Jovian Magnetic Field Models

Jack Connerney
@NASA GSFC
Code 695

March 9, 2016

MAG Field Models Outline

- Internal fields representation
- Jovian magnetosphere
- Jovian *magnetodisc* models
- Magnetic field observations from flybys
  - The non-uniqueness problem, sparse data, complex model
  - The non-potential problem, local currents, correlated errors
  - Co-estimation of internal field parameters and external field model parameters
- Observations of the Io Flux Tube (IFT) footprint (VIP4, VIT4)
  - Really “special sauce” – a fiducial marker of field line geometry to constrain the model right down on the surface of the planet
- More “special sauce” (e.g., VIPAL = VIP4 + eigenvector excursion):
  - Constraints on mapping of IFT from orbit to surface of Jupiter
  - Local electron gyrofrequency at the IFT footprint to match radio data
  - Be cognizant of the models and assumptions behind the constraints

MAG Field Models

In the absence of local currents ($\nabla \times \mathbf{B} = 0$)**,** the magnetic field may be expressed as the gradient of a scalar potential V, ($\mathbf{B} = -\nabla V$); V may have an *external* and *internal* part, often rendered via a series expansion in spherical harmonic functions:

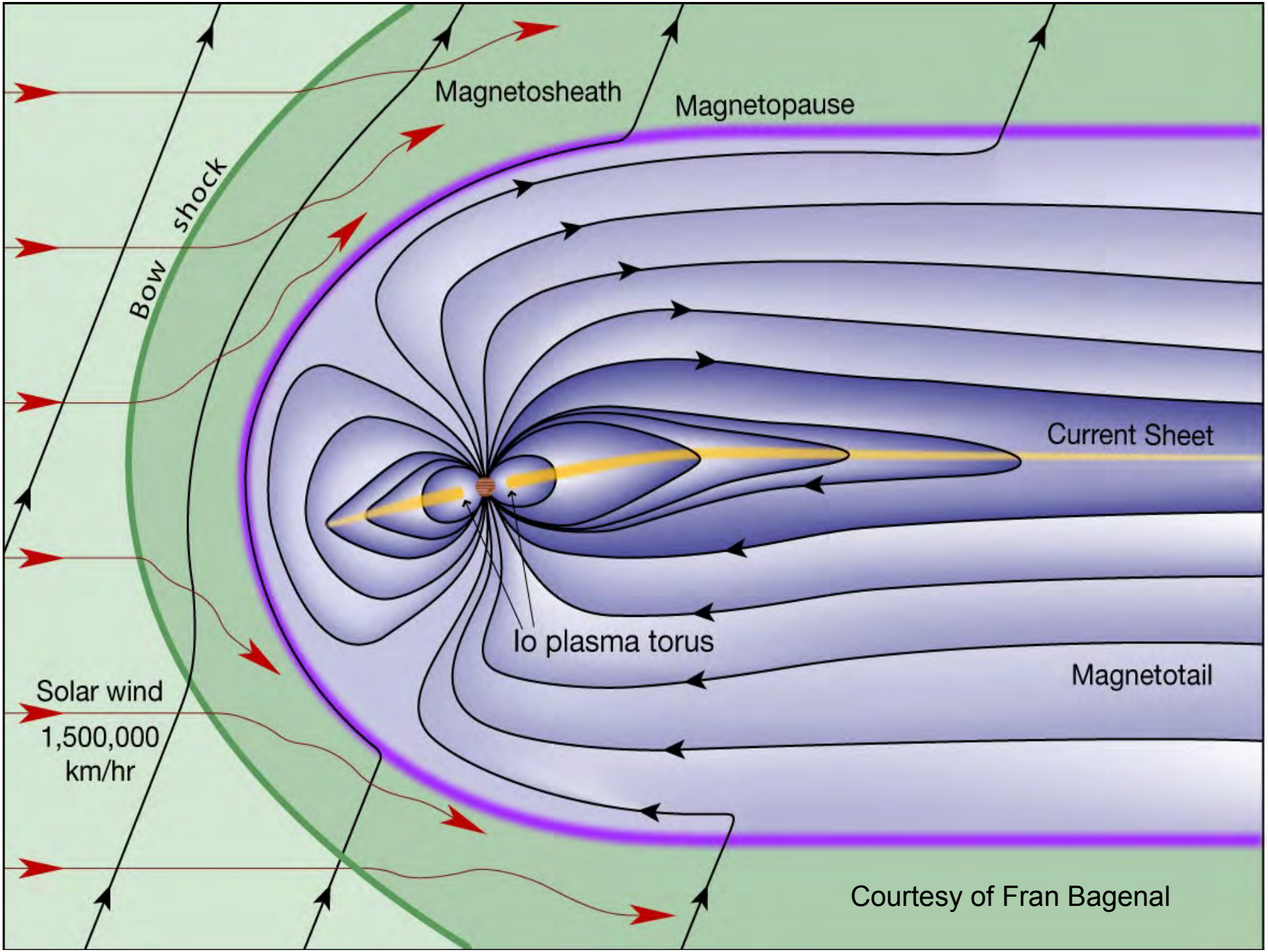
$$V = a\sum_{n=1}^{\infty}\left\{\left(\frac{r}{a}\right)^{n} T_n^e + \left(\frac{a}{r}\right)^{n+1} T_n^i\right\} \quad \text{with} \quad T_n^i = \sum_{m=0}^{n}\left\{P_n^m(\cos\theta)\left[g_n^m\cos(m\phi) + h_n^m\sin(m\phi)\right]\right\}$$

The *external* field is best handled with explicit models (*magnetodisc* models) to be discussed later; the internal field (only) is computed as follows:

