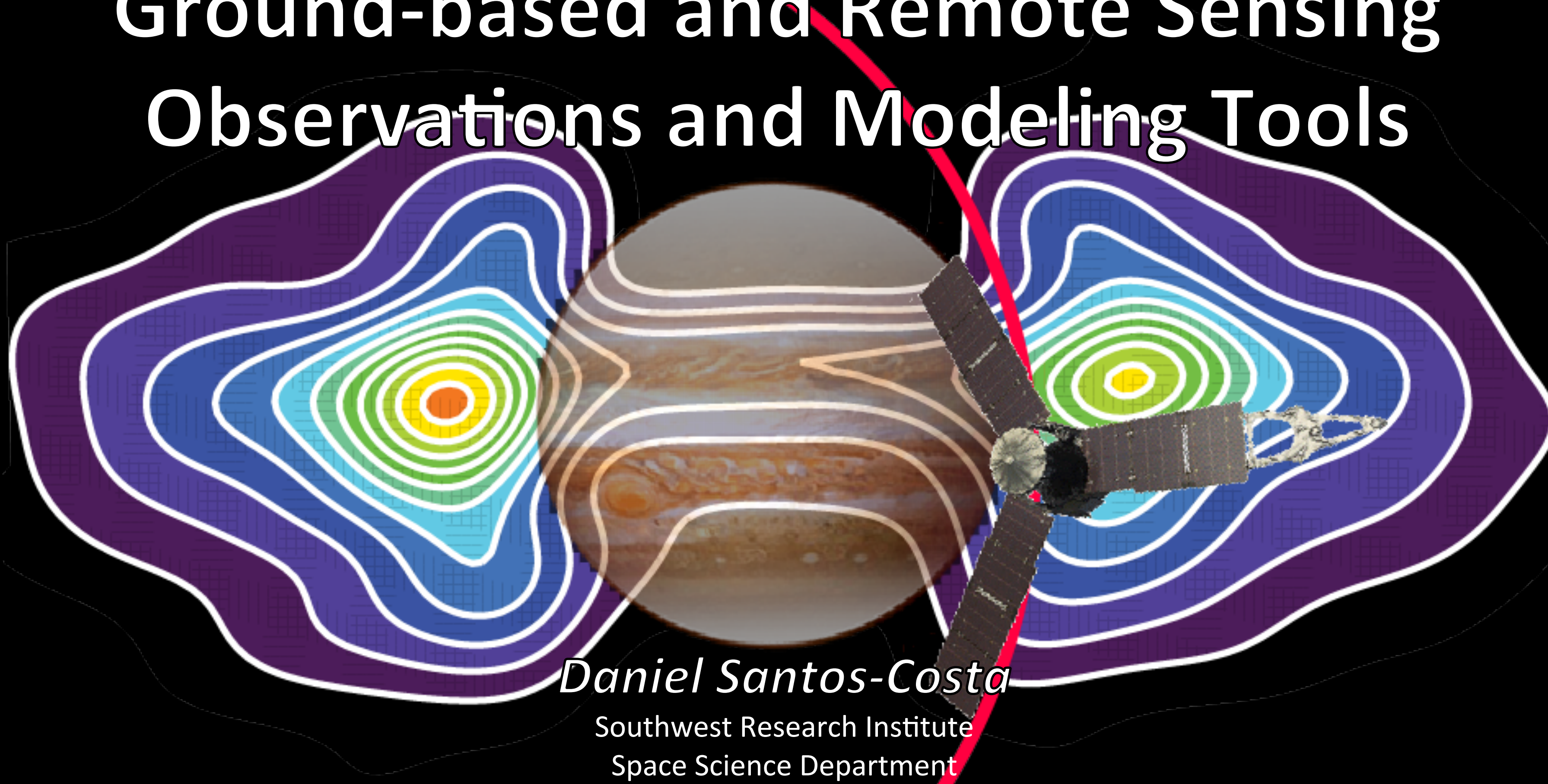
Multi-frequency Analysis of Jupiter's Electron-Belt Radiation Dynamics with Ground-based and Remote Sensing Observations and Modeling Tools



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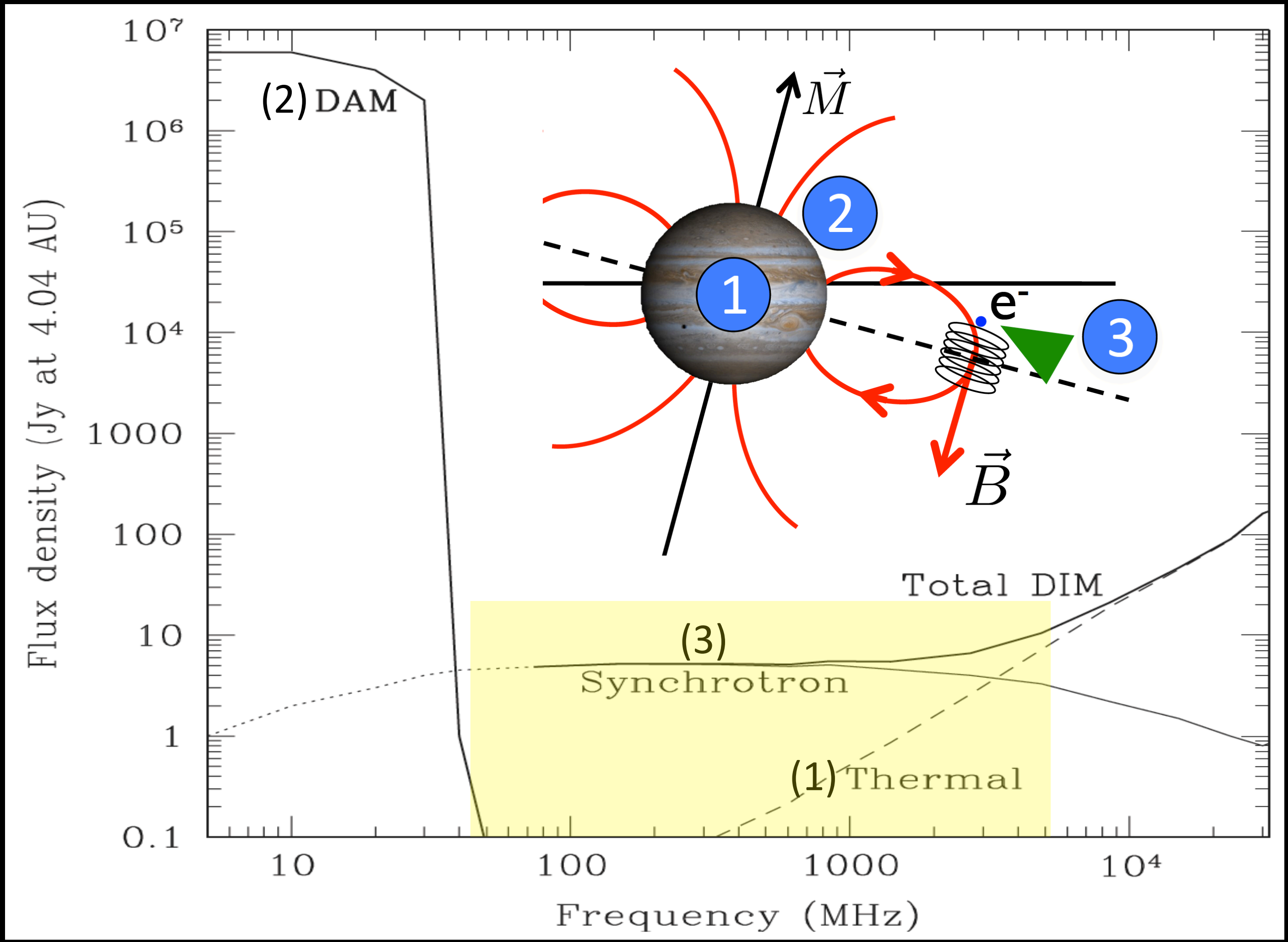
IRAP, Toulouse, 9-11 Oct 2017

OUTLINE

- Jupiter's electron belt (JRB) and synchrotron radiation (JSR):
    - *A quick introduction on JSR and JRB*
    - *Spatial & temporal variability of JSR (JRB)*
    - *Motivations*
- Correlation with solar activity and large-scale impacts
- Case Studies combining observations & modeling tools:
    - *from Ground-Based (GB) observations & JRB models*
    - *from GB and tomographic image reconstruction technique*
- ~~*Multi-frequency observations of JSR from JUNO/MWR*~~
- Summary

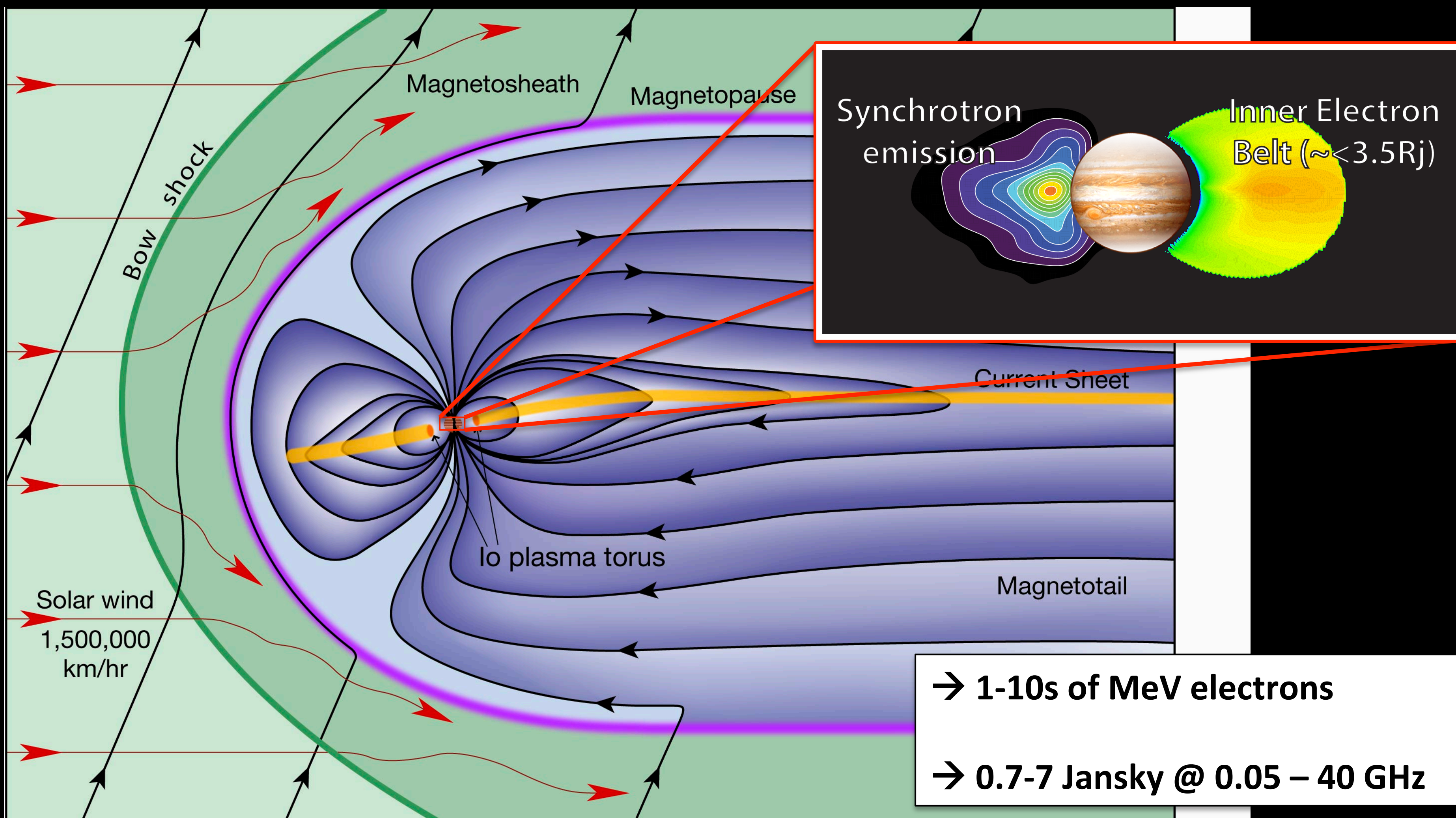
Jupiter's electron-belt radiation (JSR): a quick introduction

Jupiter Radio Emission Overview



[after Girard et al., SF2A 2016]

Jupiter's electron-belt radiation (JSR): a quick introduction

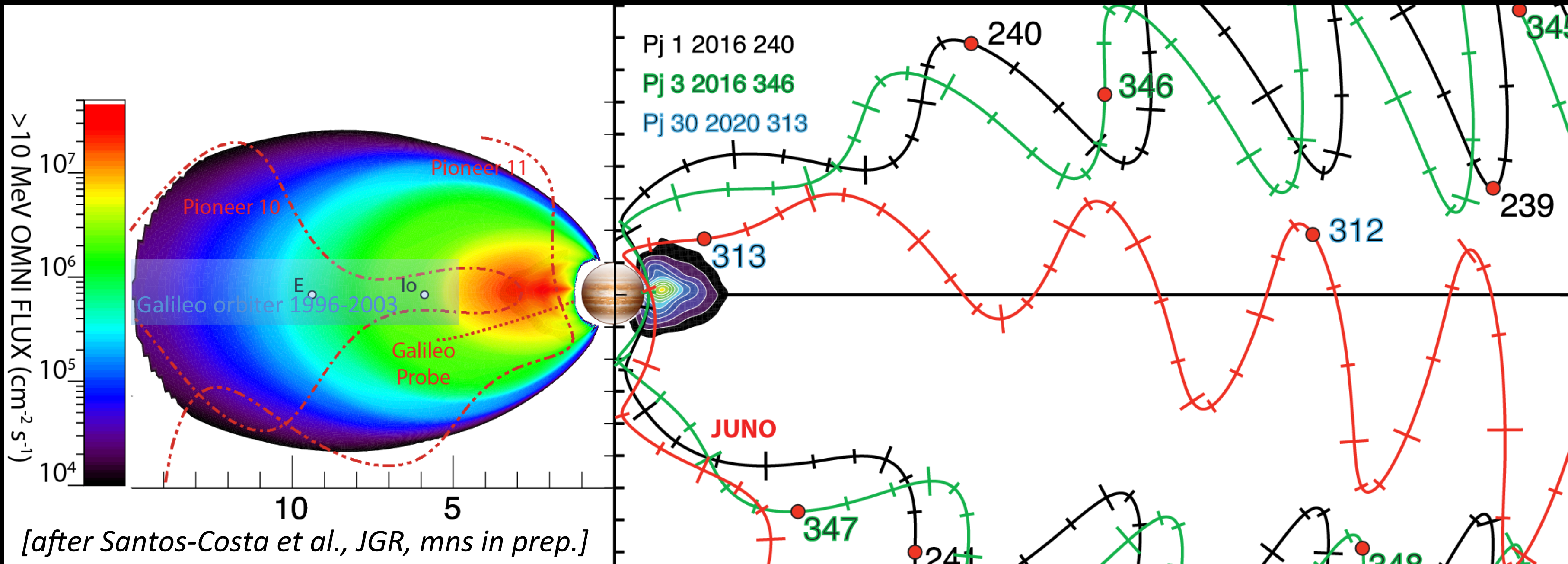


→ 1-10s of MeV electrons

→ 0.7-7 Jansky @ 0.05 – 40 GHz

[Bagenal et al., 2014]

