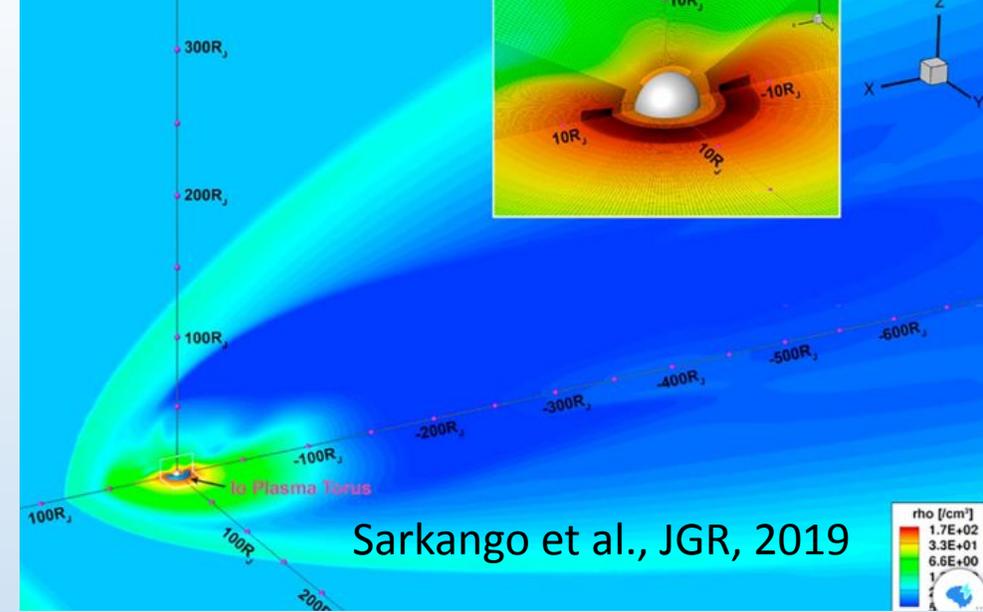


Galileo's Perspective on the Jovian Magnetosphere



Margaret G Kivelson

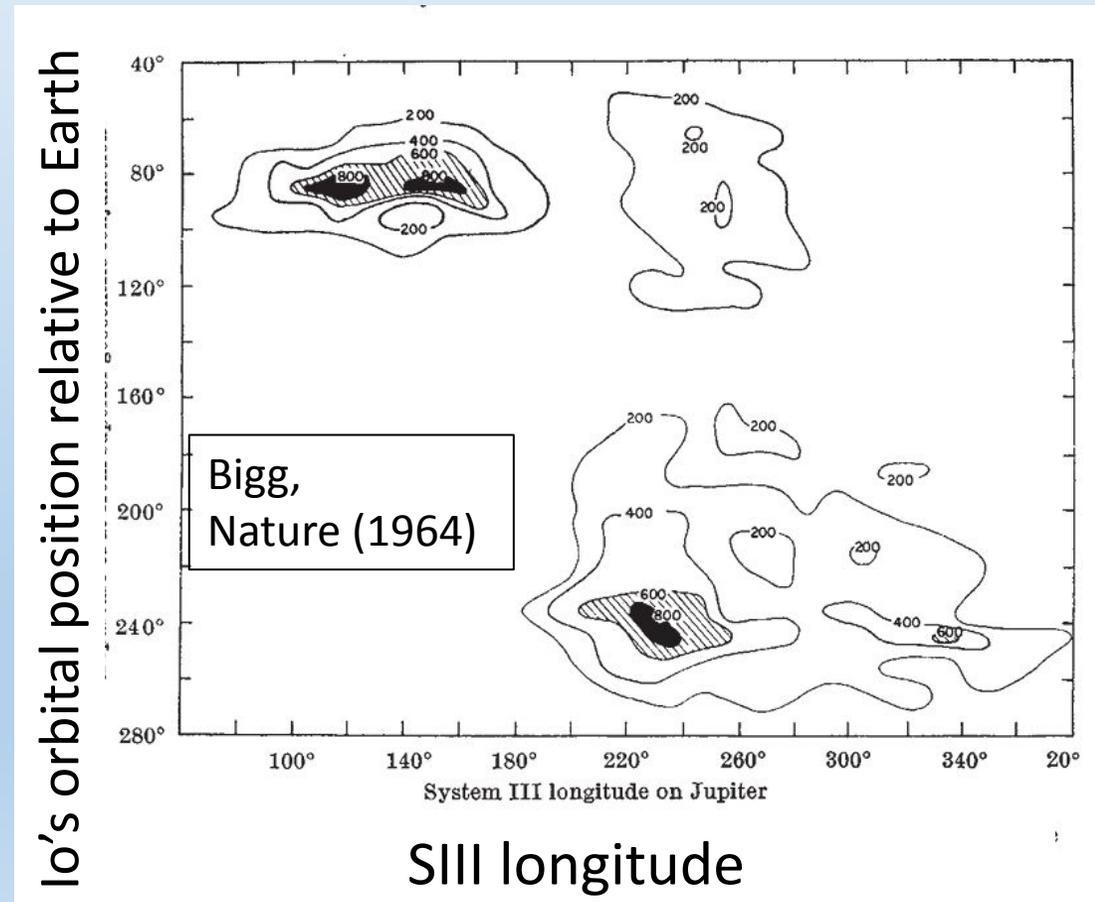
“Galileo at 30” held on Dec. 8, 2025

30th anniversary of Galileo's JOI + 1 day

Chen 100 Auditorium, Caltech

Pre-spacecraft: ground-based observations stimulated interest in magnetospheric dynamics

- The (upper) cutoff frequency of decametric radiation (~ 30 MHz – interpreted as electron gyrofrequency in the ionosphere) provided a good estimate of the planetary **dipole field intensity (>10 G)**.
- **The critical role of Io**, whose orbital position controlled intensity of decametric radiation, had been recognized (Intensity varied with Io/Jupiter/Earth angle or \sim Io's orbital position).
- **Rocking of the plane of polarization of decimetric radiation (dePater) revealed the tilt of Jupiter's dipole field.**