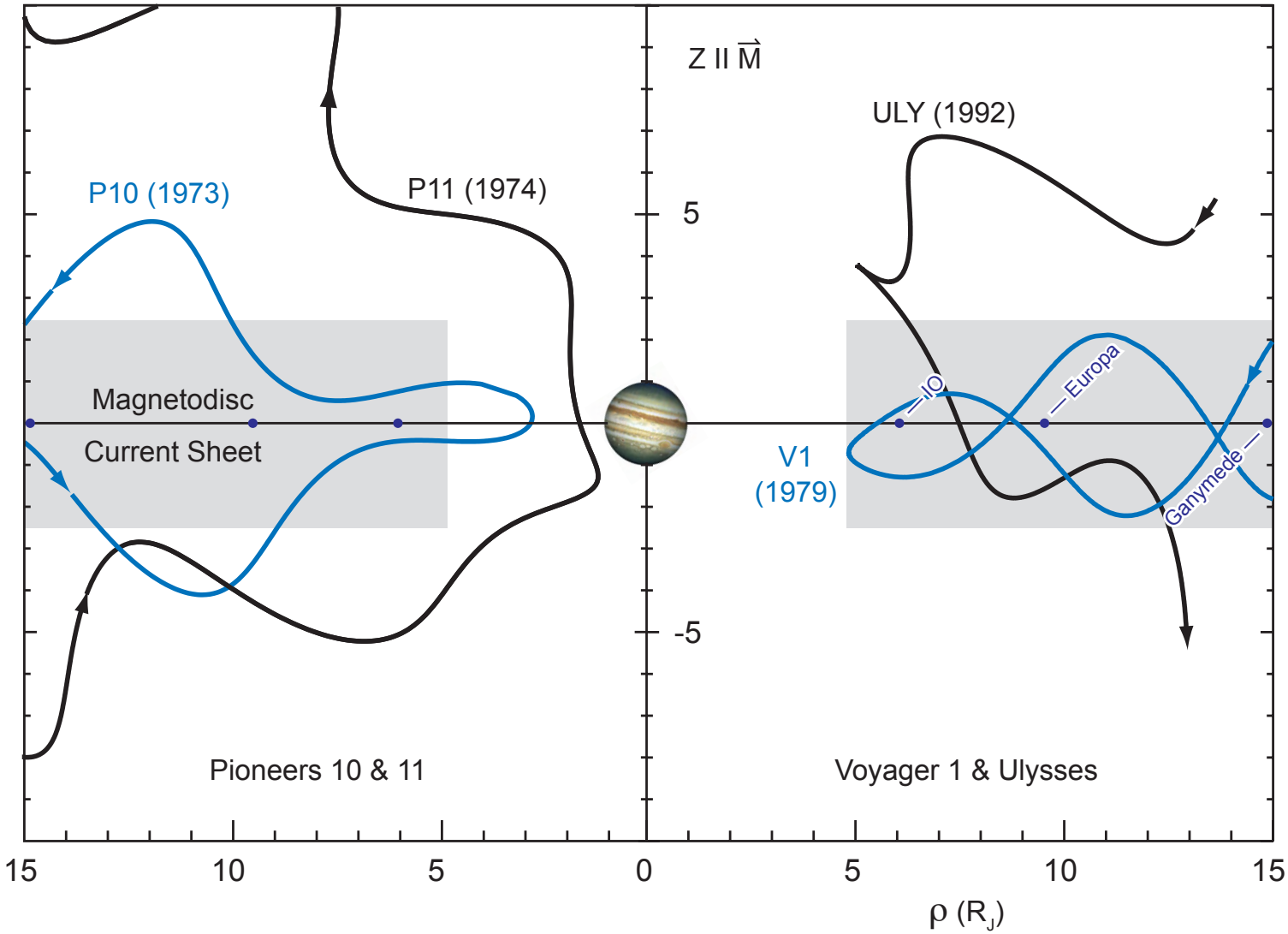
$$B_r = -\frac{\partial V}{\partial r} = \sum_{n=1}^{\infty}\sum_{m=0}^{n}\left\{(n+1)\left(\frac{a}{r}\right)^{n+2}\left[g_n^m\cos(m\phi) + h_n^m\sin(m\phi)\right]P_n^m(\cos\theta)\right\}$$

$$B_\theta = -\frac{\partial V}{r\partial\theta} = -\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left\{\left(\frac{a}{r}\right)^{n+2}\left[g_n^m\cos(m\phi) + h_n^m\sin(m\phi)\right]\frac{dP_n^m(\cos\theta)}{d\theta}\right\}$$

$$B_\phi = -\frac{-1}{r\sin\theta}\frac{\partial V}{\partial\phi} = \frac{1}{\sin\theta}\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left\{m\left(\frac{a}{r}\right)^{n+2}\left[g_n^m\sin(m\phi) - h_n^m\cos(m\phi)\right]P_n^m(\cos\theta)\right\}$$


Magnetosheath
Magnetopause
Bow shock
Current Sheet
Io plasma torus
Magnetotail
Solar wind
1,500,000
km/hr
Courtesy of Fran Bagenal

Jovian Flybys



Magnetodisc Model

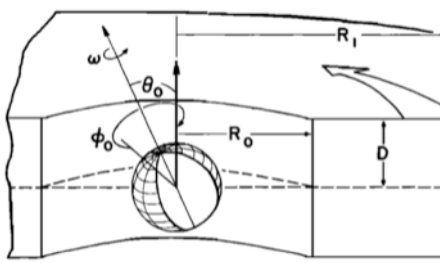
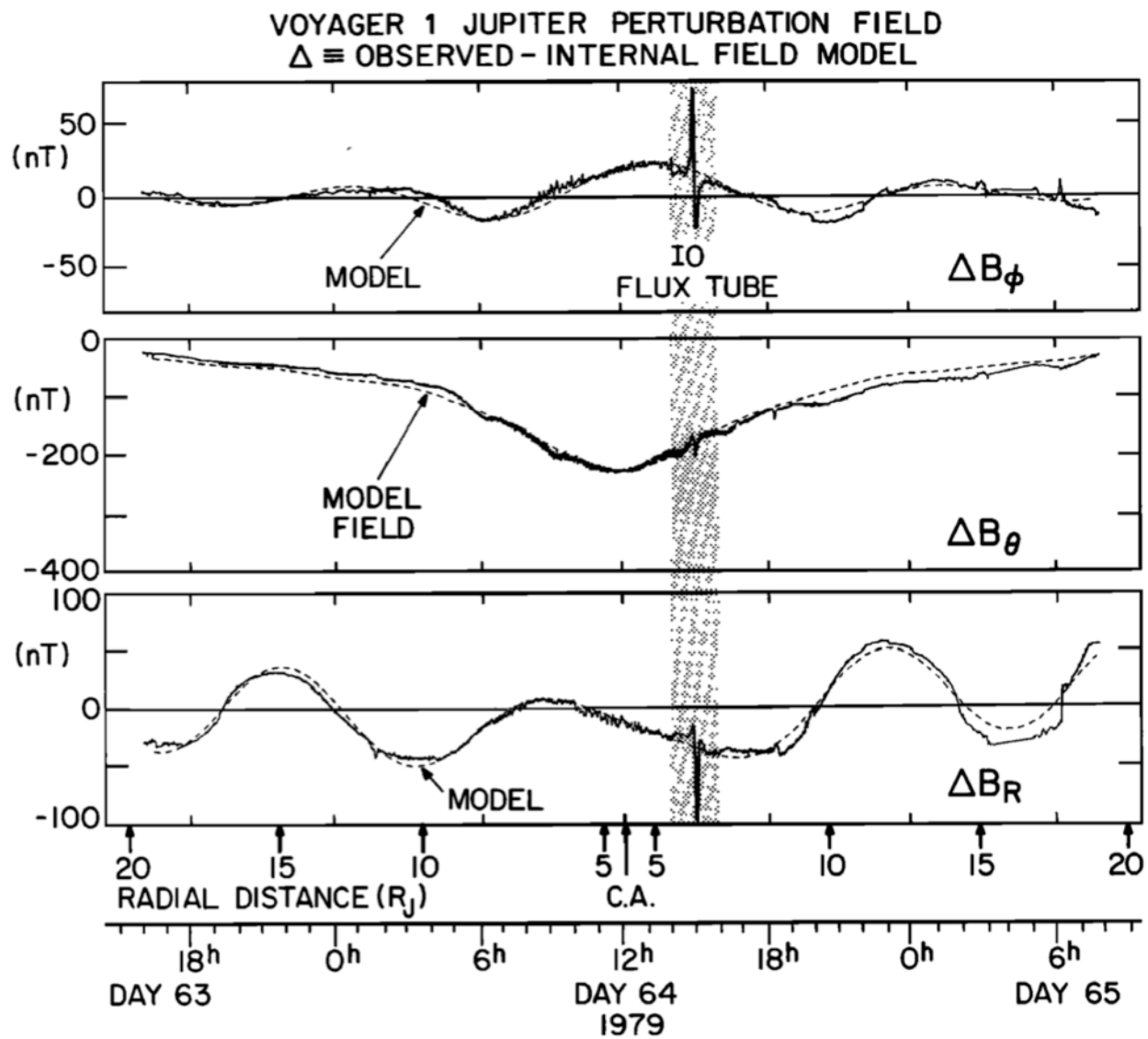


Fig. 1. A cross-section of the model current disc.



