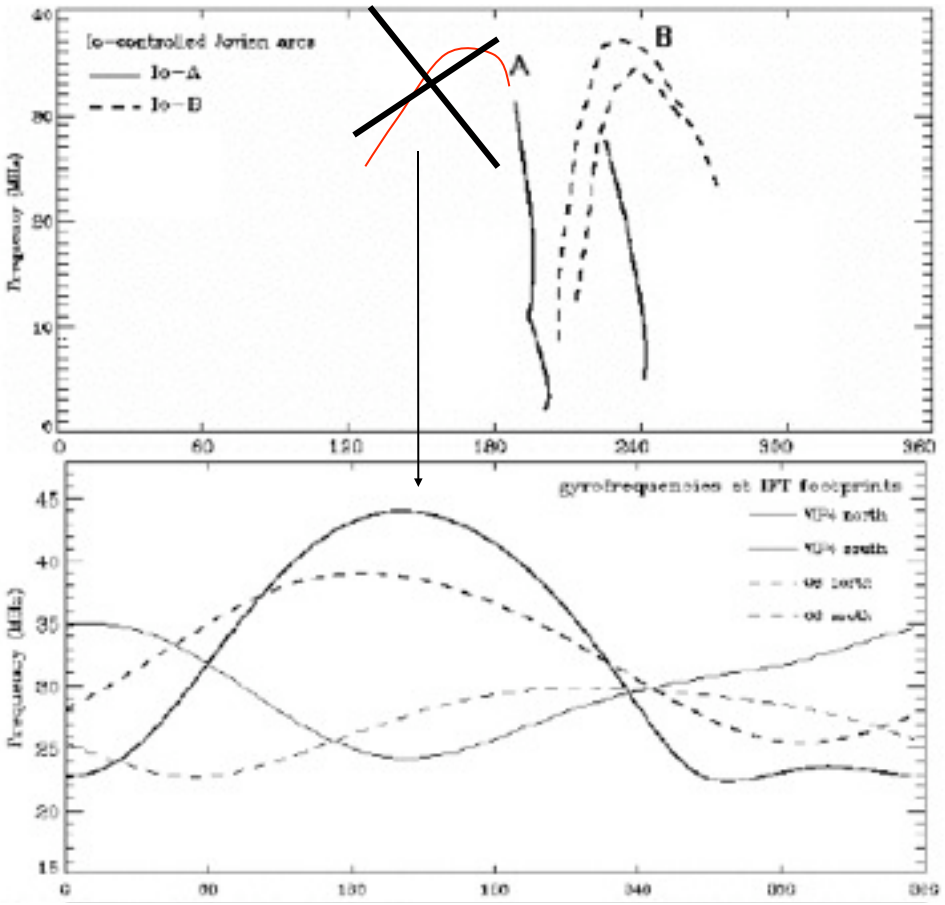
Io-B (N) and -D (S) arcs, Fixed equatorial observer, $\theta(f)=70°$, $\delta\theta=1°$, CML=351°, $\Lambda°_{Io}=105°$, $\delta=30°$