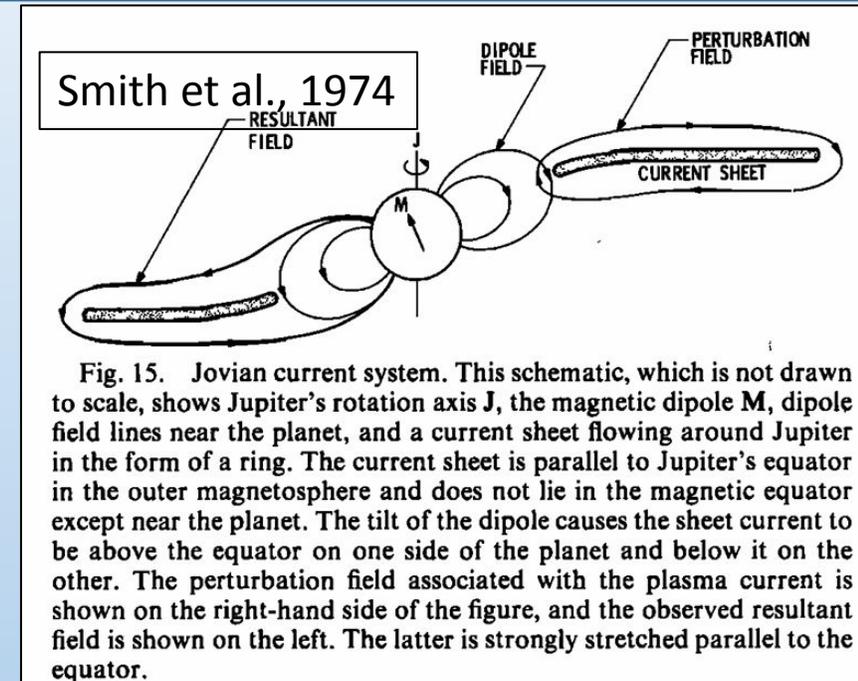


Pioneer 10 and 11 and Voyager 1 and 2 provided background

- Jupiter's magnetosphere, like Earth's, is bounded by a bow shock and a magnetopause.
- The scale of the magnetopause can change by a factor of 2.
- In the outer magnetosphere, a current sheet stretches the field.

- *Galileo characterized significant departures from local time symmetry.*

- Iogenic heavy ion plasma feeds an equatorial plasma sheet that greatly modifies the structure and dynamics of the magnetosphere.



And along came Galileo: launch – delayed and delayed but at last



John Cassani
made it happen



It wasn't all smooth sailing

NEWS | SOLAR SYSTEM

Galileo Spacecraft Anomaly Being Investigated

Engineering data returned from NASA's Jupiter-bound Galileo spacecraft last night indicate a problem with the spacecraft's tape recorder, project officials report.

Oct. 12, 1995

These problems in addition to the loss of the main antenna.



NEWS | SOLAR SYSTEM

Galileo Unexpectedly in Safing Mode

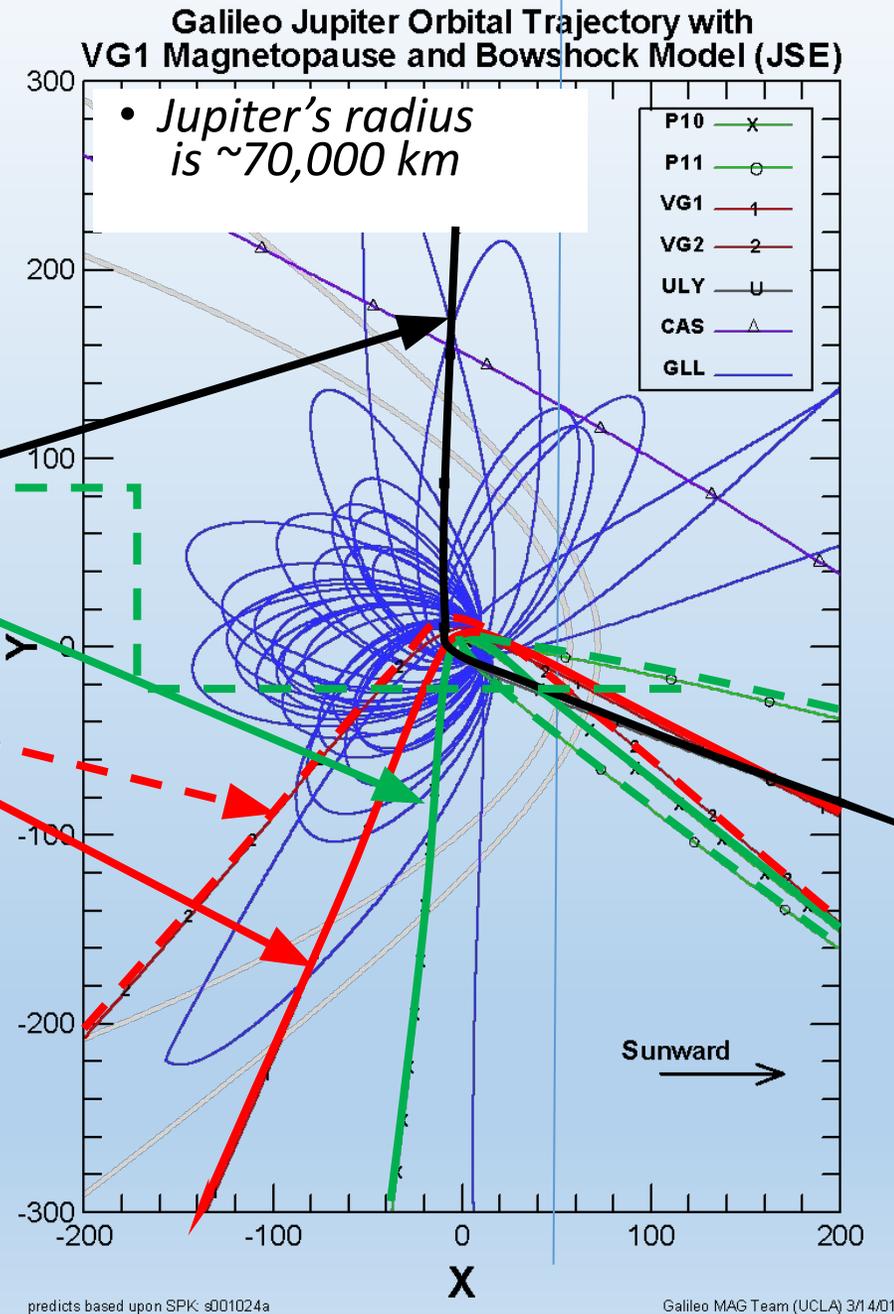
Flight controllers are working to return Galileo to normal operations after the spacecraft unexpectedly went into safing mode this week.

March 28, 1991



Data acquired over much of the equatorial magnetosphere

- Pre-Galileo, data had been acquired by:
 - Pioneer 10: 12/04/1973 at 200,000 km
 - Pioneer 11: 12/03/1974 at 42,500 km
 - Voyager 1: 3/5/1979 at 278,000 km
 - Voyager 2: 7/9/1979 at 560,000 km
 - Ulysses: c/a on 8/2/1992
- Only Ulysses and PN10 probed the magnetosphere well off the equator and large gaps in LT
- During the Galileo tour, Cassini flew by and briefly entered the dusk flank of the magnetosphere
- Later, New Horizons went down the magnetotail
- Juno came later is still going!



