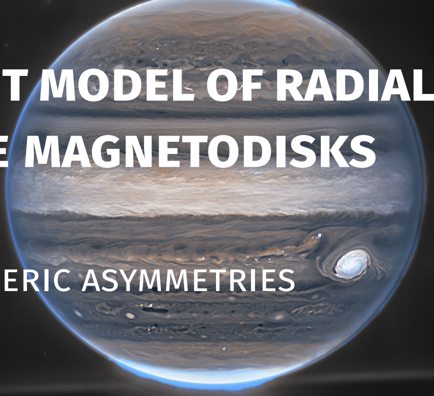
A self-consistent model of radial transport in the magnetodisks of gas giants

Including interhemispheric asymmetries



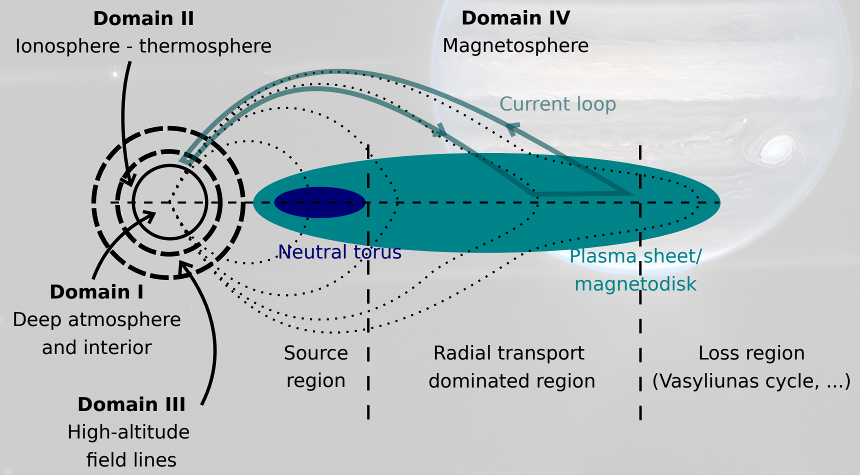
Marie Devinat
Michel Blanc, Nicolas André

1rst year PhD
IRAP, CNRS, UPS, France

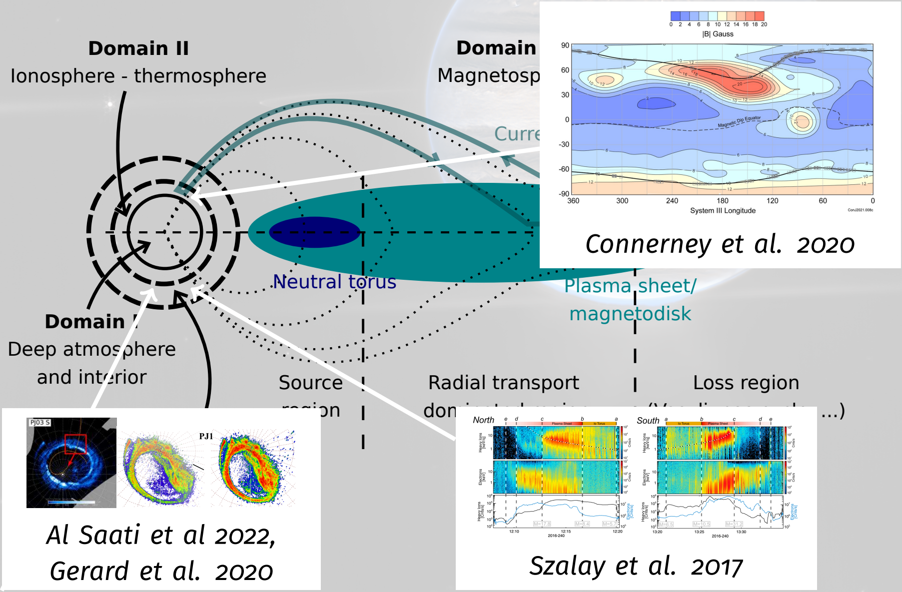
PNST, January 9, 2024

Why ?