Simulation of Radio arcs

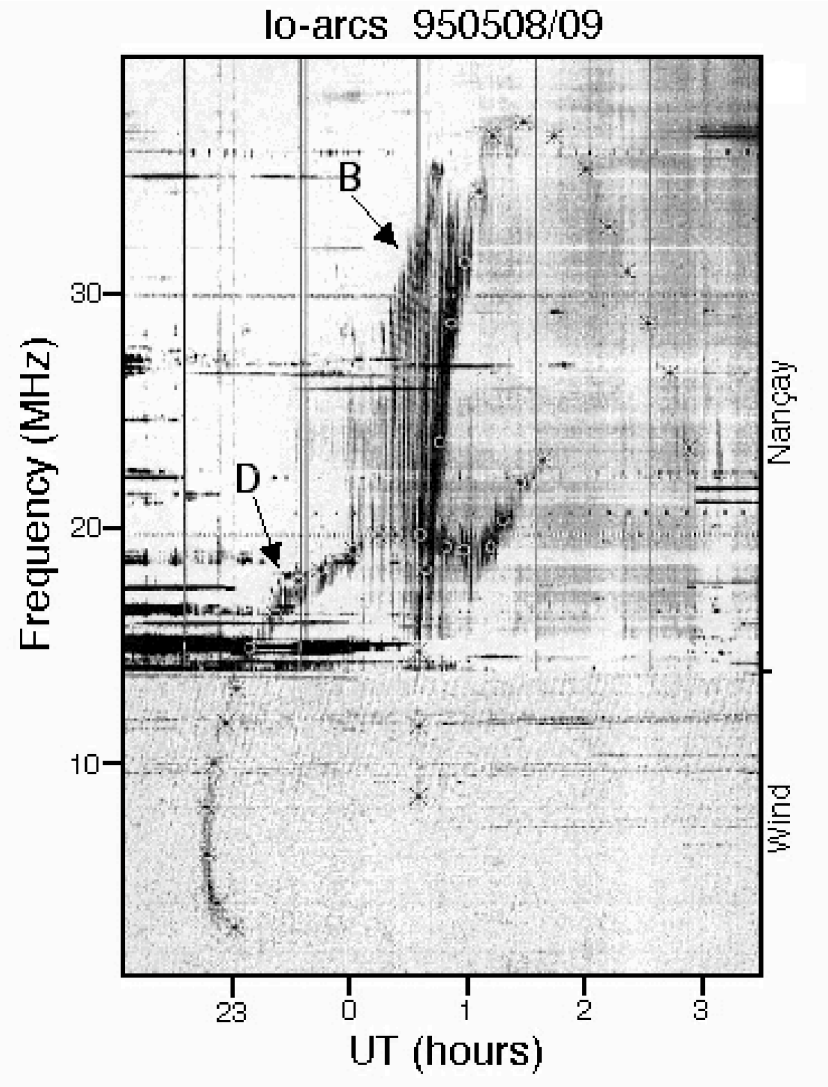


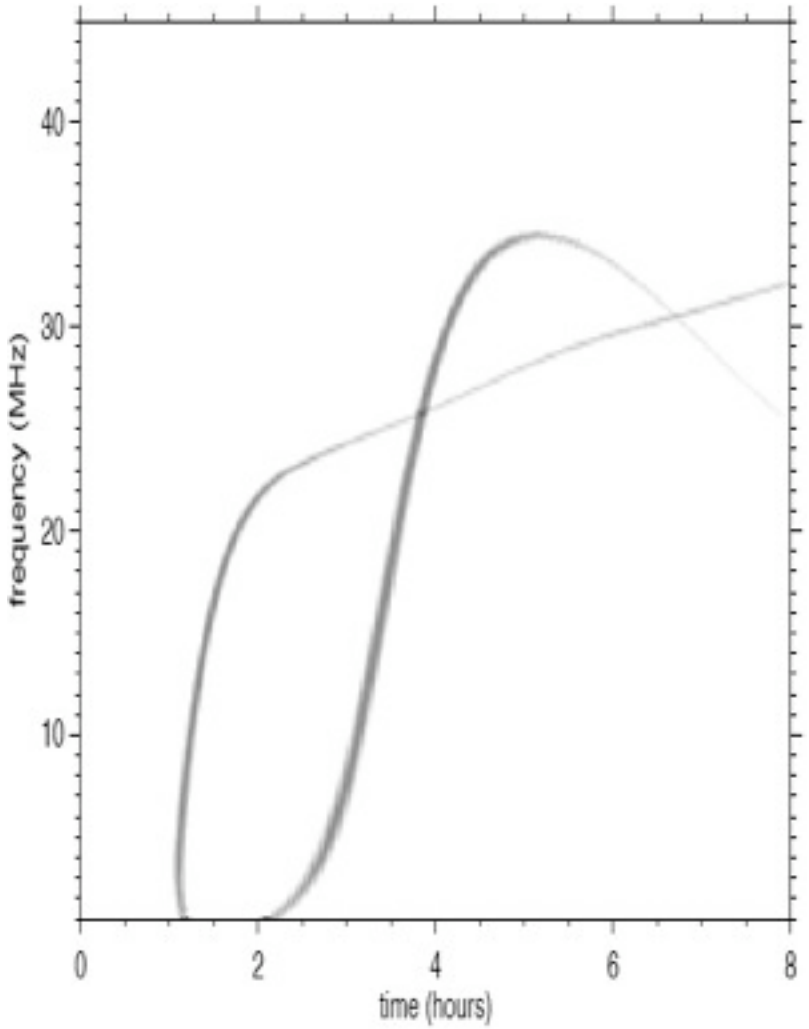


Io-B (N) and -D (S) arcs, Fixed equatorial observer, $\theta_{LC}(f) \rightarrow 70°$, $\delta\theta = 1°$, CML=351°, $\Lambda°_{Io} = 105°$, $\delta = 30°$


Io-controlled Jovian arcs
Io-A
Io-B
A
B
Frequency (MHz)
0
60
120
180
240
300
360
gyrofrequencies at IPT footprints
Frequency (MHz)
Io's longitude (°)