Galileo arrived at Jupiter in December 1995 (the anniversary that we celebrate today)



By then we knew that

- there is no jovian wind,
- Io is a prolific source of heavy ions (~ 1000 kg/s) which dominate much of magnetospheric dynamics,
- the magnetosphere can extend far beyond distances estimated from an Earth-like analogy,
- a dense plasma sheet (fed by an Io-genic source) distorts the magnetic field at large distances,
- the radiation belts contain extremely high fluxes of energetic particles.

- Galileo's spatial coverage and long duration mission (8 years starting in December, 1995) provided unique insight into magnetospheric structure and dynamics.
- Thanks to Tal Brady and many others at JPL, in situ instruments obtained low time-resolution survey data over the entire mission despite the loss of the main antenna.
- Galileo confirmed Io's role as the engine of much of the magnetospheric dynamics.
- And set the stage for further exploration (much at high latitudes) by the Juno mission.

Configuration: Near-equatorial boundary structure - 1

- Most earlier magnetopause/bow shock studies (mainly at Earth) identified its location/shape using the distribution of boundary encounters.
 - But you encounter the boundary where you are. Biased!
- For Galileo analysis, the probability of being inside/outside gave more meaningful data sets.
- Bi-modal distribution of magnetopause nose locations



(Joy, S. P. et al., 2002)

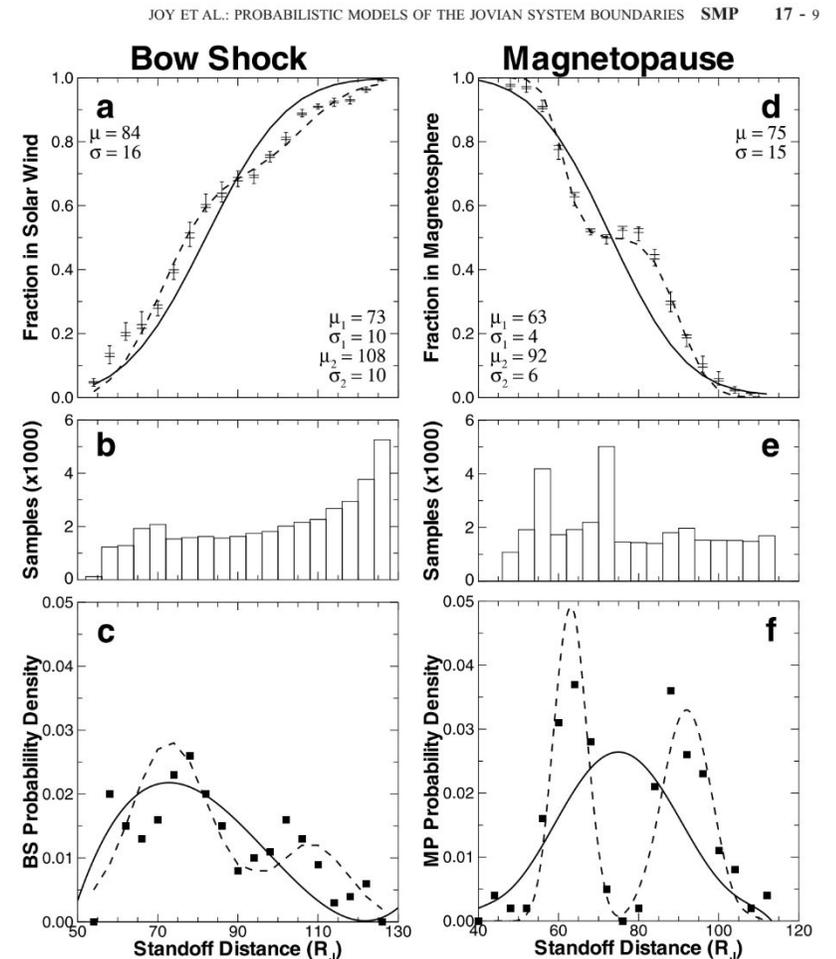


Figure 5. Top panels show the fraction of the observations outside the bow shock (a) or inside the magnetopause (d) versus standoff distance. Distribution function moments and fits are also shown. Middle panels show the number of observations in each standoff distance bin. Bottom panels show the probability densities (solid boxes) derived by numerical differentiation of the data in the top panels. See text for discussion.

Near-equatorial boundary structure - 2



- Magnetopause locations vary more rapidly with solar wind ram pressure than they would for standoff by a dipole field (*Alexeev & Belenkaya, 2005; Huddleston et al., 1998; Joy et al., 2002*).

- An order of magnitude increase in ram pressure at Earth shrinks R_{MP} to $\sim 70\%$ of the nominal value; at Jupiter such a large increase (often observed at 5 AU) displaces the dayside magnetopause to 50% of the nominal value.

- Near the equator, thermal pressure is larger than magnetic pressure for $R \geq 15 R$ (*Mauk et al., 2004*).

Sarkango, Y., Jia, X., & Toth, G. (2019).

Run 3
Parker spiral
IMF

Run 4
Forward shock
with Parker spiral
IMF

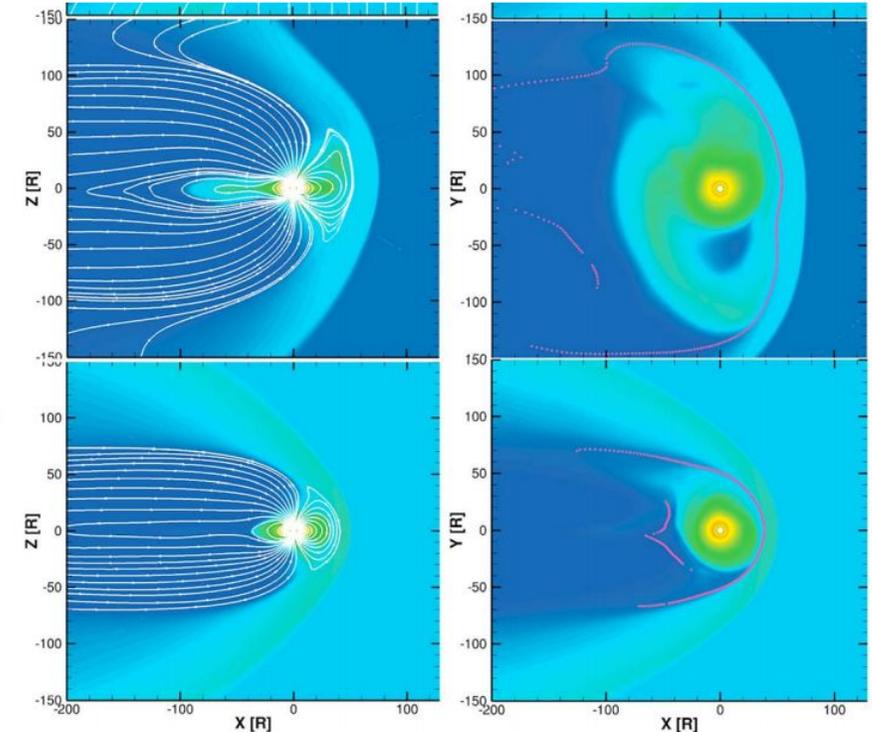
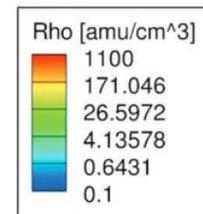


Figure 6. The magnetospheric response to each of the solar wind conditions tabulated in Table 1 at a representative instance in time. The left column shows plasma density contours and projections of magnetic field lines in the meridional plane, whereas the right column shows plasma density contours in the equatorial plane and the equatorial footprints of the last closed field lines (in magenta). IMF = interplanetary magnetic field.