Fast rotating magnetosphere with inner sources



Juno observations of Jovian asymmetries

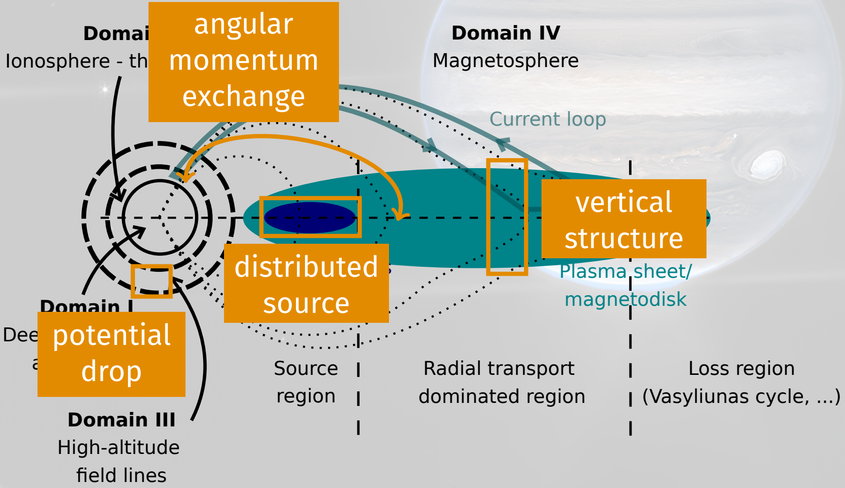


Connerney et al. 2020

Al Saati et al 2022,
Gerard et al. 2020

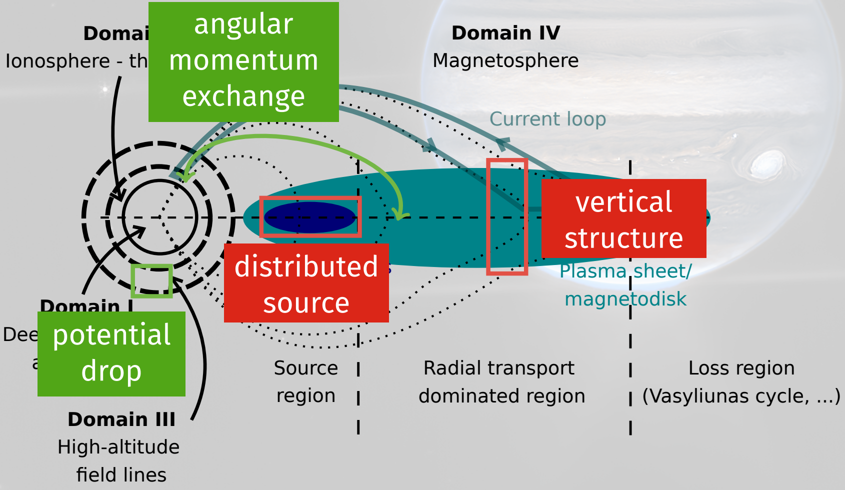
Szalay et al. 2017

Goals



Domai
Ionosphere - th
angular momentum exchange
Domain IV
Magnetosphere
Current loop
vertical structure
distributed source
Plasma sheet/ magnetodisk
Domain I
Dee
a
potential drop
Source region
Radial transport dominated region
Loss region (Vasyliunas cycle, ...)
Domain III
High-altitude field lines

GOALS



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Theoretical Modelling

Two types of models :

J transport models	M, E transport models
e.g. Cowley & Bunce 2001	*e.g. Ferriere 2001*

What has been done ?