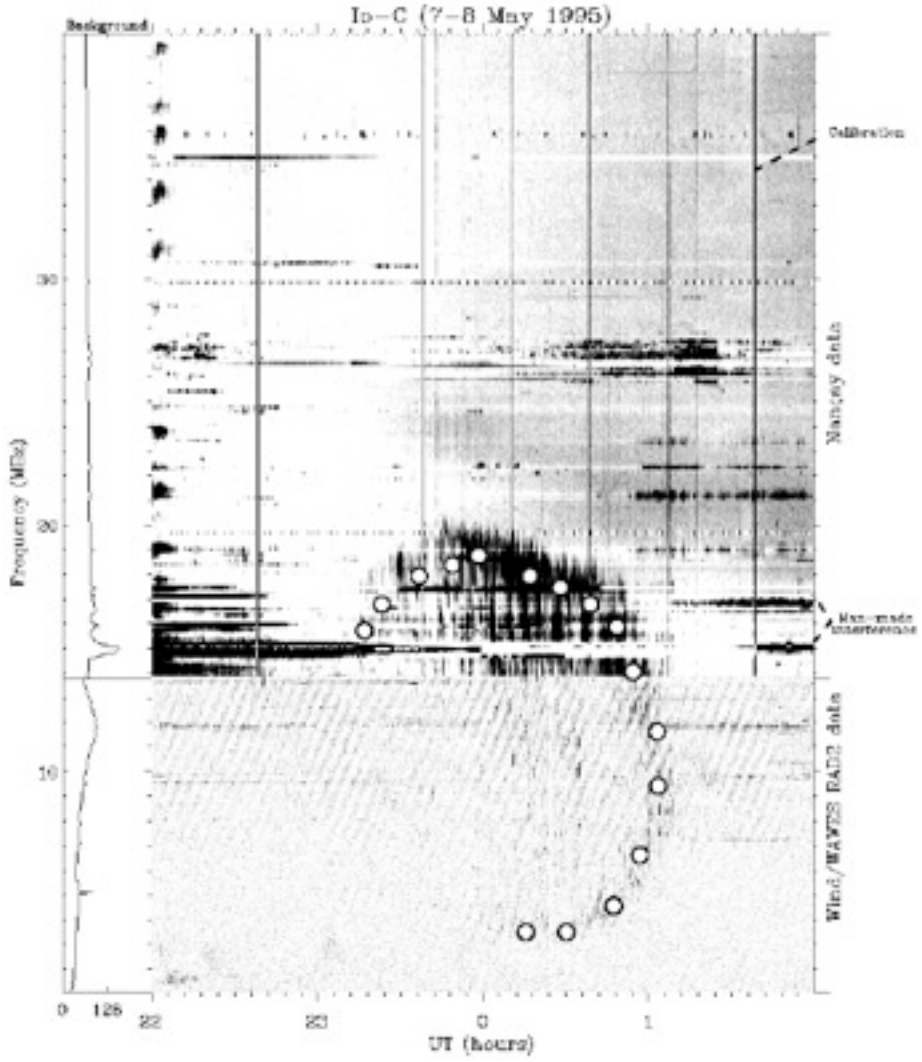
Simulation of Radio arcs

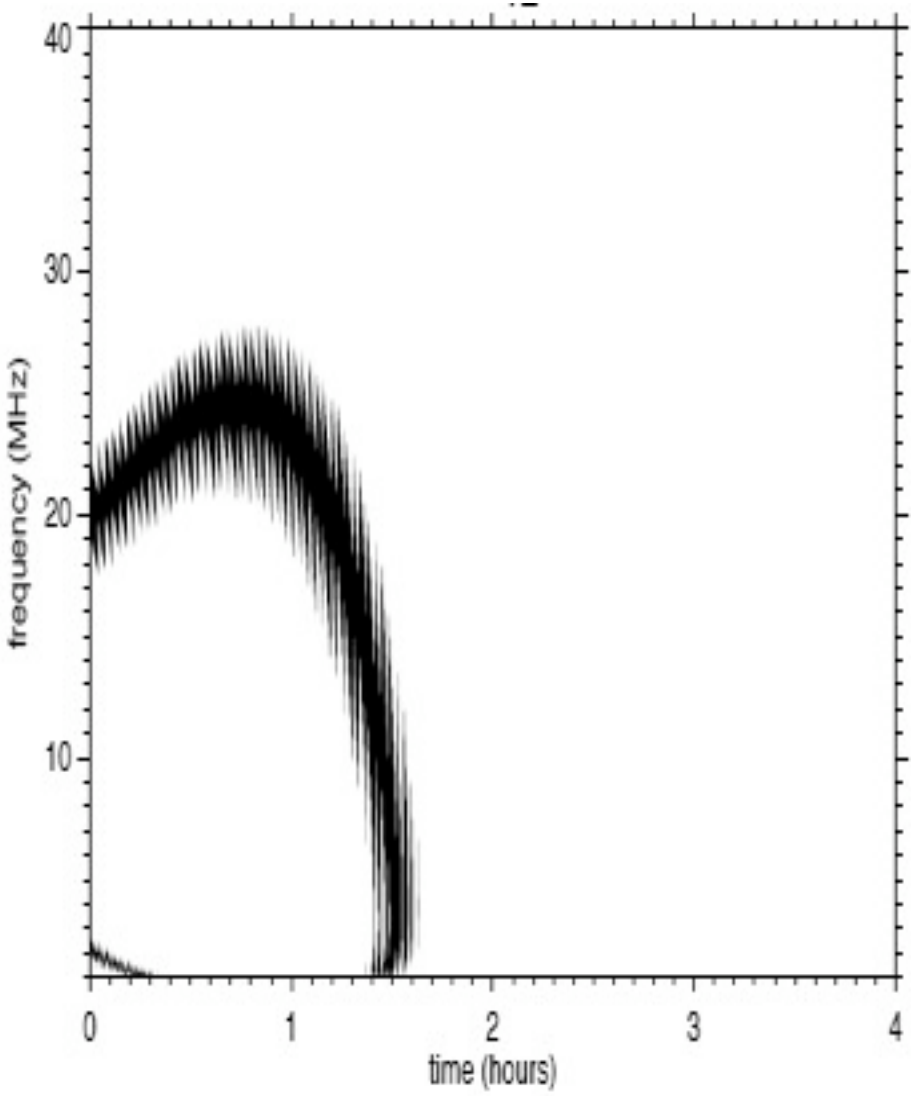




Io-B (N) and -D (S) arcs, Fixed equatorial observer, $\theta_{LC}(f) \rightarrow 90°$, $\delta\theta=1°$, CML=351°, $\Lambda°_{Io}=105°$, $\delta=30°$