Jupiter's electron-belt radiation (JSR): a quick introduction



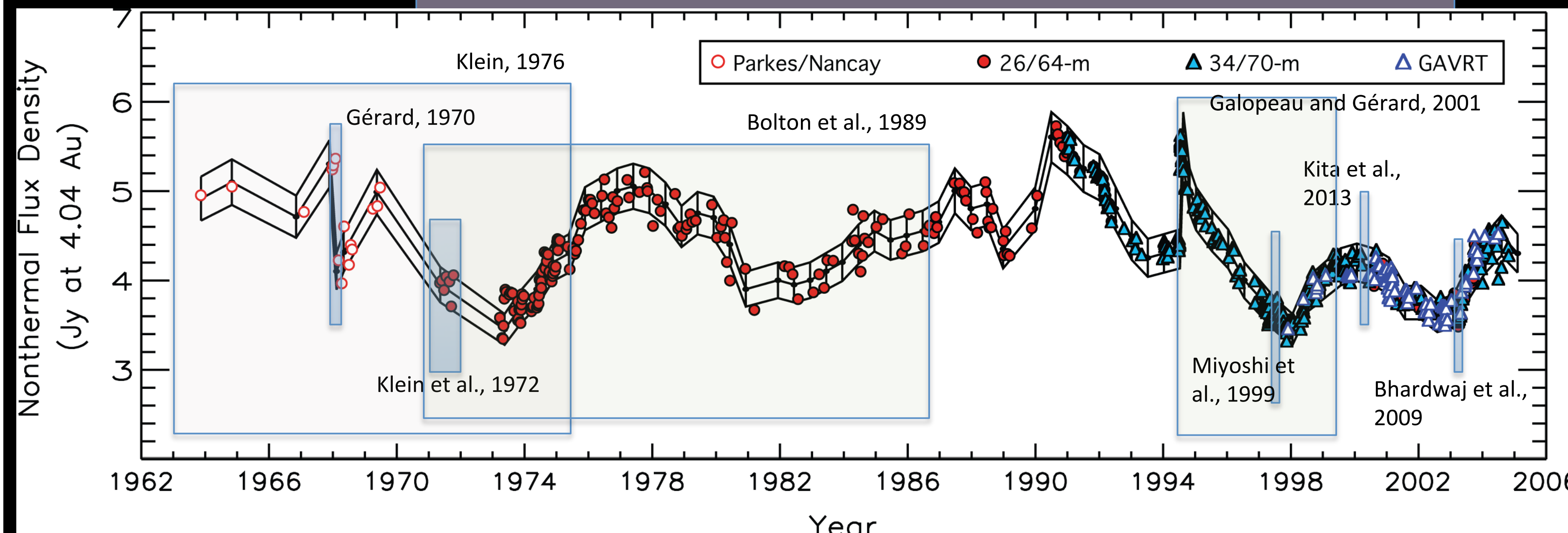
[after Santos-Costa et al., JGR, mns in prep.]

- Jupiter has an extended radiation zone up to 15-30 Rj, with significant energetic particles
- Since the Pioneer missions in the 1970s, only the Galileo orbiter (mostly > 5 Rj) and probe had provided snapshots of the Jovian radiation environment down to the upper atmosphere
- JUNO will provide little information on equatorial to mid-latitude particle populations < 10 Rj . Only JUNO/MWR will for electrons.
- Ground-based and remote sensing observations remain key tools to study J'ERB inside Io's orbit

Jupiter's synchrotron radiation (JSR): Variability on hour, day, month to year time-scales observed with *single dishes and interferometers*

- early 1960's to early 2000's:

Santos-Costa et al., 2008



History of long-term variations in the flux density of Jupiter's synchrotron radio emission at ~11-13-cm wavelength

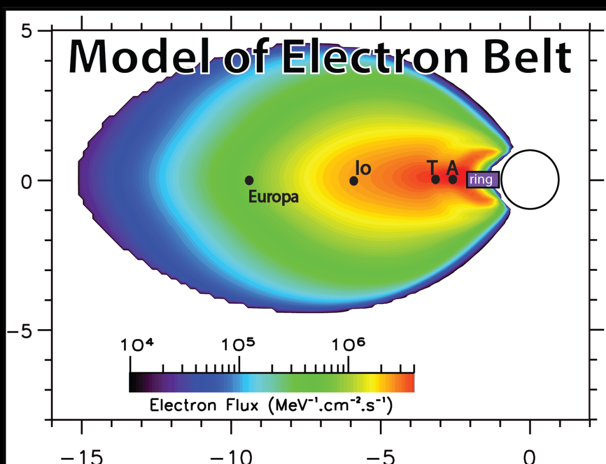
- 2005 and beyond:

1. Continuous monitoring: DSN/GAVRT (2-4 GHz, 2008⁺), IPRT (325 & 785 MHz, 2007⁺)
2. ToO with single dishes and interferometers (VLA (0.3-5 GHz), GMRT (235/610 MHz, 1.4GHz), LOFAR (50-270MHz), etc...)

Motivations for Studying Jupiter's synchrotron radiation Variability

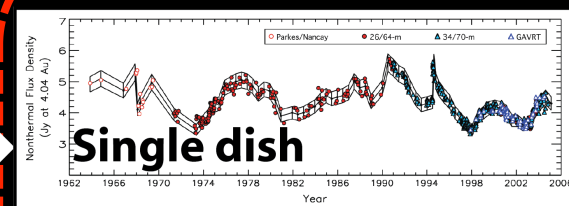
- Answer a 5 decade old science question: origins of the temporal variations of RB/SR
- Determine/Confirm the parameters controlling Jupiter's radiation zone using modeling tools
- Understand and subtract the variable contribution of background radiation sources in JUNO/MWR atmospheric measurements

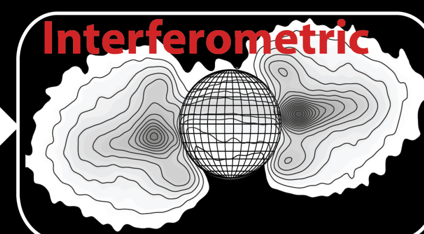
Analyze single-dish and interferometric observations to:
* Discern the control parameters
* Determine time response / relaxation times
* 3D description of temporal changes of the distributions using tomo reconstruction techniques for instance

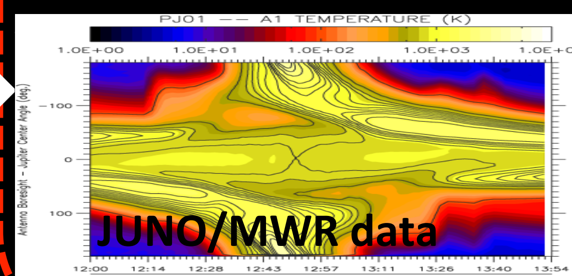


Magnetic Field Model

Synchrotron Radiation Computation Code(s)







• Jupiter's synchrotron radiation (JSR): Variability on time scales of months to years (Long-term)

1. Correlation with solar activity

- Early work: Correlation with 27-day averaged ***Solar Wind RAM pressure*** with ~2-yr time lag but *SW data were not propagated to Jupiter*!

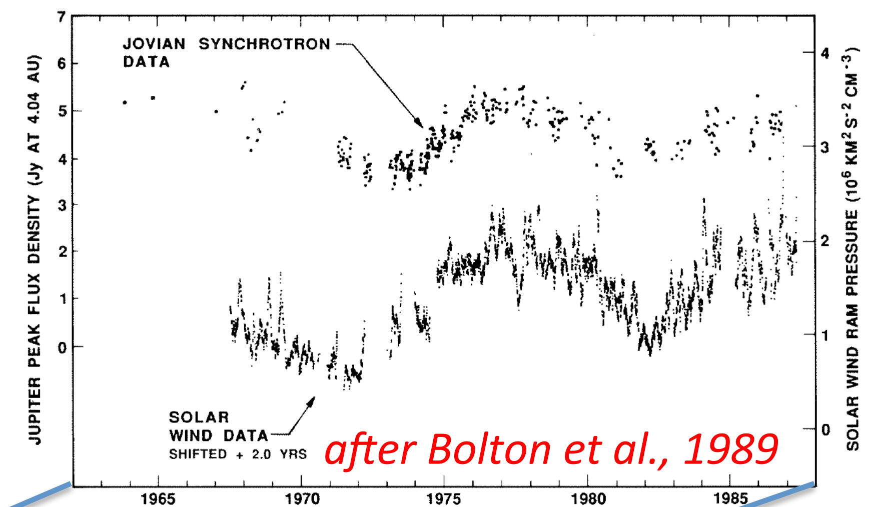
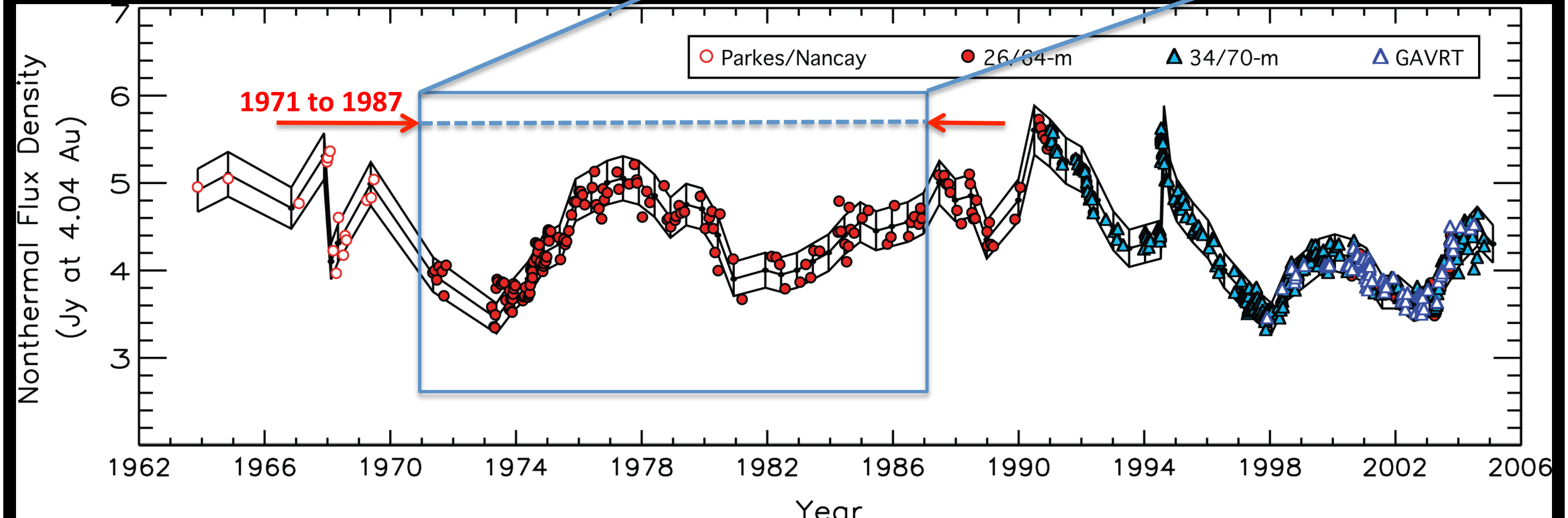


Fig. 6. The 27-day average of the solar wind ram pressure compared with the Jovian synchrotron flux density. The solar wind data have been shifted forward 2.0 years in time. The ram pressure values represent measurements at 1 AU adjusted to account for the eccentricity of the Jovian orbit.