Two types of models :

J transport models	M, E transport models
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- field-aligned currents
- (partial) M-I coupling
- ~~*B* field line bending~~
- ~~transport processes~~

$\Downarrow$

- corotational breakdown
- ionospheric properties
- response to solar wind

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M, E transport models

- interchange instability
- integrated quantites
- ~~M-I coupling~~
- ~~field-aligned dynamics~~

$\Downarrow$

- quantify M and E sources
- transport timescales
- transport modes (interchange)

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⇓

- M and E sources
- transport timescales
- transport modes (interchange)

combine both approaches

Our general modelling principles

Main hypotheses :

- axisymmetry
- multi-fluid plasma
- MHD approximation
- no time variability

Included in the model :

- M-I coupling
- high latitude (static) potential drops
- disk latitudinal extension

Global equations

thick equatorial disk

high-latitudes contribution

Mass

$$\frac{\partial M_0}{\partial t} - B_{0,eq}\frac{\partial}{\partial \alpha}\left(D_\alpha B_{0,eq}\frac{\partial M_0}{\partial \alpha}\right) = \overline{\mathcal{S}}_{m,pu} - \overline{\mathcal{L}}_m$$

Energy

$$\frac{\partial W_0}{\partial t} - B_{0,eq}\frac{\partial}{\partial \alpha}\left(D_\alpha B_{0,eq}\frac{\partial W_0}{\partial \alpha}\right) = \overline{\mathcal{S}}_q - \overline{\mathcal{L}}_q$$

Angular momentum

$$\dot{\mathcal{M}}_\perp \frac{\partial^2 \Phi_{eq}}{\partial \alpha^2} + 2\dot{\mathcal{M}}_{R/\alpha}\frac{\partial \Phi_{eq}}{\partial \alpha} = 2\pi\left(\Omega_K R_P - \frac{\partial \Phi_{eq}}{\partial \alpha}\right) B_{0,eq}\Sigma_{pu}R_{eq}^2$$

$$+ 2\pi \sum_{k=n,s}\left(\Omega_{nk}R_P - \frac{\partial \Phi_{ik}}{\partial \alpha}\right)\frac{\Sigma_{Pk}R_{ik}^2 B_{ik}}{\sin(I_k)}.$$

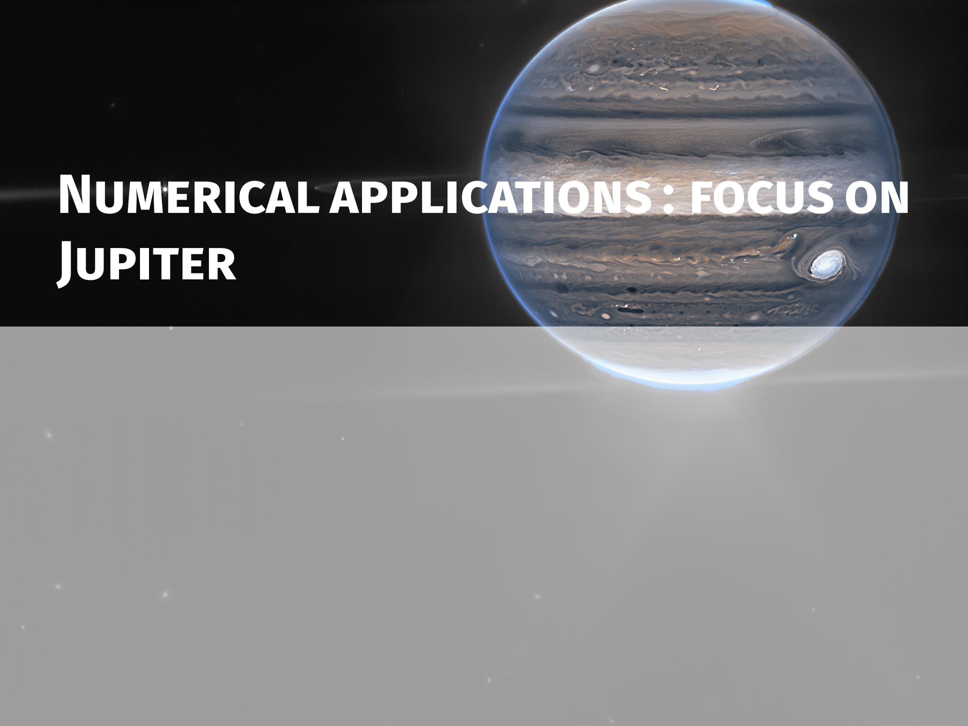
Field-aligned dynamics

$$j_{/\!/ik} = -B_{ik}\frac{\partial}{\partial \alpha}\left(\left(\Omega_n R_P - \frac{\partial \Phi_{ik}}{\partial \alpha}\right)\frac{\Sigma_{Pk}B_{ik}\sin(\theta_{ik})^2}{\sin(I_k)}\right), \text{ k = n or s}$$