Co-estimation of internal and external field model parameters is essential – they covary.

Connerney et al., 1982

Jovian Magnetodisc

CONNERNEY ET AL.: JOVIAN CURRENT SHEET AND MAGNETOSPHERE (1981) 8379

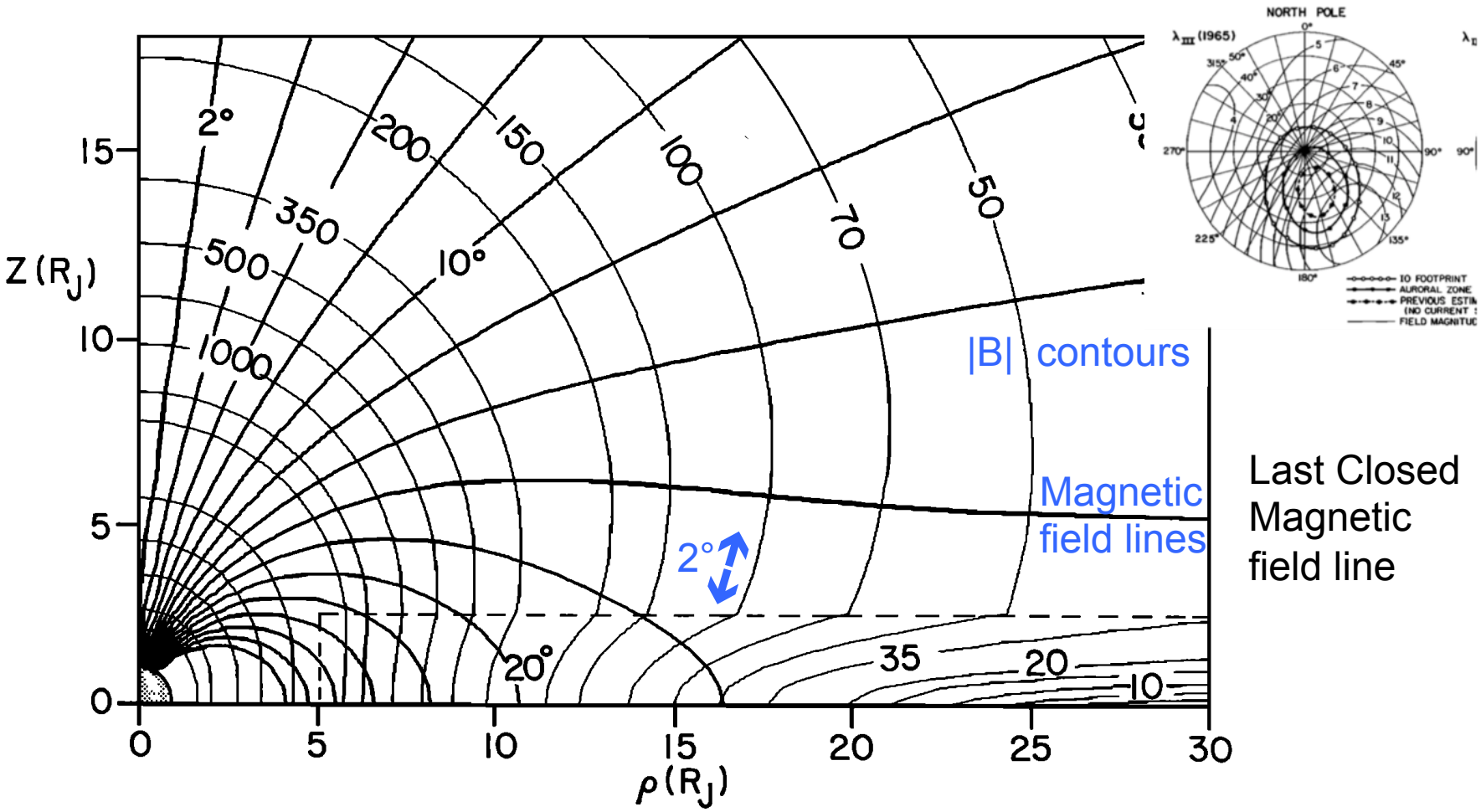


Fig. 9. Meridian plane projection of magnetosphere field lines (heavy) and isointensity contours (light) for Voyager 1 (and Pioneer 10) model. Values on field lines indicate colatitude of field line; field magnitude contours are expressed in gammas.

Jovian Field Models

Epoch		Voyager 1, and IFT	Voyager 1, IFT, Pioneer	1992.1: Ulysses	1979.2: Voyager 1	1974.9: Pioneer 11		
Coefficient Number	Coefficient	VIT 4	VIP 4	Ulysses 17ev	V1-17ev	O_6	O_4	SHA
1	g_1^0	428077.	420543.	410879.	420825.	424202.	421800.	409200.
2	g_1^1	-75306.	-65920.	-67885.	-65980.	-65929.	-66400.	-70500.
3	h_1^1	24616.	24992.	22881.	26122.	24116	26400.	23100.
4	g_2^0	-4283.	-5118.	7086.	-3411.	-2181.	-20300.	-3300.
5	g_2^1	-59426.	-61904.	-64371.	-75856.	-71106.	-73500.	-69900.
6	g_2^2	44386.	49690.	46437.	48321.	48714.	51300.	53700.
7	h_2^1	-50154.	-36052.	-30924.	-29424.	-40304.	-46900.	-53100.
8	h_2^2	38452.	5250.	13288.	10704.	7179.	8800.	7400.
9	g_3^0	8906.	-1576.	-5104.	2153.	7565.	-23300.	-11300.
10	g_3^1	-21447.	-52036.	-15682.	-3295.	-15493.	-7600.	-58500.
11	g_3^2	21130.	24386.	25148.	26315.	19775.	16800.	28300.
12	g_3^3	-1190.	-17597.	-4253.	-6905.	-17958.	-23100.	6700.
13	h_3^1	-17187.	-8804.	-15040.	8883.	-38824.	-58000.	-42300.
14	h_3^2	40667.	40829.	45743.	69538.	34243.	48700.	12000.
15	h_3^3	-35263.	-31586.	-21705.	-24718.	-22439.	-29400.	-17100
16	g_4^0	-22925.	-16758.					
17	g_4^1	18940.	22210.					
18	g_4^2	-3851.	-6074.					
19	g_4^3	9926.	-20243.					
20	g_4^4	1271.	6643.					
21	h_4^1	16088.	7557.					
22	h_4^2	11807.	40411.					
23	h_4^3	6195.	-16597.					
24	h_4^4	12641.	3866.					
Magnetodisc								
	R_0	5.	5.	7.1	5. (UR)			
	R_1	56.	56.	128. (UR)	56.			
	D	3.1	3.1	3.3	3.1			
	$\mu_0 I_0/2$	185.	185.	137.	185.			
	Θ_0	6.5	6.5	8.2	6.5			
	Φ_0	206.	206.	200.	206.			