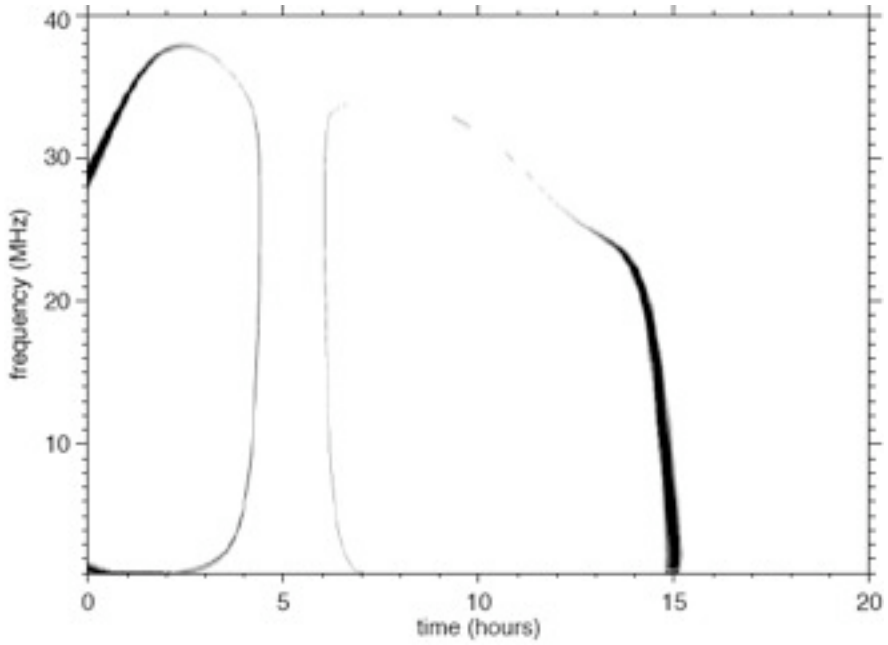
Simulation of Radio arcs

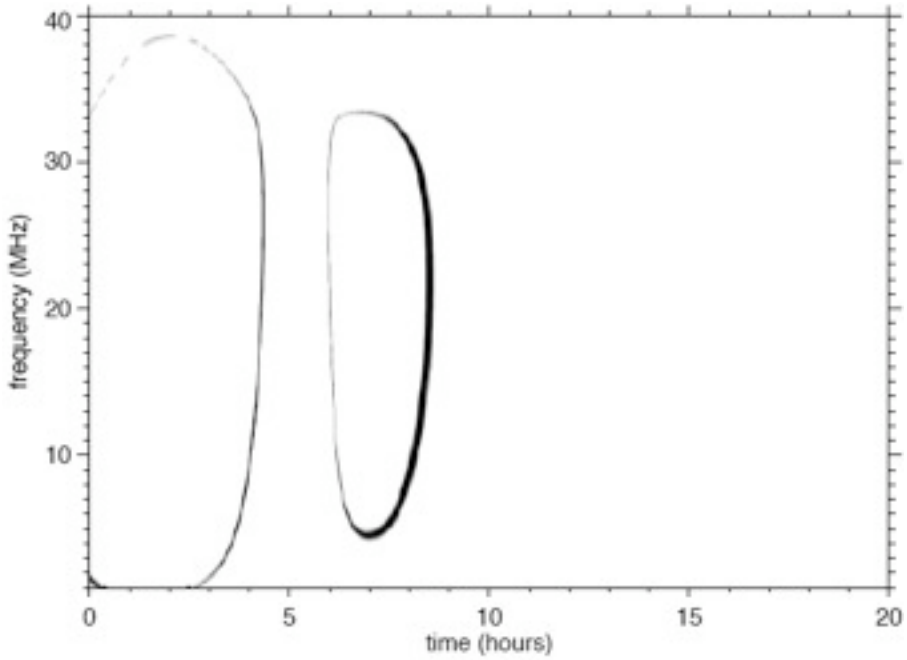




Io-C arc (S), Fixed equatorial observer, $\theta_{LC}(f) \rightarrow 70°$, $\delta\theta = 1°$,
CML=143°, $\Lambda°_{Io} = 113°$, $\delta = 30°$

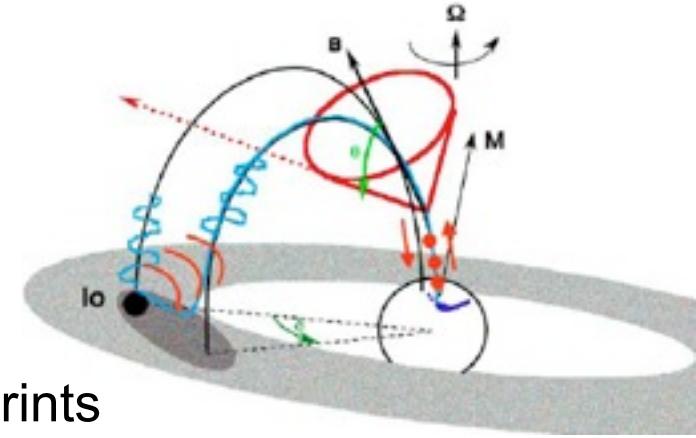
Simulation of JUNO radio observations





Io-Jupiter emissions, JUNO orbiting observer (2 ≠ phases),
$\theta_{LC}(f) \rightarrow 70°$, $\delta\theta = 2°$, $\delta = 30°$

JUNO radio studies of satellite-Jupiter interactions



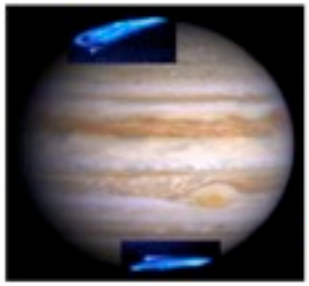
- Dynamic spectrum + GP + B model
  - direct identification of galilean satellite footprints
  - instantaneous lead/lag angle versus (long,lat)

    ⇒ type of interaction (Afvén, Slow shock…)

  - radio beaming versus frequency

    ⇒ energy source (loss-cone, shell/horseshoe…)