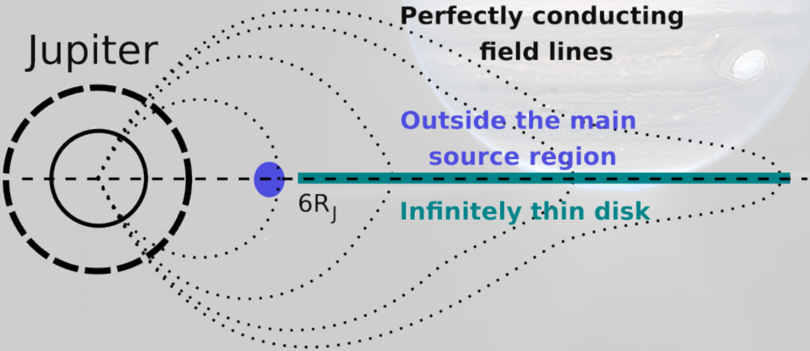
$$j_{/\!/ik} = K(\Phi_{ik} - \Phi_{eq}), \text{ k = n or s}$$

Devinat, Blanc, André (2023), "A self-consistent model of radial transport in the magnetodisks of gas giants including interhemispheric asymmetries", submitted *JGR:Space Physics*

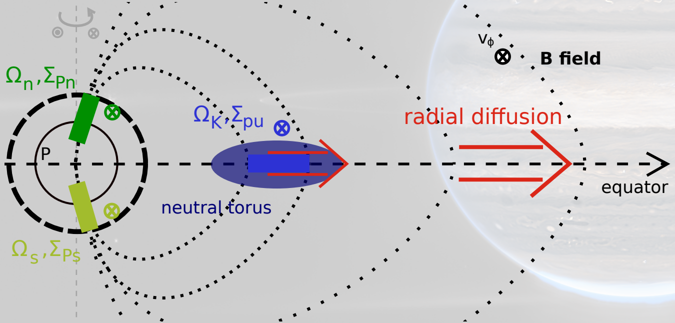
Numerical applications : focus on Jupiter



(Simplified) Jovian case : assumptions



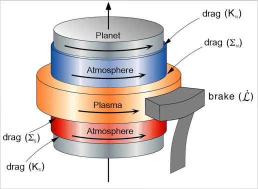
(Simplified) Jovian case : equations



$$\Omega^* = \frac{S_n\Omega_{nn} + S_S\Omega_{ns}}{S_n + S_S} \qquad S_k = \frac{\Sigma_{Pk} R_{ik}^2 B_{ik}}{\sin(I_k)}$$

$$\frac{\dot{M} R_{eq}}{B_{0,eq}} \frac{\partial \Omega}{\partial R_{eq}} + 2\frac{\dot{M}}{B_{0,eq}}\Omega = 2\pi(S_n + S_s)(\Omega^* - \Omega)$$

Hill 1979, Pontius 1997



Brooks et al. 2019

$$\frac{R_{eq}}{B_{0,eq}} \frac{\partial \Omega}{\partial R_{eq}} + 2 \frac{1}{B_{0,eq}} \Omega = 4\pi \frac{S}{\dot{M}} \left(\Omega^* - \Omega \right)$$

(Simplified) Jovian case : equation → numbers

$$\frac{R_{eq}}{B_{o,eq}} \frac{\partial \Omega}{\partial R_{eq}} + 2 \frac{1}{B_{o,eq}} \Omega = 4\pi \frac{S}{\dot{M}} \left(\Omega^* - \Omega\right)$$

(constant) normalisation factor

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(constant) normalisation factor