• Jupiter's synchrotron radiation (JSR): Long-term Variability

2. Correlation found with solar wind

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, A01204, doi:10.1029/2007JA012396, 2008

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Investigating the origins of the Jovian decimetric emission's variability

D. Santos-Costa,[1] S. J. Bolton,[1] R. M. Thorne,[2] Y. Miyoshi,[3] and S. M. Levin[4]

- synchrotron emission data for period 1971-2002

- propagated Solar Wind (SW) data from Earth's to Jupiter's heliocentric positions (NASA/NSSDC's OMNI data) for period 1963-mid 2000's

- used in-house SW propagation tool that incorporates Parker's theory [1963] and a basic concept of solar wind's magnetic structure [Hundhausen , 1972, 1995] -> "ballistic approach"

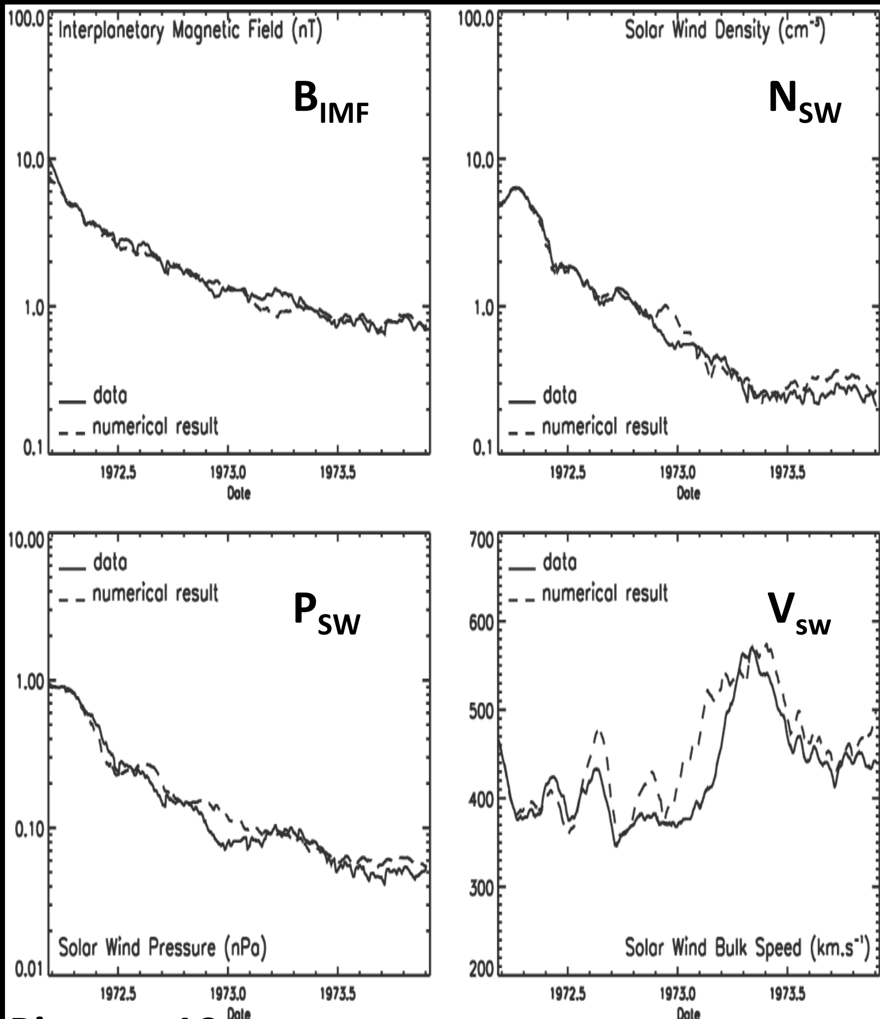
- Tested the model with SW data collected by Pioneer 10/11 and Voyager ½ en route to Jupiter (averaged over 1 solar radiation (SR) to 3 SRs)

- predicted SW parameters @ Jupiter were averaged (1-yr bin) for correlation study

after Santos-Costa et al., 2008

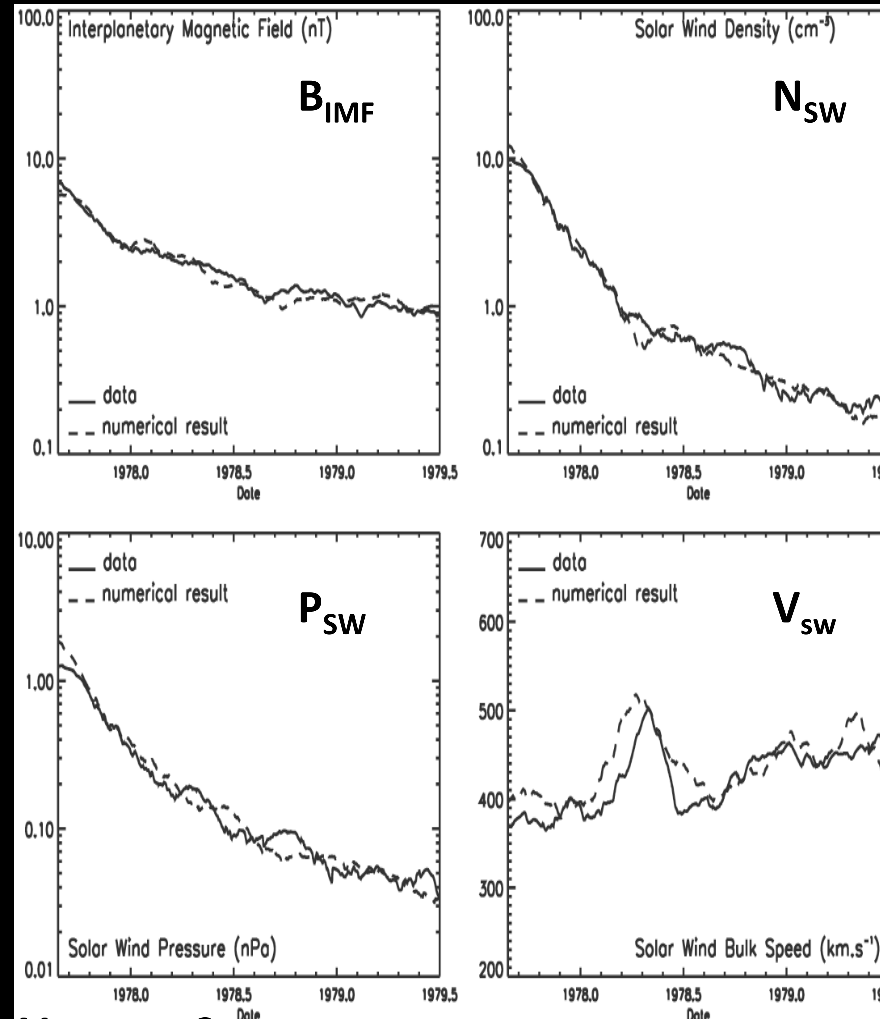
• Jupiter’s synchrotron radiation (JSR): Long-term Variability

2. Correlation found with solar wind



Pioneer 10

Figure 6. Comparisons results between numerical calculations of solar wind parameters and measurements made by Pioneer 10 while en route to the giant planet (from Earth’s to Jupiter’s heliographic position) (see subsection 3.1).



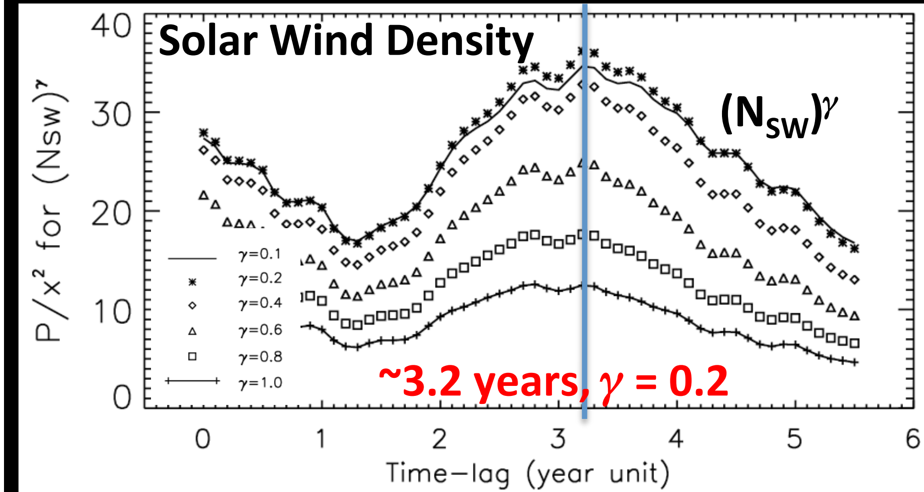
Voyager 2

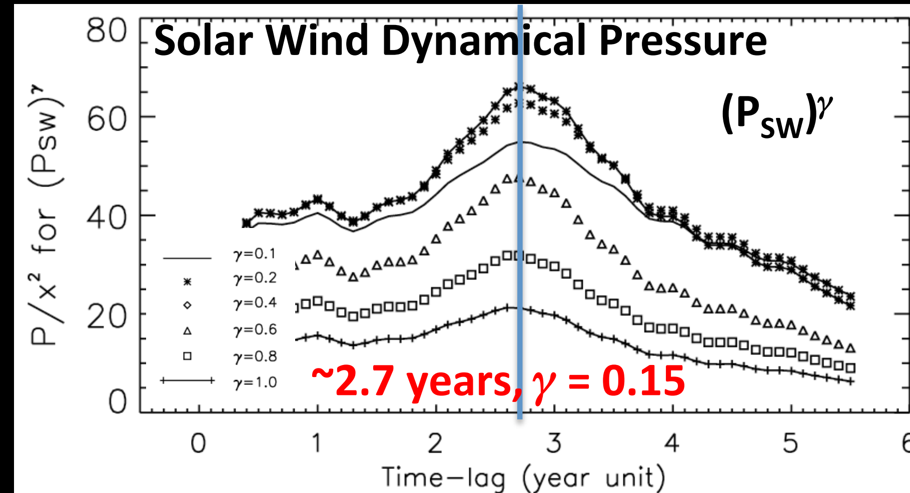
Figure 7. Comparisons results between numerical calculations of solar wind parameters and measurements made by Voyager 2 while en route to the giant planet (from Earth’s to Jupiter’s heliographic position) (see subsection 3.1).