Schmidt normalized spherical harmonic coefficient in nT, referenced to Jupiter system III (1965) coordinates, and 1 Rj = 71,398 km for Ulysses; 1 Rj = 71,323 km for Voyager 1. Voyager 1 17ev model from *Connerney et al.* [1982]. Models VIP4 and VIT4 used the magnetodisc model fitted to Voyager 1 observations (V1-17ev) as fixed parameters.

The notation "UR" refers to unresolved parameters. Pioneer 11 O4 model coefficients as tabulated for system III (1965) by *Acuña et al.* [1983] (originally (1957 system III) from *Acuña and Ness* [1976]).

Pioneer 11 SHA model originally (1957 System III) from *Smith et al.*, [1976].

Jovian Field Models

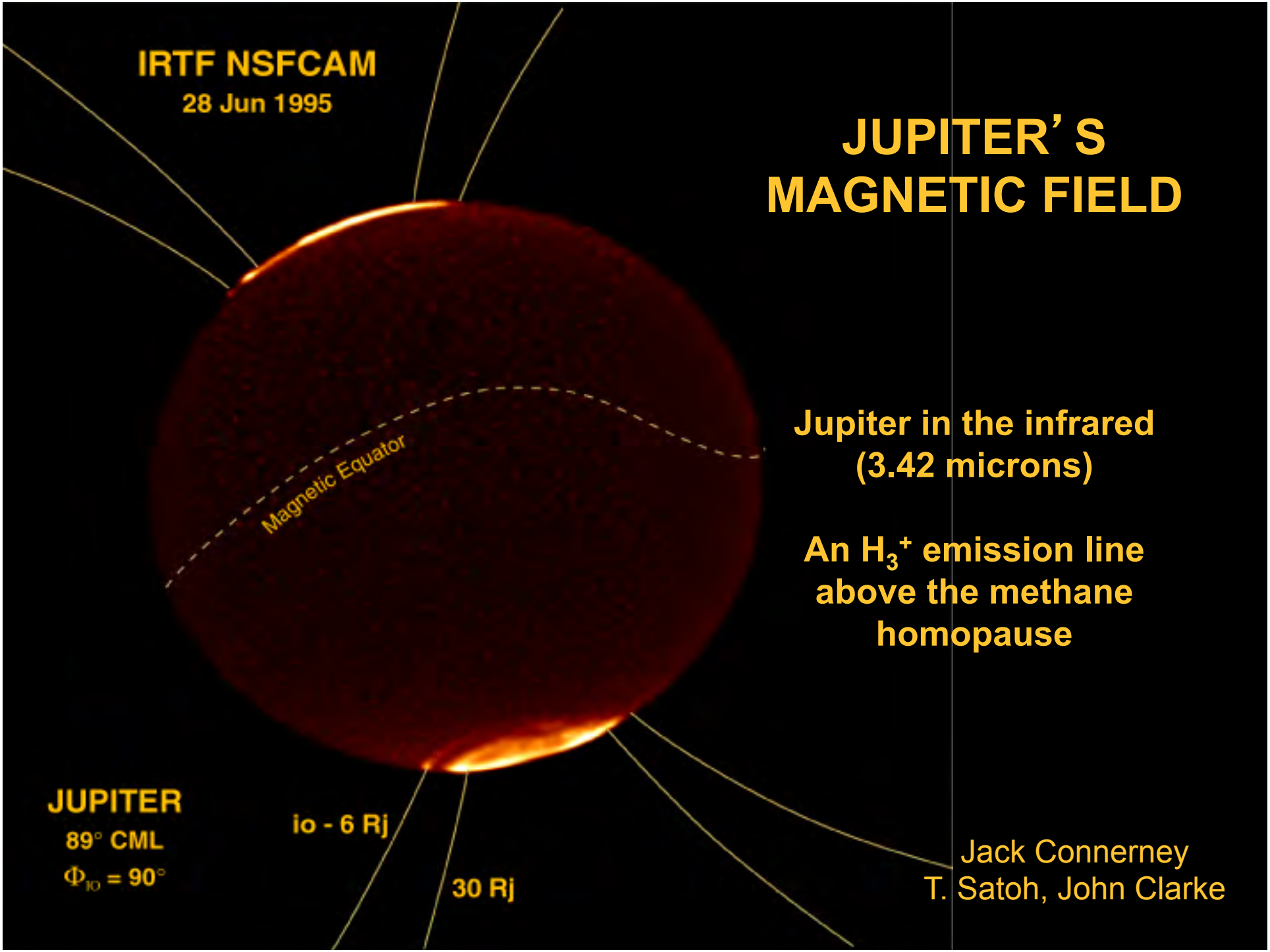
PARAM.	COEFF.	VIT4_16ev	VIP4	O6	V1 17ev
1	g_1^0	428077.	420543.	424202.	420825.
2	g_1^1	-75306.	-65920.	-65929.	-65980.
3	h_1^1	24616.	24992.	24116.	26122.
4	g_2^0	-4283. (.83)	-5118.	-2181.	-3411.
5	g_2^1	-59426.	-61904.	-71106.	-75856.
6	g_2^2	44386. (.85)	49690.	48714.	48321.
7	h_2^1	-50154.	-36052.	-40304.	-29424.
8	h_2^2	38452. (.85)	5250.	7179.	10704.
9	g_3^0	8906. (.79)	-1576.	7565.	2153. (UR)
10	g_3^1	-21447. (UR)	-52036.	-15493.	-3295. (UR)
11	g_3^2	21130.	24386.	19775.	26315.
12	g_3^3	-1190.	-17597.	-17958.	-6905.
13	h_3^1	-17187. (UR)	-8804.	-38824.	8883. (UR)
14	h_3^2	40667.	40829.	34243.	69538.
15	h_3^3	-35263. (.88)	-31586.	-22439.	-24718.
16	g_4^0	-22925. (UR)	-16758. (.83)		
17	g_4^1	18940. (UR)	22210. (.47)		
18	g_4^2	-3851. (UR)	-6074. (.96)		
19	g_4^3	9926. (.75)	-20243. (.83)		
20	g_4^4	1271. (UR)	6643. (UR)		
21	h_4^1	16088. (UR)	7557. (UR)		
22	h_4^2	11807. (UR)	40411. (.94)		
23	h_4^3	6195. (.65)	-16597. (.91)		
24	h_4^4	12641. (UR)	3866. (UR)		