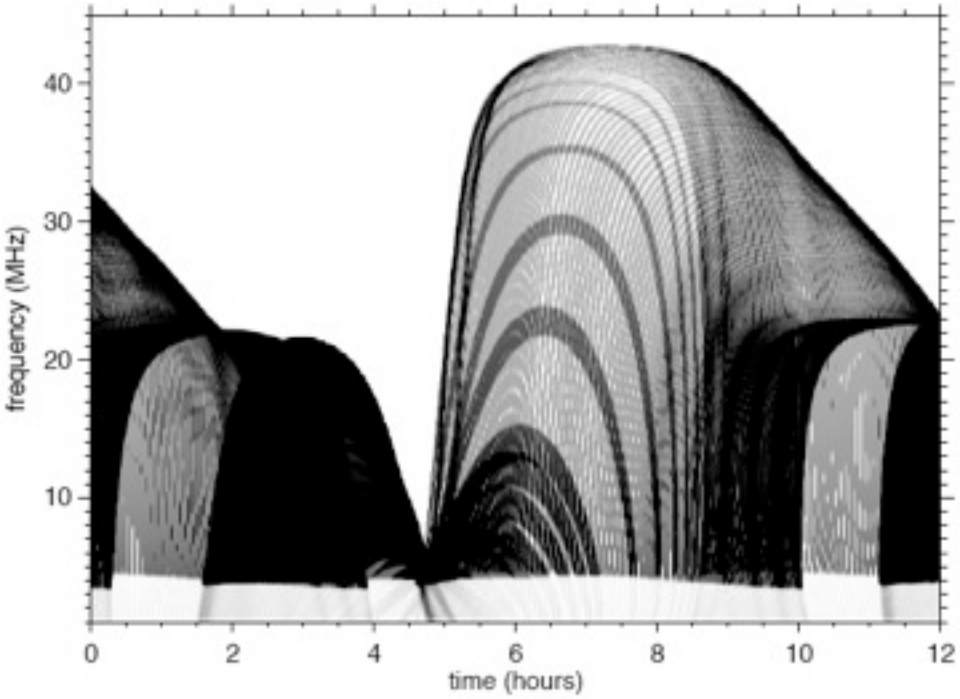
→ correlation with UV (IR) measurements

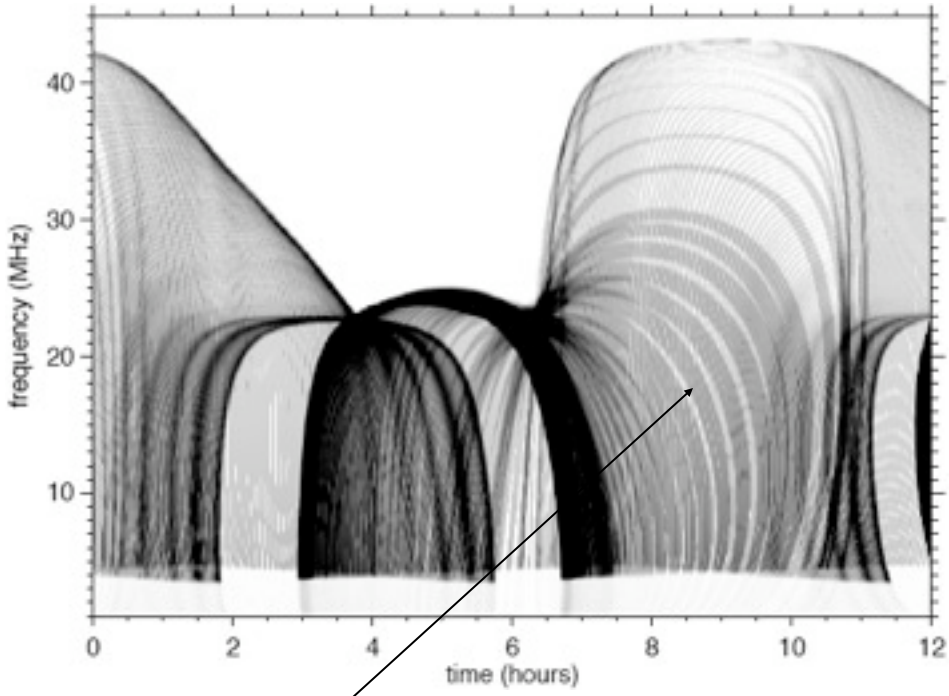


⇒ dynamics of interactions

⇒ origin of radio arcs

JUNO radio studies of Jovian auroras





« lesser arcs »