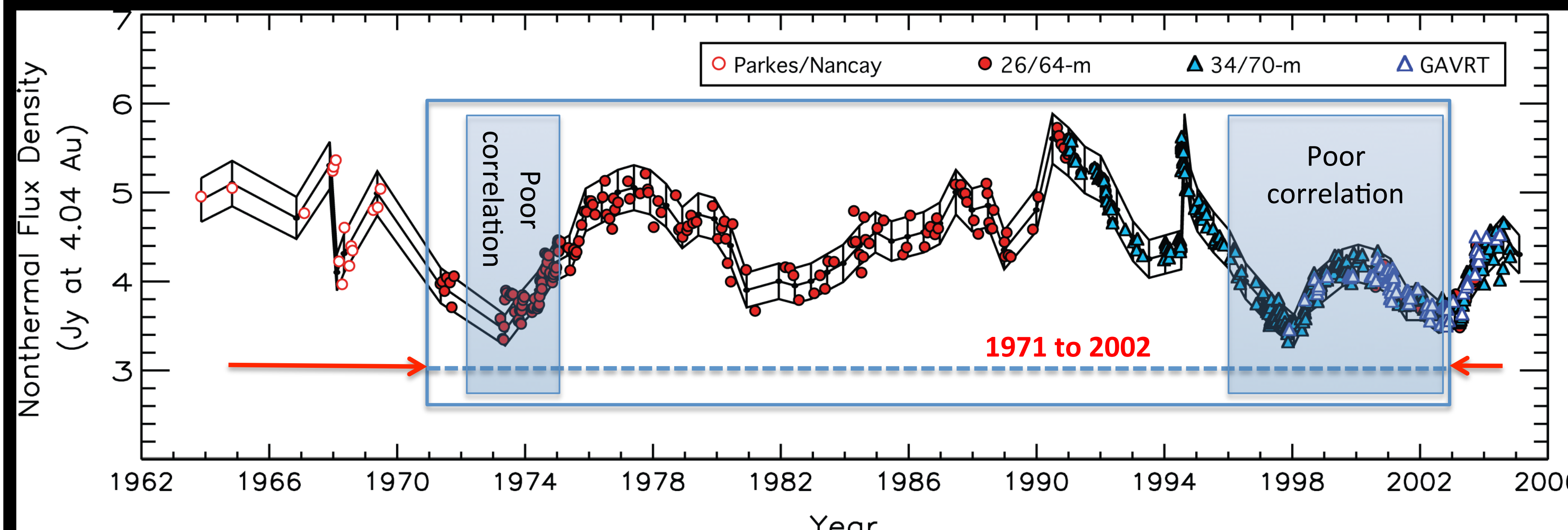
after Santos-Costa et al., 2008

• Jupiter's synchrotron radiation (JSR): Long-term Variability

2. Non-linear correlation with solar wind P_{SW} and N_{SW}



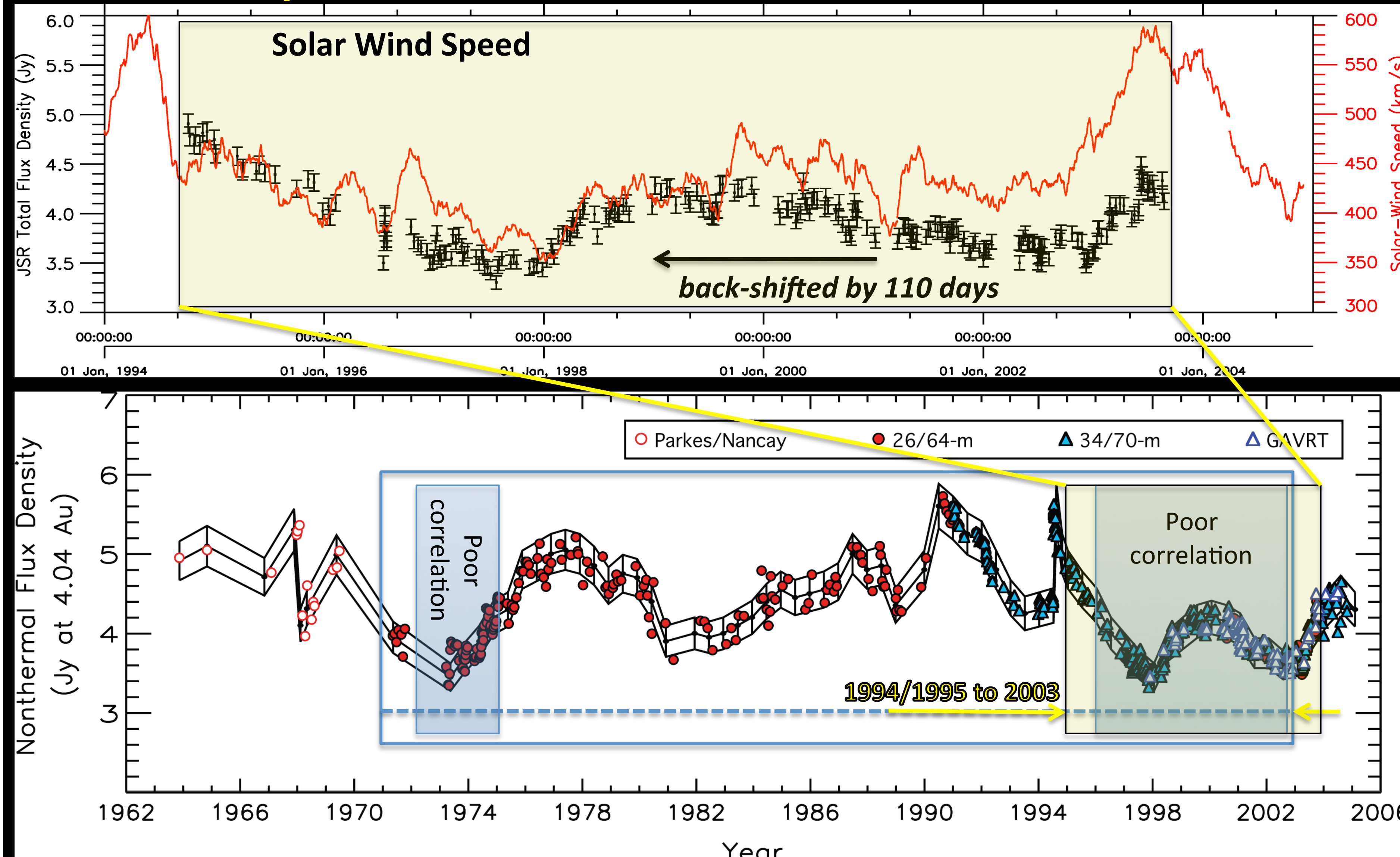




after Santos-Costa et al., 2008

• Jupiter's synchrotron radiation (JSR): Long-term Variability

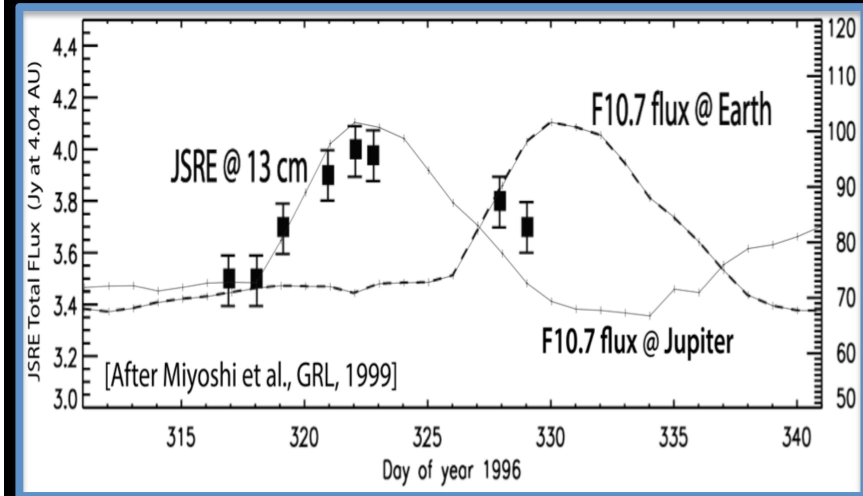
3. Correlation found with solar wind SPEED

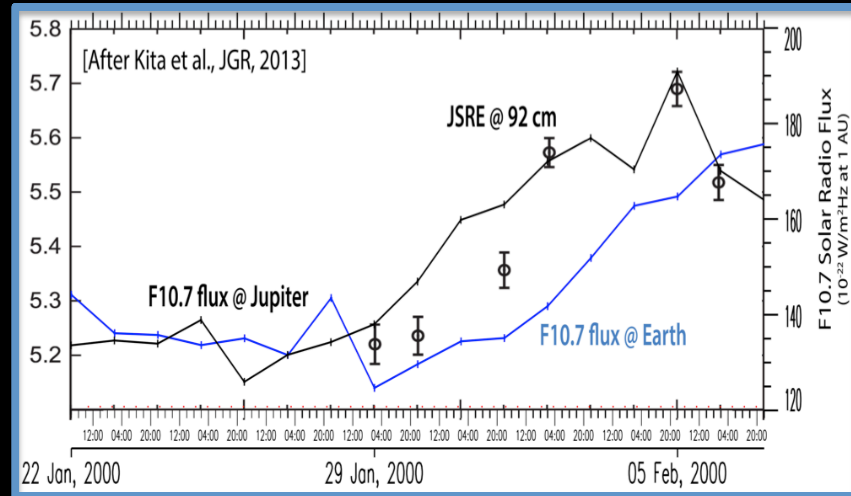


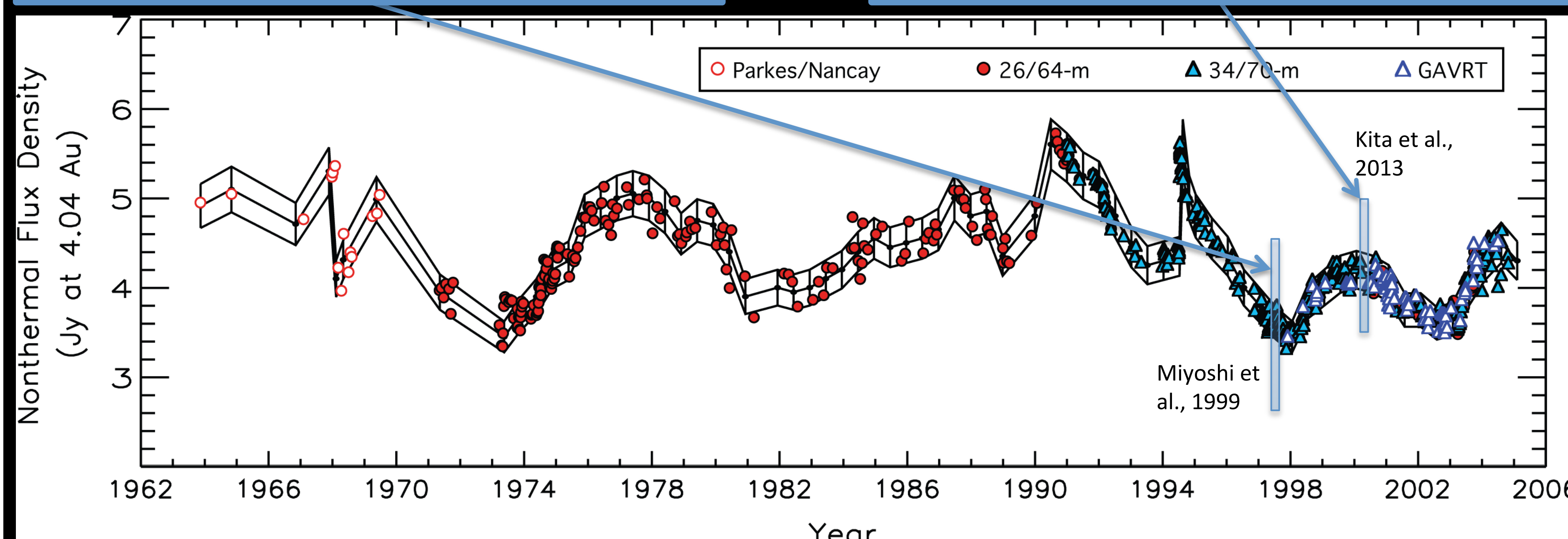
Courtesy of Santos-Costa

• Jupiter's synchrotron radiation (JSR): Variability on day/week scales

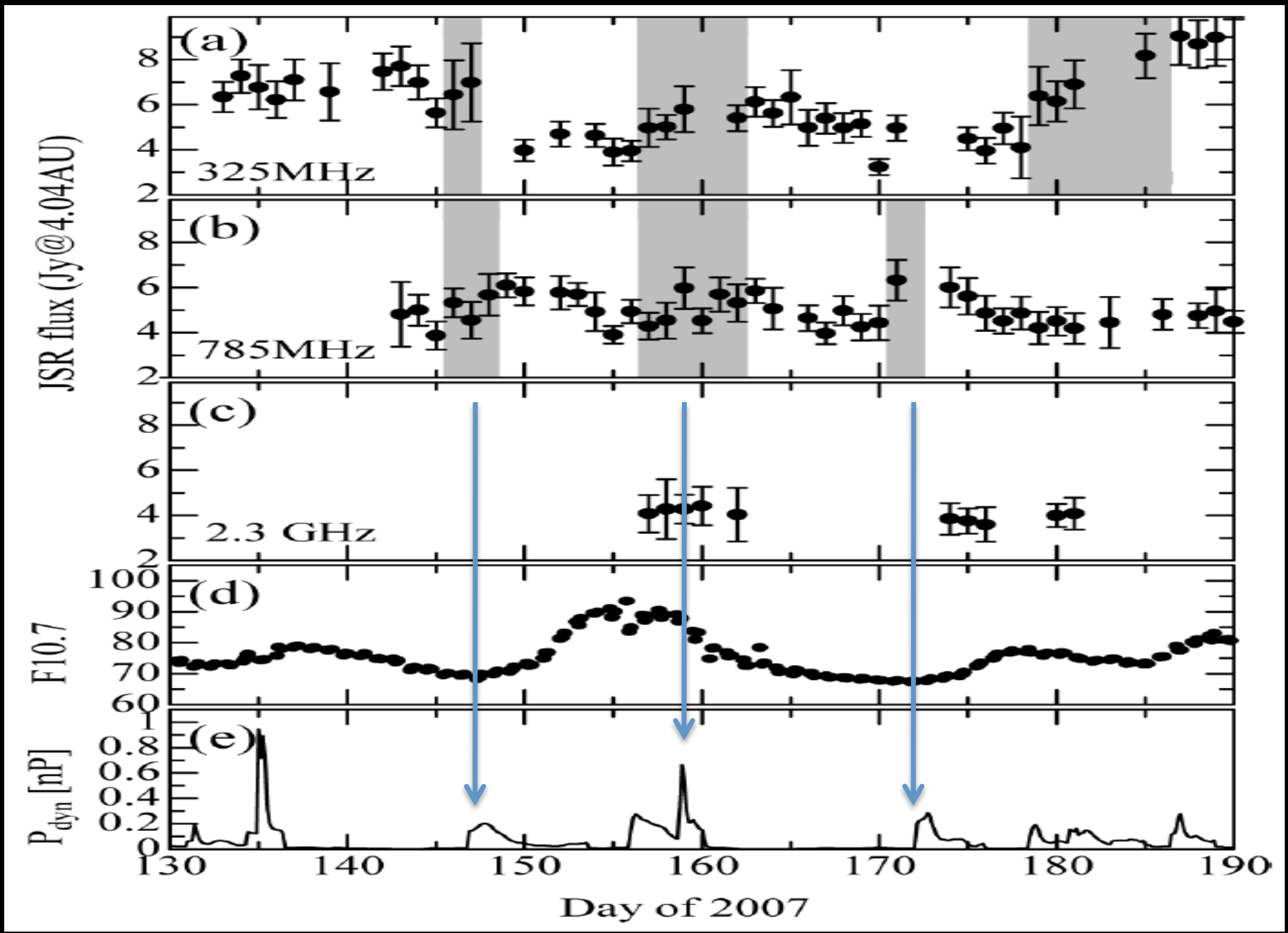
-> Correlation found with Solar Radiation (EUV/$F_{10.7cm}$)







• Jupiter's synchrotron radiation (JSR): Variability on hour/day scales



-> Correlation found with P_{SW} ?

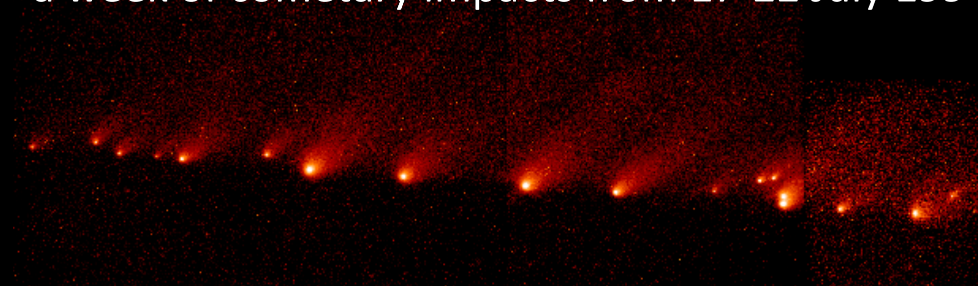
after Tsuchiya et al., AdGEO, 2009 (Murakami et al., GRL 2016)

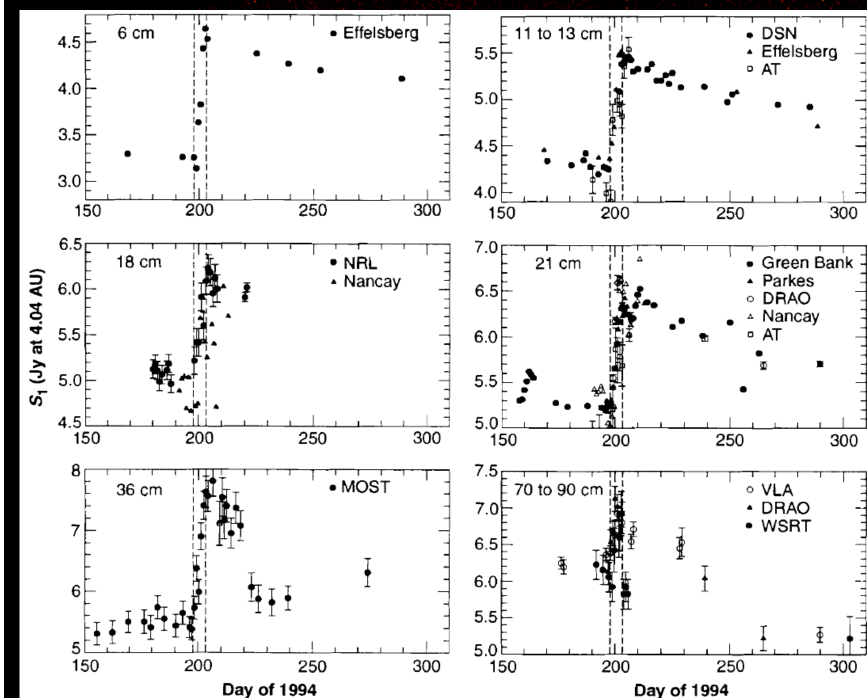
• Jupiter's synchrotron radiation (JSR): Variability < hour

-> Quasi-periodic 40 minute bursts linked to magneto-inertial oscillations of Jupiter's inner radiation belt ? [Y.-Q. Lou, Ast. J., 2001]

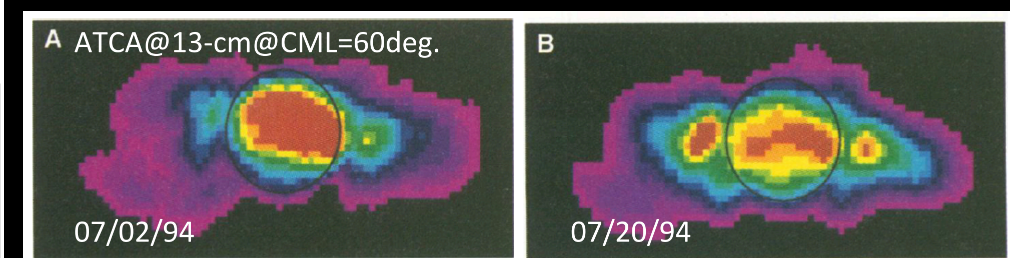
Jupiter’s synchrotron radiation (JSR): *Variations on week to month time scales linked to large-scale impacts*

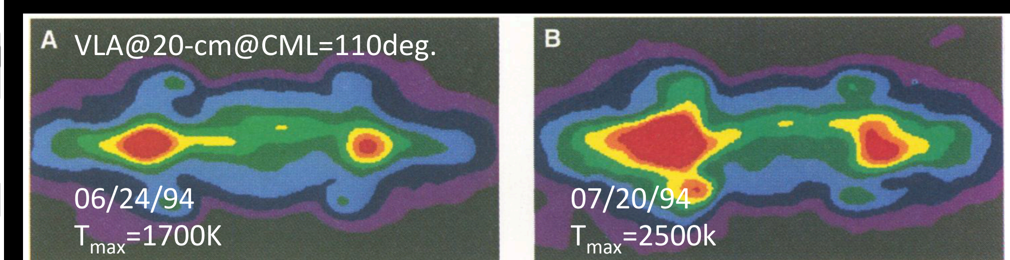
1. Collision of Shoemaker-Levy 9 comet with Jupiter: a week of cometary impacts from 17-22 July 1994





Enhancement was wavelength-dependent with intensity variations of 10 to 13% at 90 to 70 cm, 39% at 36 cm, 20 to 22% at 21 to 18 cm, 25 to 26% at 13 to 11 cm, and 43% at 6 cm.

