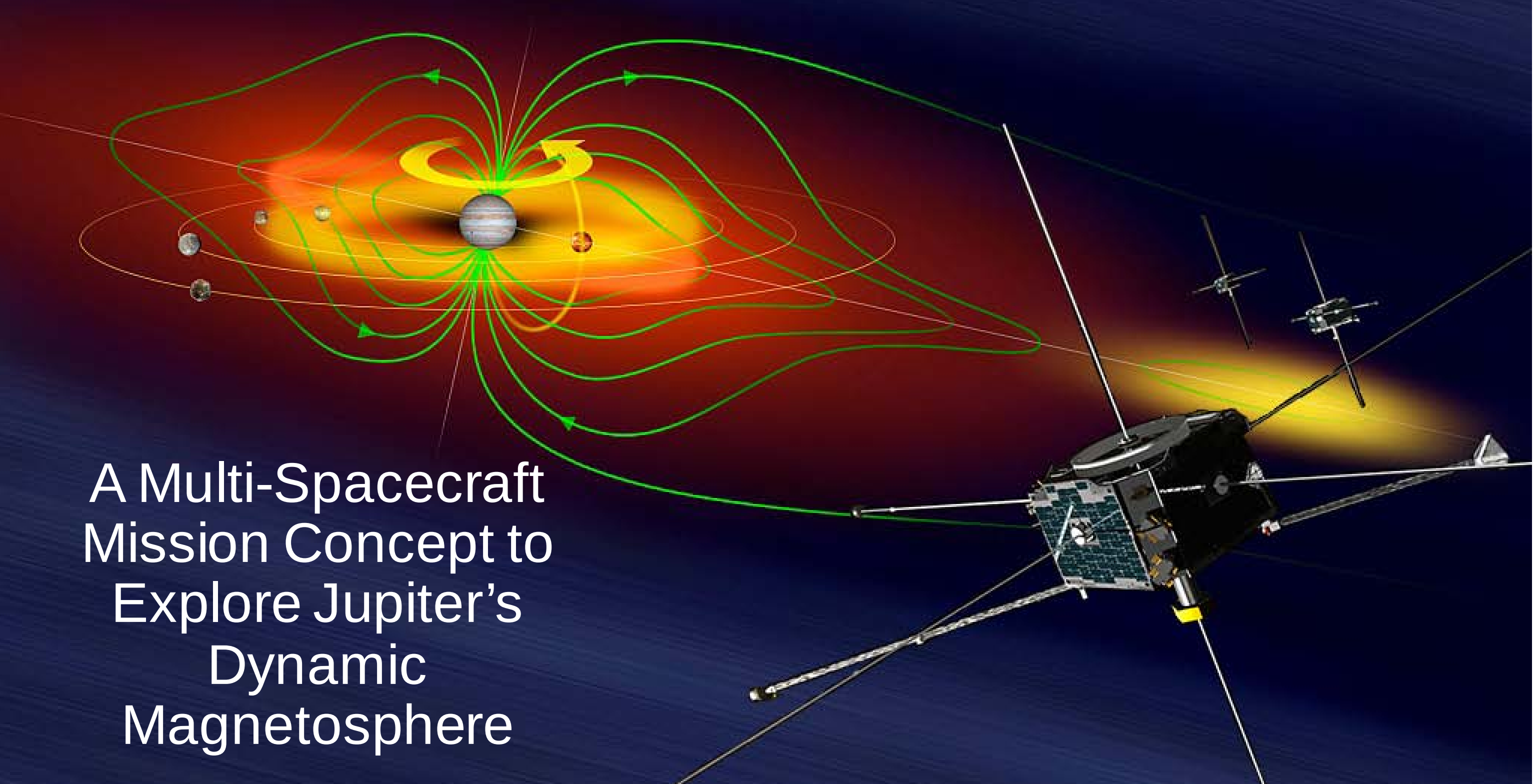
Jovian Orbiters Like THEMIS (JOLT)



A Multi-Spacecraft Mission Concept to Explore Jupiter's Dynamic Magnetosphere

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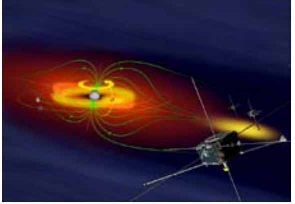
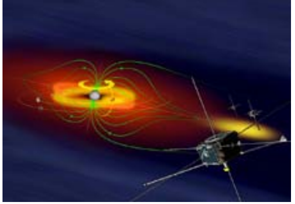