$S = \frac{S_n+S_s}{2}$ $\leftarrow S_k = \frac{\Sigma_{Pk}R^2_{ik}B_{ik}}{\sin(I_k)} \leftarrow$ ionosphere measurements (Juno)

$\dot{M}$ $\leftarrow$ existing modelling

(Simplified) Jovian case : equation → numbers

$\Omega(R_{eq}) \Leftarrow$ $\quad \frac{R_{eq}}{B_{0,eq}} \frac{\partial \Omega}{\partial R_{eq}} + 2 \frac{1}{B_{0,eq}} \Omega = 4\pi \frac{S}{\dot{M}} (\Omega^* - \Omega)$

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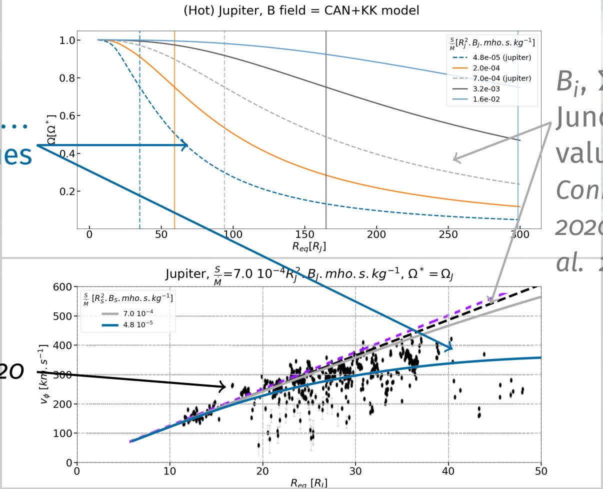
Exploration of the parameter space

B_i, Σ_P, ...
fitted values



B_i, Σ_P, ...
Juno measured values from *Connerney et al. 2020, Al Saati et al. 2022*

Juno data
Kim et al. 2020

On the whole...

Summary

We combined two existing approaches into a **new formalism for the global transport** of mass, angular momentum and energy in the **gas giant magnetospheres**.

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- Application, Jovian case :
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  - parameters space exploration

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- Application, Jovian case :
  - interhemispheric asymmetries
  - parameters space exploration
- Application, Kronian case (check paper!) :
  - influence of the disk thickness
  - radial evolution of parameters

Devinat, Blanc, André (2023), "A self-consistent model of radial transport in the magnetodisks of gas giants including interhemispheric asymmetries", submitted *JGR:Space Physics*

Perspectives

- Further theoretical developments :
  - more consistent interhemispheric asymmetries,
  - other asymmetries (longitude, local time, . . .),
  - energy source (turbulence),
  - sources and losses,
  - temporal variability.

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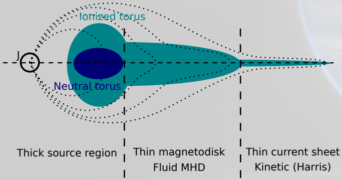
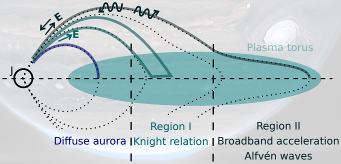
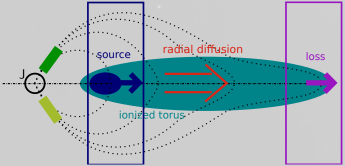
- Possible applications:
  - exploration of Jupiter's innermost and outermost regions,





  - intermittent loading of plasma from Io and tail release,



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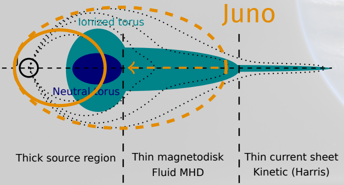

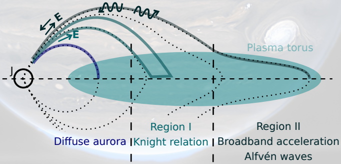

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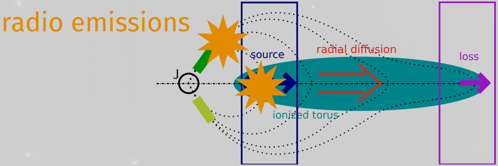

Louarn et al. 2014

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- Possible applications:
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PhD ...

from Juno to JUICE...