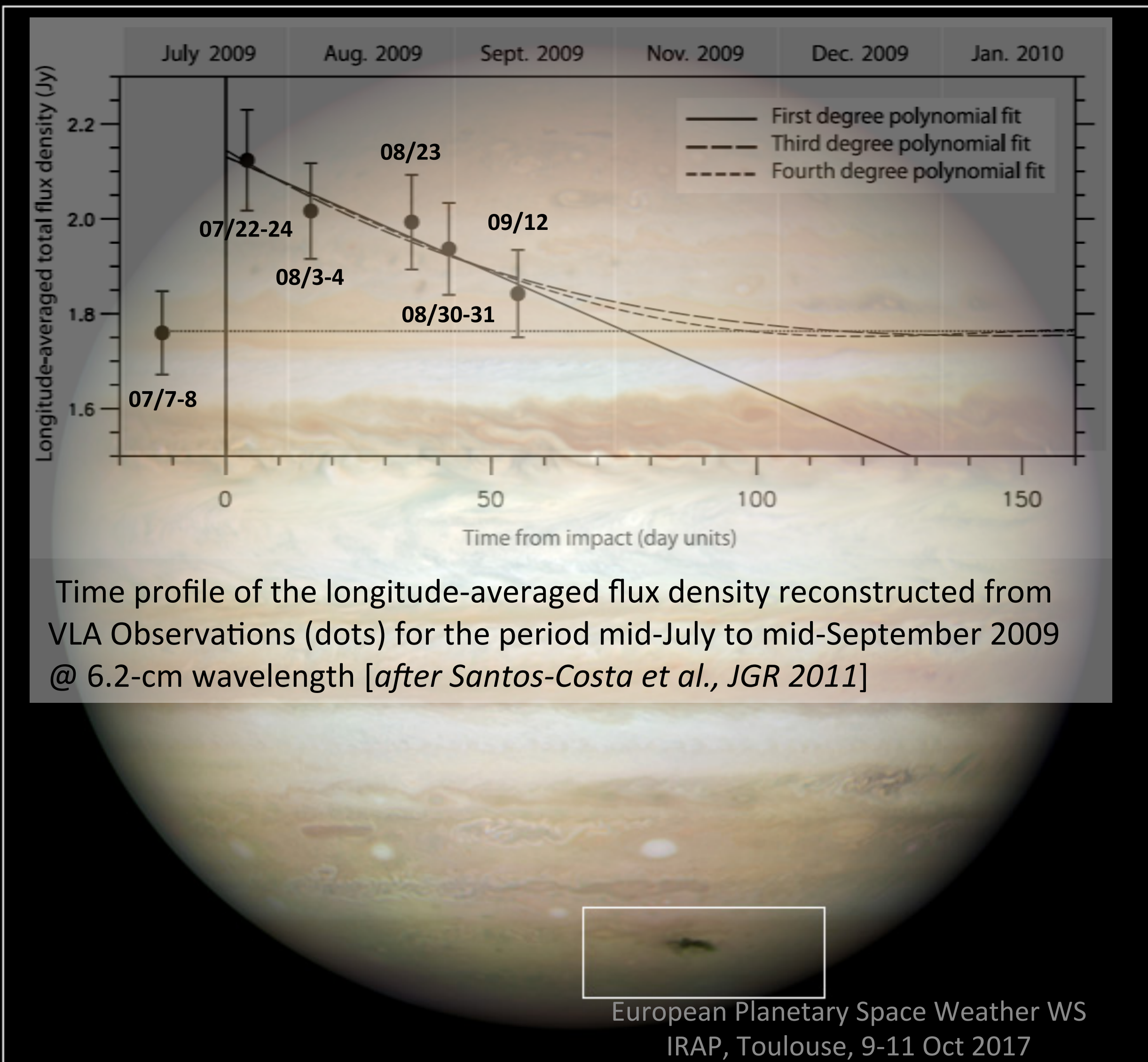




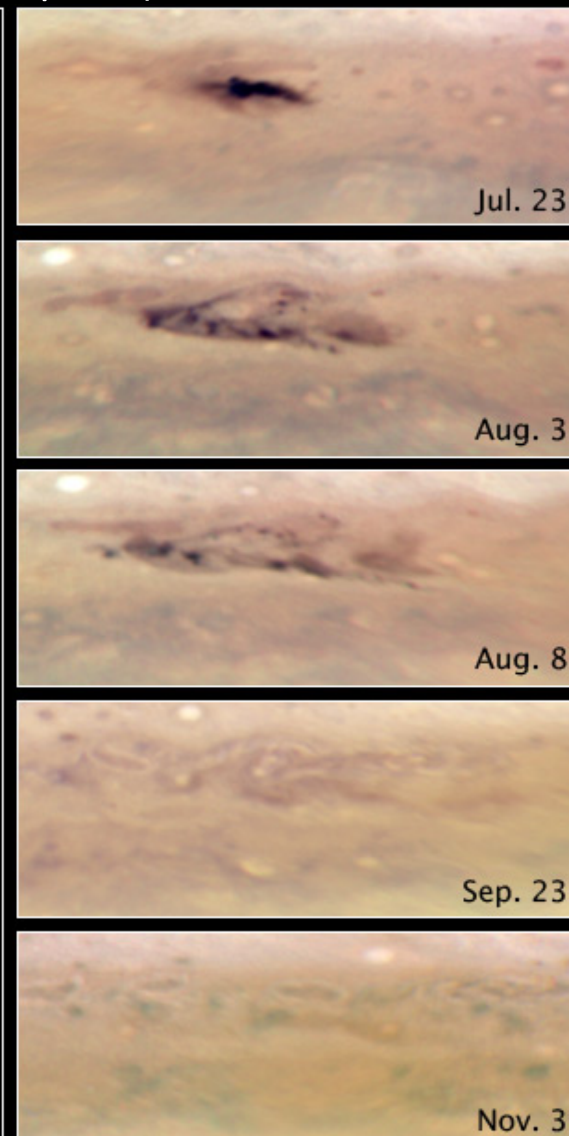
after de Pater et al., Science, 1995

Jupiter's synchrotron radiation (JSR): *Variations on week to month time scales linked to large-scale impacts*

2. The 2009 Jupiter Impact event: July 19, 2009 ("Wesley impact")



Time profile of the longitude-averaged flux density reconstructed from VLA Observations (dots) for the period mid-July to mid-September 2009 @ 6.2-cm wavelength [*after Santos-Costa et al., JGR 2011*]

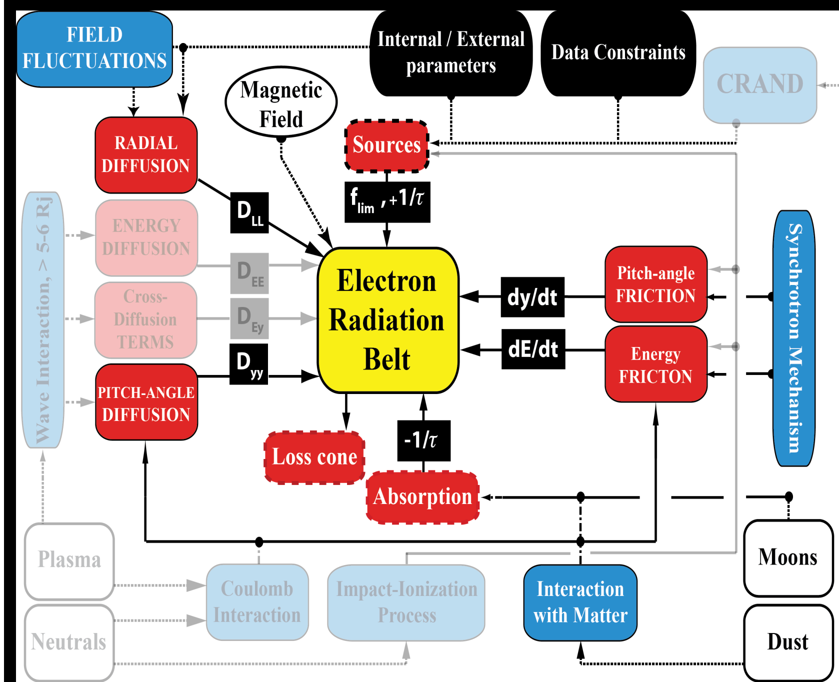


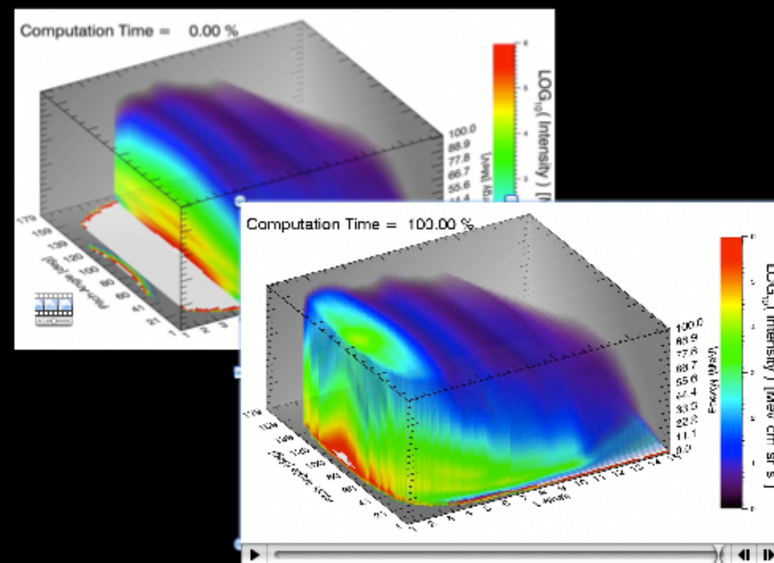
Analysis of JSR from physics-based model of RB (< Io’s orbit)

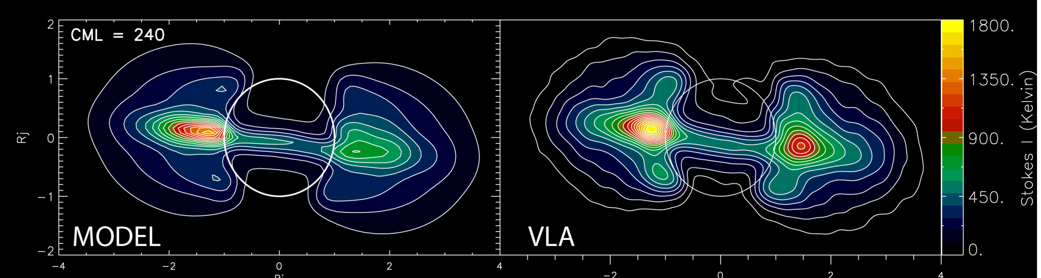
In the magnetospheric region delimited between the planet and Galilean moon Io, the distributions of keV to MeV electrons are calculated from the governing 3-D Fokker-Planck diffusion transport equation [after Santos-Costa et Bourdarie, 2001; Santos-Costa and Bolton, 2008]:

$$\frac{\partial f}{\partial t} + \frac{1}{G'}\sum_{i=1}^{2}\frac{\partial}{\partial Q_i}\left[\left(\frac{dQ_i}{dt}\right) f(E,y,L)\right] = \frac{1}{G'}\sum_{i=1}^{2}\sum_{j=1}^{2}\frac{\partial}{\partial Q_i}\left[G' D_{ij}\frac{\partial f(E,y,L)}{\partial Q_j}\right] + (S)$$

$$-(L) + \frac{1}{G}\frac{\partial}{\partial L}\left[G D_{LL}\frac{\partial f(M,J,L)}{\partial L}\right]_{M,J}$$







[after Santos-Costa et al., 2017; EPSC 2017, OPS3 poster # P52]

Analysis of JSR from physics-based model of RB

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, A01204, doi:10.1029/2007JA012396, 2008

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Investigating the origins of the Jovian decimetric emission's variability