Composition

Low energy ions

- The low energy plasma of the plasma sheet is dominated by sulfur and oxygen ions.



Bagenal et al., 2016

Energetic particles

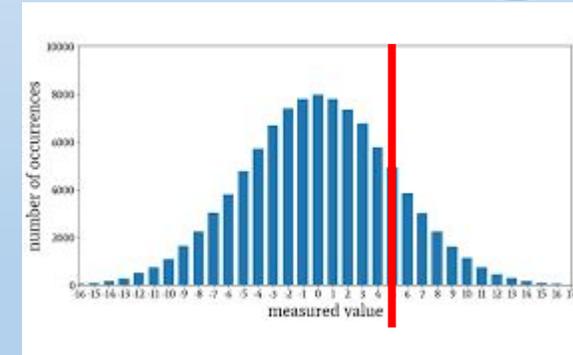
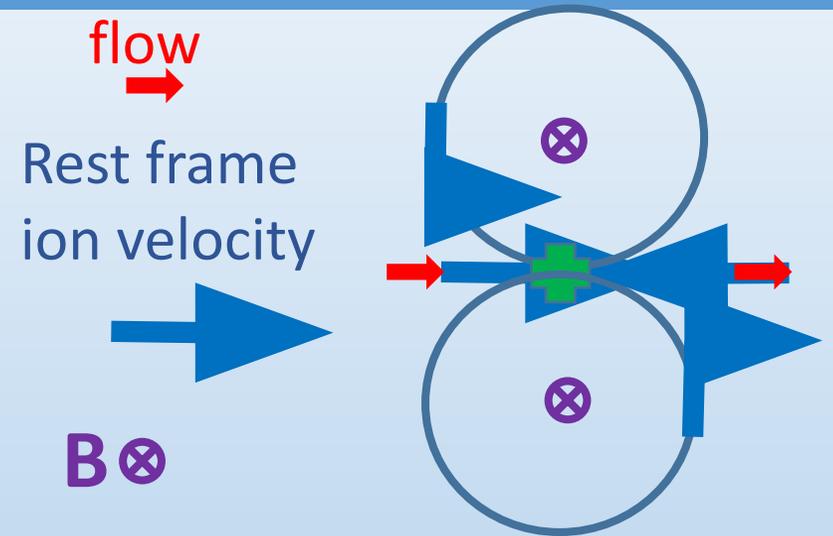
- For energetic (≥ 50 keV) ions, protons dominate the density and pressure beyond $R = 7 R_j$;
(Mauk et al., 2004).





How flow velocity is measured by EPD

- Galileo rotated about a roughly Earth-pointing axis.
- EPD stepped through ion energy.
- Assume only one species.
- With **B** into the slide and detector set to *measure incident energy or for a given ion mass, the velocity:*
 - Ions moving across the flow:
 $v = \text{ion gyro-speed}$
 - Ions flowing from the left
 $v = \text{ion gyro-speed} + \text{flow speed}$;
 - Ions coming from the right,
 $v = \text{ion gyro-speed} - \text{flow speed}$;
 - The ions from the lower gyro-energy band are typically more numerous.



- Measuring at a fixed energy and knowing how the background ion distribution varies with energy, one can infer the flow velocity.

Flows - 2



EPD characterized flows at all local times over much of the equatorial magnetosphere (Krupp et al.)

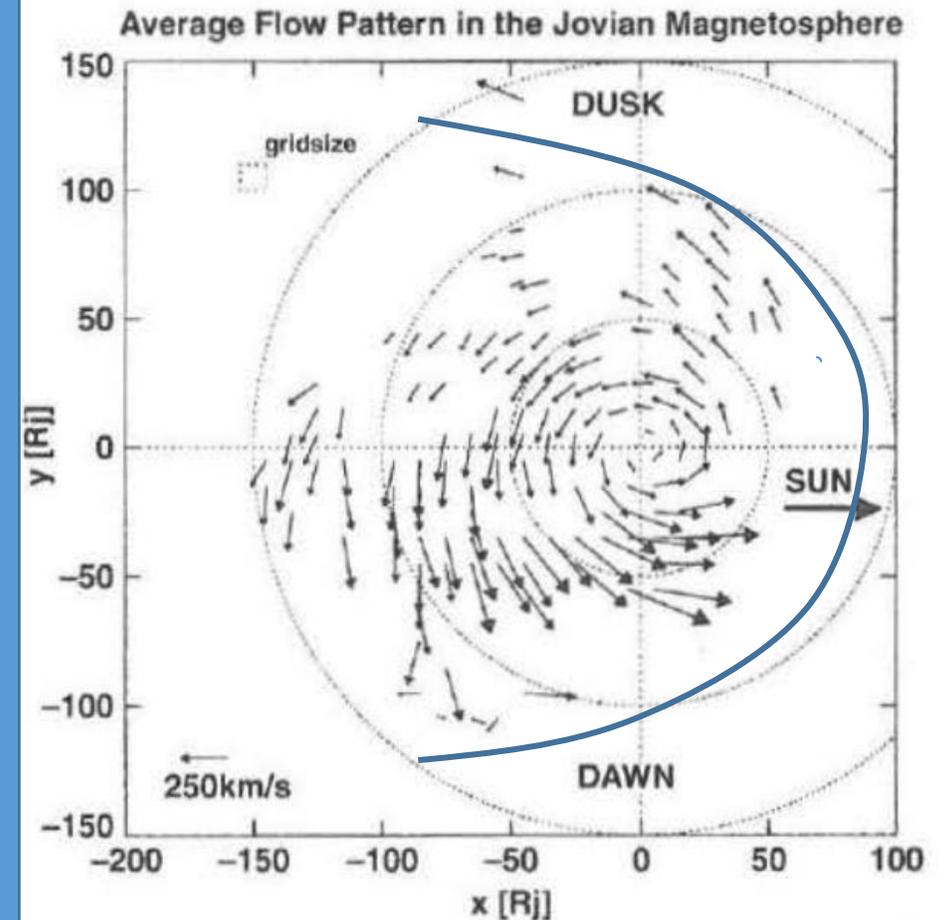
- Here flow established from energetic particle asymmetries vs. angle about **B**.
- Considerable dawn-dusk differences.
- Flow down tail not constrained by data, especially in the evening sector.