Jovian Field Models

- Connerney, J. E. P., Acuña, M. H., Ness, N. F., and Satoh, T. (1998). New models of Jupiter's magnetic field constrained by the Io flux tube footprint. *Journal of Geophysical Research-Space Physics* **103**(A6): 11929-11939.
  - **VIP4** model, to 4th degree and order, but not all coefficients resolved.
  - *In-situ* MAG observations and IFT footprint observations.
- Connerney, J. E. P., "Planetary Magnetism", Volume 10: Planets and Satellites, in *Treatise in Geophysics*, eds. G. Schubert, T. Spohn, Elsevier, Oxford, UK, 2007.
  - **VIT4** model, to 4th degree and order, IFT observations w/ B from $V1_{theta}$
- Grodent, D., Bonfond, B., Gerard, J.-C., *et al*. (2008). Auroral evidence of a localized magnetic anomaly in Jupiter's northern hemisphere. *Journal of Geophysical Research* **113:** A09201 (doi:10.1029/2008JA013185).
  - Conceptual magnetic anomaly, not a proposed field model
- Hess, S. L. G., Bonfond, B., Zarka, P., and Grodent, T. (2011). Model of the Jovian magnetic field topology constrained by the Io auroral emissions. *Journal of Geophysical Research* **116:** A05217 (doi:10.1029/2010JA016262).
  - **VIPAL**, adds to VIP4, constraint on mapping IFT footprint to surface longitude
  - Adds constraint on |B| at IFT foot to model Jovian radio emissions
  - Not possible to fit *in-situ* MAG data as well as one would like

Jovian Field Models

- <u>Io Flux Tube Footprint is a superb constraint</u>
  - Tells us how the field geometry behaves right down to the surface, where no direct observations of B exist.
  - Io provides the constraint over 360 degrees longitude and in both hemispheres.
  - And, Io's in a Goldilocks orbit: maps to polar regions, but maintains sufficient |B| at equator (~2000 nT) to be uninfluenced by external fields.
  - Co-estimation of internal field parameters and external field model parameters is essential – they are inseparable along flyby trajectories.
- Ganymede, in contrast, lies too far away to be very useful as an internal field constraint (~70 nT |B| at equator).
  - Useful as a monitor of the magnetodisc currents: constrains the integrated azimuthal current.
  - Use the Io – Europa – Ganymede footprints separation as a very precise monitor of magnetodisc current variation with time (though direct observations indicate fairly stable configuration).



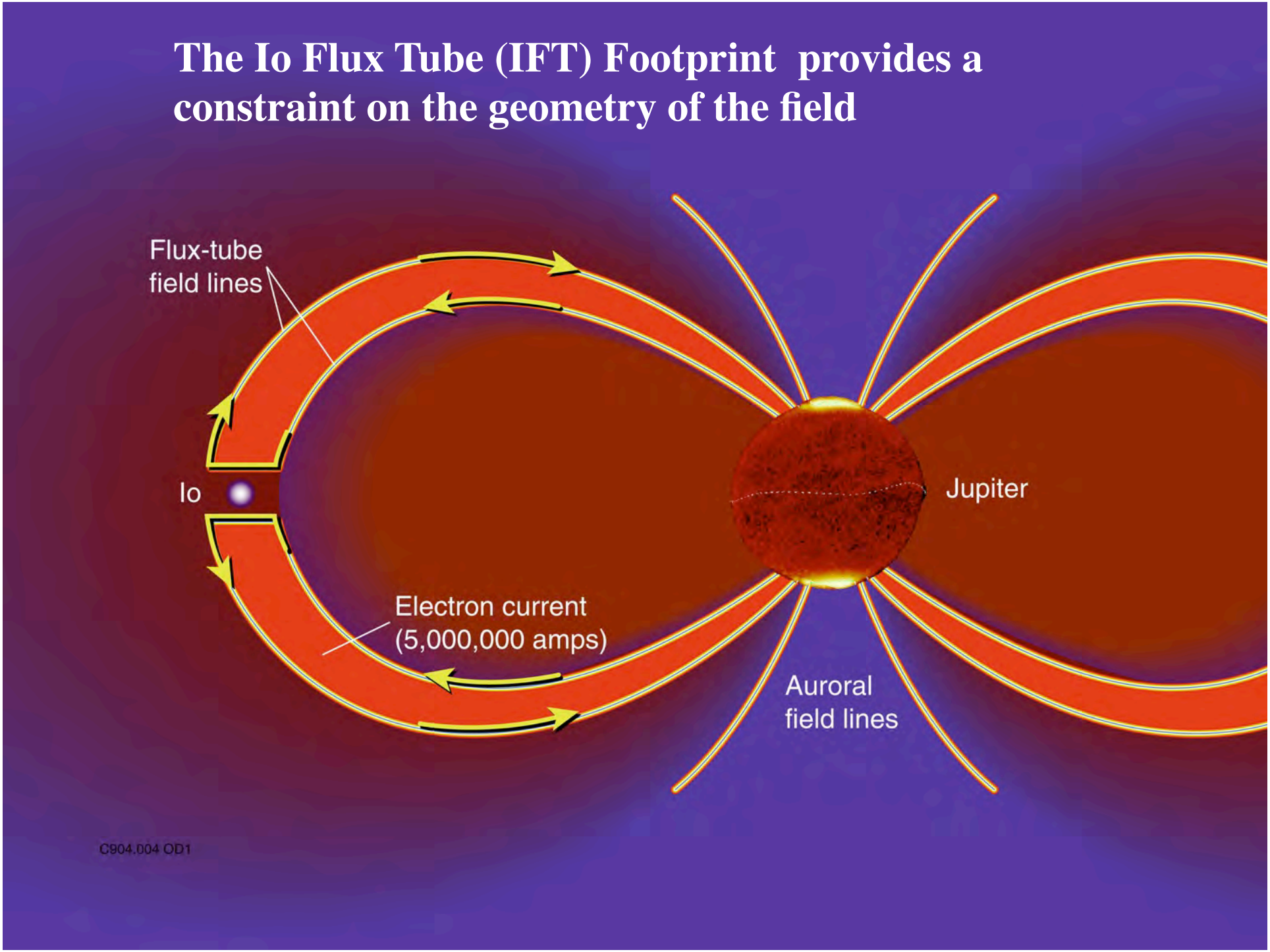
JUPITER'S MAGNETIC FIELD

Jupiter in the infrared (3.42 microns)