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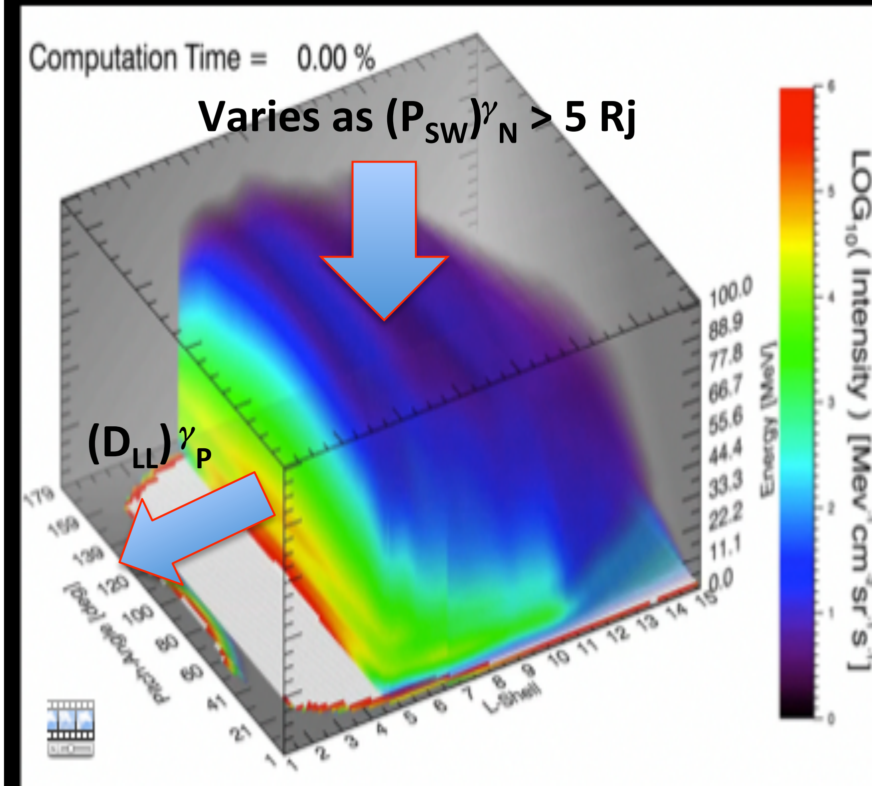


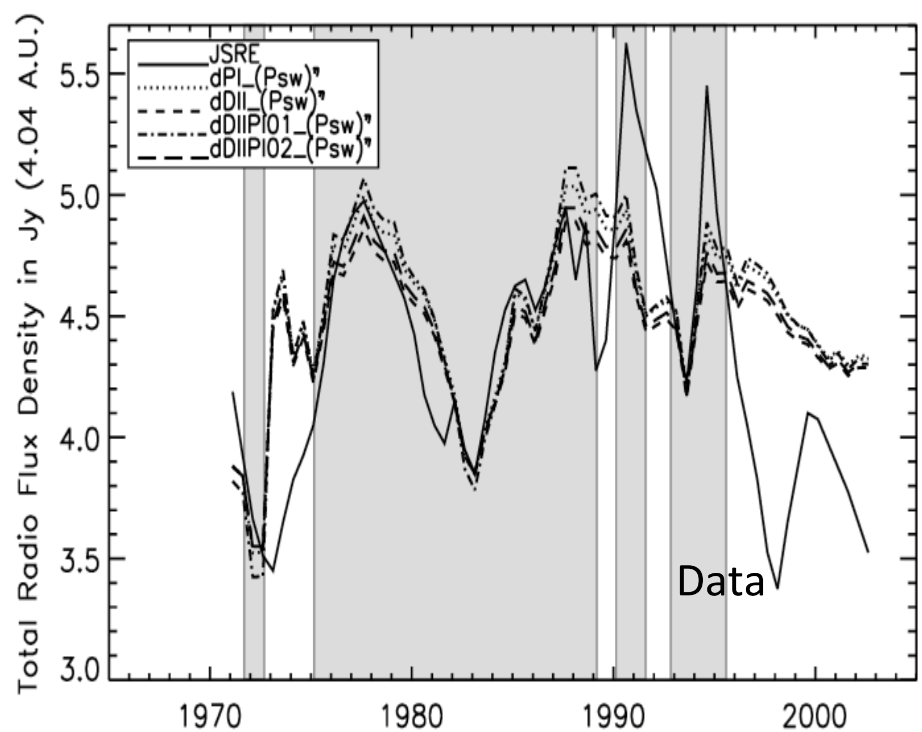
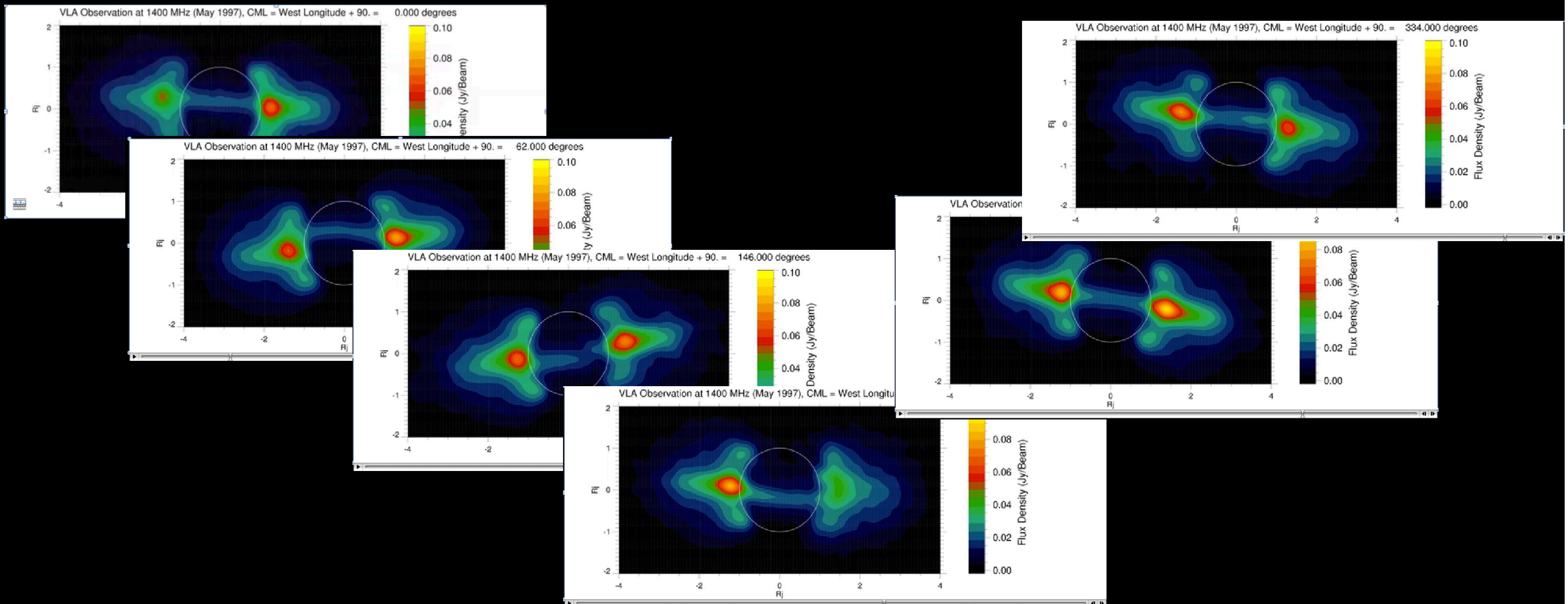


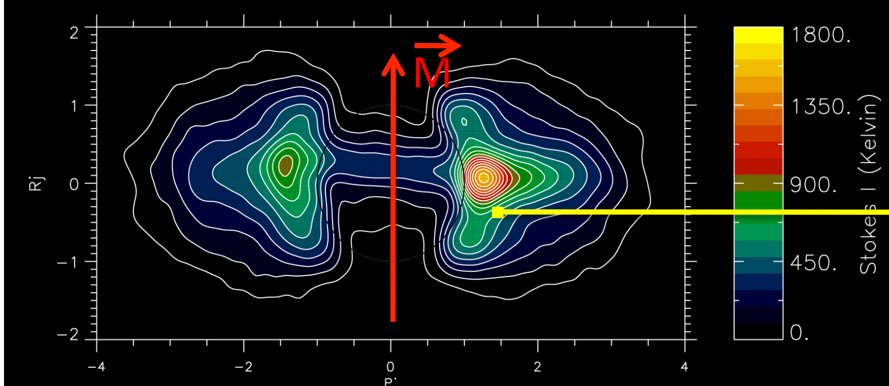
Table 2. γ Values Providing a Good Fit Between *JSRE* and $(SWP)^{\gamma}$ for Each $dPI^{\alpha} \oplus dDLL^{\beta a}$

α	β	$\gamma_{N_{sw}}$	$\gamma_{P_{sw}}$	Period 1971–2002 P_{coeff}/χ^2	Period 1975–1988 P_{coeff}/χ^2	Period 1975–1995 P_{coeff}/χ^2
1	**0**	0.25	0.35	0.588/0.213	0.868/0.035	0.682/0.088
0	**1**	0.35	0.50	0.585/0.193	0.867/0.028	0.683/0.096
1	**1**	0.15	0.15	0.590/0.220	0.868/0.005	0.682/0.003
0.5	**0.5**	0.30	0.40	0.588/0.198	0.868/0.004	0.682/0.002

Analysis of JSR from 3-D image reconstruction technique



Methodology:



$$\left(\int_E B\sin(\alpha)F\left(\frac{\nu}{\nu_c}\right)N(\alpha(s),E)\,\mathrm{d}E\right)$$

$$\boxed{T_{px}(\mathrm{CML,\ x,\ y})} = \frac{c^2}{2k\nu^2}\frac{S}{\Omega_B} = \underbrace{\boxed{\frac{c^2}{2k\nu^2}R_J}}_{1/\eta}\int \boxed{\varepsilon(\nu,\alpha,E,\vec{r})}\,\mathrm{d}s$$

Analysis of JSR from 3-D image reconstruction technique

Methodology:

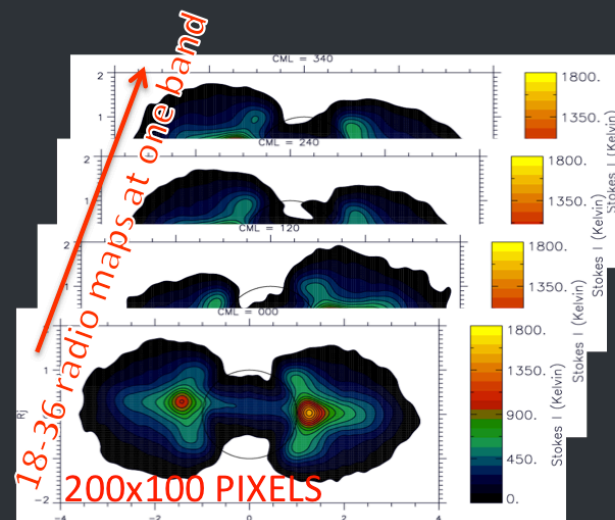
1. Solve an over determined system of linear equations A.X=B matrix
2. For a given CML_l / $Pixel_{ij}$, the linear equation is defined as [after Santos-Costa et al., 2014]:

$$\Sigma a_{ijkl} \,.\, \varepsilon_{ijk} = (\eta/\Delta s).T_{ikl}$$

$$\begin{bmatrix} A \end{bmatrix} \cdot \begin{bmatrix} \varepsilon(x,y,z) \end{bmatrix} = \begin{bmatrix} \text{maps} \end{bmatrix}$$

A: 200x200x 100xNb_{map} Coefficients

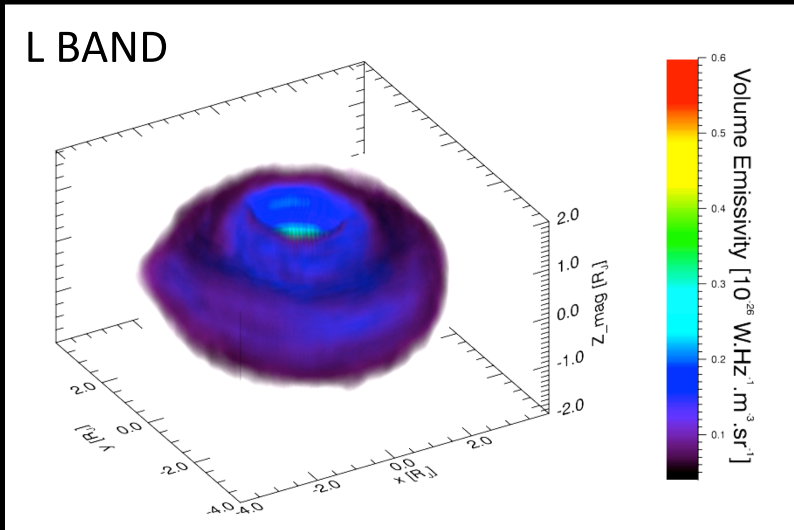
ε(x,y,z): 200x200x100 Number of radio point sources



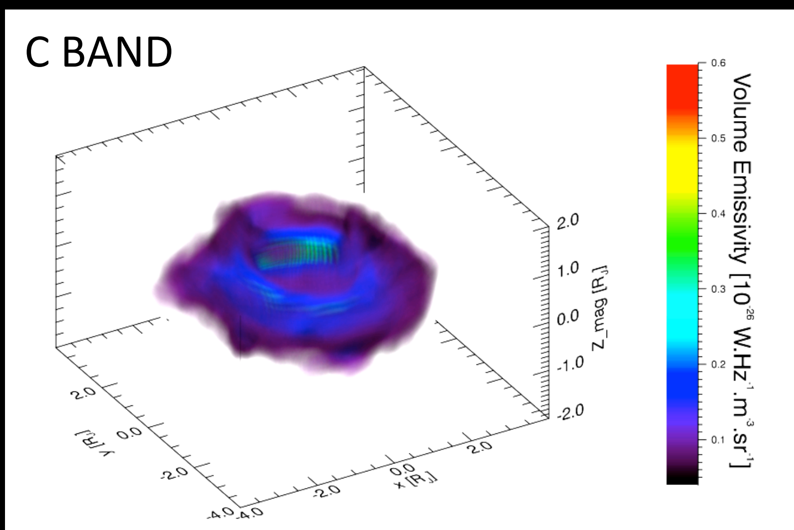
200x100xNb_{map} pixels (i.e. Brightness temperatures)