- The rate of transport of magnetic flux at equator

$$= \int_{1R_J}^{Magnetopause} (\hat{\phi} \times \mathbf{B}) v_{\phi} r dr$$

must be conserved, so if v_{ϕ} is smaller at dusk than at dawn, $\langle B_z(\text{dusk}) \rangle$ should be larger than $\langle B_z(\text{dawn}) \rangle$ over part of the radial range unless the boundary is very dawn-dusk asymmetric.

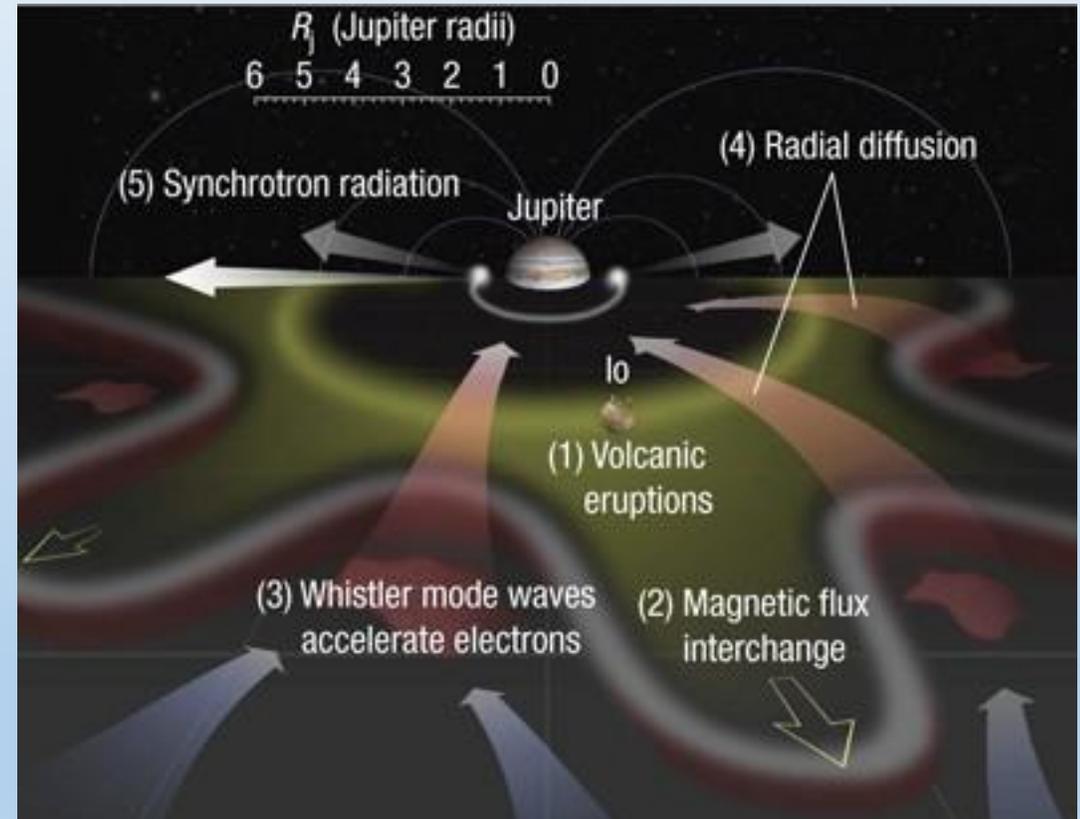
- **No evidence for larger B near dusk, but conservation of magnetic flux has not been tested.**



Adapted from Woch et al (2004)

Transport in the equatorial magnetosphere

- With a continuous source of new ions in the inner magnetosphere, the issue of transport becomes critical.
- Plasma linked to B moves out.
 - How is magnetic flux conserved: large scale stirring? Or small scale “interchange”?

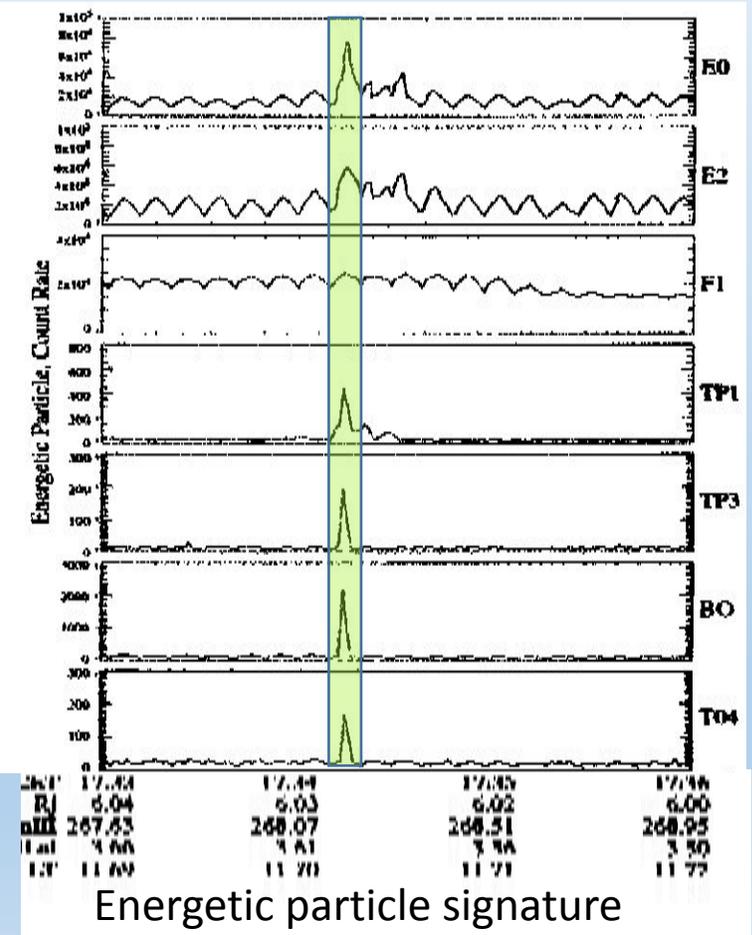
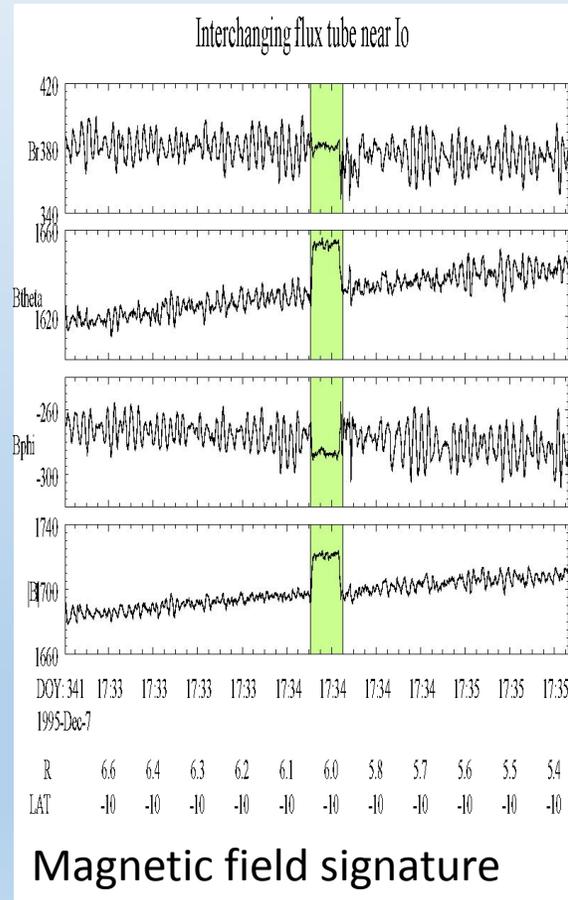