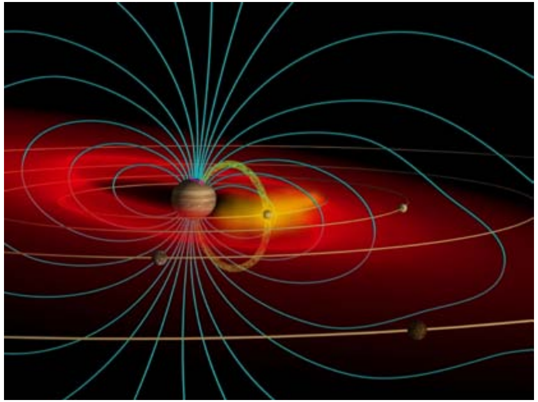
Overview

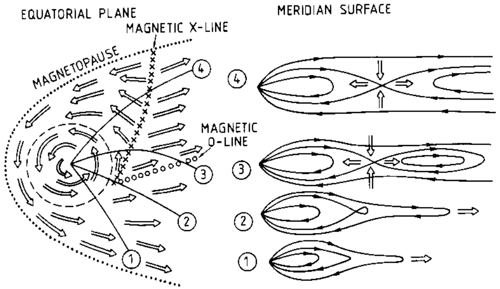
- Jupiter's magnetosphere and magnetotail
  - What we don't know about them
- What is required to understand this dynamic system?
- What have we learned from terrestrial magnetosphere studies?
- The THEMIS mission:
  Studying the Earth's magnetosphere with multiple, small spacecraft
- Can we apply these lessons to Jupiter? JOLT:
  Jovian Orbiters Like THEMIS
- Estimates of a JOLT mission (proof of concept, not concept study)
- JOLT appears to fit within the requirements of a Discovery mission

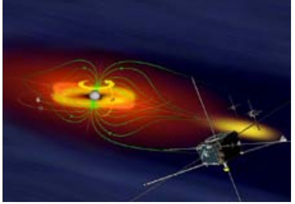


Jupiter’s magnetosphere

- Plasma from Io drives magnetospheric dynamics
  - ~1000 kg/s of heavy ions
  - These ions have to go somewhere
  - ~50% transported outward, 50% lost as fast neutrals
- Inside ~50 R_J plasma rotated with planet
  - Corotational drives inner m.sphere dynamics
  - Radial transport by Rayleigh-Taylor driven interchange
  - Reasonably well-understood, similar process at Saturn
- At some point plasma breaks free (with reconnect)
  - Plasma flows down-tail
  - Dynamics dive dynamic and complex polar aurora
  - May energize heavy ions and energetic electrons

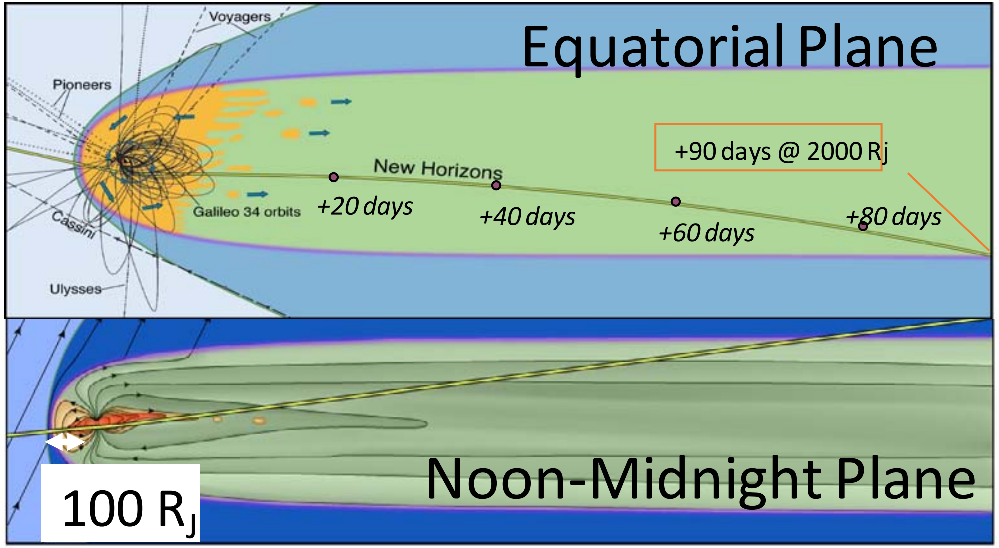






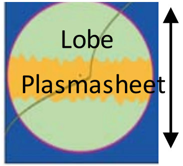
Jupiter’s Magnetotail: What we thought before 2007