Analysis of JSR from 3-D image reconstruction technique

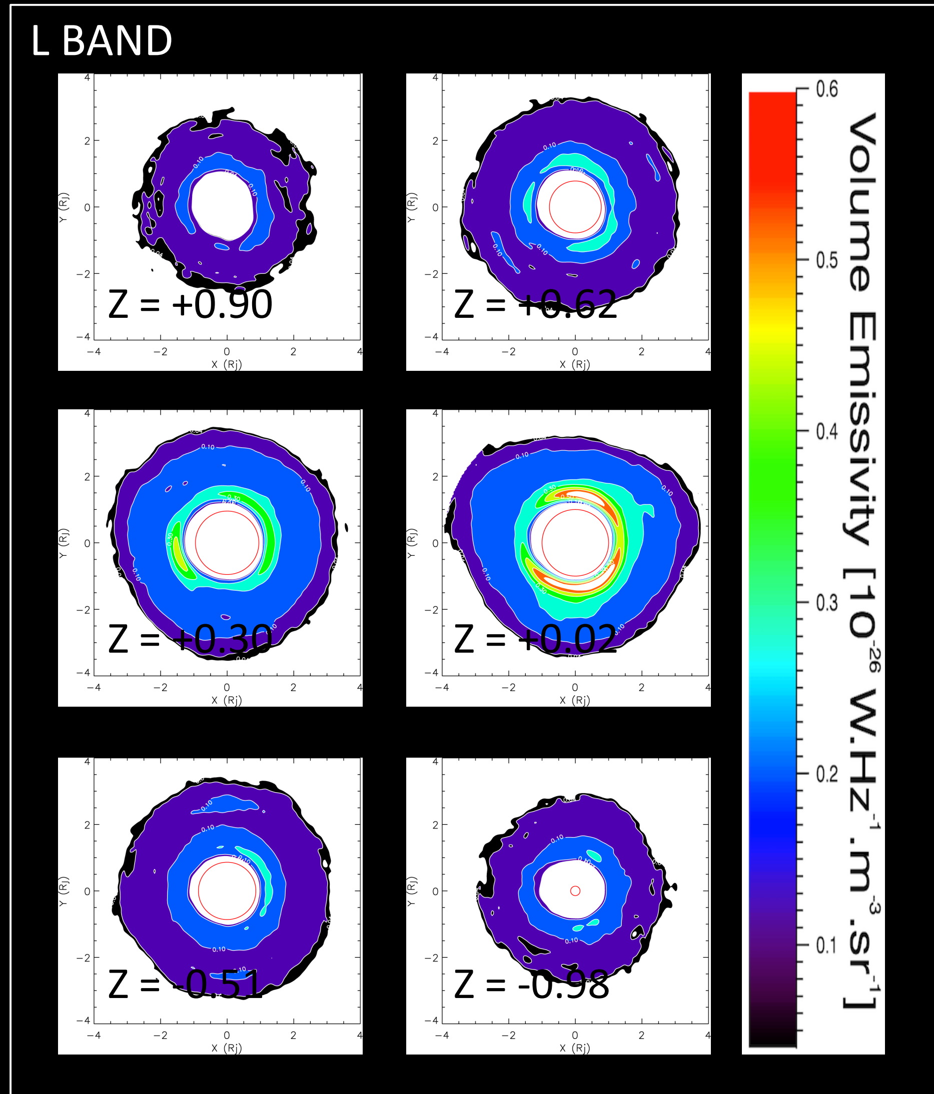
L BAND



C BAND

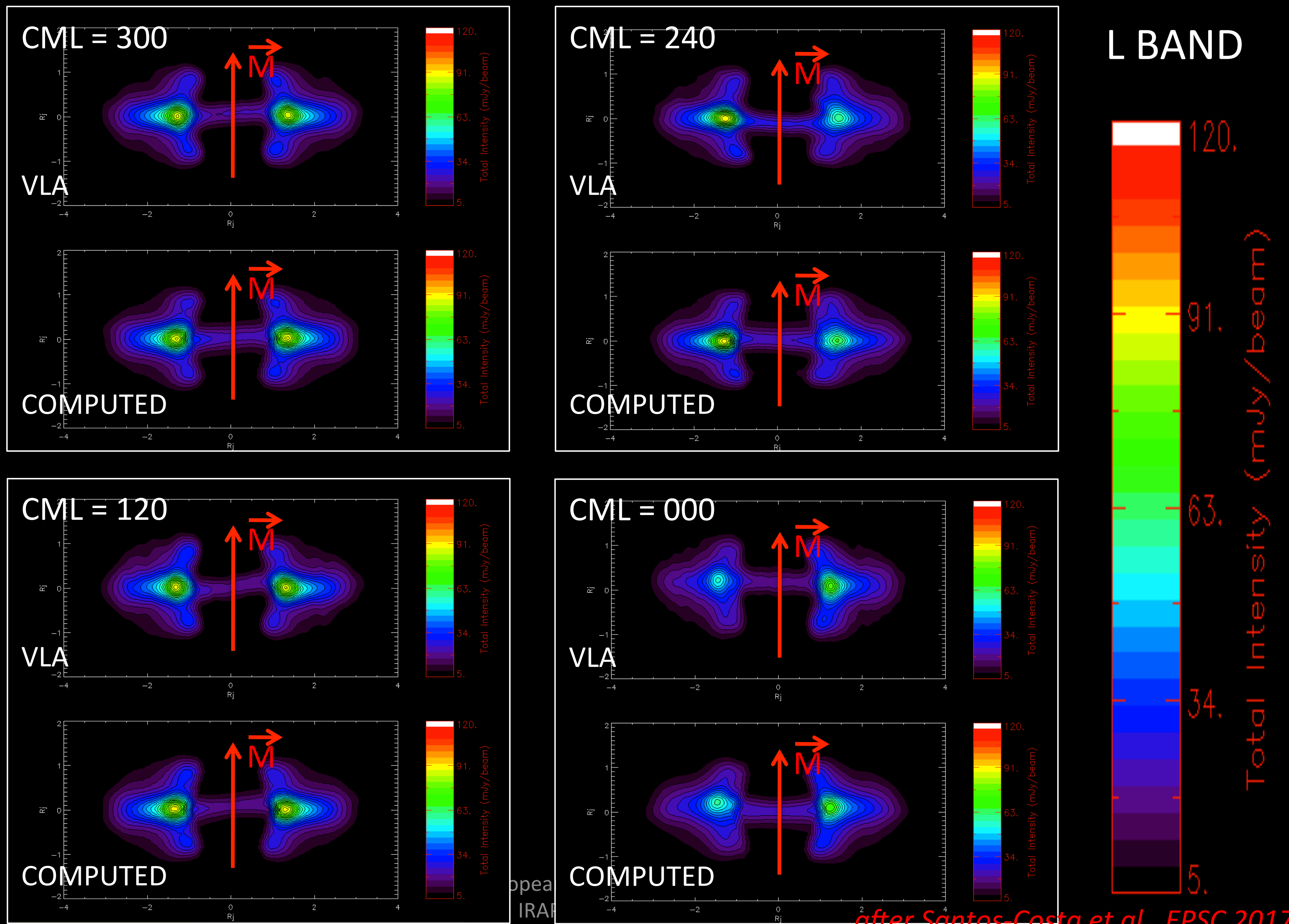


L BAND



after Santos-Costa et al., EPSC 2017

Analysis of JSR from 3-D image reconstruction technique



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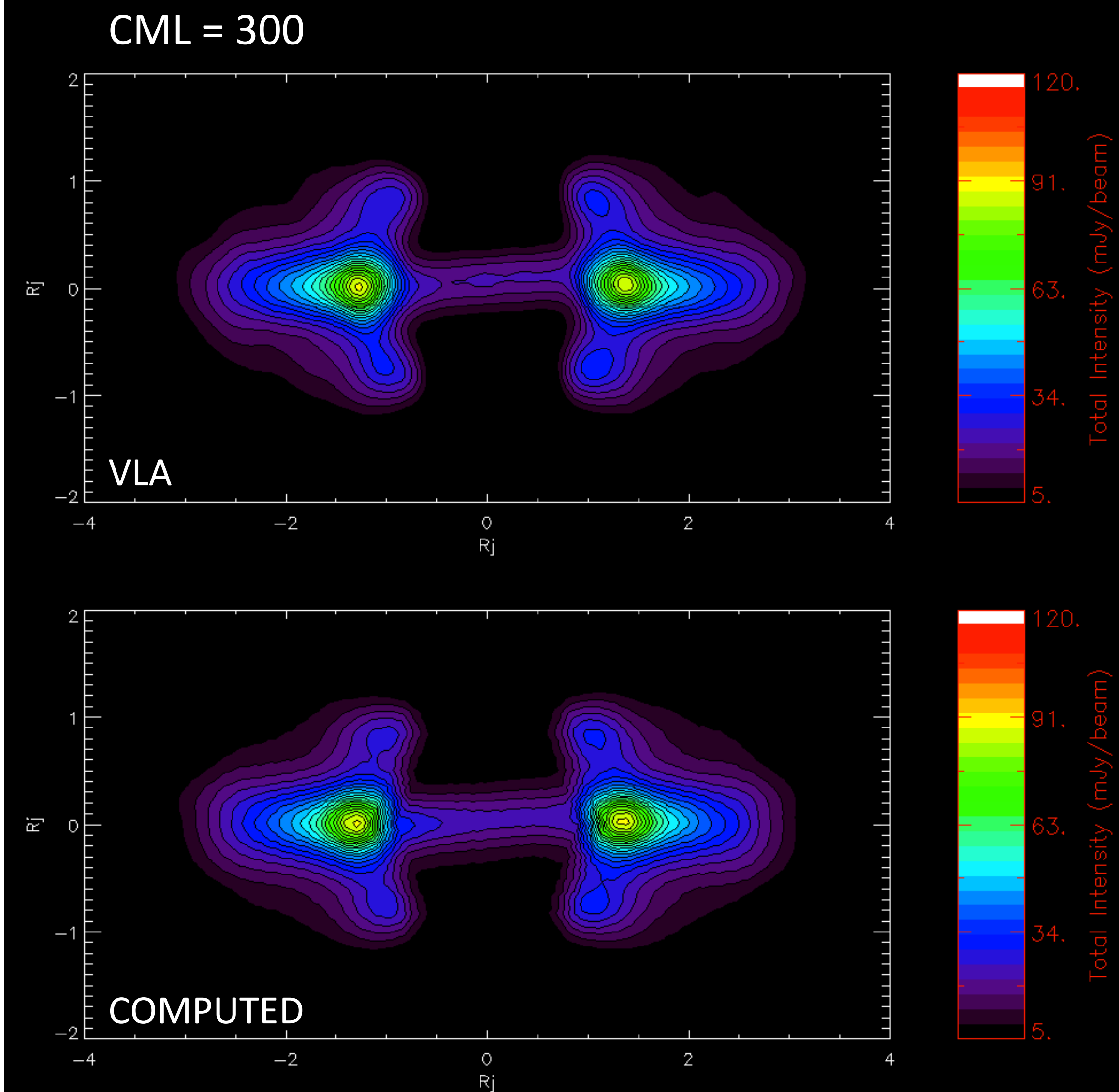
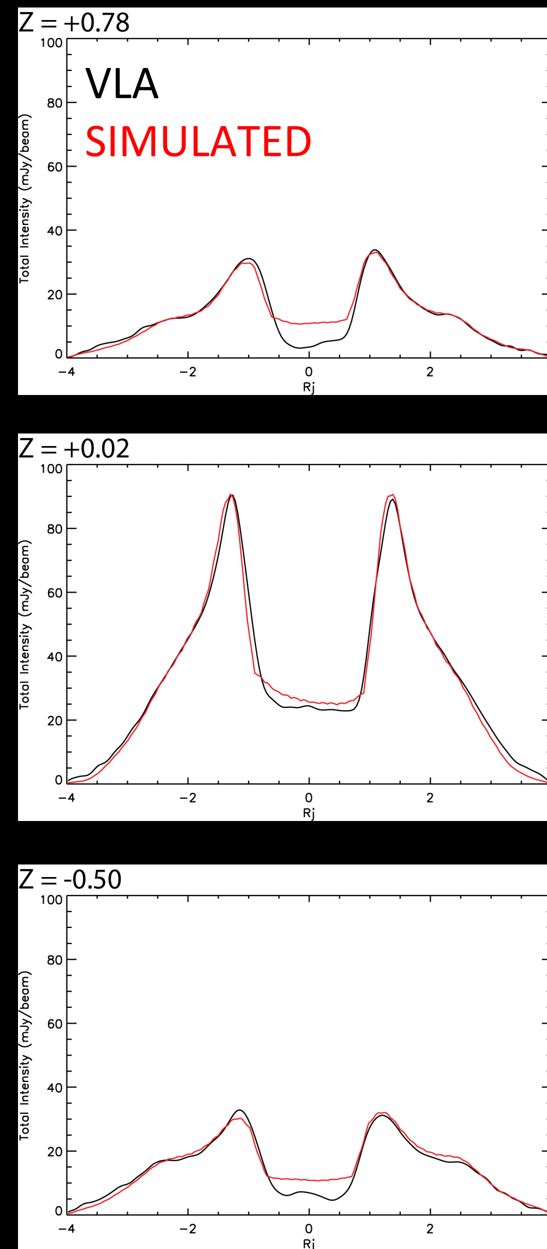
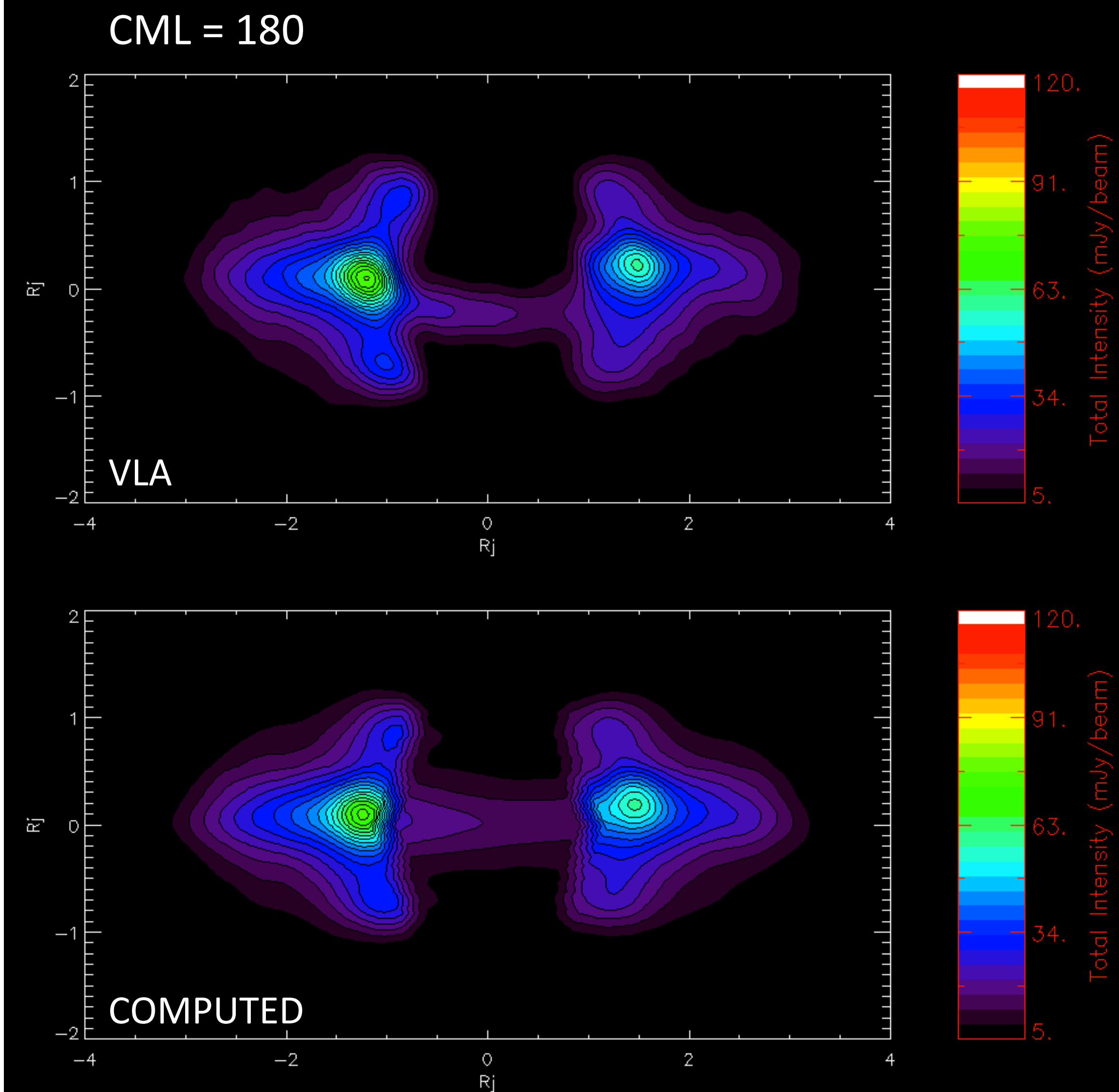
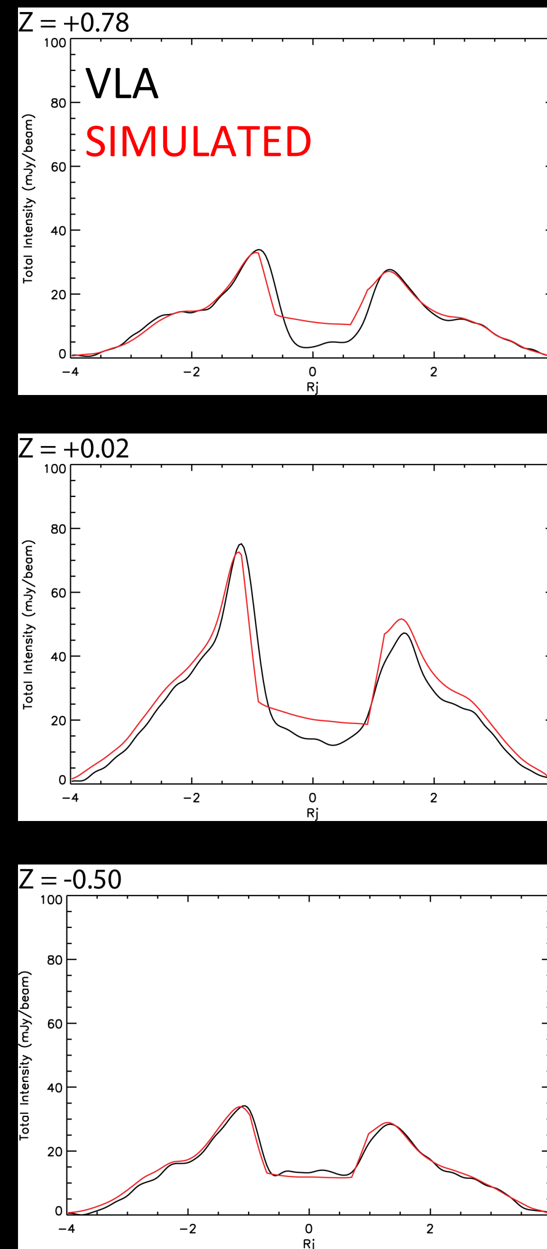