Thank you for listening !

N/S ionospheric asymmetries at Jupiter

Ionospheric properties from *Connerney et al. 2021* (magnetic field along the Io footprint), and *Al Saati et al. 2022* (Pedersen conductance).

	North				South			
	Σ_{pn} $[mho]$	B_{in} $[G]$	λ_{in} $[^\circ]$	S_n $[R_J^2.B_J.mho]$	Σ_{ps} $[mho]$	B_{is} $[G]$	λ_{is} $[^\circ]$	S_s $[R_J^2.B_J.mho]$
Mean	2	12	70	0.7	3	10	-70	0.8
E1	0.8	5	80	0.03	1	8	-60	0.5
E2	11	20	55	18	12	12	-75	3

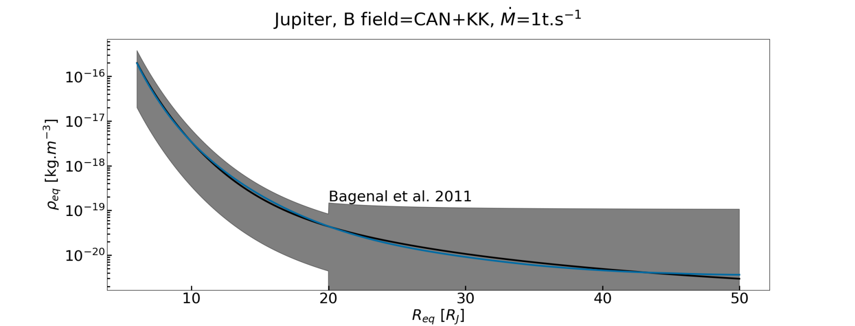
$$S = \frac{S_n+S_s}{2} = 0.3(E1), 0.7(Mean), 10(E2)$$
$$R_J^2.B_J.mho = 2.05 \times 10^{12} m^2.T.mho$$

<u>Note :</u> from comparison with data, $\frac{S}{\dot{M}} \approx 4.8\ 10^{-5}\ R_J^2.B_J.mho.s.kg^{-1}$
$\Rightarrow S \approx 0.05 - 0.07 R_J^2.B_J.mho$ ($\dot{M} = 1 - 1.5 t.s^{-1}$)

(Simplified) Jovian case : density curve

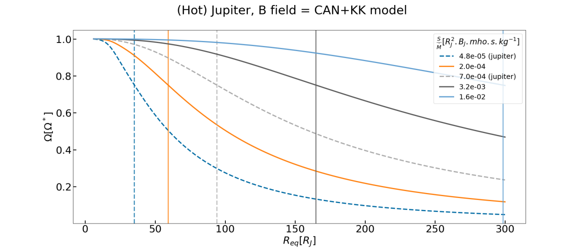
$$D_\alpha B_{0,eq} \frac{\partial M_0}{\partial \alpha} = \frac{\dot{M}}{2\pi R_P B_{0,eq}(\alpha_0)}, \qquad D_\alpha = D_{\alpha 0} \left(\frac{R_{eq}}{R_P}\right)^\beta$$

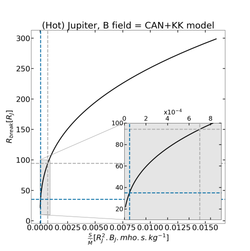
$$\rho_{0,eq}(R_{eq}) = \rho_{0,eq}(R_{eq0}) - \frac{\dot{M} B_{0,eq} R_P^{\beta-2}}{2\pi(2-\beta) H B_{0,eq}(R_{eq0}) D_{\alpha,0}} (R_{eq}^{2-\beta} - R_{eq0}^{2-\beta})$$