- Organized magnetotail
  - Earth-like current sheet
  - Low density lobes
  - Extending across entire tail
- Large-scale transport
  - Periodic or steady reconnection
  - Releases ”plasmoids” which then flow away down-tail
- Largely based on:
  - Theory and modeling
  - Terrestrial data
  - Analogy to Earth’s magnetotail

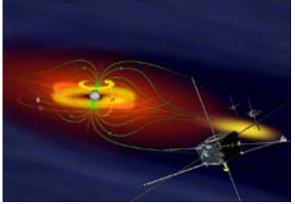


What we expected…

Tail Cross-Section

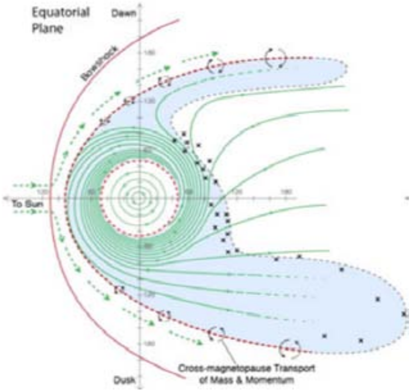


300 -500 R_J

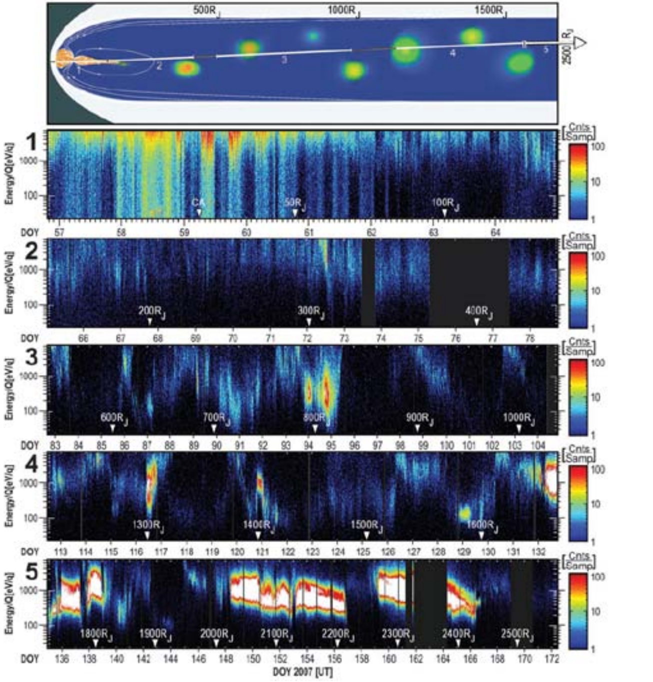


What we thought before 2007 was wrong

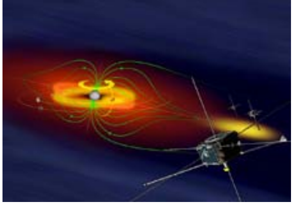
- *New Horizons* Jupiter encounter in 2007
  - Only observations in Jupiter’s deep magnetotail
  - Only measured plasma and energetic particles
- Revealed a very disorganized magnetotail
  - Many small, transient events
  - No evidence of large (cross-tail) plasma sheet
- Led to new theories:
  - “Drizzel” of small, frequent plasma “blobs” not large-scale plasmoids
  - Small-scale reconnection driven by Kelvin-Helmholtz instability, not large-scale X line