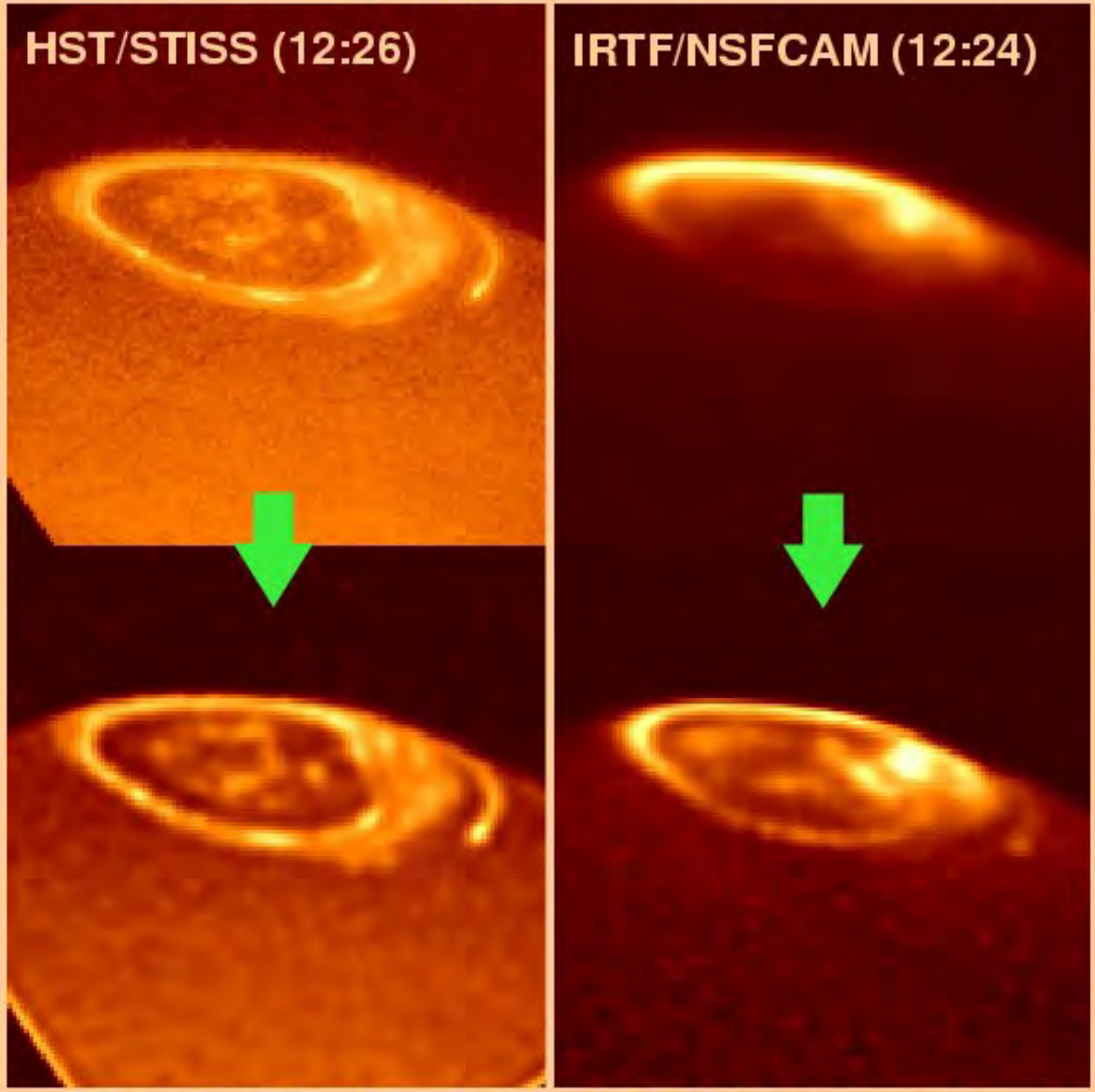
An H_3^+ emission line above the methane homopause

Jack Connerney
T. Satoh, John Clarke

The Io Flux Tube (IFT) Footprint provides a constraint on the geometry of the field