after Santos-Costa et al., EPSC 2017

Analysis of JSR from 3-D image reconstruction technique





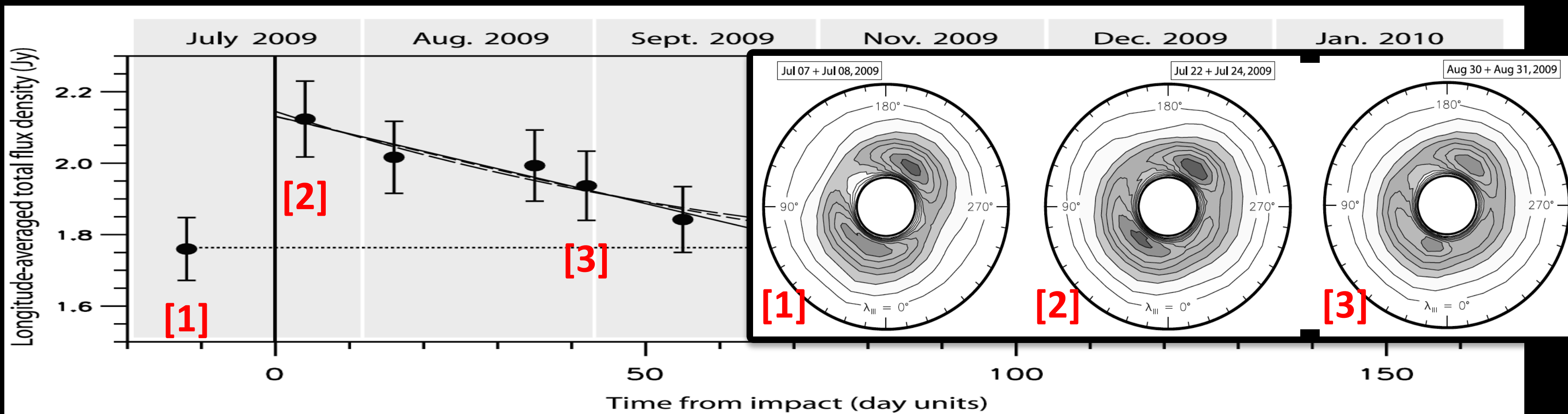
after Santos-Costa et al., EPSC 2017

European Planetary Space Weather WS
IRAP, Toulouse, 9-11 Oct 2017

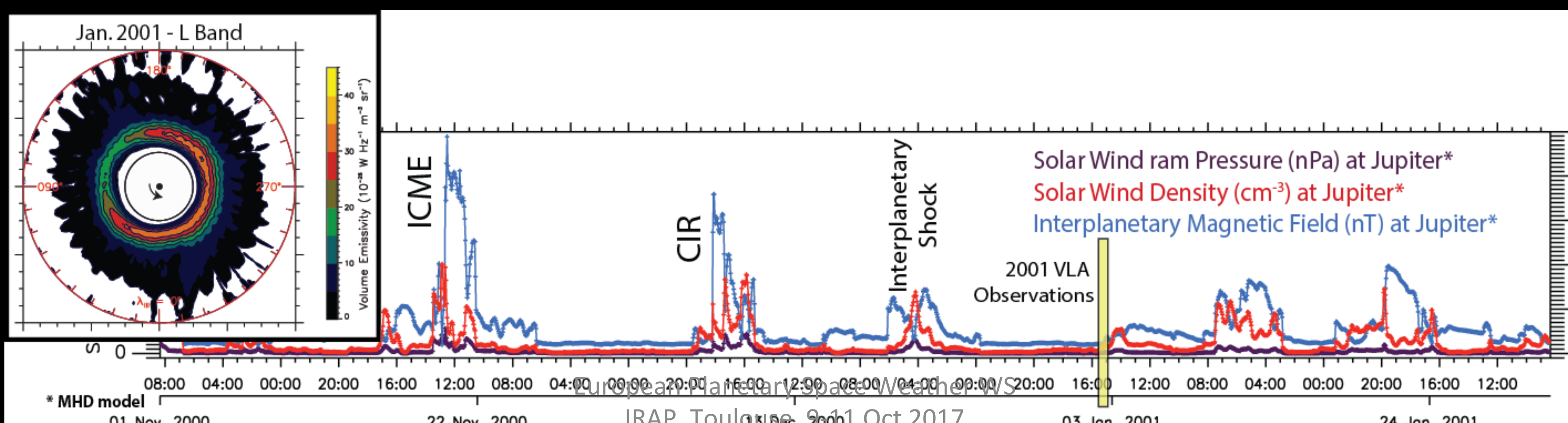
3-D image reconstructions of JSR: results from past studies (equatorial)

Tomographic image reconstruction had been used to:

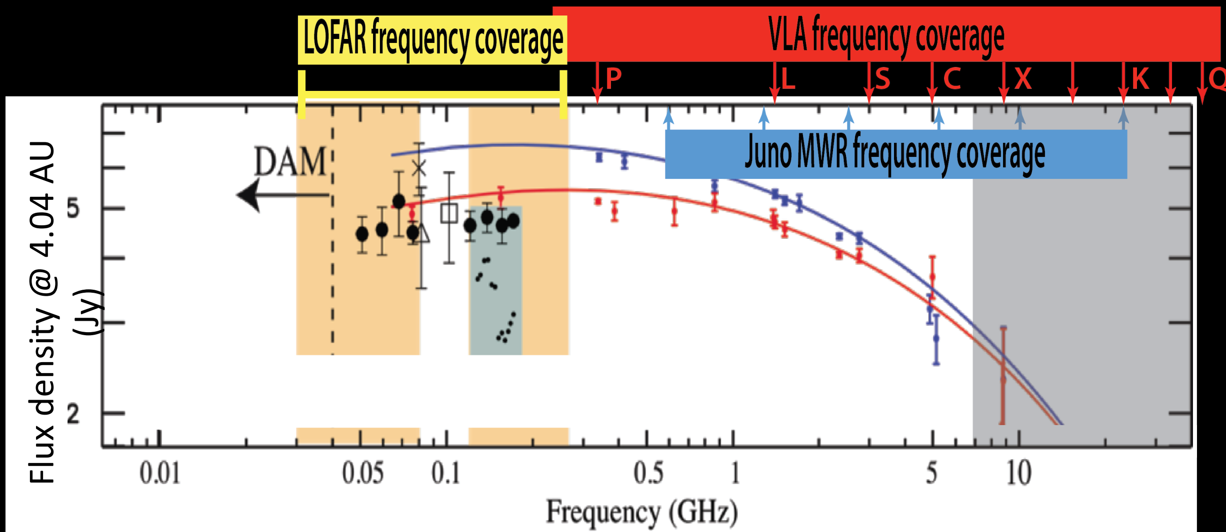
1. depict the equatorial temporal and spatial changes in the JSR/RB during asteroid-type impact [e.g. Santos-Costa et al., JGR 2011].

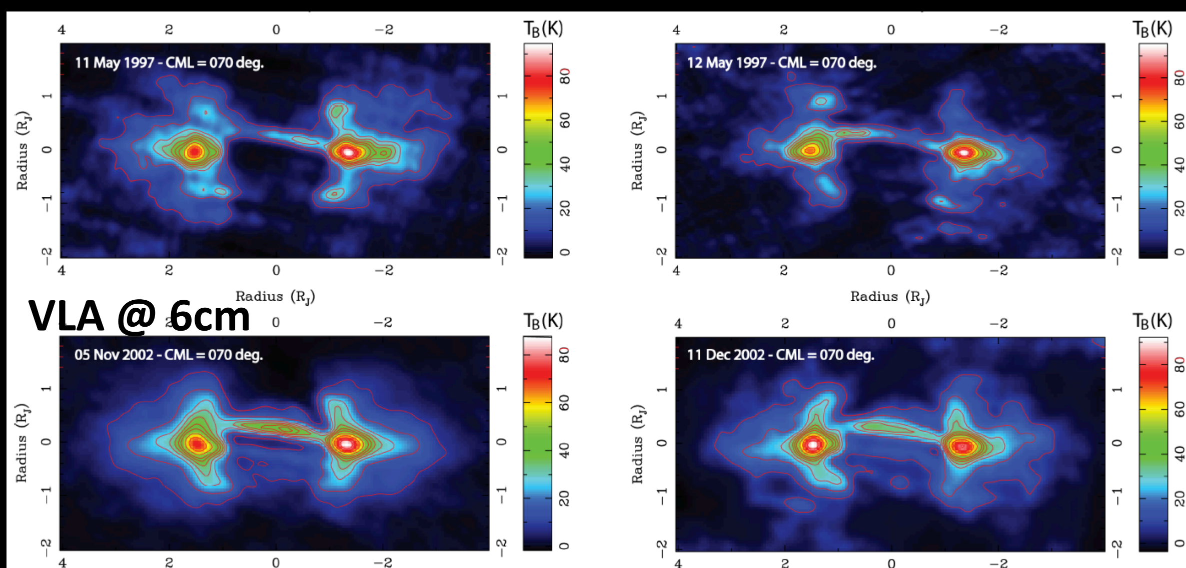


2. witness the likely response of equatorial RB region / the magnetosphere [e.g. Santos-Costa et al., A&A 2014] to SW features during Cassini flyby of Jupiter.



SUMMARY





- variability in total flux density and changes in 2D spatial distributions observed at P, L, S, C, X bands

- variations are frequency dependent and larger at shorter frequencies, except during comet/asteroid impacts

- physics-based simulation of observed JSR variations can be reproduced for different case scenarios; but they do not allow to really determine the key control parameters

- self-consistent model of JSR retrieved from tomographic techniques will provide additional constraints for physics-based models to determine how Jupiter's RB is controlled spatially over time