What we saw

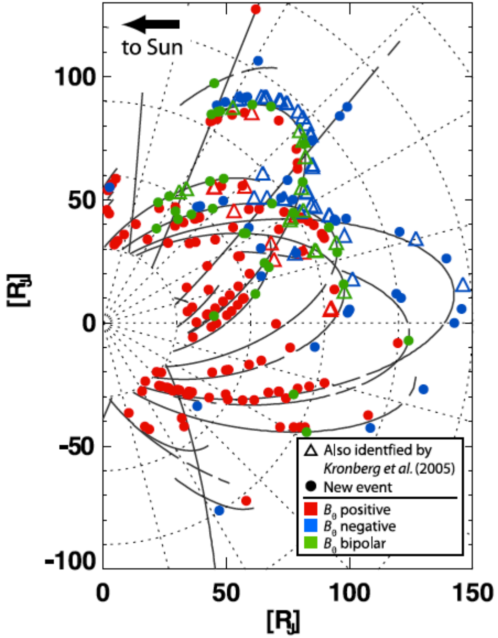


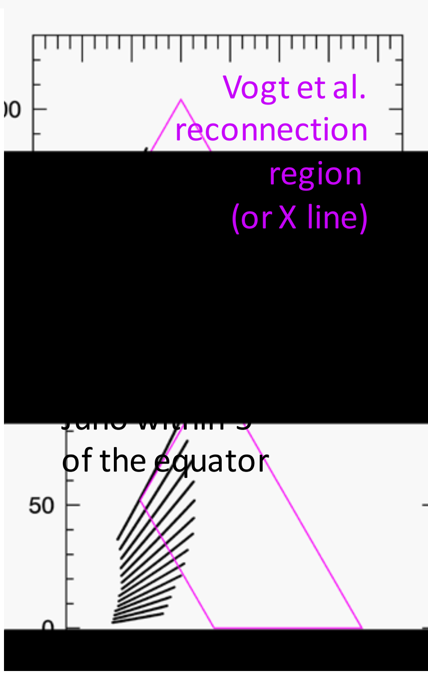
From McComas et al., 20007

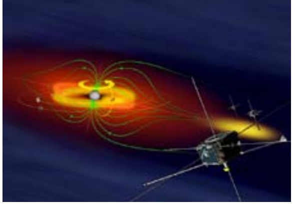


Hasn’t this been done before?

- Aspects of Jupiter’s magnetosphere has been studied
  - Outer magnetosphere and the magnetotail have not well studied or understood
  - Not planetary magnetospheres are not once-and-done science
    - Like geology or atmospheric science
- New Horizons?
  - Single flyby, no magnetometer
- Galileo?
  - Very low data rate, E.g. <2 bps MAG
- Juno?
  - Focus on polar magnetosphere & aurora
  - Trajectory (near equator) doesn’t cross X line or reconnection region
- All were single point measurements

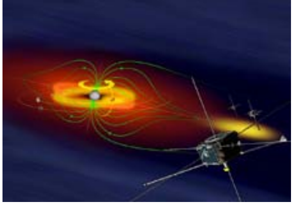






How have similar phenomena been studies at the Earth?

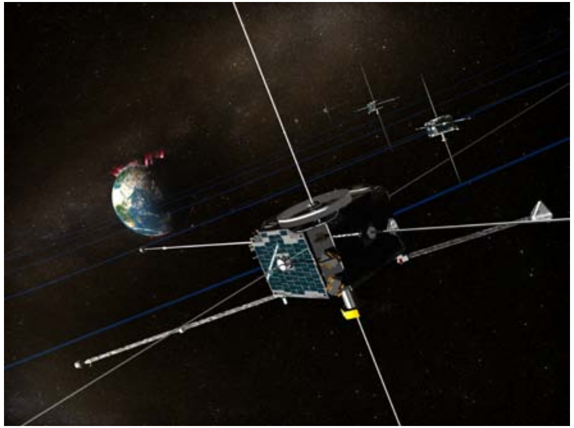
- Similar problem solved at Earth by THEMIS
  - “Time History of Events and Macroscale Interactions during Substorms”
  - Followed dynamic events from magnetotail reconnection to Earth
- Five small spacecraft (77 kg dry mass, 26 W plus eclipse heater)
  - 5 good (not excellent) particles and fields instruments on spacecraft
  - Spinning spacecraft, optimal for simple P&F instruments
  - No remote sensing instruments
  - Ground based magnetic field stations and full-sky aurora imaging
- Synchronized orbits (1-, 2- and 4-day period)
  - Spacecraft lined up at apoapsis, from the deep tail to the plasmasphere
  - Apoapsis of 10 (2x), 20 and 32 R_E
- Something similar to this proven approach will work at Jupiter