Sources every ° in 90°-270° along auroral oval N,
JUNO orbiting observer (2 ≠ phases),
$\theta_{LC}(f) \rightarrow 70°$, $\delta\theta = 1°$

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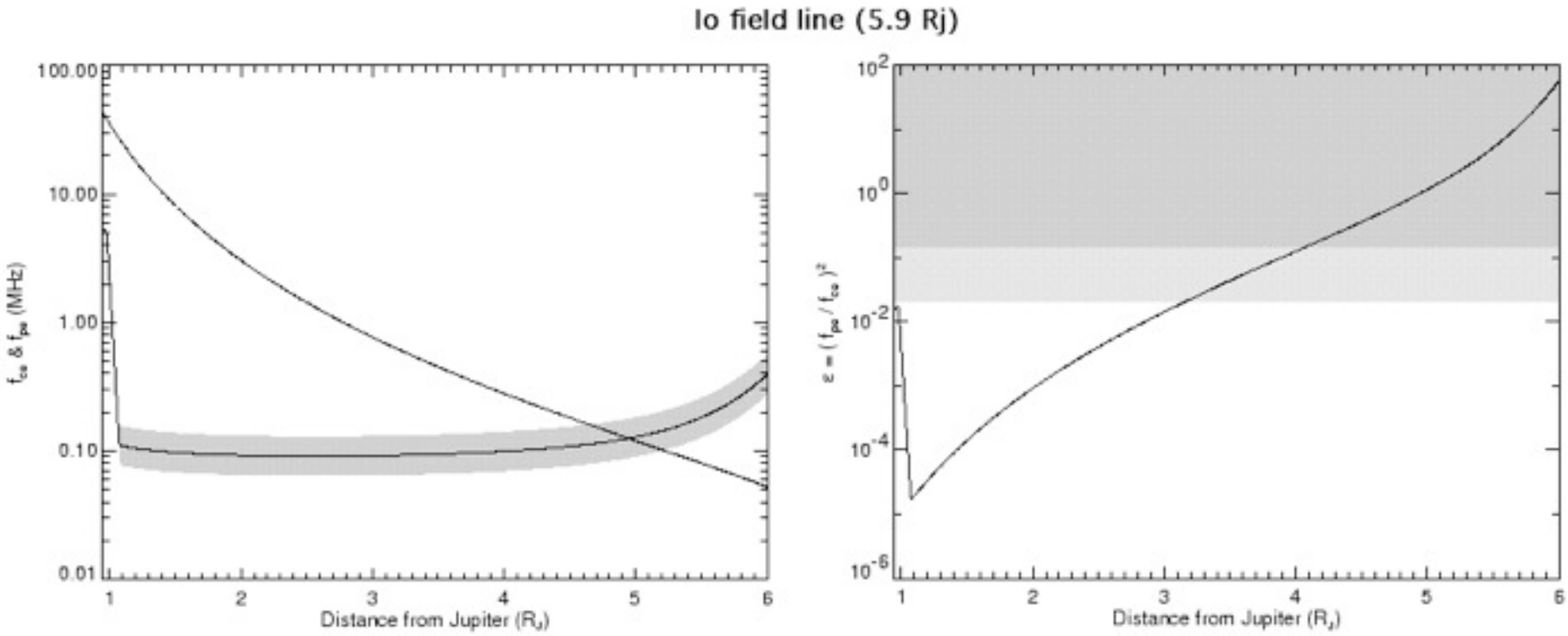
- Radio Astronomy Science with JUNO