Horne, R., Thorne, R., Glauert, S. *et al.* Gyro-resonant electron acceleration at Jupiter. *Nature Phys* **4**, 301–304 (2008).



Transport: evidence for interchange near Io

- The primary source (~ 1 ton/s) of magnetospheric plasma is Io, in the inner magnetosphere.
- Must move out to maintain steady state, Where? How?
- Just beyond Io's orbit, Galileo encountered anomalous flux tubes.
- Consistent with localized inward-moving flux tubes filled with energetic particles from the outer magnetosphere replacing outward-moving flux tubes filled with low energy plasma from the inner magnetosphere.



Galileo's extensive LT coverage gave data needed to develop a global model of the current sheet and of B



Jupiter's current sheet properties vary with r and local time.

Near Io's orbit, the current sheet lies in the centrifugal equator. Farther out, it moves closer to the dipole magnetic equator in the middle magnetosphere and in the magnetotail it bends so that it is parallel to the solar wind.

Because of the dipole tilt, the current sheet (embedded in the plasma sheet) oscillates up and down (up is along the spin axis). The delay in NS displacement increases with distance from Jupiter.

Model of Khurana et al. takes all these features into account and fits data well.

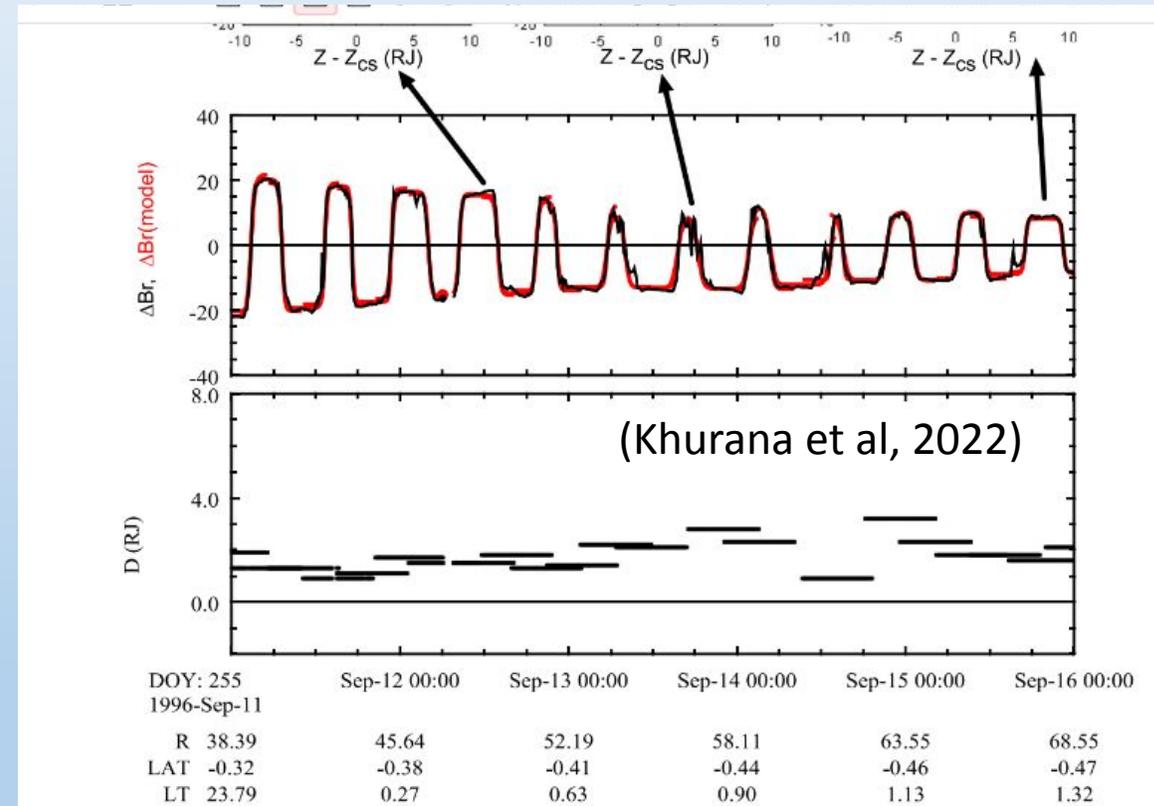


Figure 12. Obtaining current sheet half-thickness from modeling radial component of the difference field (ΔB_r). Here we use the same interval as in Figure 11. In the middle panel, the observed ΔB_r is shown in black whereas the modeled ΔB_r is shown in red. The bottom panel shows the current sheet half-thickness obtained from the best fit. The top panels show the data (blue crosses) and the fits (red diamonds) for three intervals plotted against the distance of the spacecraft from the current sheet. The extent of the current sheet is marked by two red vertical lines in these panel. It can be seen that satisfactory fits to the magnetic field are obtained even in the interval when the current sheet was displaced northward (top middle panel).