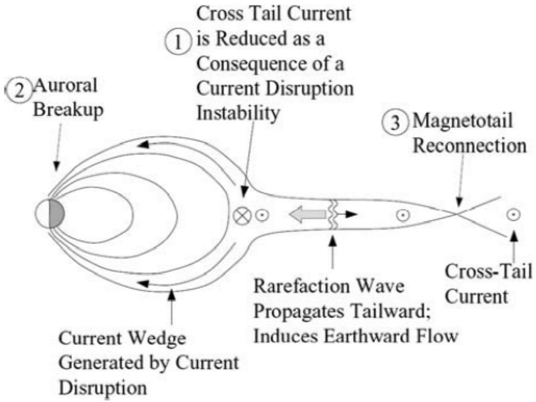


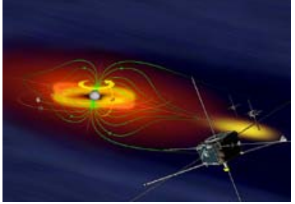
Time History of Events and Macroscale Interactions during Substorms (THEMIS)

Laboratory for Atmospheric and Space Physics
University of Colorado Boulder
Johns Hopkins Applied Physics Laboratory
Boston University
Lancaster University

- THEMIS mission launched Feb 2007
  - Medium Explorer, $173 million (~$225 FY17)
  - 2 year prime mission all still working (10.5 yrs. so far)
- Environment (e.g. radiation) essentially solar or planetary not like low Earth orbits (high apoapsis)
- 5 instruments with common data processing unit
  - Arguably more like "suite" of P&F instruments flown on some planetary missions (e.g. ASPERA)
- Two outermost spacecraft now orbit the moon
  - ARTEMIS "Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun

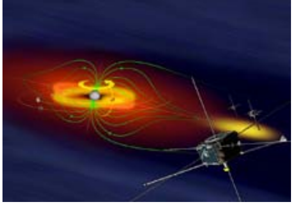






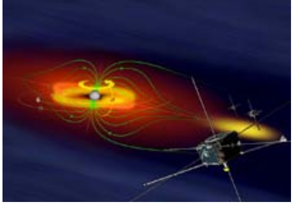
The THEMIS Payload

	Mass [kg]	Power [W]	Slow survey data rate [bps]	Notes
Flux gate magnetometer	1.33	0.85	46	2-m boom
Search coil magnetometer	1.76	0.09	46	1-m boom
Electric field instrument	12.22	0.24	93	50-m, 40-m & 7-m antennas
Electrostatic analyzer	2.87	1.70	463	Ions and electrons
Solid State Telescope	1.35	1.20	648	
Instrument Data Processing Unit	4.25	8.00		
Total	23.78	12.08	1296	



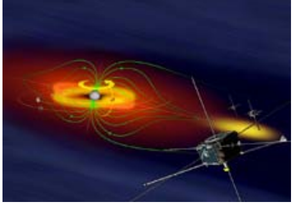
Could THEMIS go to Jupiter?

- No, but something like it could, as a Discovery mission
- What would that take?
  - This is not a concept study report, it is a rough proof of concept (CML 2.5)
- Example mission concept:
  - Use THEMIS payload as a model payload
  - Assume a 1.5-m high gain antenna and expanded solar panels
  - Four identical spacecraft
  - All spacecraft on a 15 x 150 R_J orbit in a “string of pearls” configuration
- The mass, power, propulsion, telemetry and budget seem to fit
- Other concepts would also fit
  - 3-spacecraft plus carrier vehicle concept has also been considered
  - Many other potential orbital configurations possible



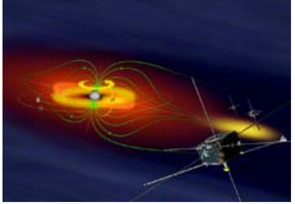
Getting to Jupiter

- Spacecraft separate immediately after launch
  - No carrier vehicle and truly identical spacecraft
  - Greater flexibility on final science orbits
  - But requires separate navigation and maneuvers
    - Yes, that means four orbital insertion maneuvers…
- Cruise to Jupiter:
  - 5-year trajectory with deep space maneuver and Earth flyby
  - C_3 of under 31 km^2/s^2 at launch
  - ~900 m/s deep space maneuver
- Approach and orbital insertions staggered by 10 days
  - Puts spacecraft on ”string of pearls” configuration along same orbit