  [P. Z. & French RAR team]
- **Conclusions**

- Arc morphology
- Source locations
- Jovian B model test & constraints
- Alfvén wave reflections torus - ionosphere
- Slow shock excited by Io ?
- Radio beaming → free energy source / e- acceleration
- Shell & loss-cone/e^- conics driven CM emission

LF limit of Io arcs at ~1-2 MHz

- Cyclotron-Maser theory → $f_{pe}/f_{ce} < 0.385$ in radiosource [Le Quéau et al., 1985]
- AKR source in-situ measurements → $f_{pe}/f_{ce} < 0.14$ [Hilgers, 1992]



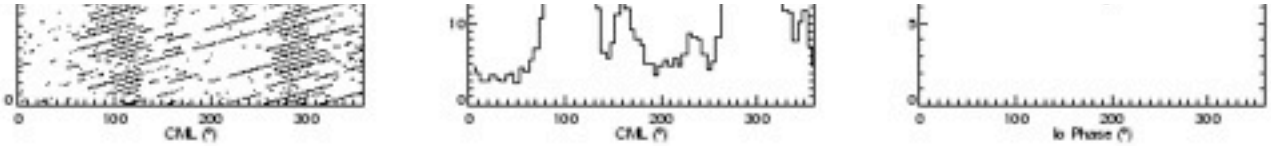
[Zarka, Crary, Queinnec, P&SS, 2001]

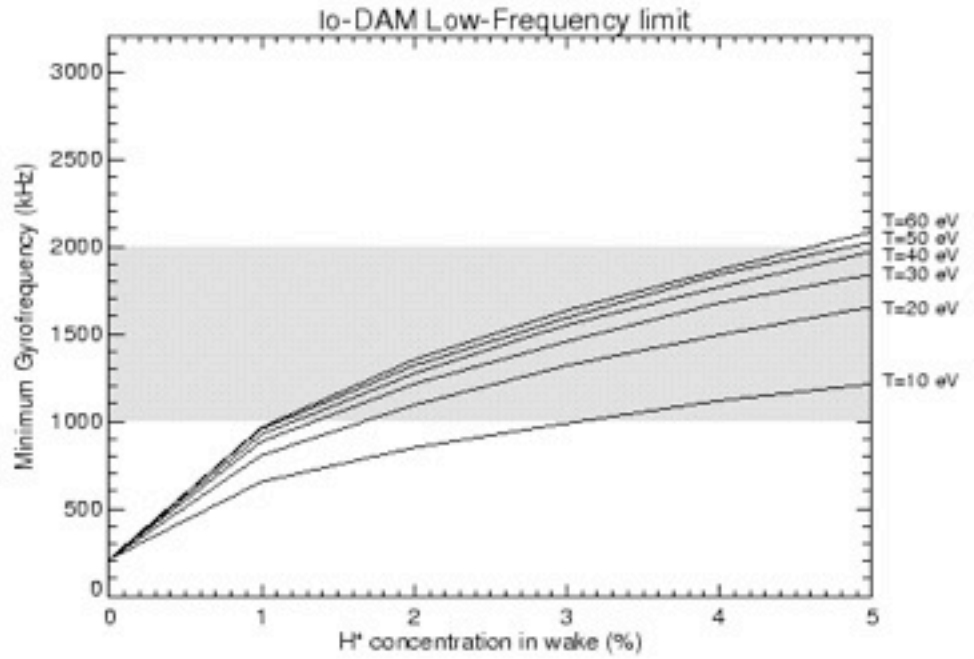
→ LF limit of radio component = $f_{ce}\ (f_{pe}/f_{ce})_{max} \sim 1$ MHz