Global dynamics and the Vasylunas cycle

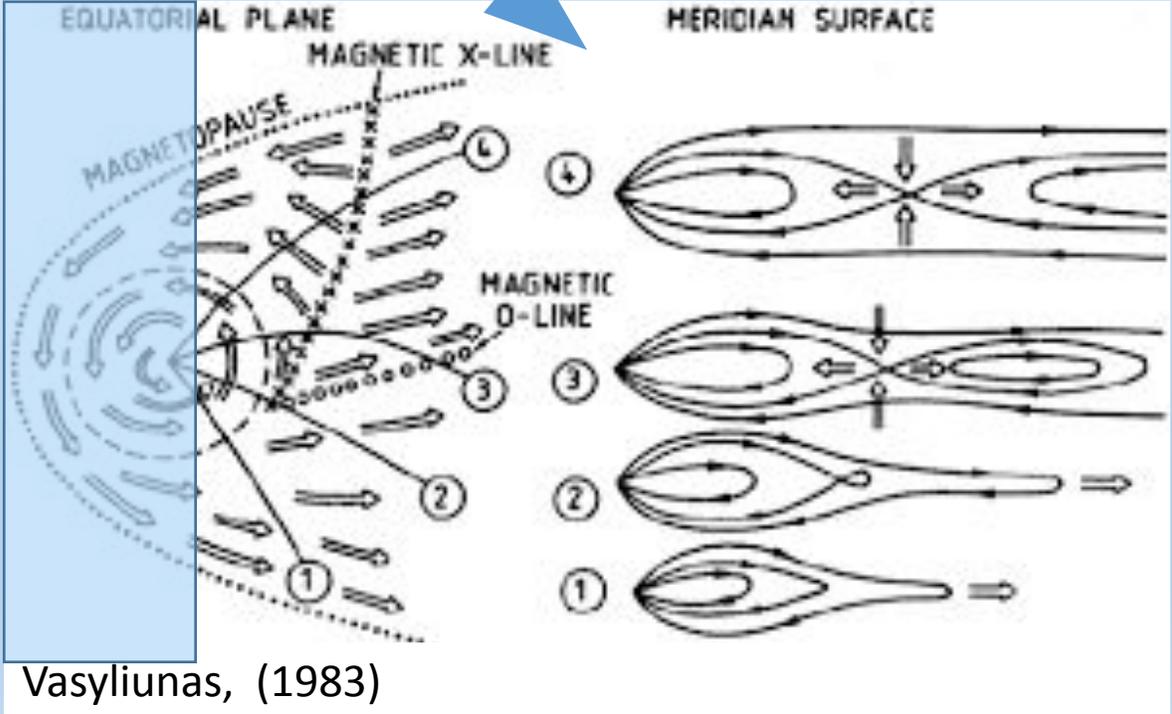


Substorms

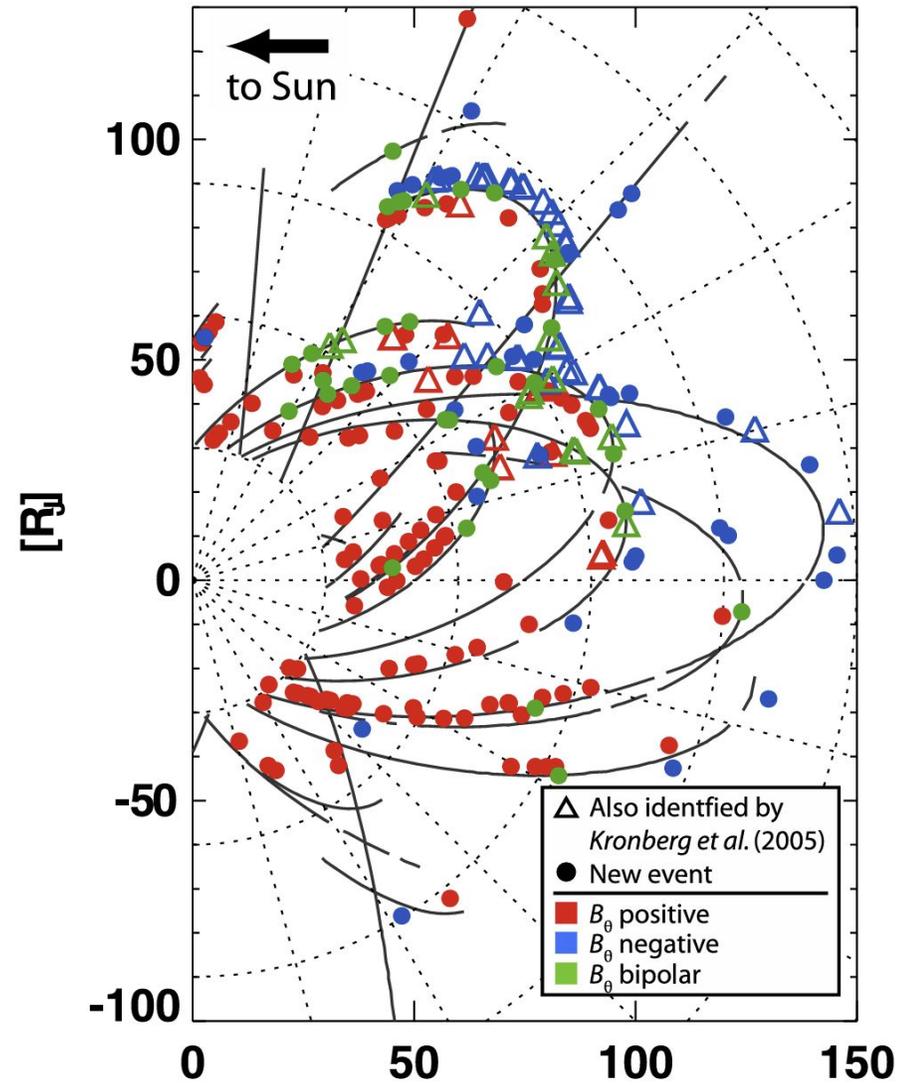
Reconnection in the magnetotail

Predicted

Observed

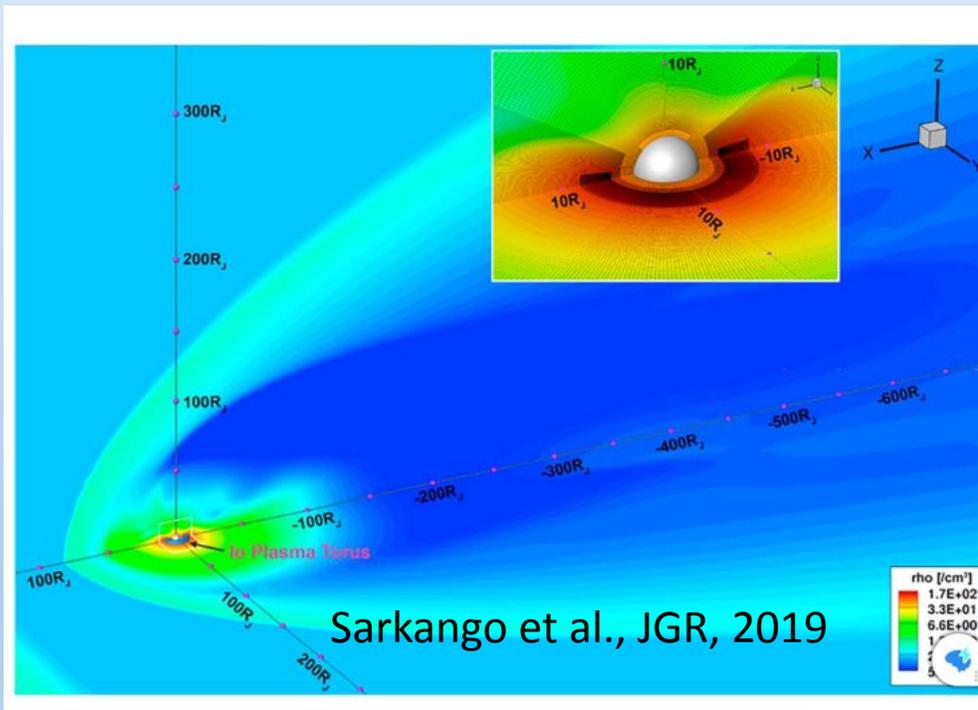


Vasyliunas, (1983)



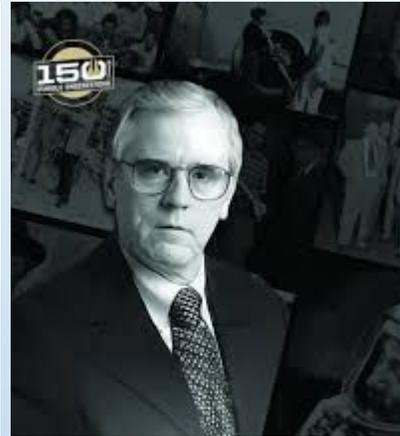


Simulations have become central to interpretation



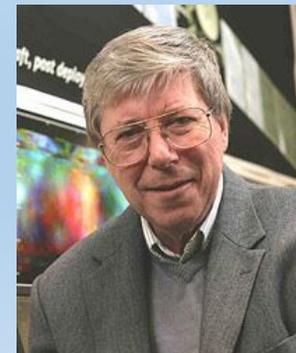
- Simulations now reproduce many of the observed features and suggest new questions that can be investigated in data.

Lots of people collaborated



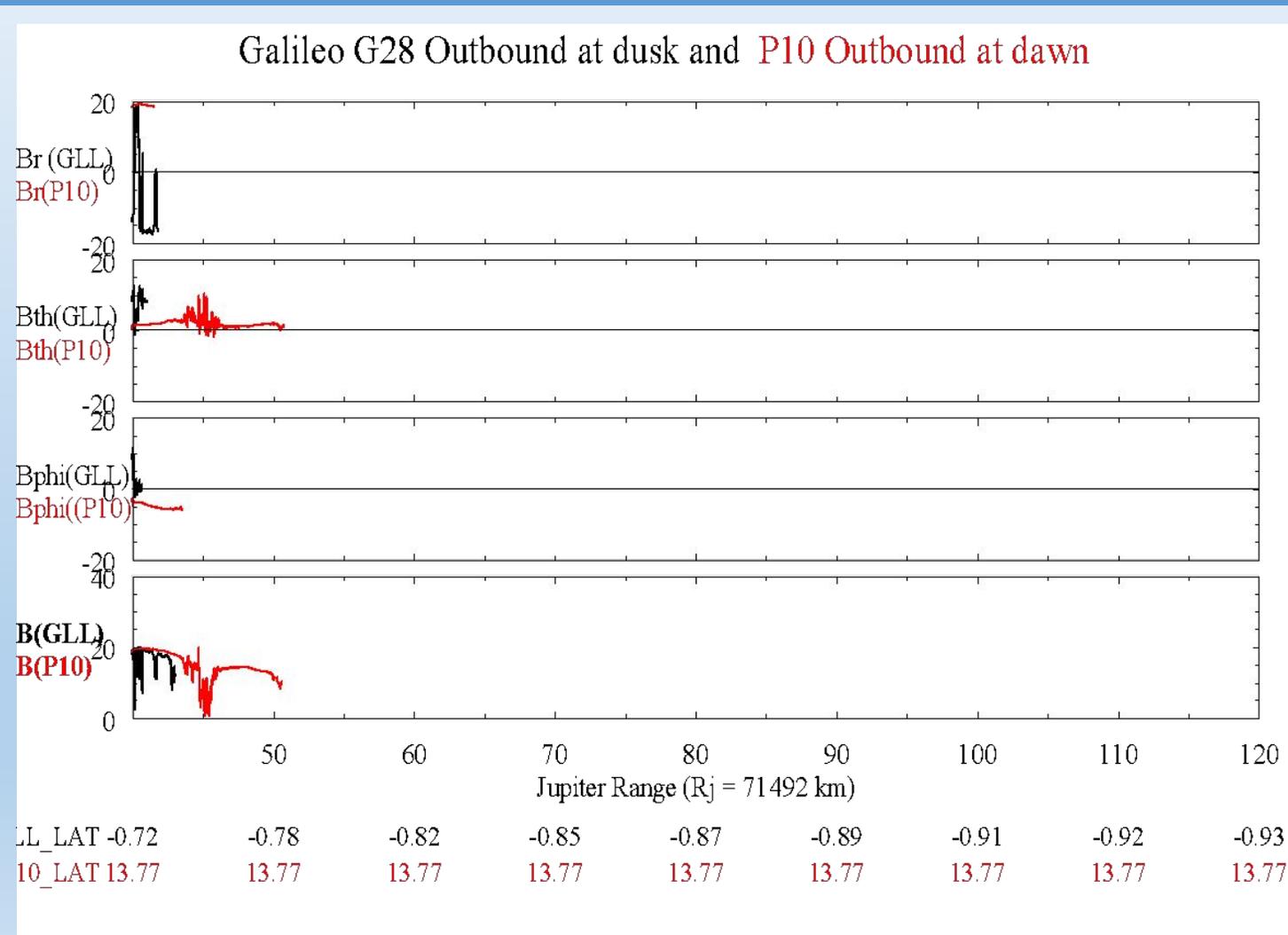
Senior scientists and engineers
From JPL and many other institutions
And colleagues, and lucky students.

**What a privilege it was to have
participated in the Galileo project!!!**



end

Puzzle: Compare field magnitude for GLL outbound near dusk with PN10 outbound near dawn



- Conservation of magnetic flux requires the average value of $\Delta\phi \int_0^{m_{gp}} dR R |\mathbf{v} \times \mathbf{B}|$ to be the same for cuts along all meridians unless significant flux is removed by reconnection with the sw.
- PN10 outbound pre dawn, G28 outbound near dusk are similar relative to the noon-midnight axis.
- Field magnitudes are almost the same but flows are much slower near dusk.
- How is magnetic flux conserved?
- Different solar wind conditions?