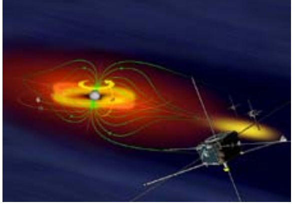
Orbital Insertion and Science Orbits

- Orbital insertion at 4 R_J
  - As close as possible without worrying about the
- 1053 m/s Δv orbital insertion to 4 x 150 R_J equatorial orbit
- 683 m/s Δv to raise periapsis, to a 15 x 150 R_J orbit
  - 92.4 day orbital period
  - Spacecraft out of high-radiation environment for rest of mission
- None of these maneuvers requires high precision
  - 145 R_J versus 150 R_J would have virtually no impact on science
- Total Δv (DSM, JOI, PRM) of 2636 m/s
- Initial local time of apoapsis is around 0300
  - Precesses at ~7.5 deg (1/2 hour of local time) per orbit
- Nominal mission is three years, final apoapsis local time of 2100
- Extended mission and/or disposal options are TBD



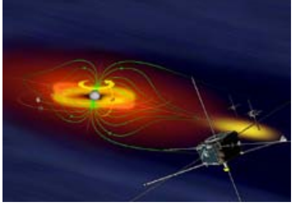
Telecommunications and Downlink

- Estimates based on MarCO (actually IRIS 2.1) with a 1.5 m dish
  - Only changes are free space loss, spacecraft antenna gain, receiver antenna gain (34-m not 70-m station)
  - Supports downlink at 897 bps
- But… Discovery missions are supposed to use Ka not X band
  - Advertised as 4x increase, but transmitter efficiency may be an issue
- Particle and field data compress well (assume 4:1 lossless)
  - Past missions have used less efficient (Rice) compression
  - Baseline more CPU power and more efficient routines
- 14,300 bps downlink and 1024 bps collection rate
  - 1024 bps acceptable; higher THEMIS rates are for microphysics
  - 1.5, 8-hour downlinks per spacecraft per week
  - High (6 tracks/week) for whole constellation, but extreme time flexibility



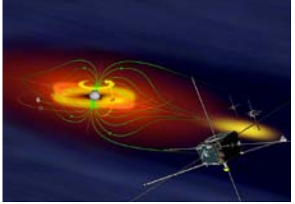
Power and Mass

- Telecommunications assumed to requite 35 W over THEMIS
- Total power 75 W total
  - Requires 50 kg (four 1.5 x 1.5 m wings)
- Add 15 kg (guess) for 1.5 m antenna
- Assume 2750 m/s Δv available for propulsion
  - I_{SP} of 280 s, tank mass equal to 10% propellant mass
- Otherwise THEMIS-like
- Total dry mass 210 kg, 540 kg wet mass (with 20% margin)
- 2160 kg plus launch adaptors for total launch mass
- An Atlas V (421) can put 2365 kg on a 31 km^2/s^2 C_3 trajectory



Budget

- Discovery 13 and 14 were cost-caped at $450 million
- The current concept (or concepts) have many possible trades
  - Too many variations, not sufficiently defined for formal cost estimate
- This is based heavily on THEMIS ($173 million, ~$225 FY17)
- But planetary missions are more expensive (Class A/B not C/D)
- Without doing a cost model, is this still plausible?
- If GRACE and GRAIL are a valid analogy, JOLT is probably ok
  - GRACE is a terrestrial gravity mapper and technology pathfinder
  - GRAIL, Discovery 11, was a lunar gravity mapper based on GRACE
  - GRACE cost $127 million, GRAIL $375 (~$170 and ~405 in FY17 $)
- Assuming a JOLT would cost twice as much as THEMIS is plausible
  - This is certainly debatable, probably more of a challenge that engineering



Conclusions

- The dynamics of the Jovian magnetotail is one of the great unknowns of planetary, magnetospheric science
  - Based on the available data, we mostly know that we don't understand it
  - Drives dynamics polar aurora and particle energization
  - Similar, poorly-understood tail dynamics also present at Saturn
- Similar processes and problems have been solved at Earth
- THEMIS traced flow of energy, mass and magnetic flux in the tail
  - This requires multiple spacecraft, making simultaneous measurements
  - This does not require very sophisticated (resource-intense) instruments
    - Just instruments which are good enough for the job, and in the right places
- The same approach can work for studies of Jupiter's magnetotail
  - Building on experience from the Earth's magnetosphere
  - Small spacecraft are fine and we know the critical measurements
- Such a mission should be within the scope of a Discovery mission