LF limit of Io arcs at ~1-2 MHz

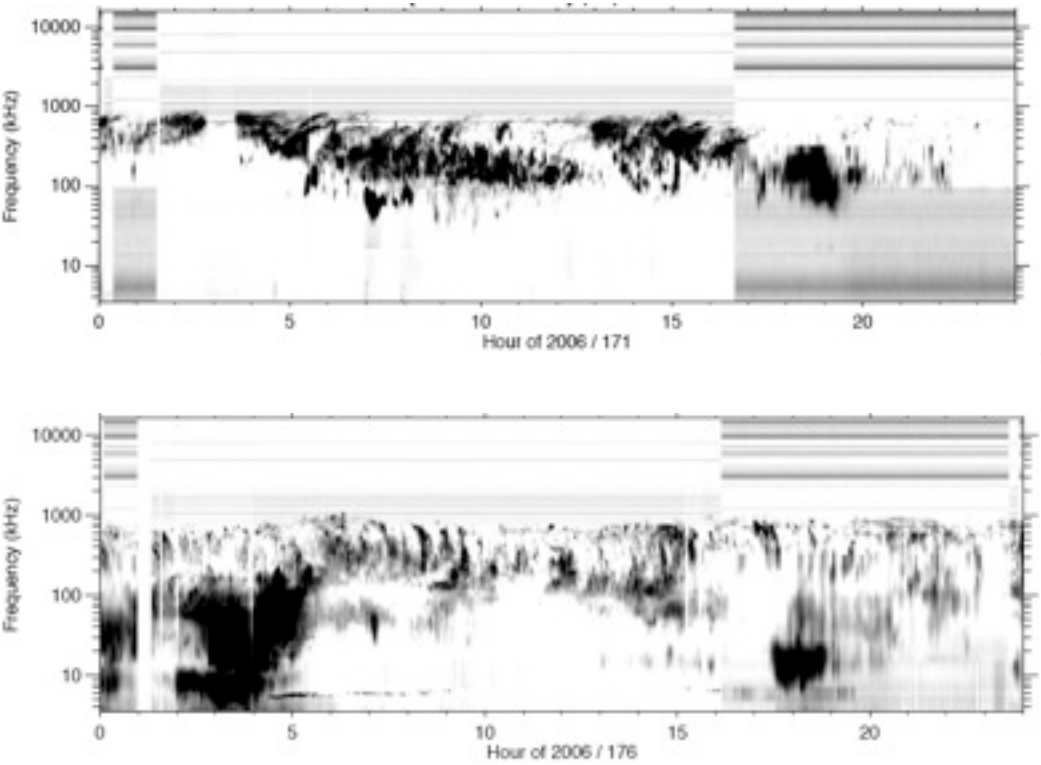
- Io-DAM : 1-2 MHz & L~6

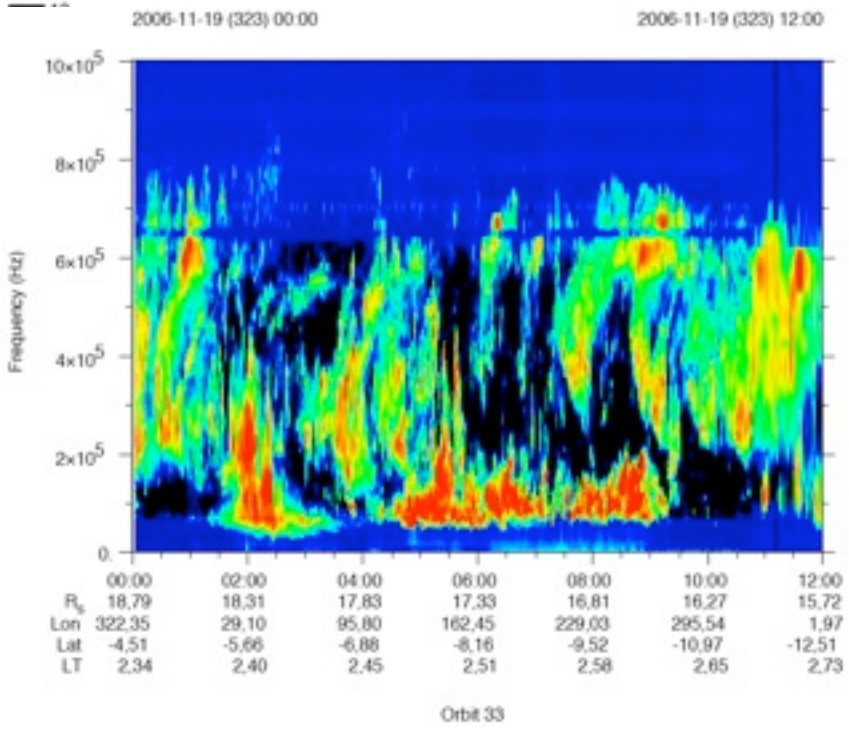
  → H+ concentration in Io's wake ≥ 1-3% for T=60-10 eV





Saturn's radio arcs ?





A suivre ...