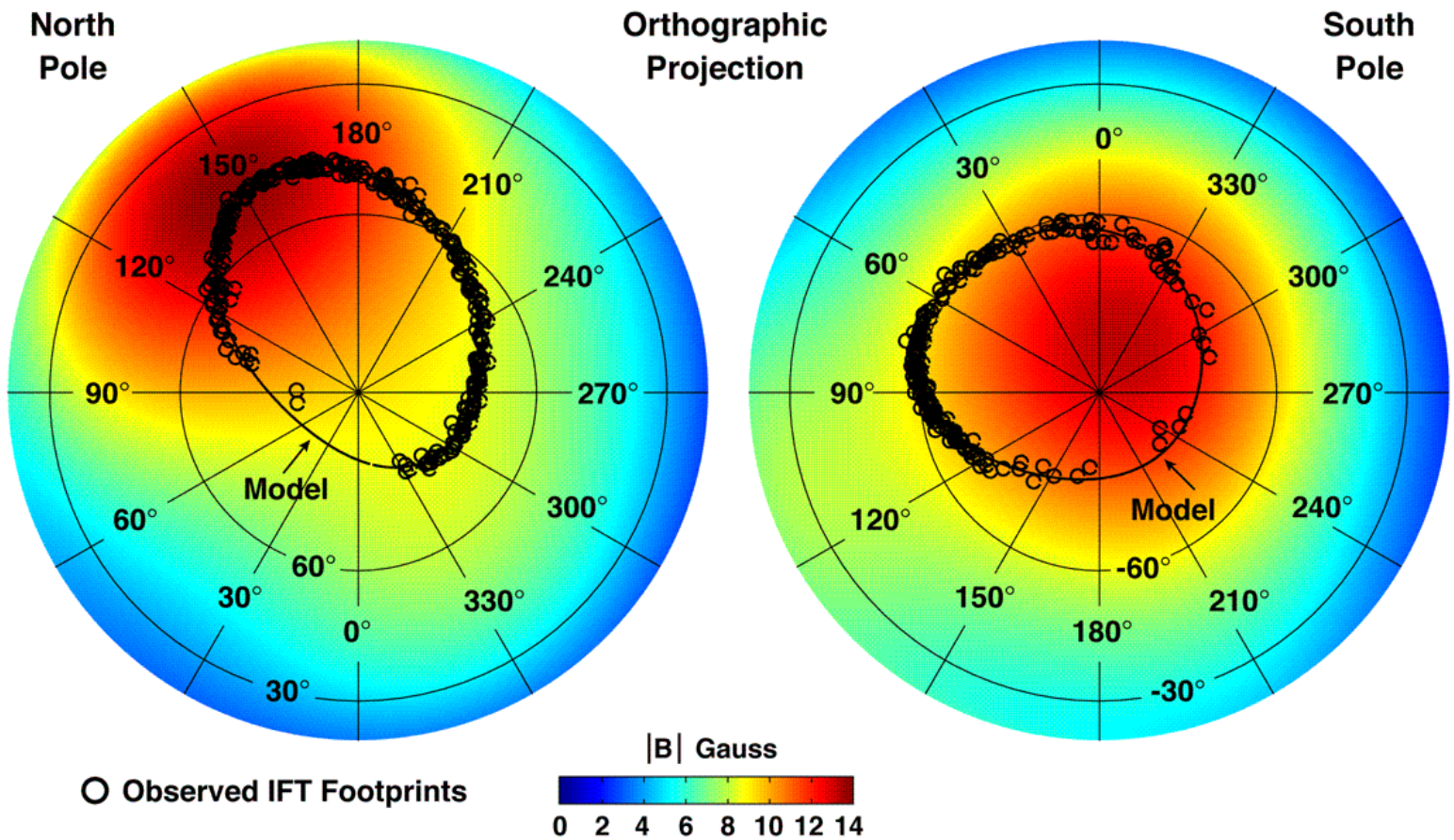
Comparison Between UV and IR Aurorae



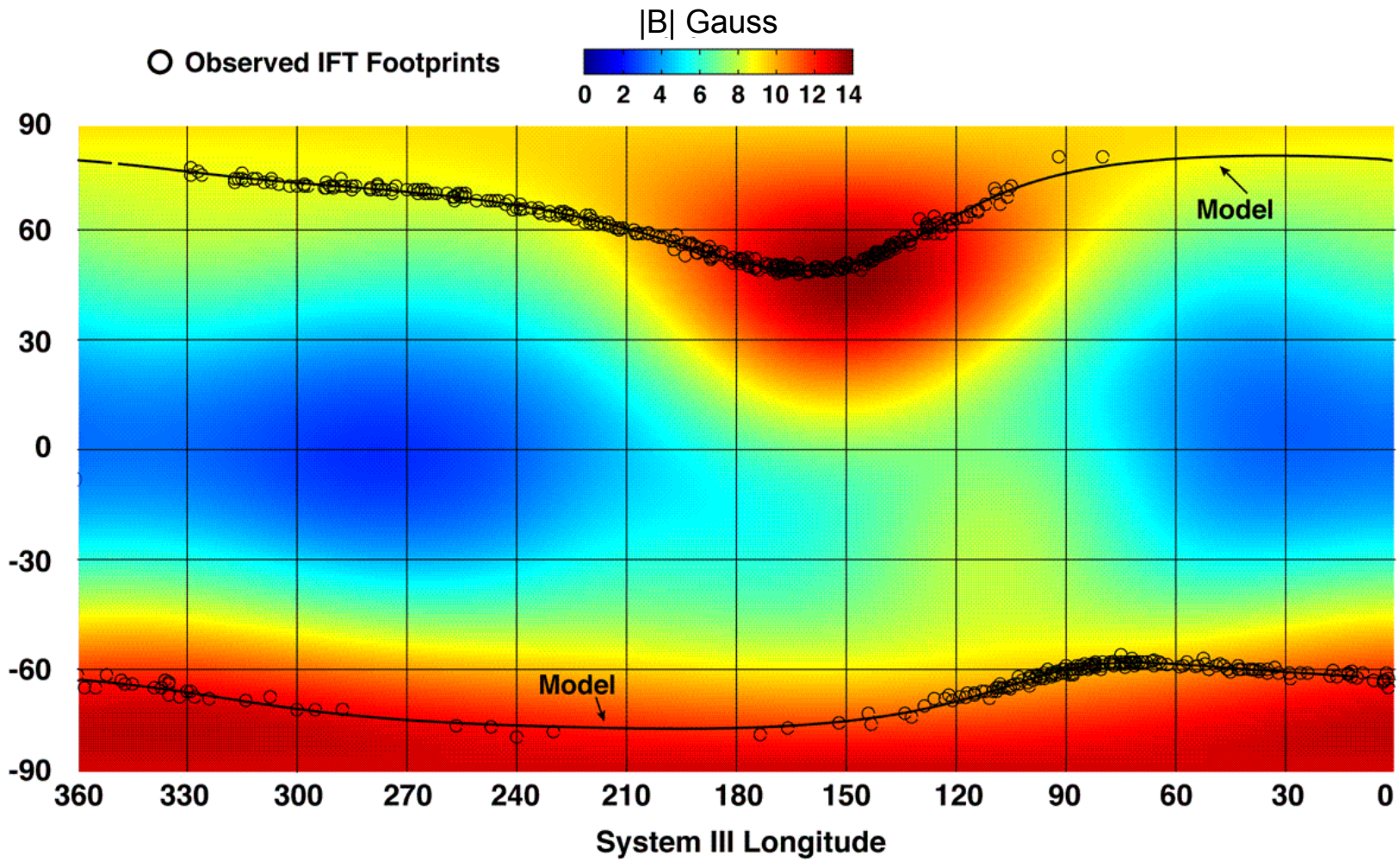
December 16, 2000 (UT) Observations

Jovian Magnetic Field Models

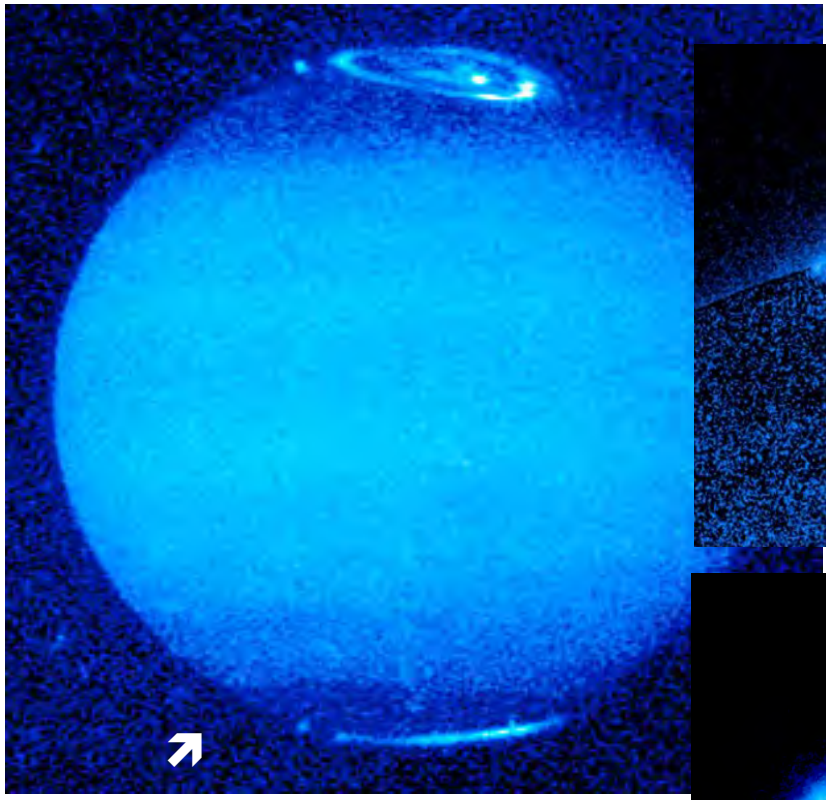
IFT Footprints and Model

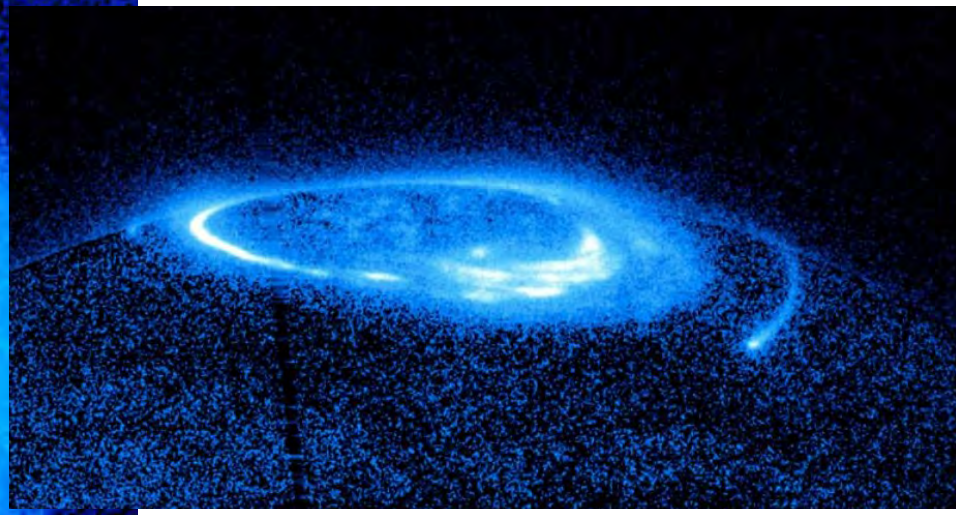


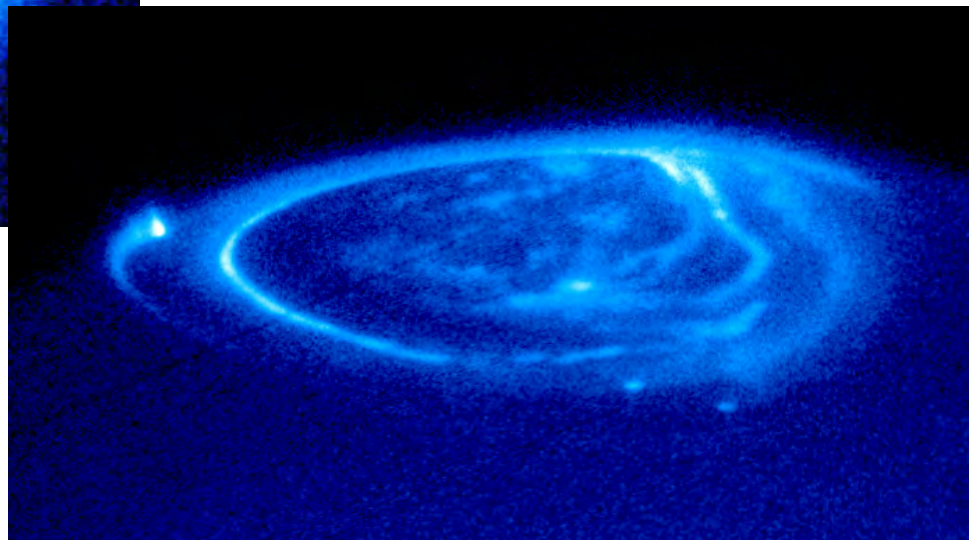
Jovian Magnetic Field Models



Jovian UV Aurora



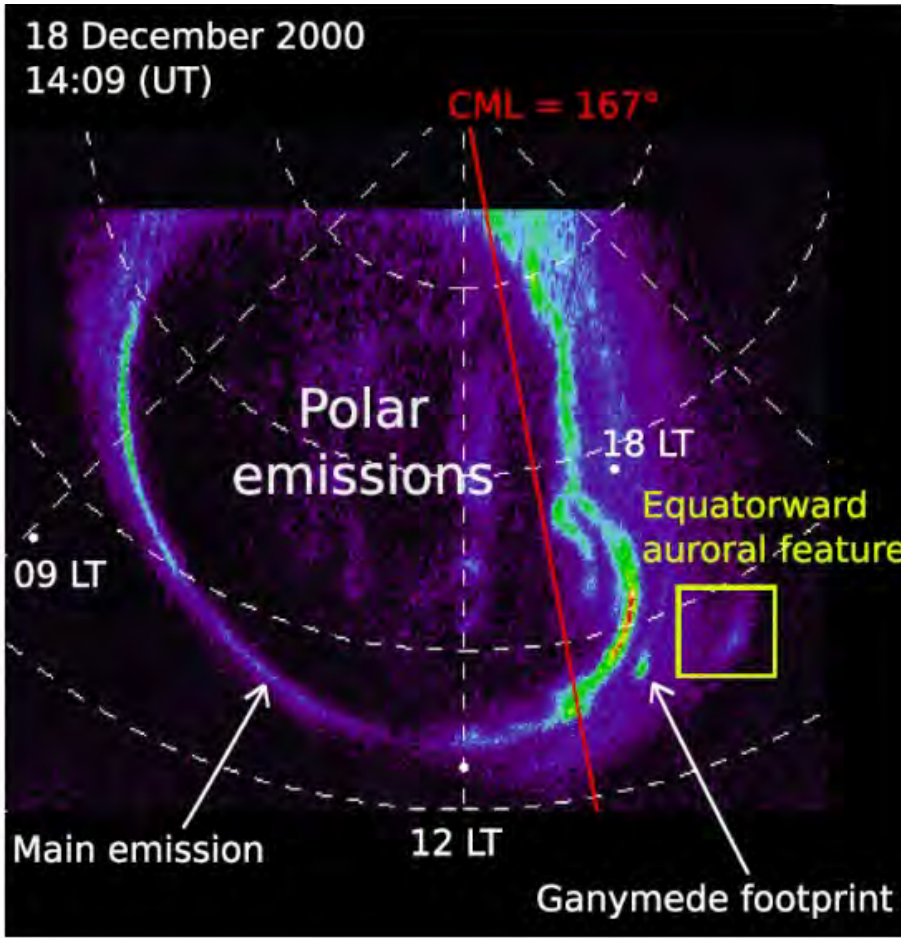


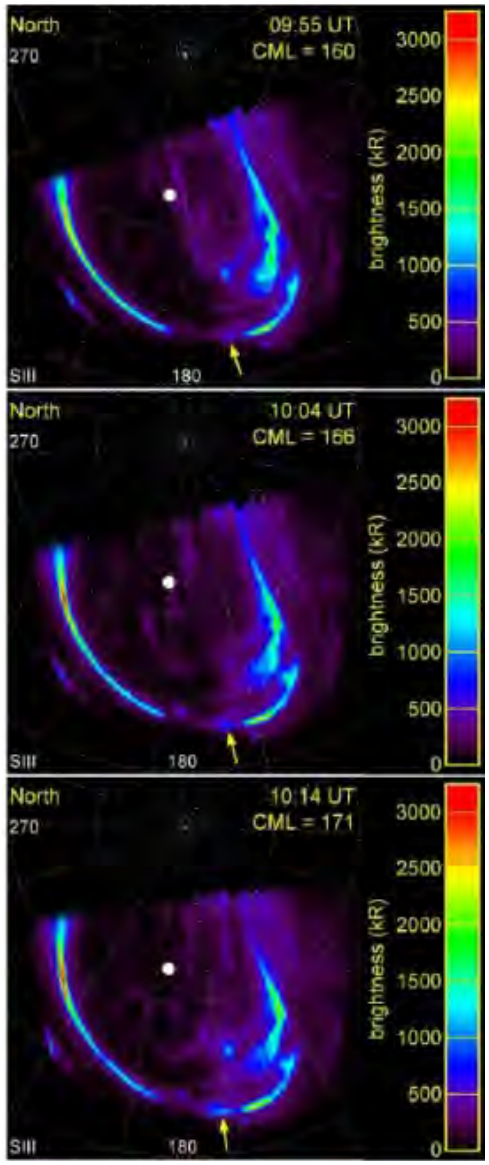


The big picture

Not easily interpreted; obvious multiple L-shells illuminated; observation bias; local time? Kink and no kink?

Jovian UV Aurora





UV Aurora on dusk flank does not illuminate a constant L shell – dawn-dusk dissonance.

MAG Models Summary

- The Juno Project has adopted the VIP4 magnetic field model as part of the Project Jupiter environments definition.
  - This is an engineering consideration only, i.e., the spacecraft and its subsystems are designed to operate in this environment.
  - There is no Project requirement regarding use of specific field model for science analysis.
- For generation of science sequence and planning products, it would be useful if instrument teams would include projections based on the VIP4 model (along with any others considered).
  - Allows teams to compare results directly with at least one common reference model.
- Juno MAG will provide interim spherical harmonic magnetic field models during science phase for use by the community.
- Expect an update as global longitude coverage improves, e.g.,
  - After orbit 7 (90 degree delta phi)
  - After orbit 11 (45 degree); and after orbit 19 (22 ½ degree)

IFT Footprints and Model