$\beta = 5.6$

(Simplified) Jovian case : Jovian-like systems





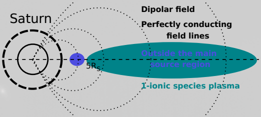
Parameters ranges :

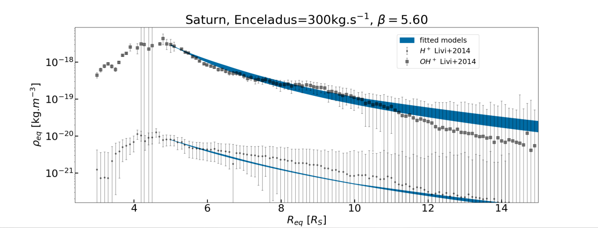
$S = \frac{S_n+S_s}{2} = 0.3$ to $10\ R_J^2.B_J.mho$

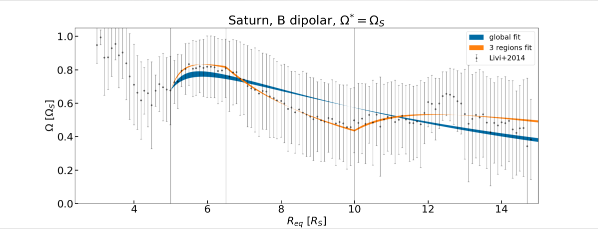
$\dot{M} = 0.6$ to $1.5\ t.s^{-1}$

(Simplified) Kronian case : numerical results

Vertically thick disk : influence on density and rotation curves



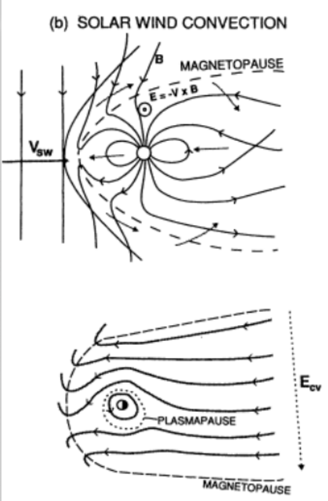




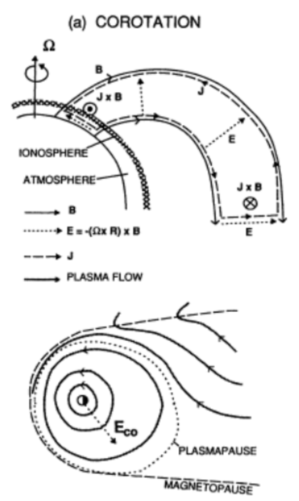
$\Rightarrow \frac{S}{\dot{M}}$ likely varies with distance to the planet.

Earth and Jupiter magnetospheres

Earth
Dungey cycle



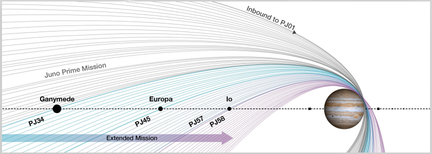
Jupiter
Vasyliunas cycle



Bagenal et al. 1992

Juno and JUICE

Juno
Polar orbit

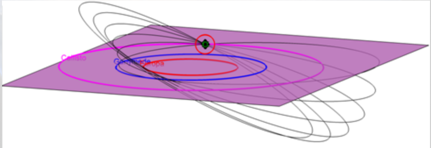


NASA/JPL-Caltech

Payload

- JADE (IRAP)
- JEDI
- FGM
- Waves
- UVS, JIRAM

JUICE
Equatorial orbit



ESA/SRE(2011)18 Yellow Book

Payload

- PEP (IRAP)
- RPWI (IRAP)
- J-MAG
- UVS, MAJIS

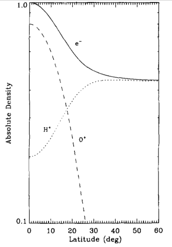
Field-aligned plasma distribution

Aim: Measure the plasma distribution along field lines

Steps:

- Determine when Juno follows a B shell
- Examine the JADE i-e data
- Trace moments along trajectory
- Compare to models

Maurice 1997



Results: