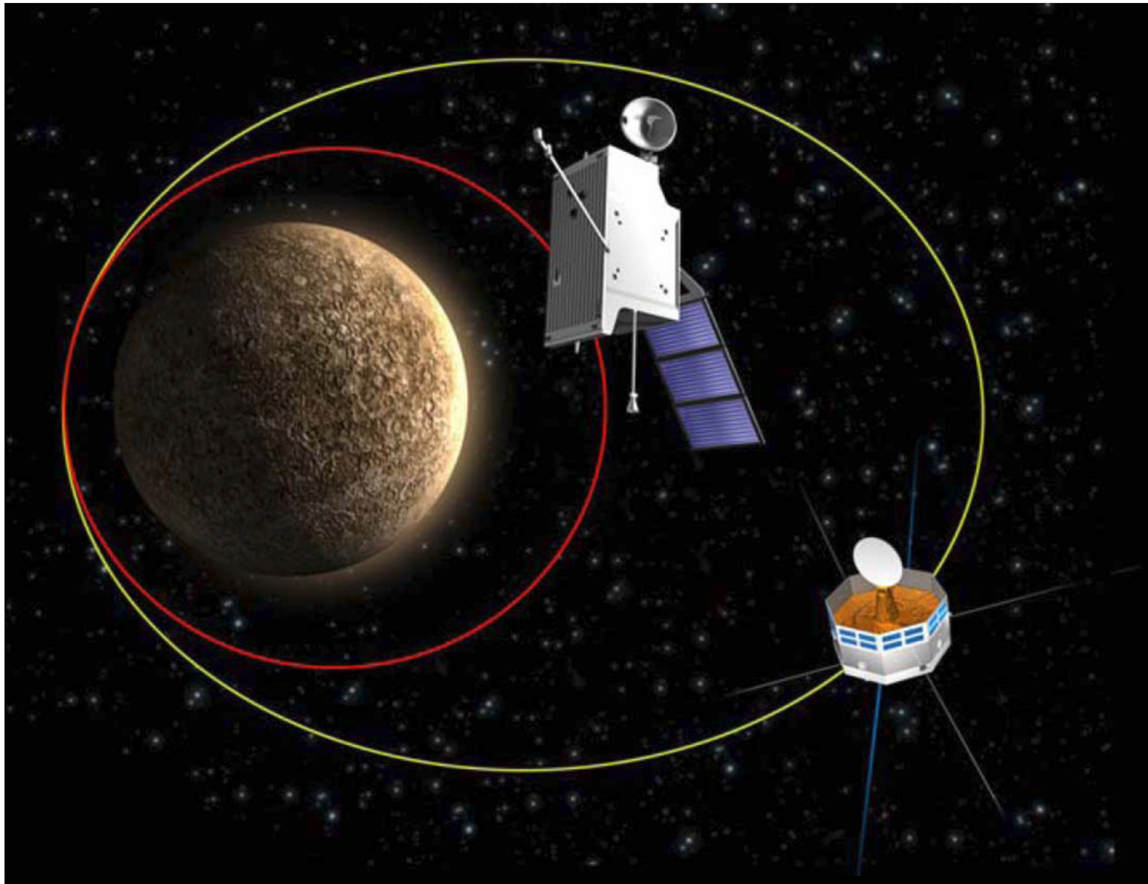


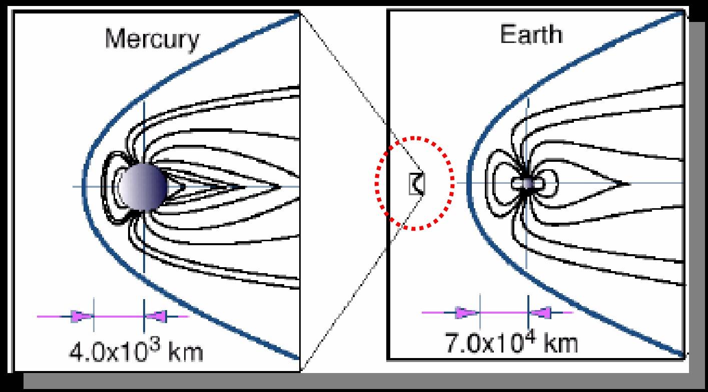
Mercury's magnetosphere :
(some) Bepi Colombo science possibilities

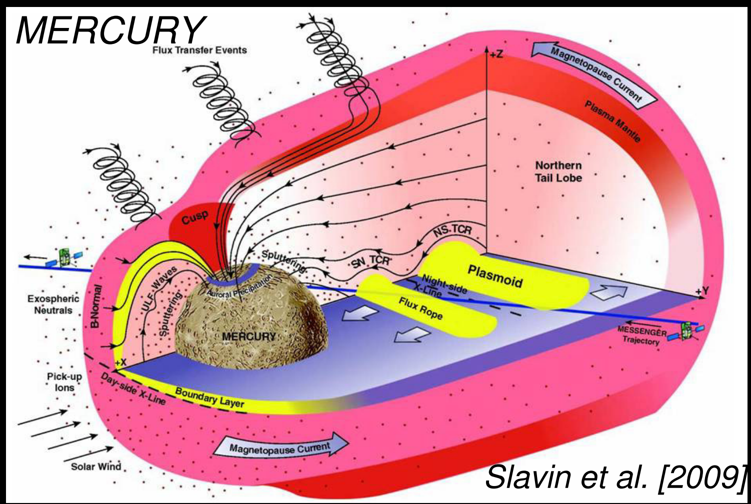
Dominique Delcourt

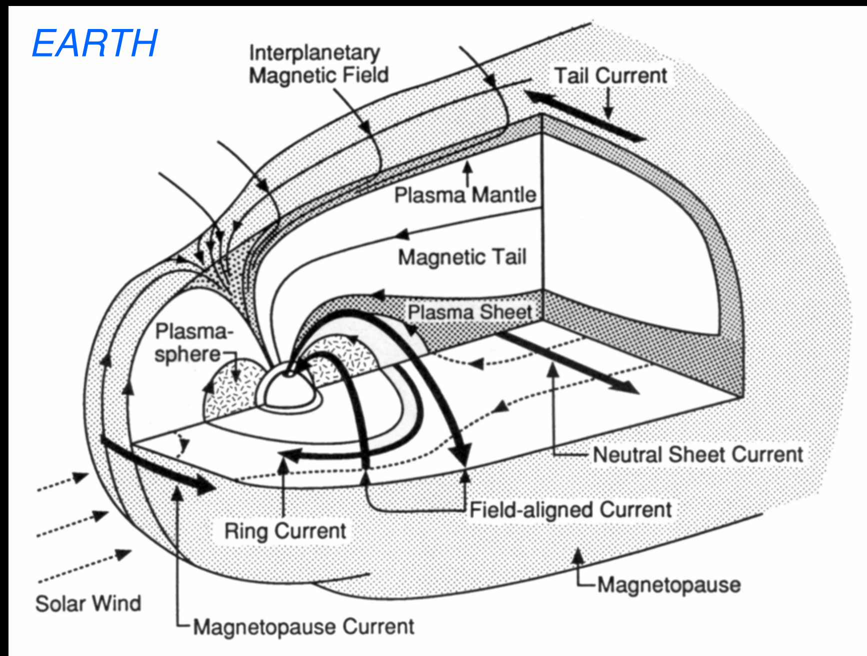
LPP, Ecole Polytechnique-CNRS-UPMC

Nature's original patterns are reproduced on various scales and in various contexts

Mercury's magnetosphere



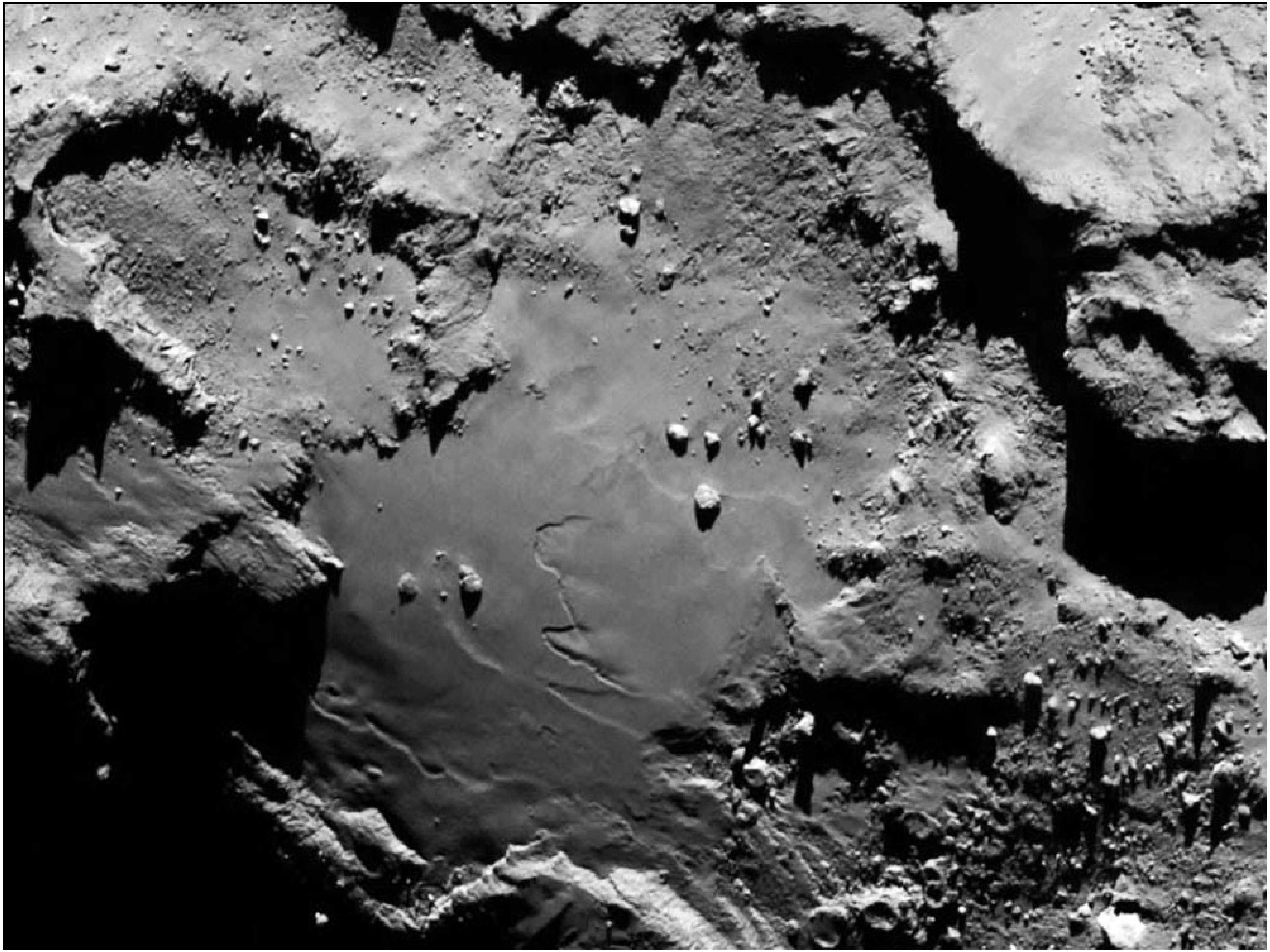


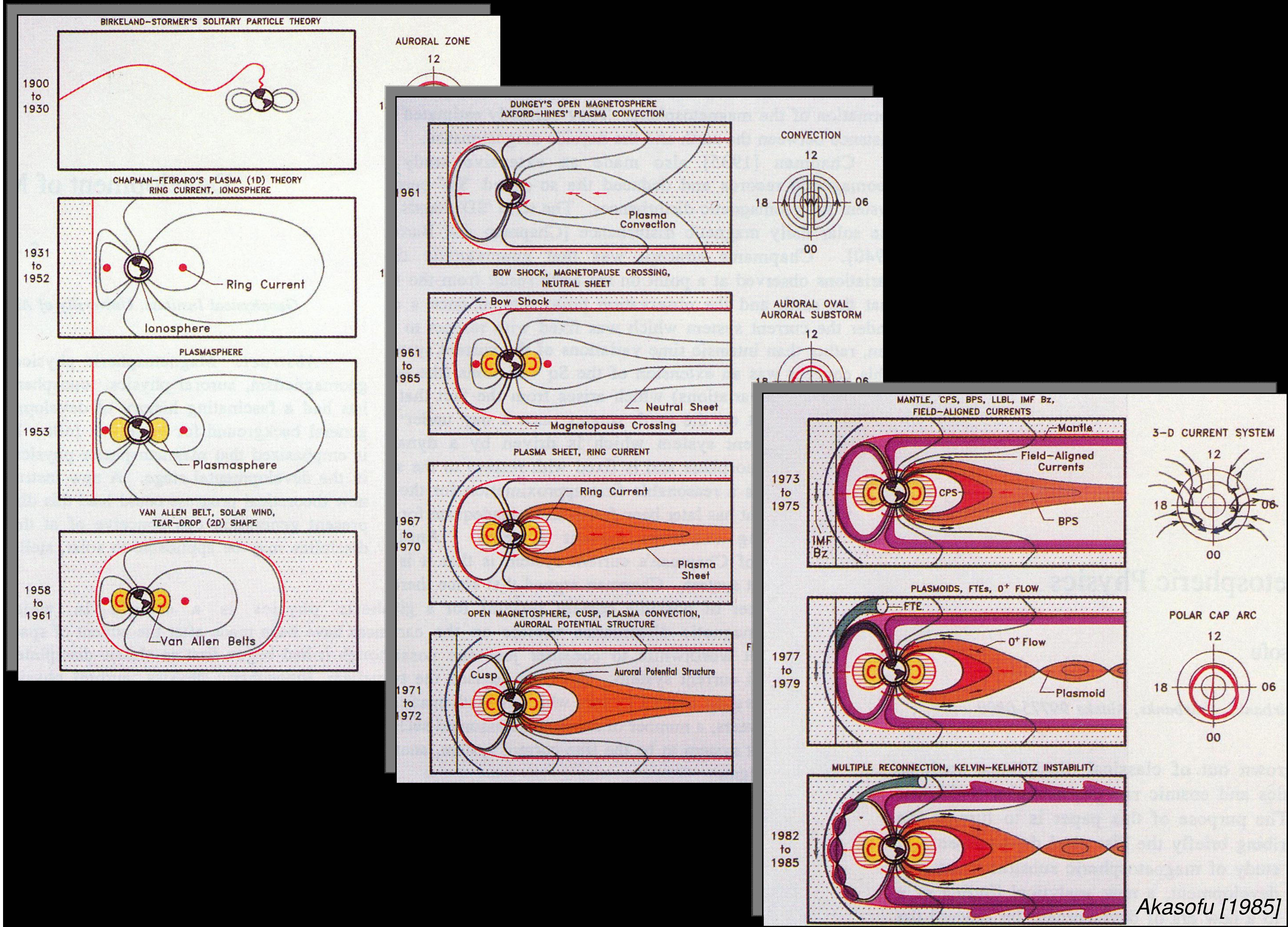


- *Different boundary conditions*

  (tenuous atmosphere, solar wind parameters)
- *Different spatial and temporal scales*

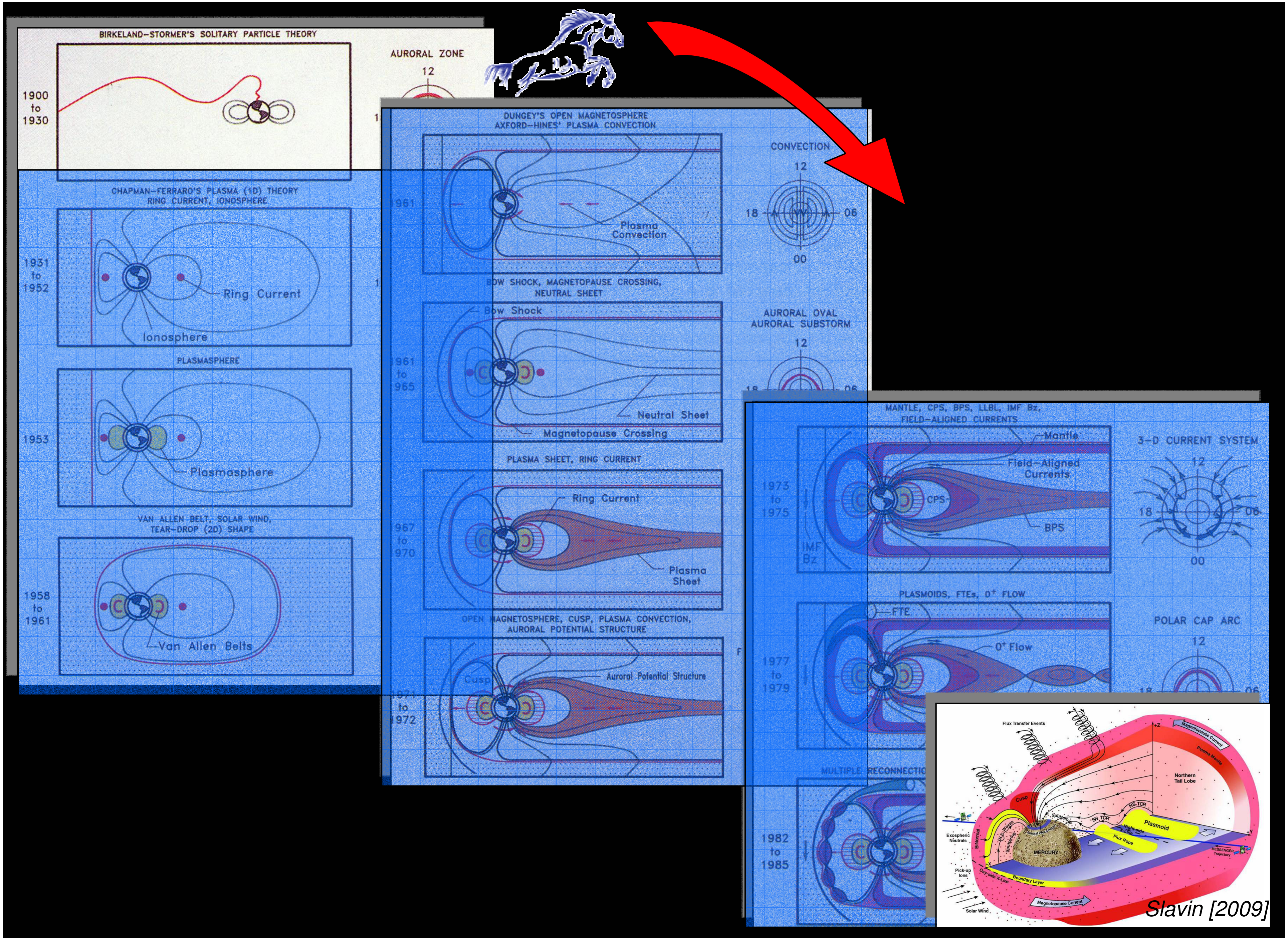
  (~1:8 and ~1:30, respectively)





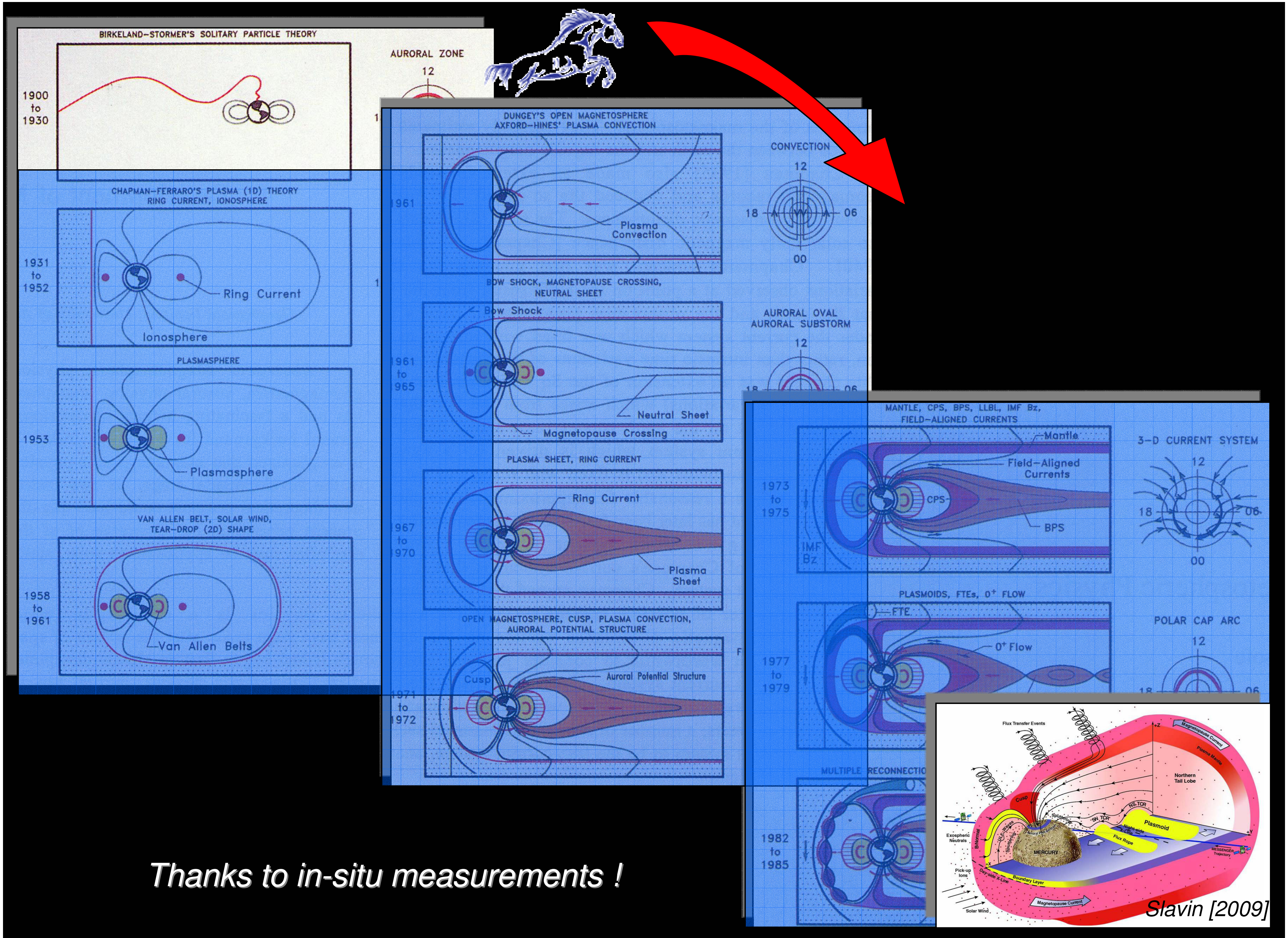
Akasofu [1985]

...



BIRKELAND–STORMER'S SOLITARY PARTICLE THEORY
AURORAL ZONE
1900 to 1930
CHAPMAN–FERRARO'S PLASMA (1D) THEORY
RING CURRENT, IONOSPHERE
1931 to 1952
Ring Current
Ionosphere
PLASMASPHERE
1953
Plasmasphere
VAN ALLEN BELT, SOLAR WIND,
TEAR-DROP (2D) SHAPE
1958 to 1961
Van Allen Belts
DUNGEY'S OPEN MAGNETOSPHERE
AXFORD–HINES' PLASMA CONVECTION
1961
Plasma Convection
CONVECTION
12
18
06
00
BOW SHOCK, MAGNETOPAUSE CROSSING,
NEUTRAL SHEET
Bow Shock
Neutral Sheet
Magnetopause Crossing
AURORAL OVAL
AURORAL SUBSTORM
PLASMA SHEET, RING CURRENT
Ring Current
Plasma Sheet
OPEN MAGNETOSPHERE, CUSP, PLASMA CONVECTION,
AURORAL POTENTIAL STRUCTURE
Cusp
Auroral Potential Structure
MANTLE, CPS, BPS, LLBL, IMF Bz,
FIELD-ALIGNED CURRENTS
Mantle
Field-Aligned Currents
CPS
BPS
1973 to 1975
IMF Bz
3-D CURRENT SYSTEM
PLASMOIDS, FTEs, O+ FLOW
FTE
O+ Flow
1977 to 1979
POLAR CAP ARC
1982 to 1985
Flux Transfer Events
Northern Tail Lobe
Cusp
Plasmoid
Flux Rope
MERCURY
Magnetopause Current
Solar Wind
Slavin [2009]

...



Thanks to in-situ measurements !

...

launch year

Mariner-10 :
1974-1975 (3 flybys)

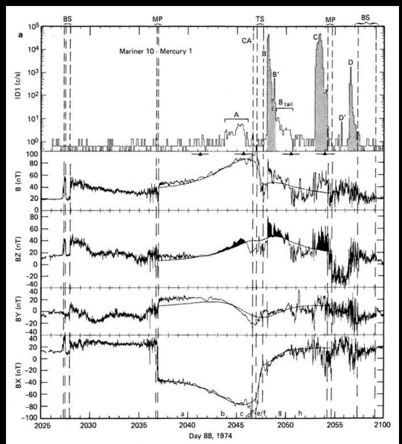
1973

launch year

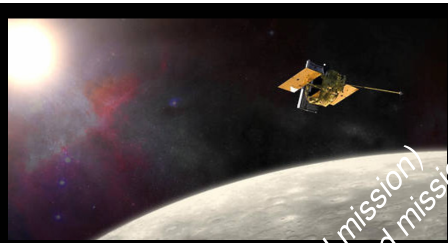
? magnetosphere ?

mini-magnetosphere

- magnetic field
- energetic particles



Christon et al. [1987]



Mariner-10 :
1974-1975 (3 flybys)

MESSENGER :
2011-2012 (nominal mission)
2012-2015 (extended mission)

1973 — 2004 — **launch year**

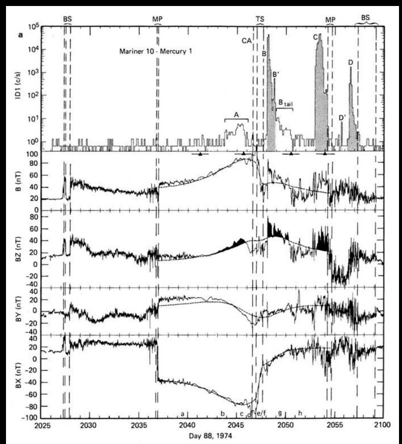
? magnetosphere ?

mini-magnetosphere

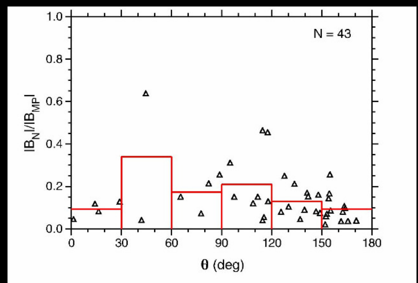
highly dynamical mini-magnetosphere

- magnetic field
- energetic particles

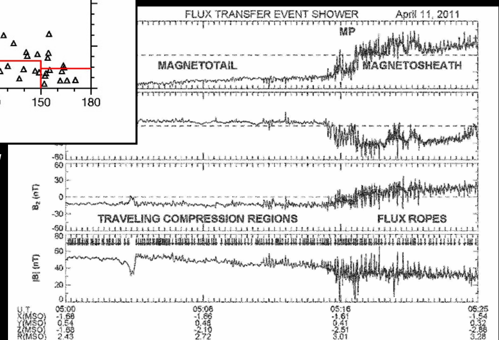
- magnetic field
- energetic particles
- plasma (ions)



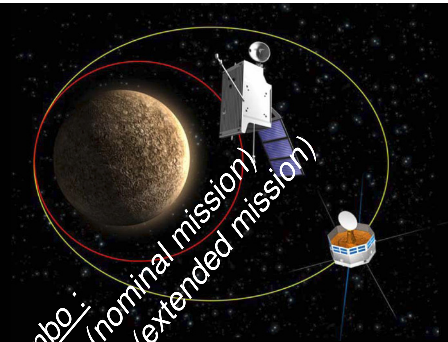
Christon et al. [1987]



DiBraccio et al. [2013]



Slavin et al. [2012]



Mariner-10 :
1974-1975 (3 flybys)

MESSENGER :
2011-2012 (nominal mission)
2012-2015 (extended mission)

Bepi Colombo :
2024-2025 (nominal mission)
2025-2026 (extended mission)

1973 — 2004 — 2017 — **launch year**

? magnetosphere ?

mini-magnetosphere

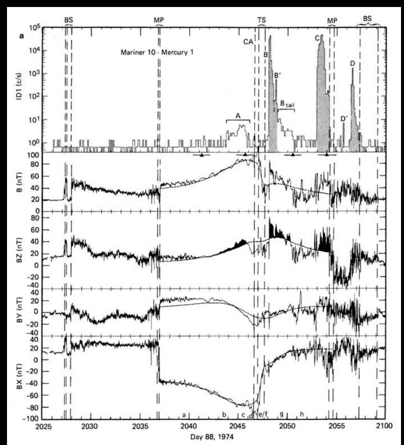
highly dynamical
mini-magnetosphere

???
highly dynamical
mini-magnetosphere

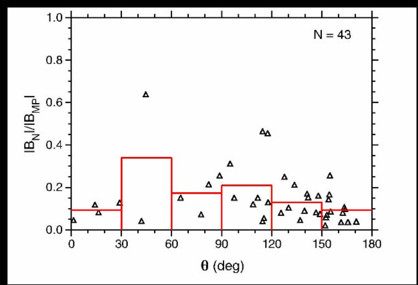
- magnetic field
- energetic particles

- magnetic field
- energetic particles
- plasma (ions)

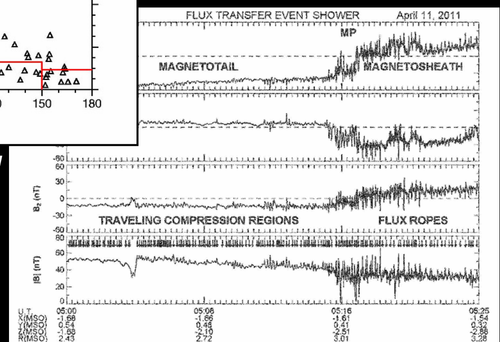
MMO : comprehensive plasma instrumentation
MPO : • magnetic field
• ions and neutrals



Christon et al. [1987]

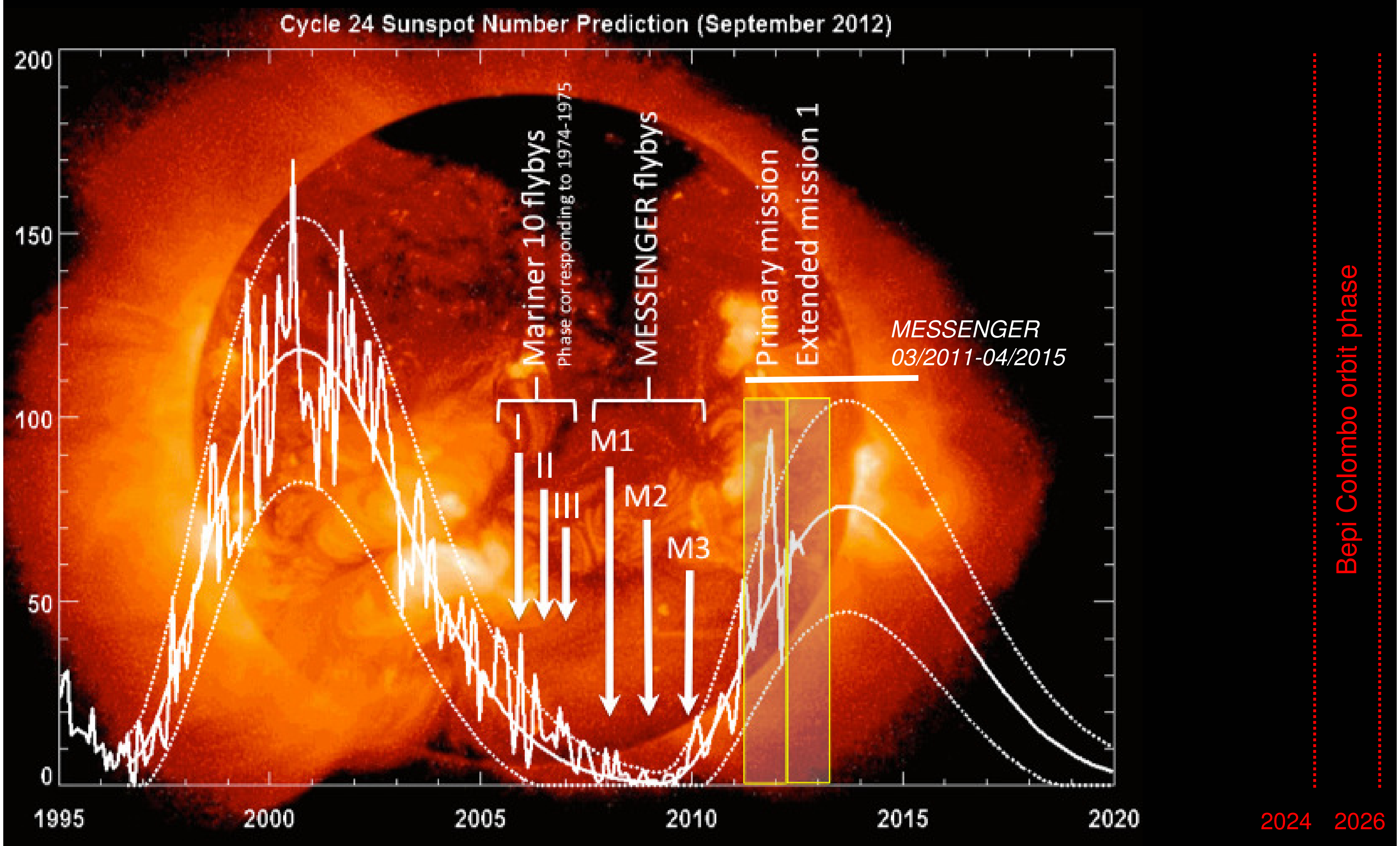


DiBraccio et al. [2013]



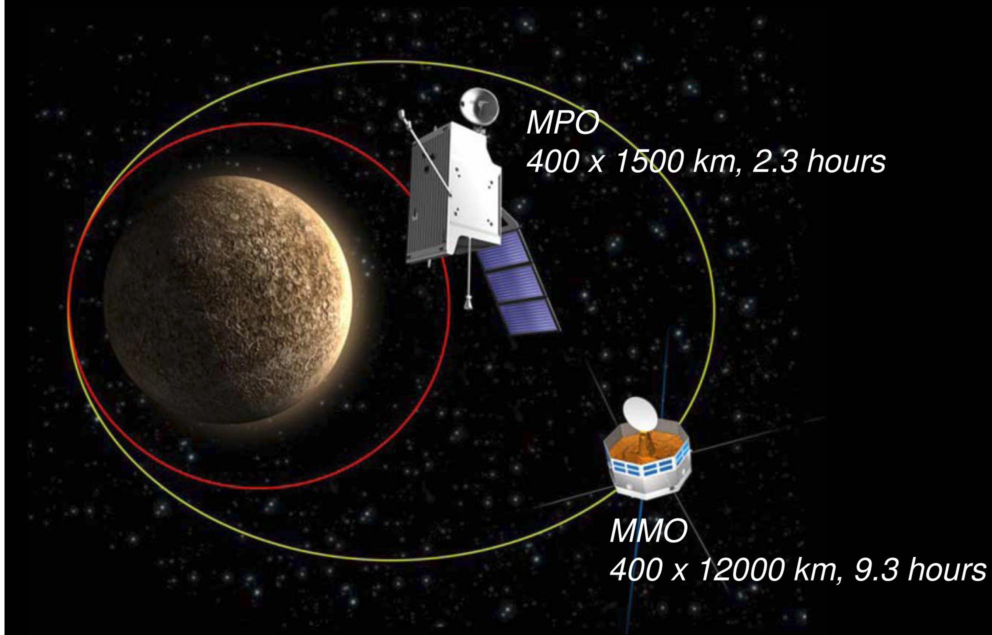
Slavin et al. [2012]

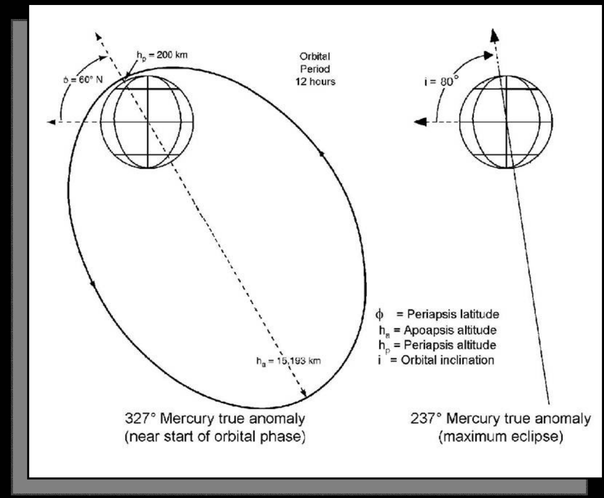
1. Different epochs ☞ Different science possibilities



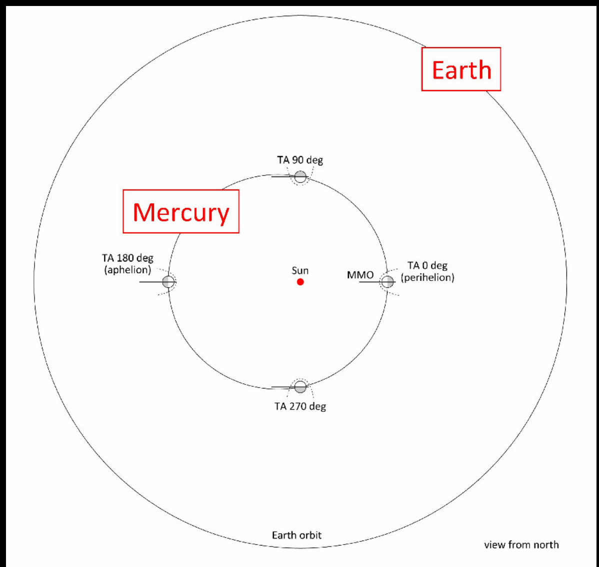
McNutt et al. [2012]

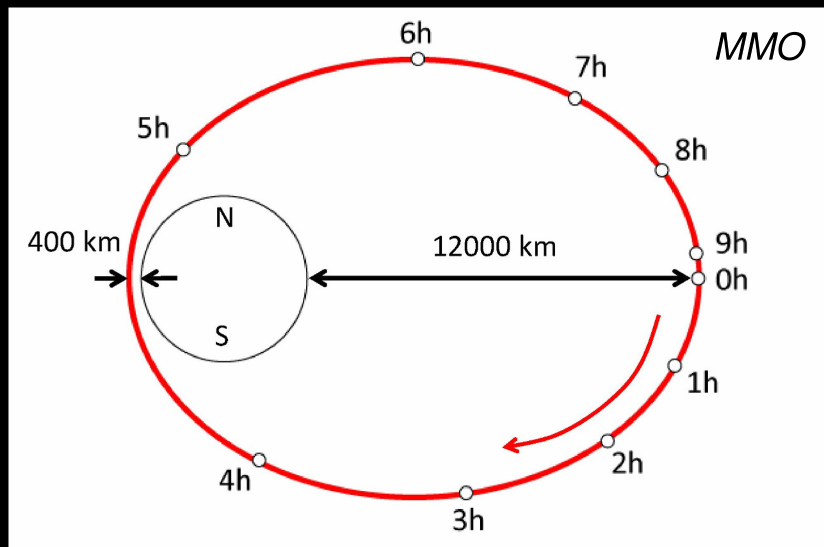
2. Different orbits ☞ Different science possibilities



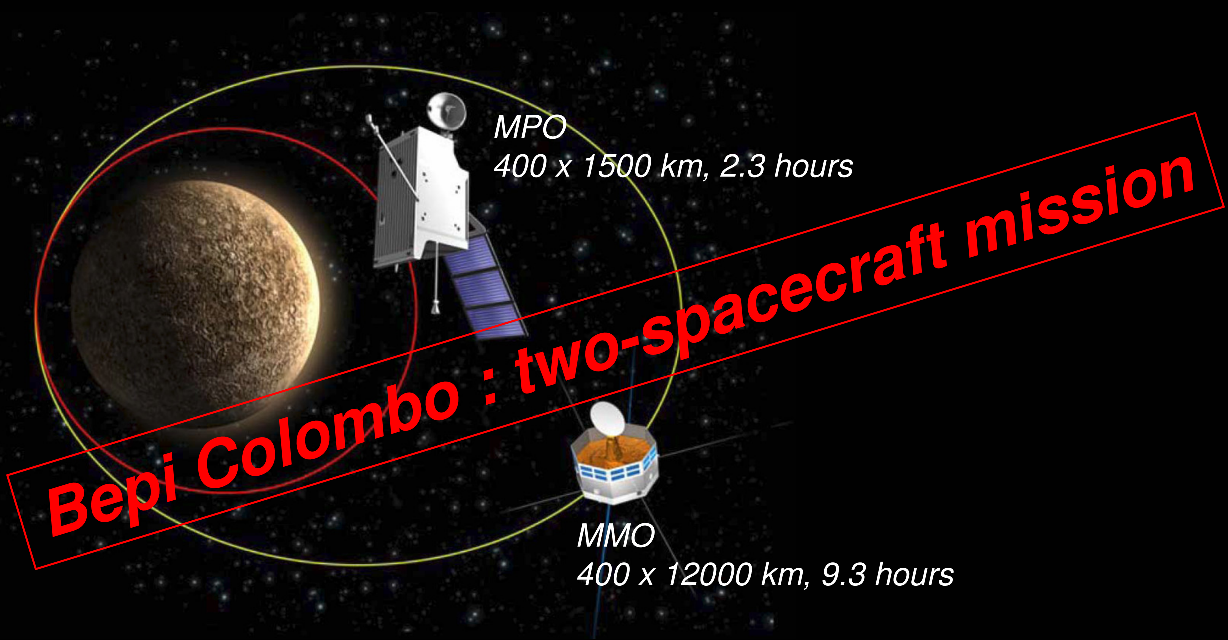


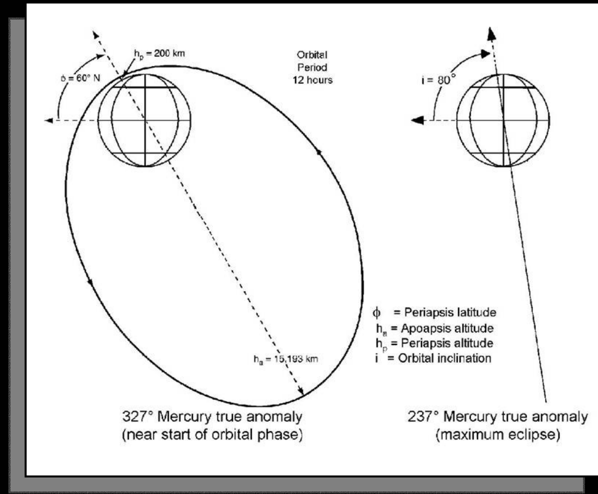
MESSENGER
nominal mission : 200 x 15000 km, 12 hours
extended mission : 200 x 10000 km, 8 hours



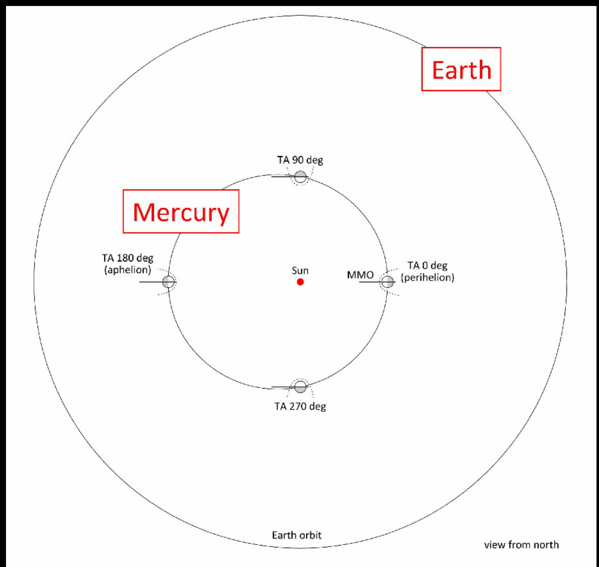


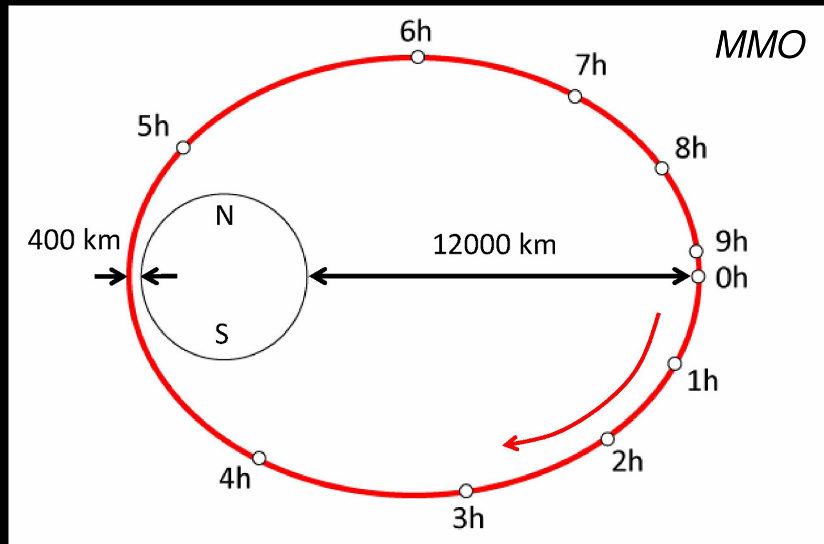
2. Different orbits ☞ Different science possibilities



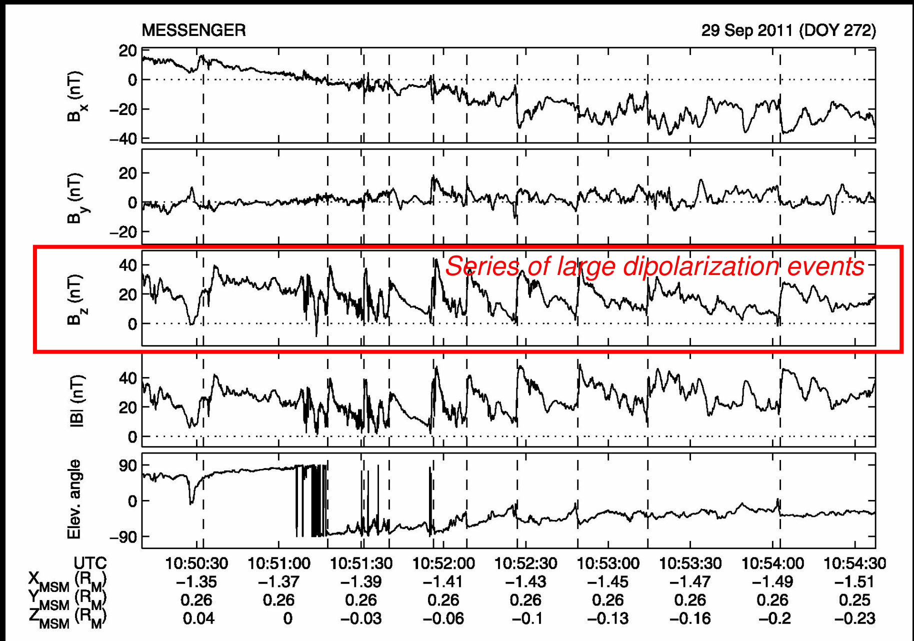


MESSENGER
nominal mission : 200 x 15000 km, 12 hours
extended mission : 200 x 10000 km, 8 hours



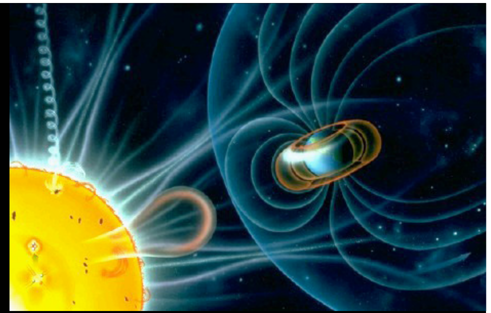


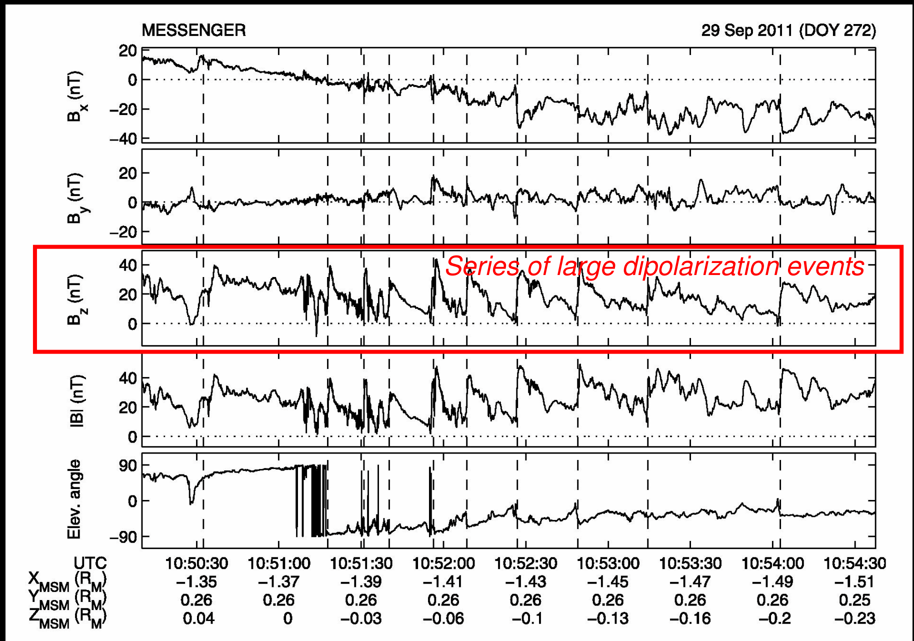
2. Different orbits ☞ Different science possibilities



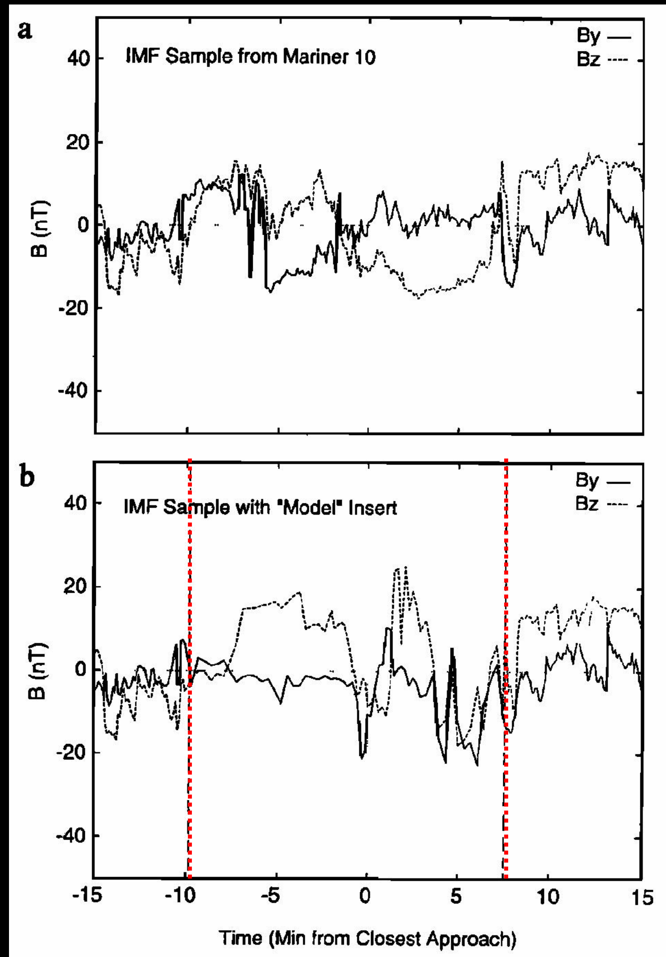
Sundberg et al. [2012]

2. Different orbits ☞ Different science possibilities



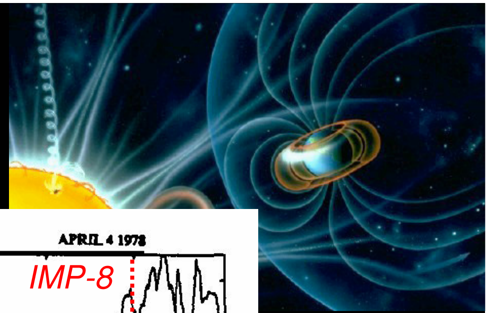


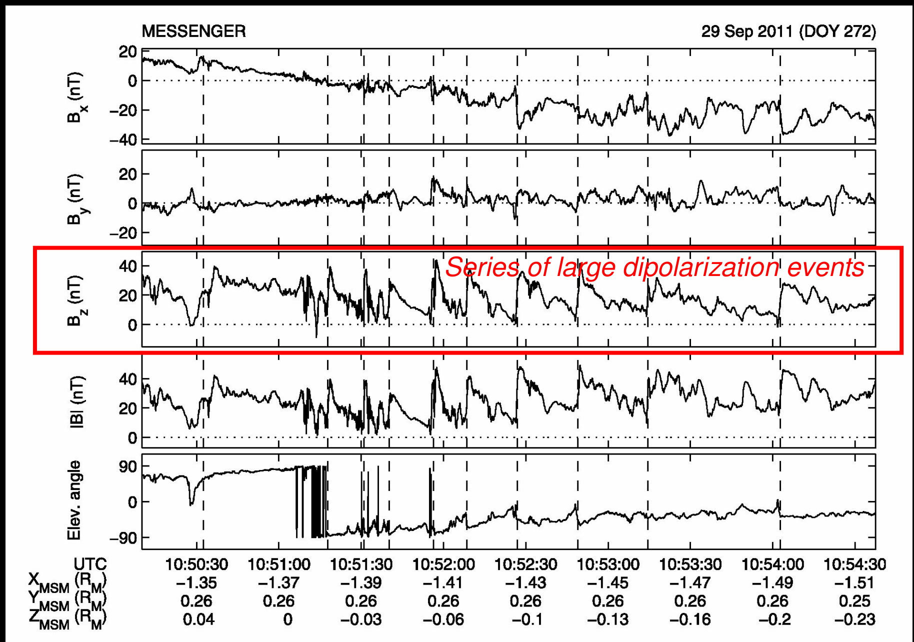
Sundberg et al. [2012]



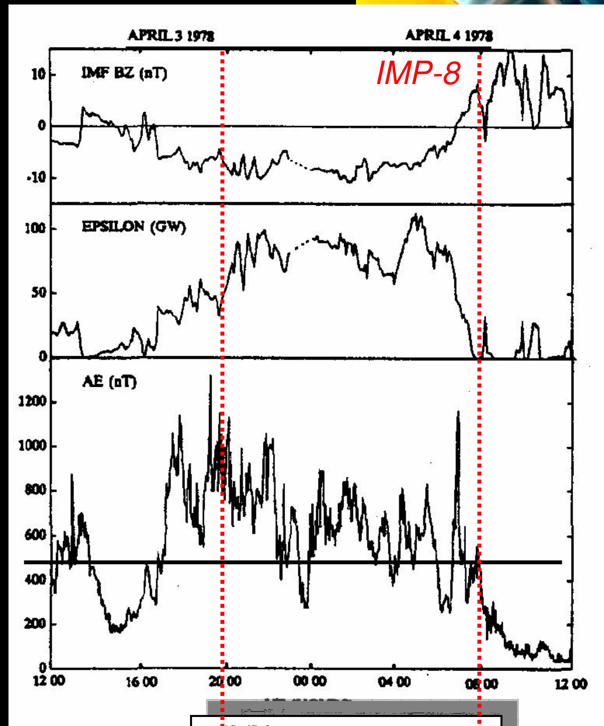
Luhmann et al. [1998]

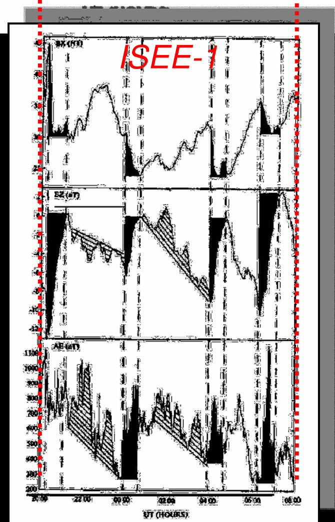
2. Different orbits ☞ Different science possibilities





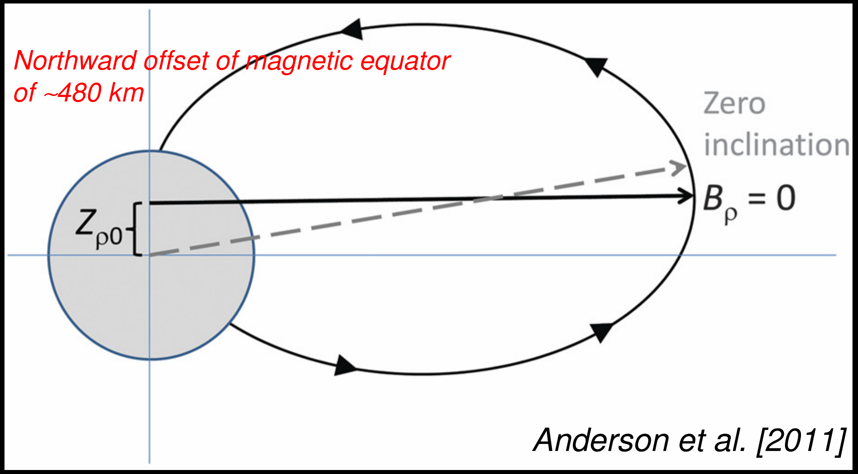
Sundberg et al. [2012]

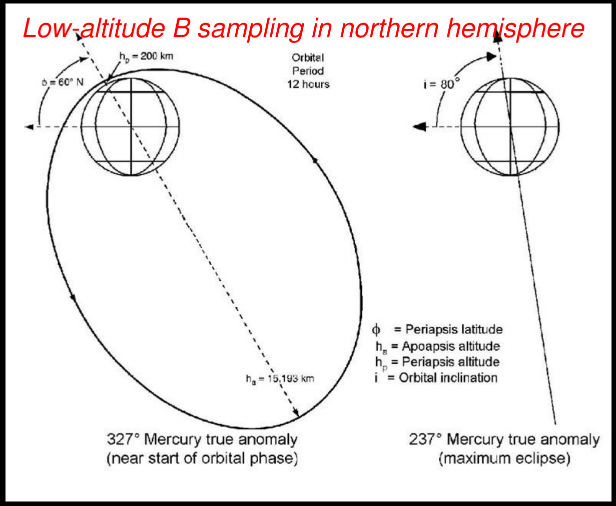




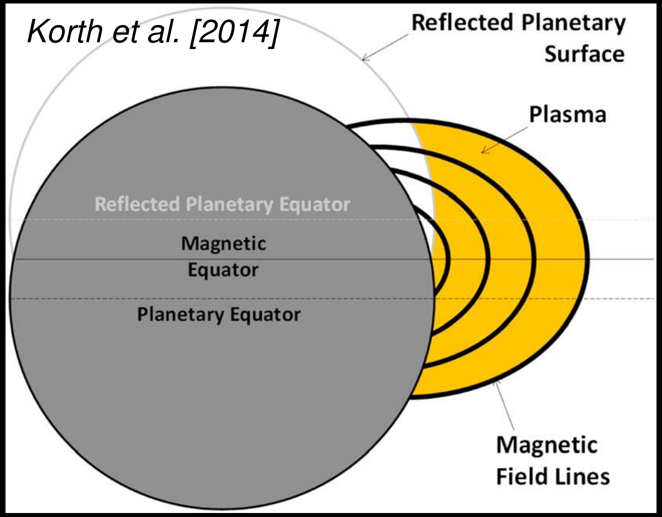
Jacquey et al. [1993]

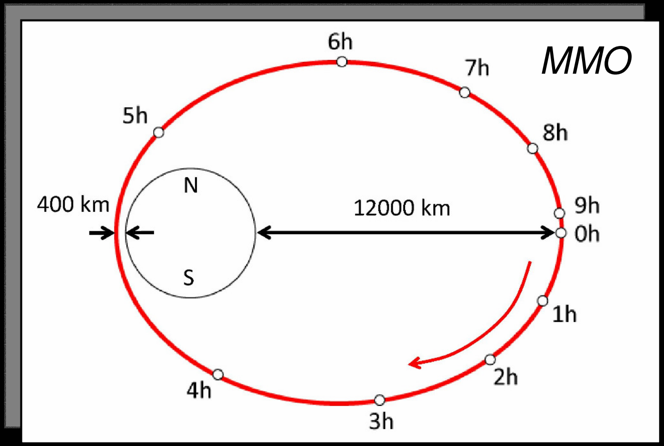
2. Different orbits ☞ Different science possibilities





MESSENGER
nominal mission : 200 x 15000 km, 12 hours
extended mission : 200 x 10000 km, 8 hours

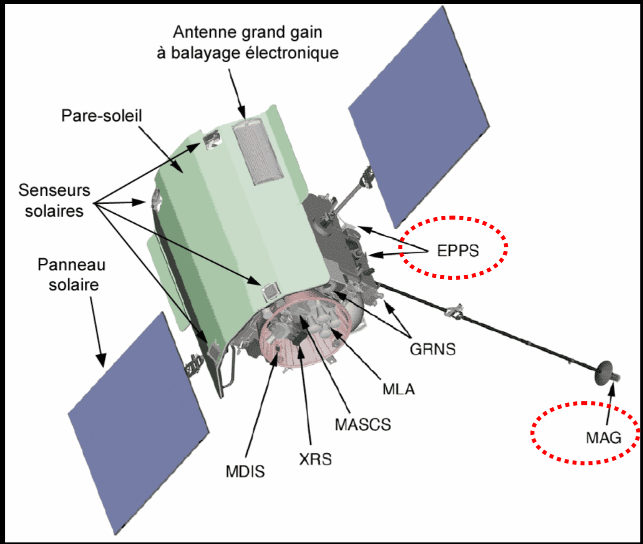




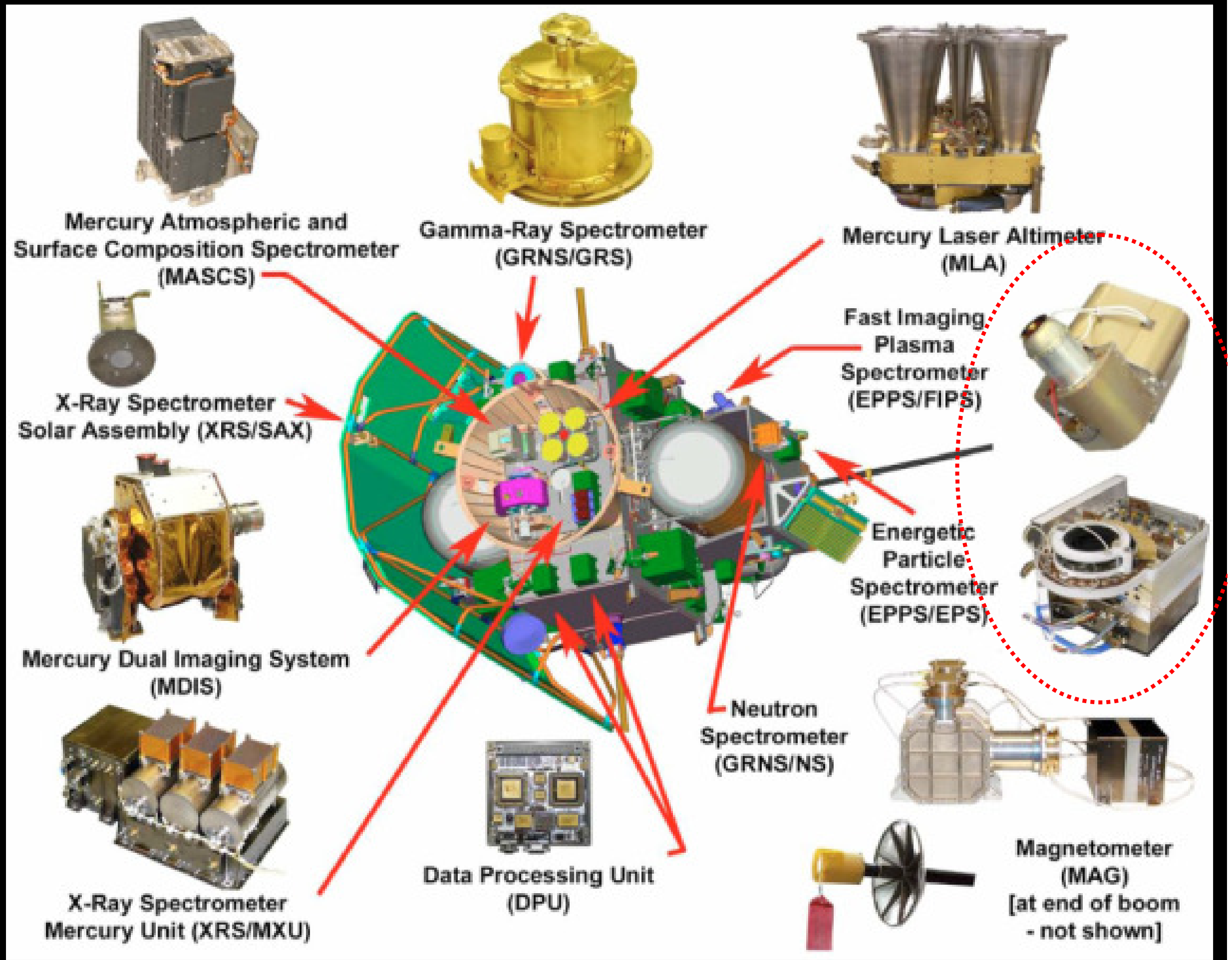
☞ *field-aligned currents [Blomberg and Cumnock, 2004]*

☞ *« offset dipole » versus « dipole + quadrupole » ?*

3. Different payloads ☞ Different science possibilities



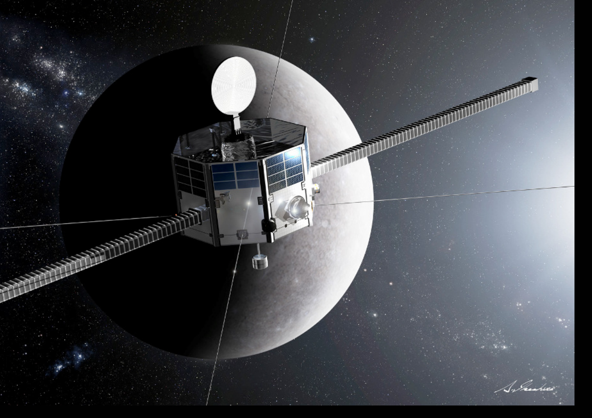
MESSENGER



3. Different payloads ☞ Different science possibilities

Bepi Colombo science:

Interior - Core/mantle, composition, magnetic field
Surface - Morphology, composition, temperature
Exosphere - Composition, dynamics, sources/sinks, coupling
Magnetosphere - Composition, dynamics, sources/sinks, coupling

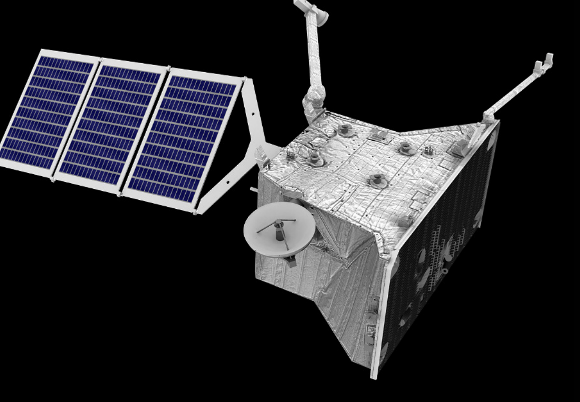


Mercury Magnetospheric Orbiter (MMO, JAXA)

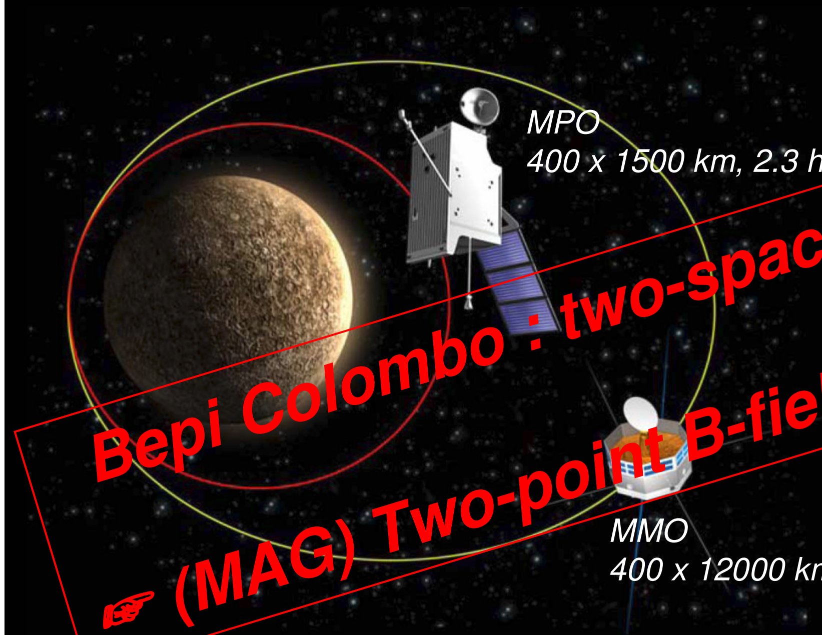
MERMAG	***magnetometer***
MPPE	***Mercury Plasma Particle Experiments (MEA, MIA, MSA, HEP, ENA)***
PWI	***Plasma Wave Investigations (SORBET, MEFISTO, EWO, LF-SC, DB-SC, WPT, AM2P)***
MSASI	*exosphere imager*
MDM	*dust analyzer*

Mercury Planetary Orbiter (MPO, ESA)

BELA	*laser altimeter*
ISA	*radio science*
MERMAG	***magnetometer***
MERTIS	*IR spectrometer*
MGNS-MANGA	*γ-neutron spectrometer*
MIXS / SIXS	*X spectrometer*
PHEBUS	*UV spectrometer*
SIMBIO-SYS	*imager, visible-NIR spectrometer*
SERENA	***Search for Exospheric Refilling and Emitted Natural Abundances (ELENA, MIPA, PICAM, STROFIO)***

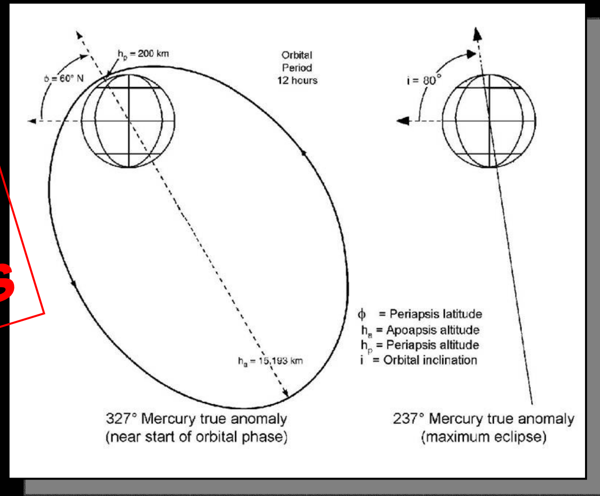


3. Different payloads ☞ Different science possibilities



Bepi Colombo : two-spacecraft mission

☞ (MAG) Two-point B-field measurements



MESSENGER
nominal mission : 200 x 15000 km, 12 hours
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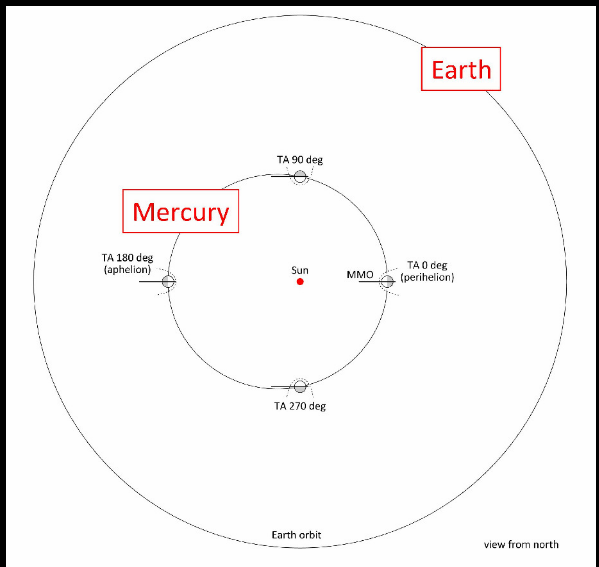
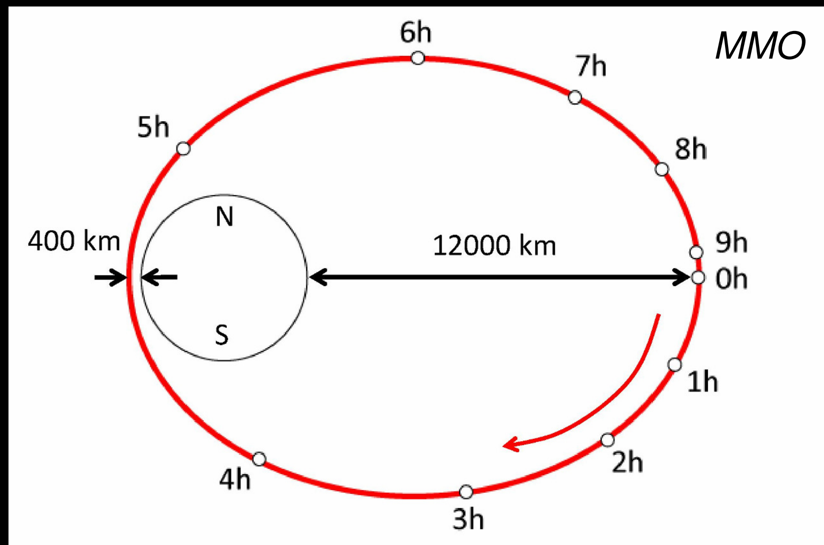
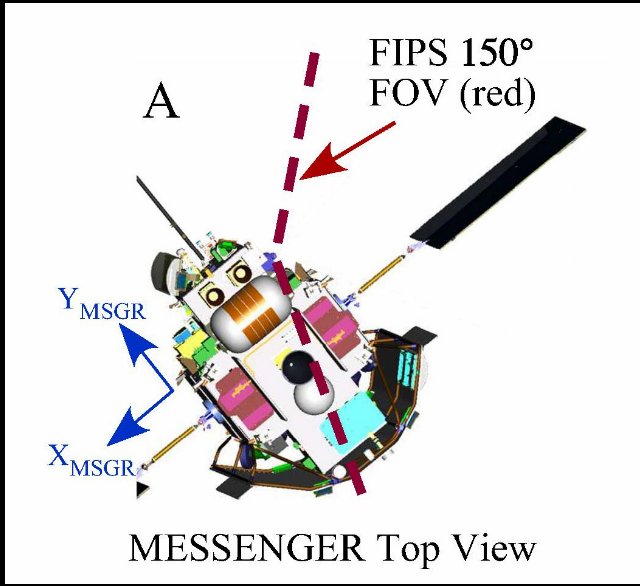
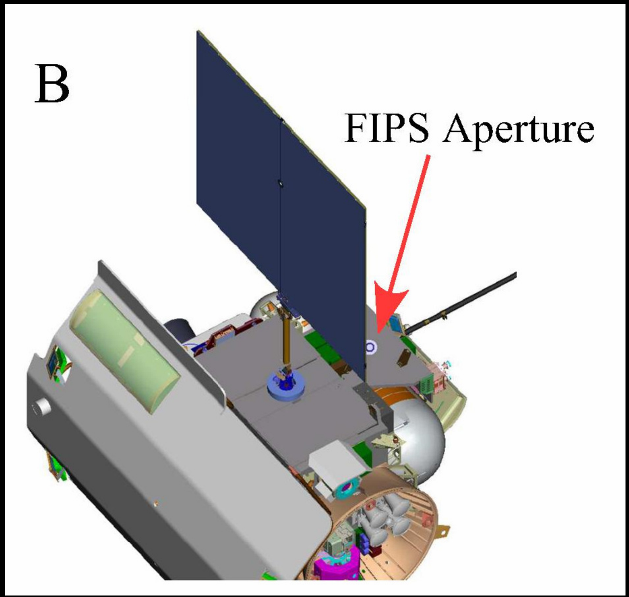






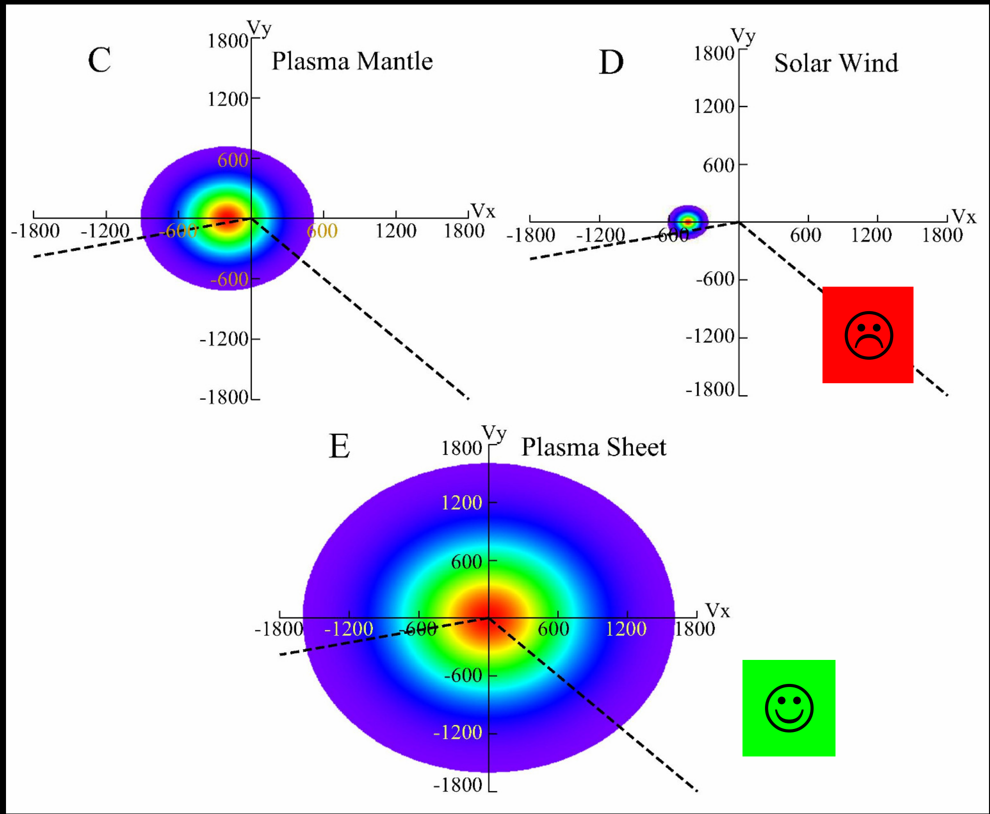


Raines et al. [2010]

Three-dimensional Ion Distributions

FIPS ion measurements :

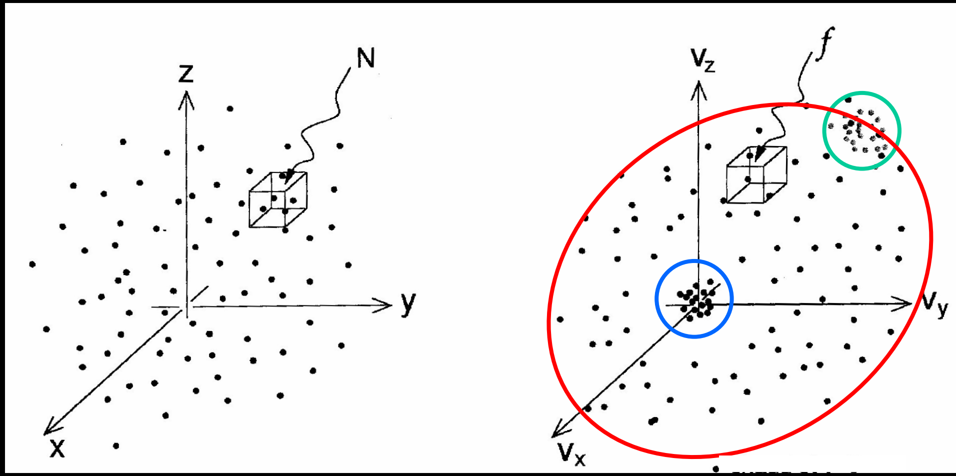
- full energy range (0.05-13 keV/q) scanned in 8 s
- 15° angular resolution over 1.4π steradian FOV



Three-dimensional Ion Distributions

N particles in 3-D volume element of configuration space

distribution of these N particles in 3-D velocity space (cold quasi-stagnant, cold beam, hot)



3D distribution function $f = \dfrac{N}{dx\,dy\,dz\,dv_x\,dv_y\,dv_z}$

3D distribution function f is not an abstract quantity

It is measured indirectly from directional differential flux : $f = \dfrac{m^2}{2E} j$

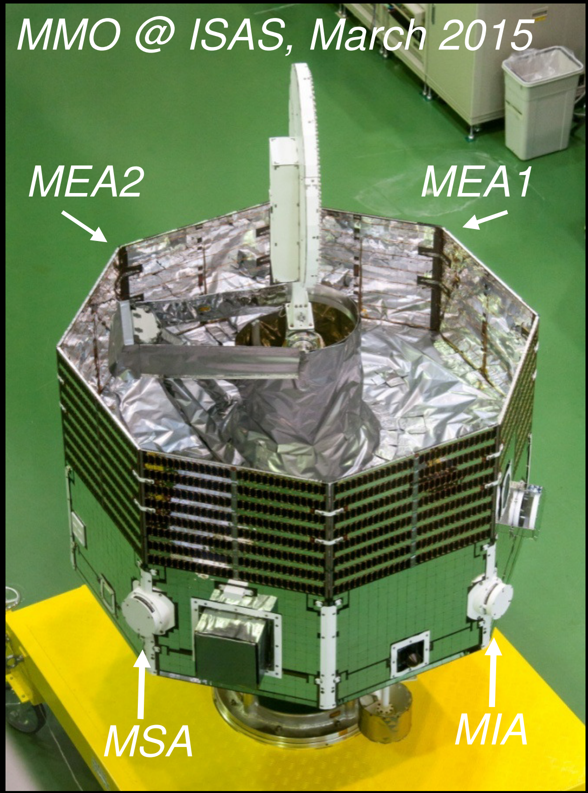
j being obtained from particle count rate : $j = \dfrac{C}{G\,E}$

☞ 0^{th} order moment = number density

☞ 1^{st} order moment = bulk velocity

☞ 2^{nd} order moment = pressure tensor

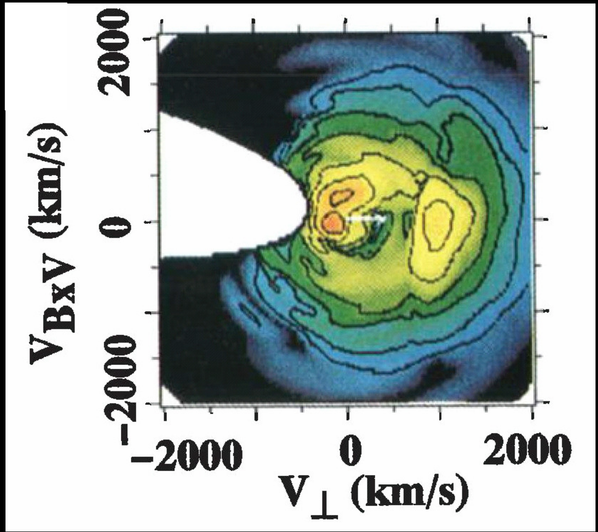
Hence, information on particle populations and dynamics



Onboard MMO, 3D distributions obtained in 1 s

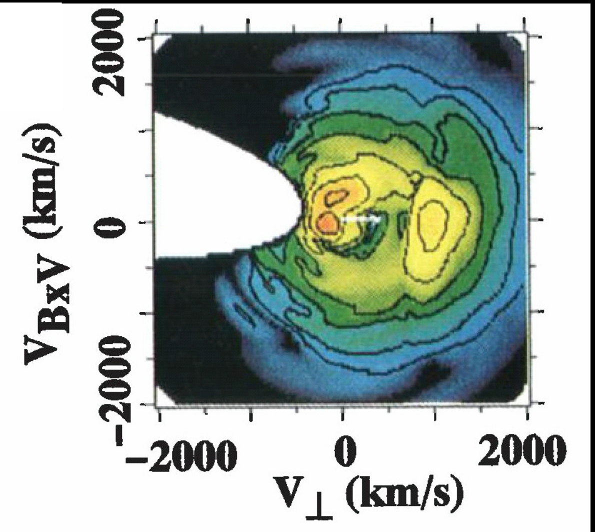
- electrons from MEA 1-2 (3 eV/q - 30 keV/q)
- ions from MIA (5 eV/q – 30 keV/q) and MSA (1 eV/q – 38 keV/q ; mass : 1-60)

Three-dimensional Ion Distributions

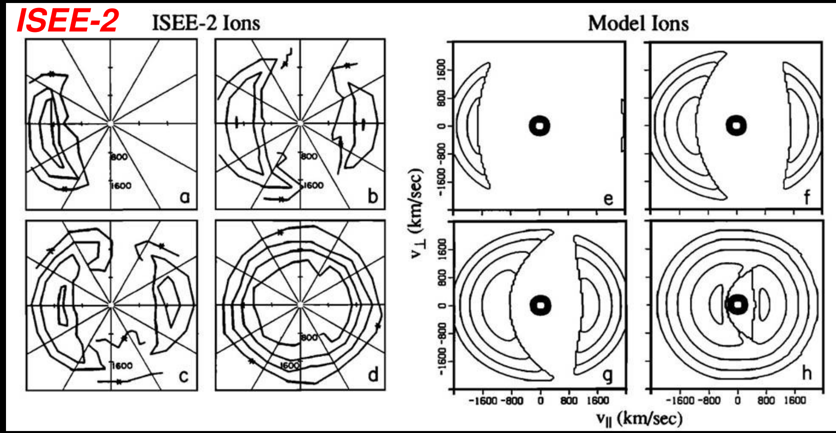


Hoshino et al. [1998]

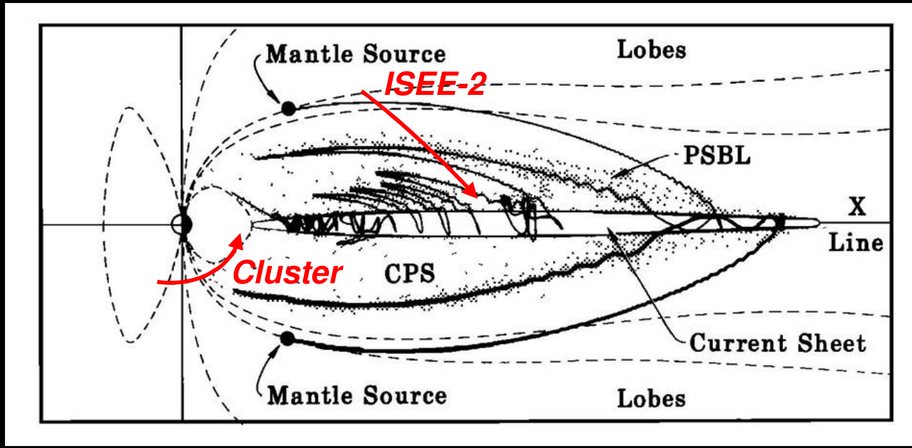
Three-dimensional Ion Distributions



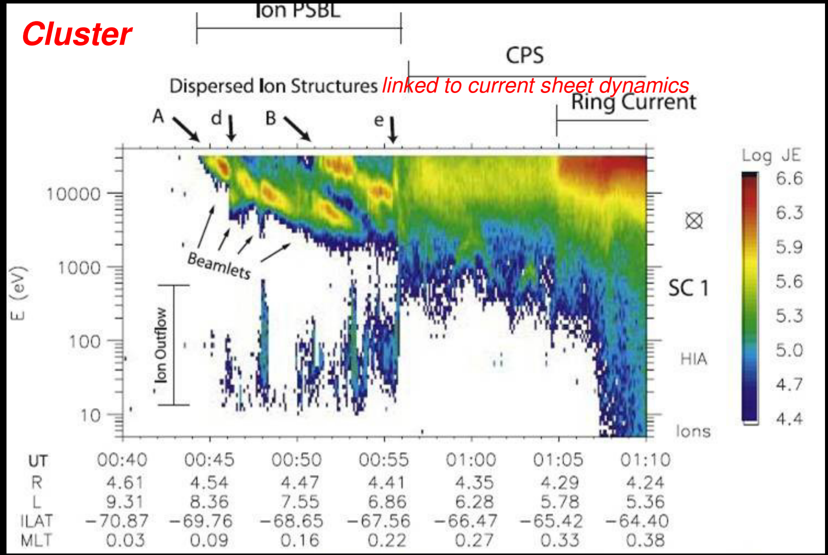
Hoshino et al. [1998]



Onsager et al. [1991]

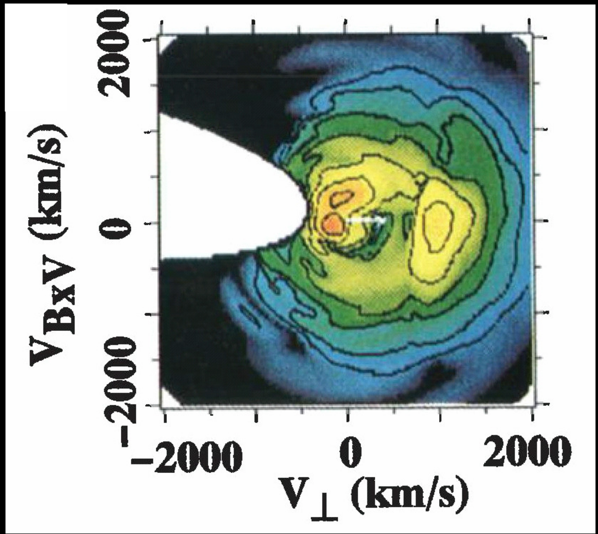


Ashour-Abdalla et al. [1993]

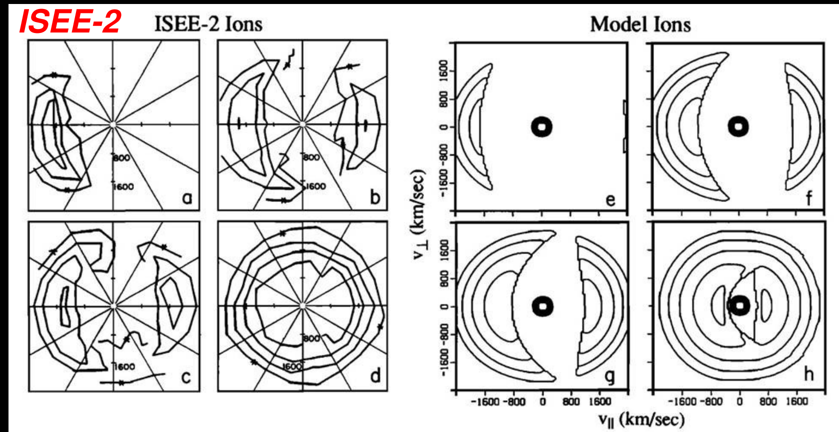


Keiling et al. [2004]

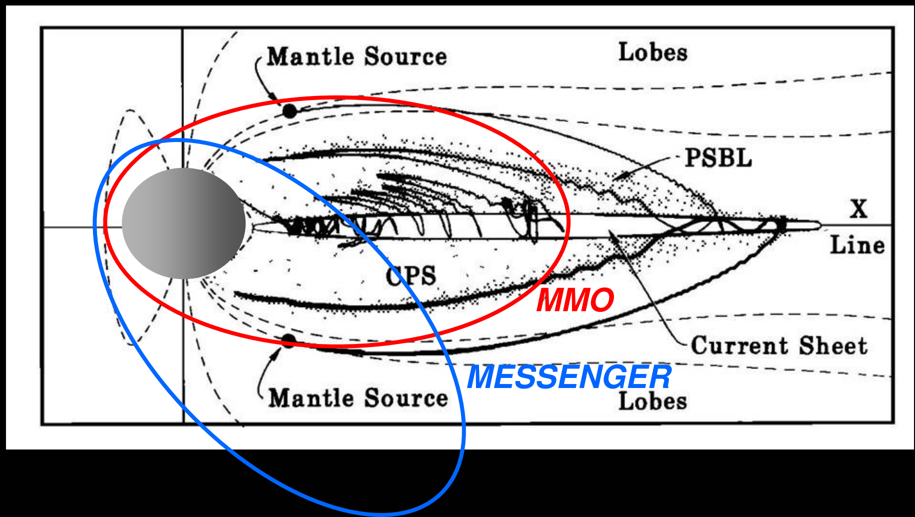
Three-dimensional Ion Distributions

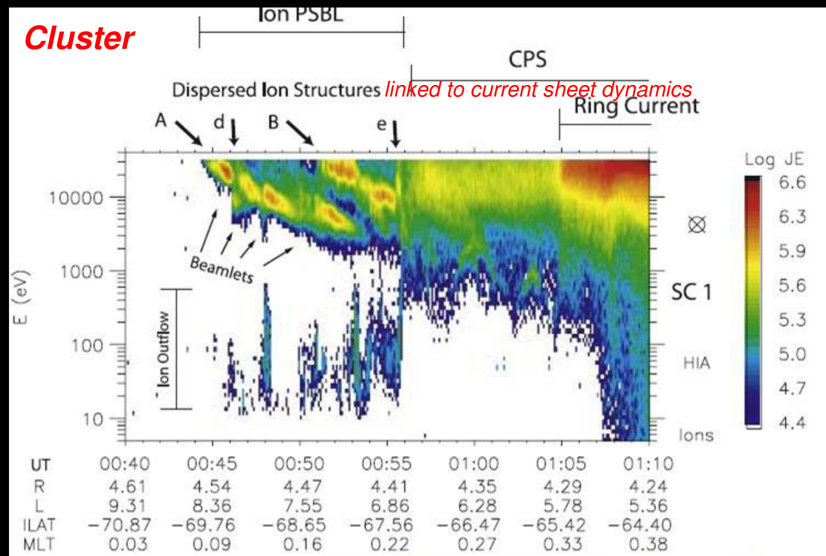


Hoshino et al. [1998]



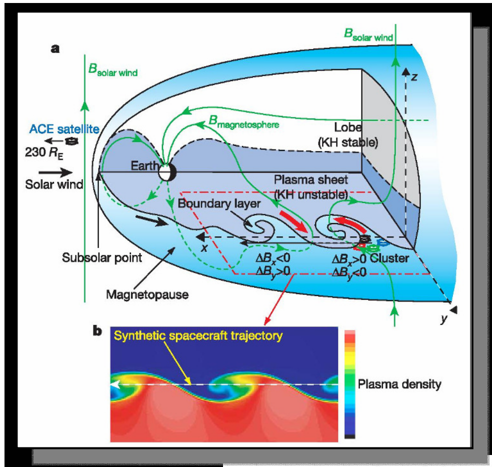
Onsager et al. [1991]



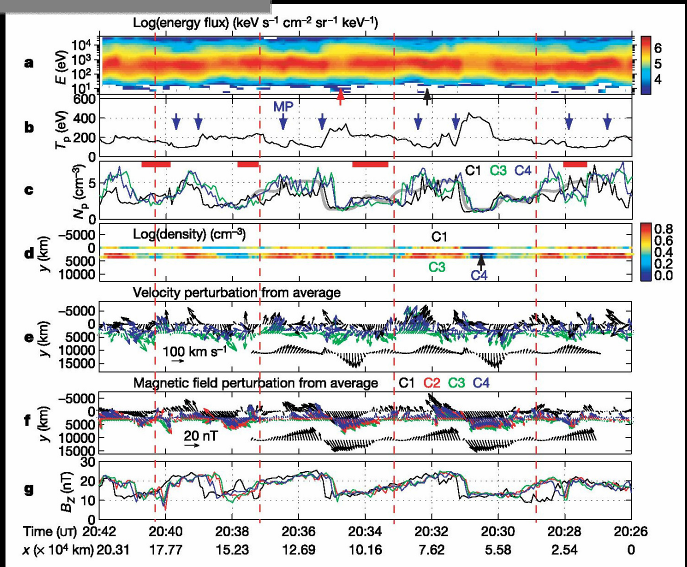


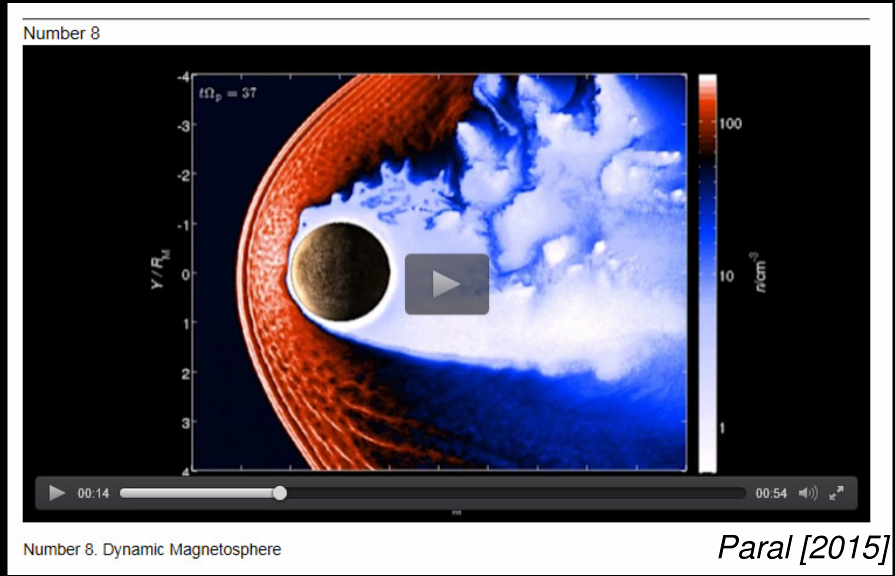
Keiling et al. [2004]

Three-dimensional Ion Distributions



Hasegawa et al. [2004]



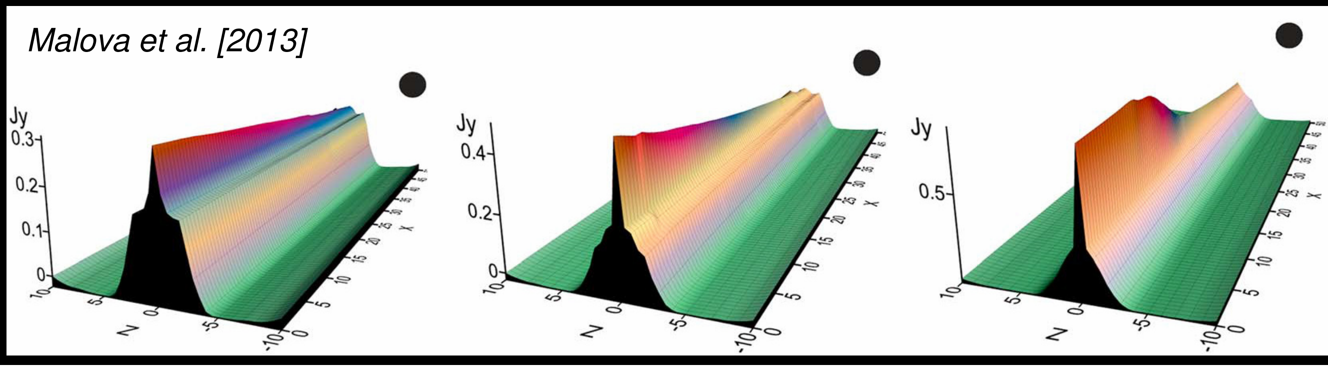


Paral [2015]

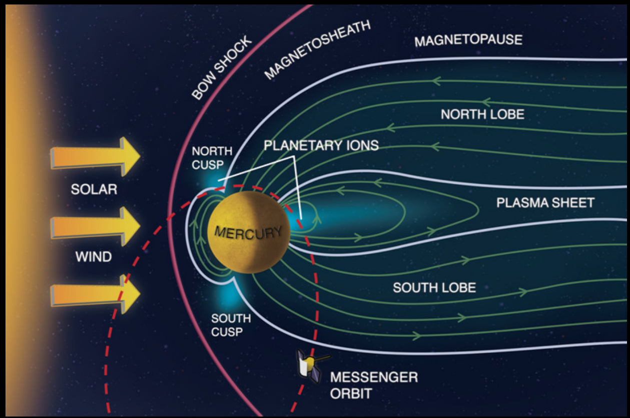
☞ *Large velocity shear layer with small K-H growth rate on dawnside*

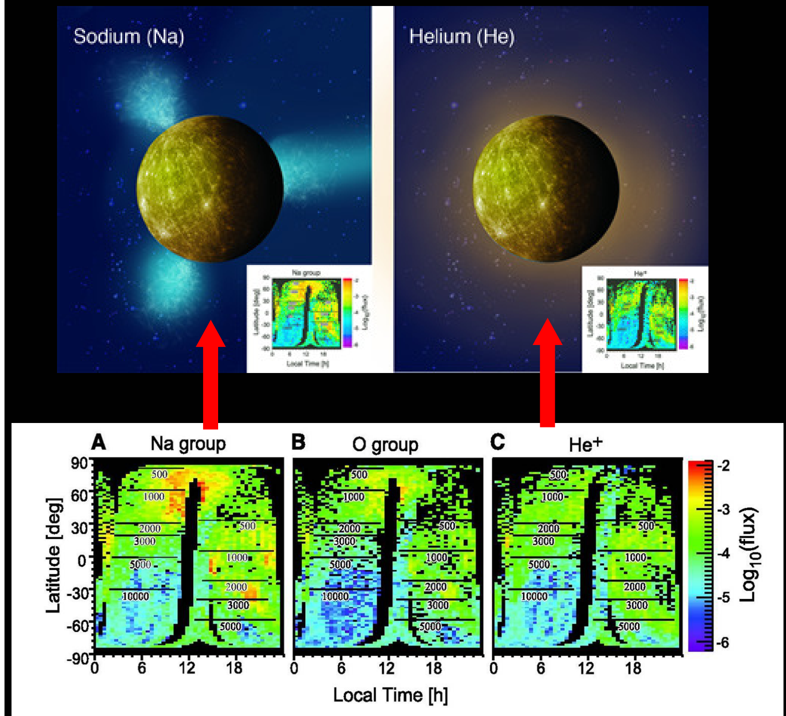
☞ *Structure of magnetotail current sheet*

Malova et al. [2013]

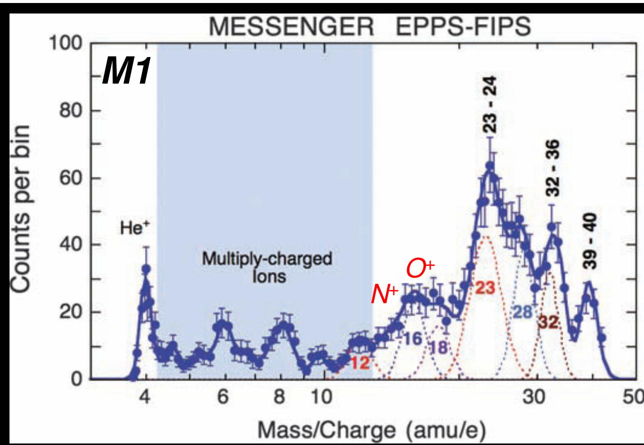


Composition

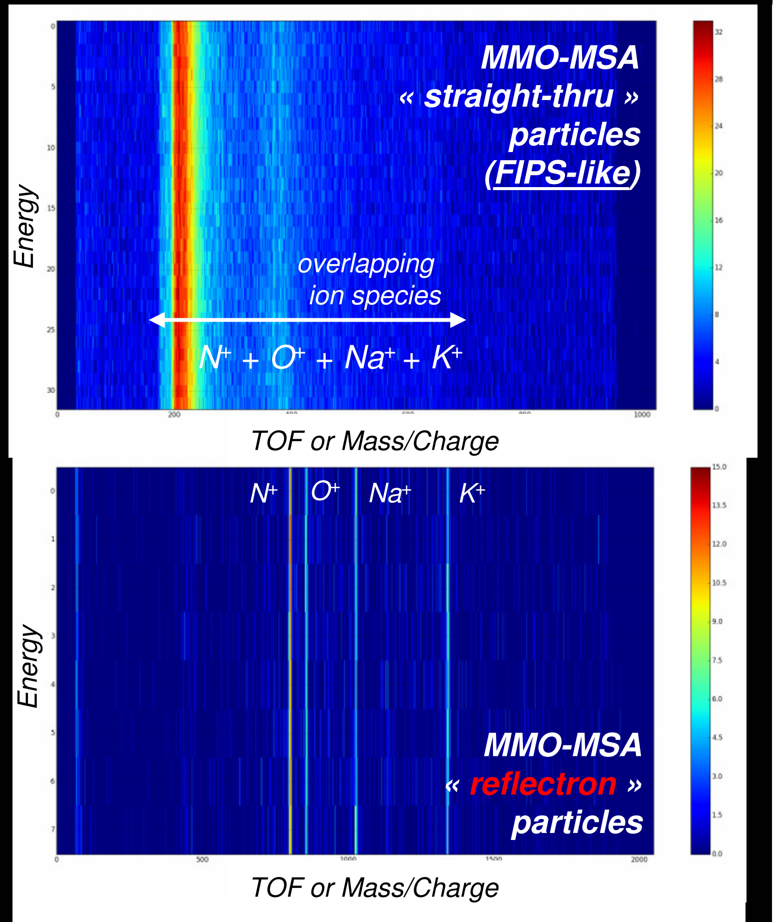




Zurbuchen et al. [2011]



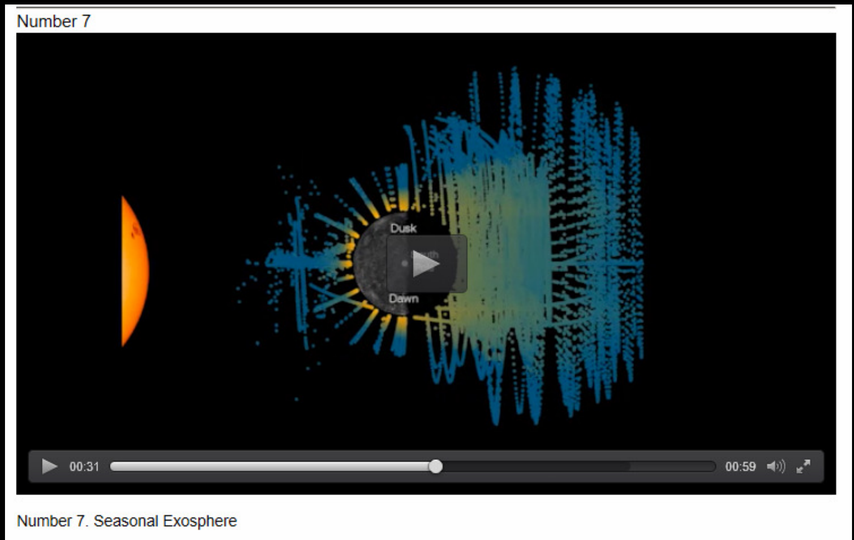
Zurbuchen et al. [2008]



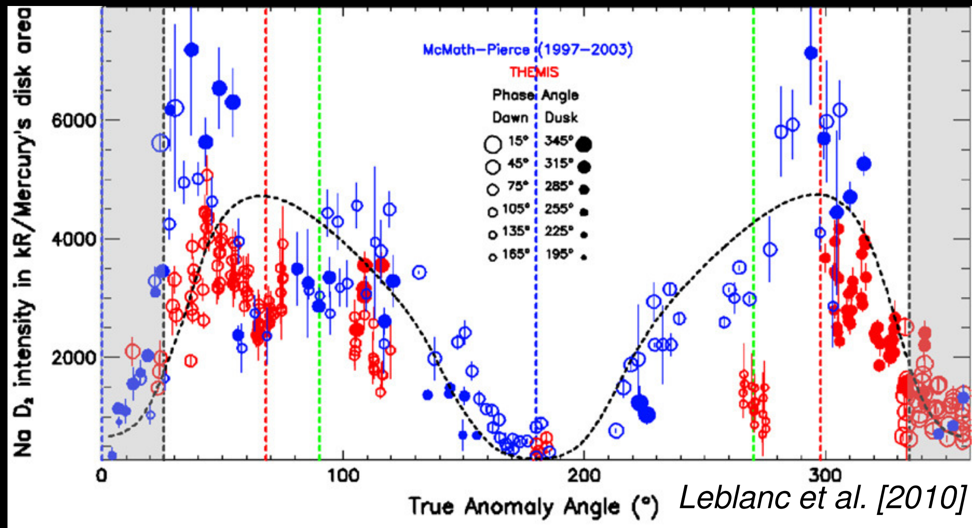
Composition

Baumgardner et al. [2008]

☞ *Coupling with exosphere*
(UV spectrometer but not only)



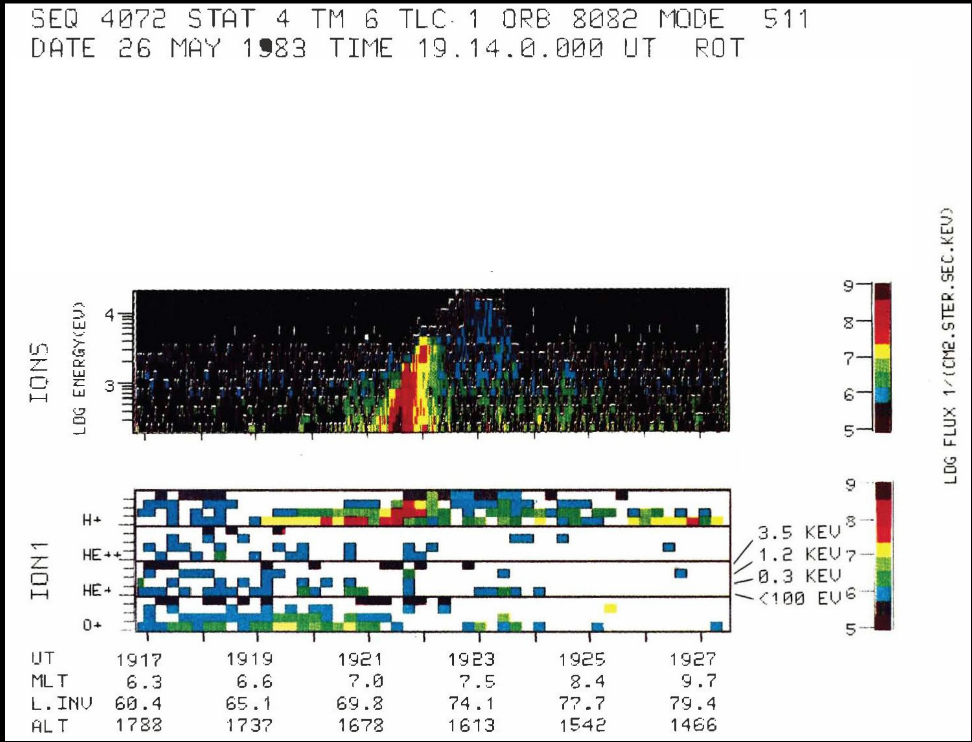
Number 7. Seasonal Exosphere



Leblanc et al. [2010]

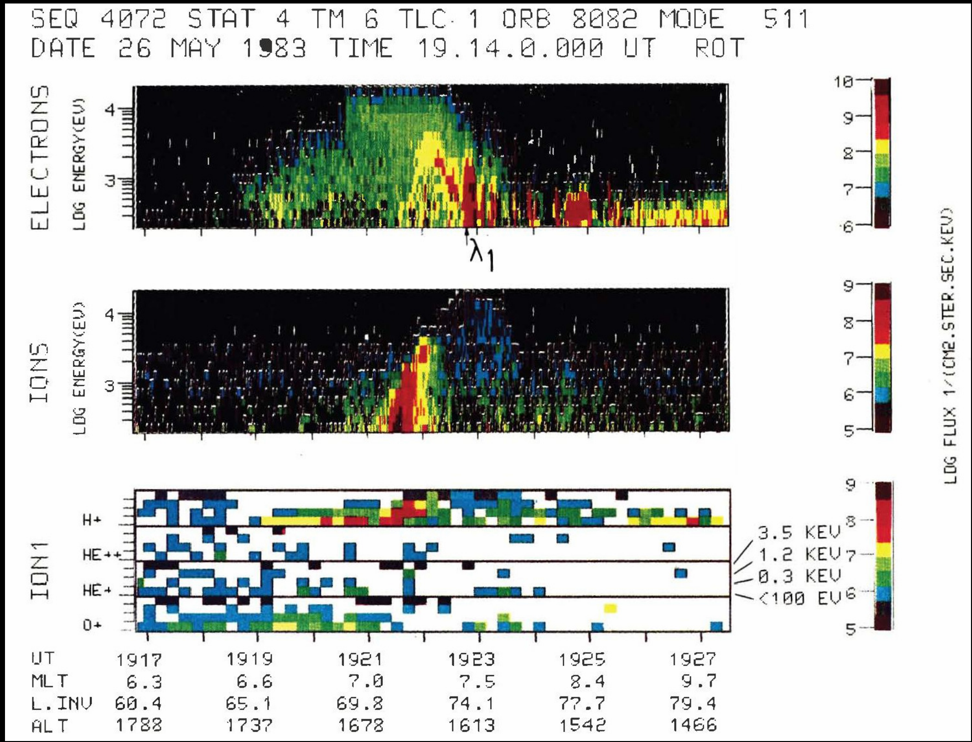
☞ *Exospheric Na content not constant*
over a complete Mercury's cycle

Electron measurements



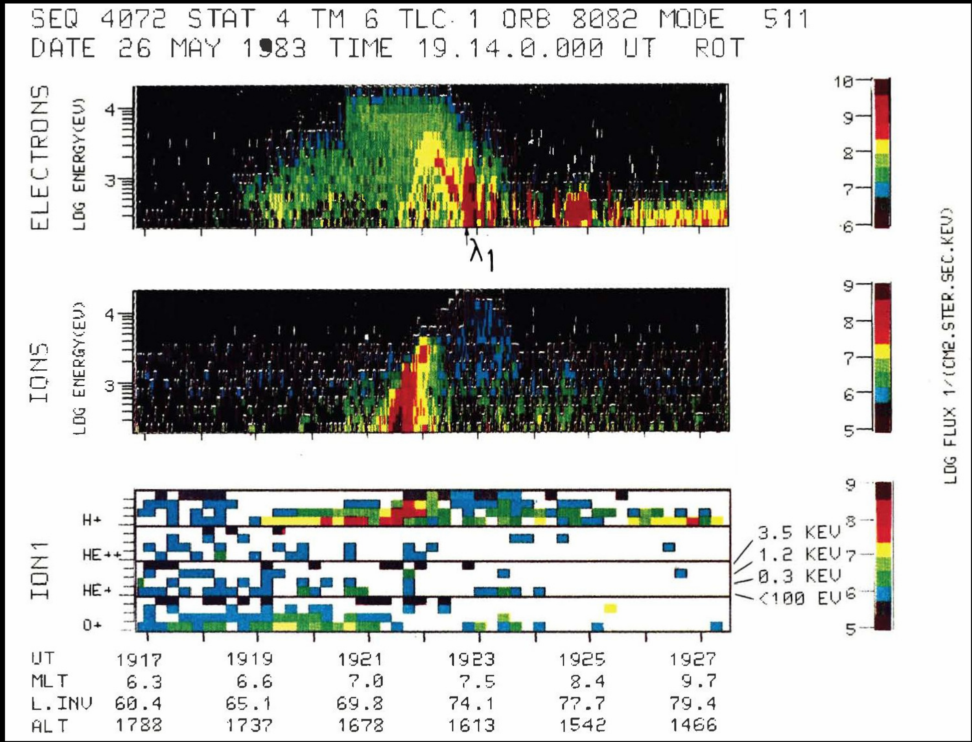
Bosqued et al. [1986]

Electron measurements

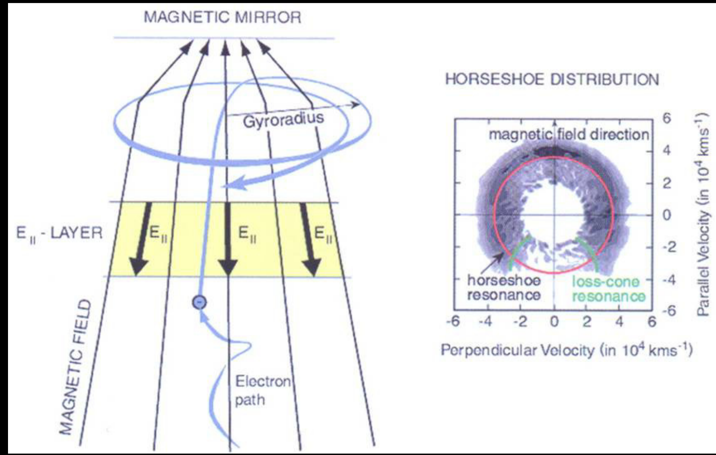


Bosqued et al. [1986]

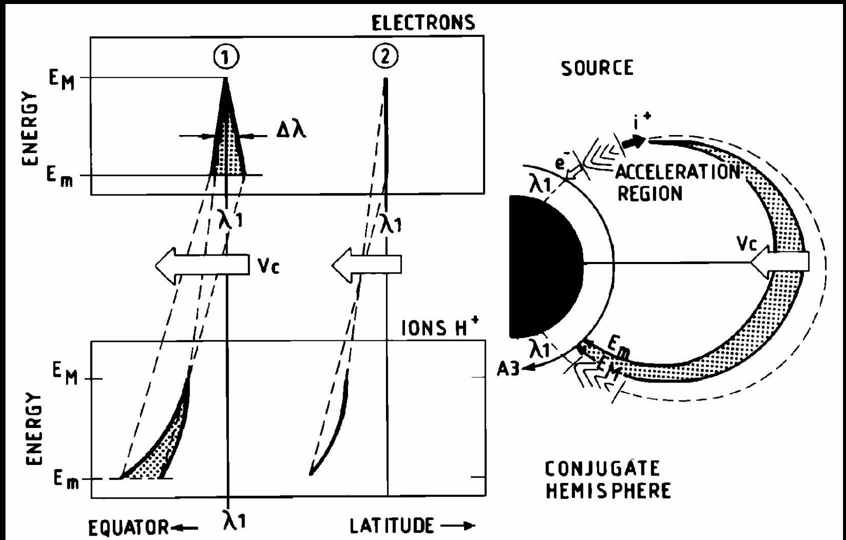
Electron measurements



Bosqued et al. [1986]

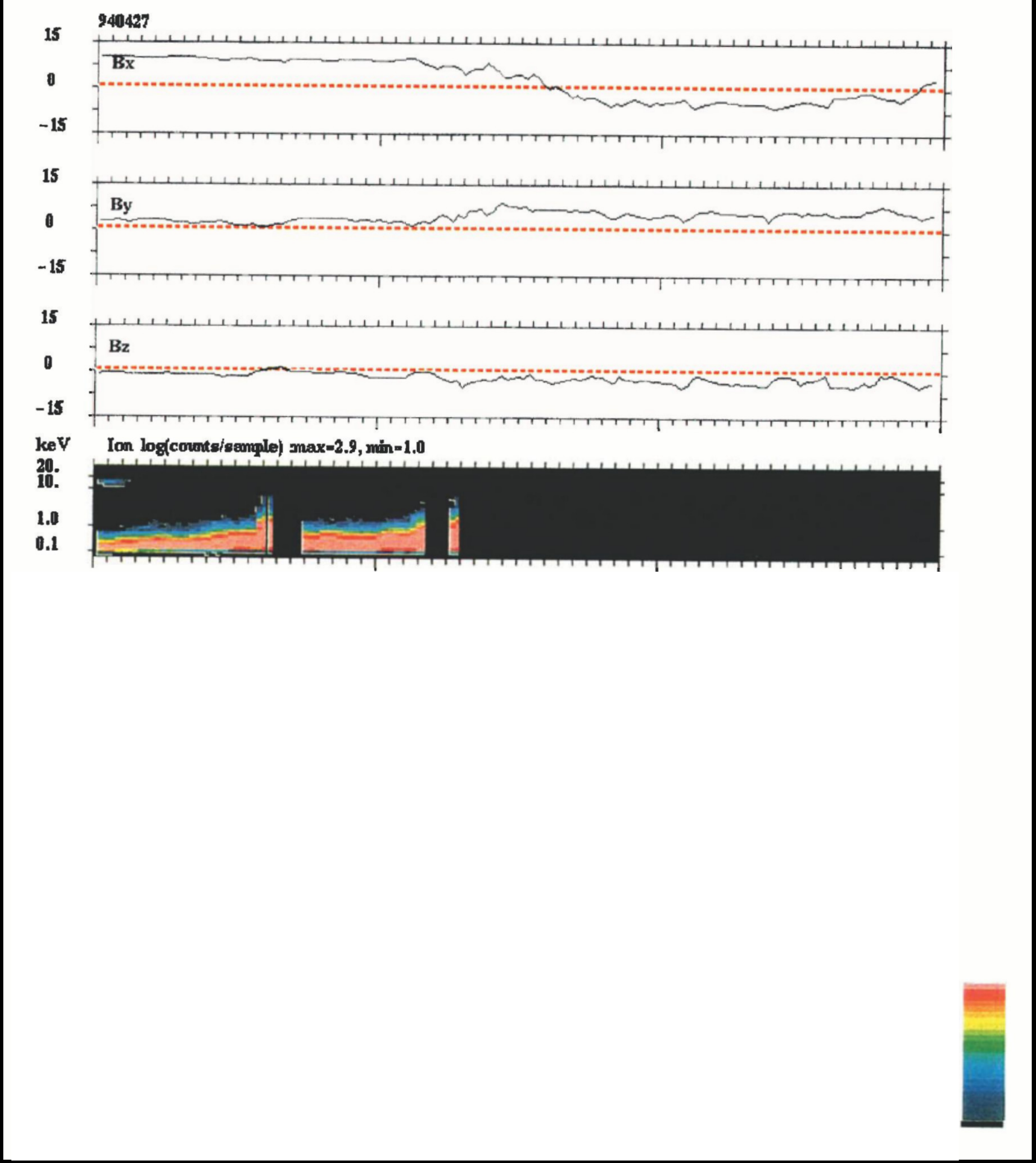


Blomberg et al. [2007]



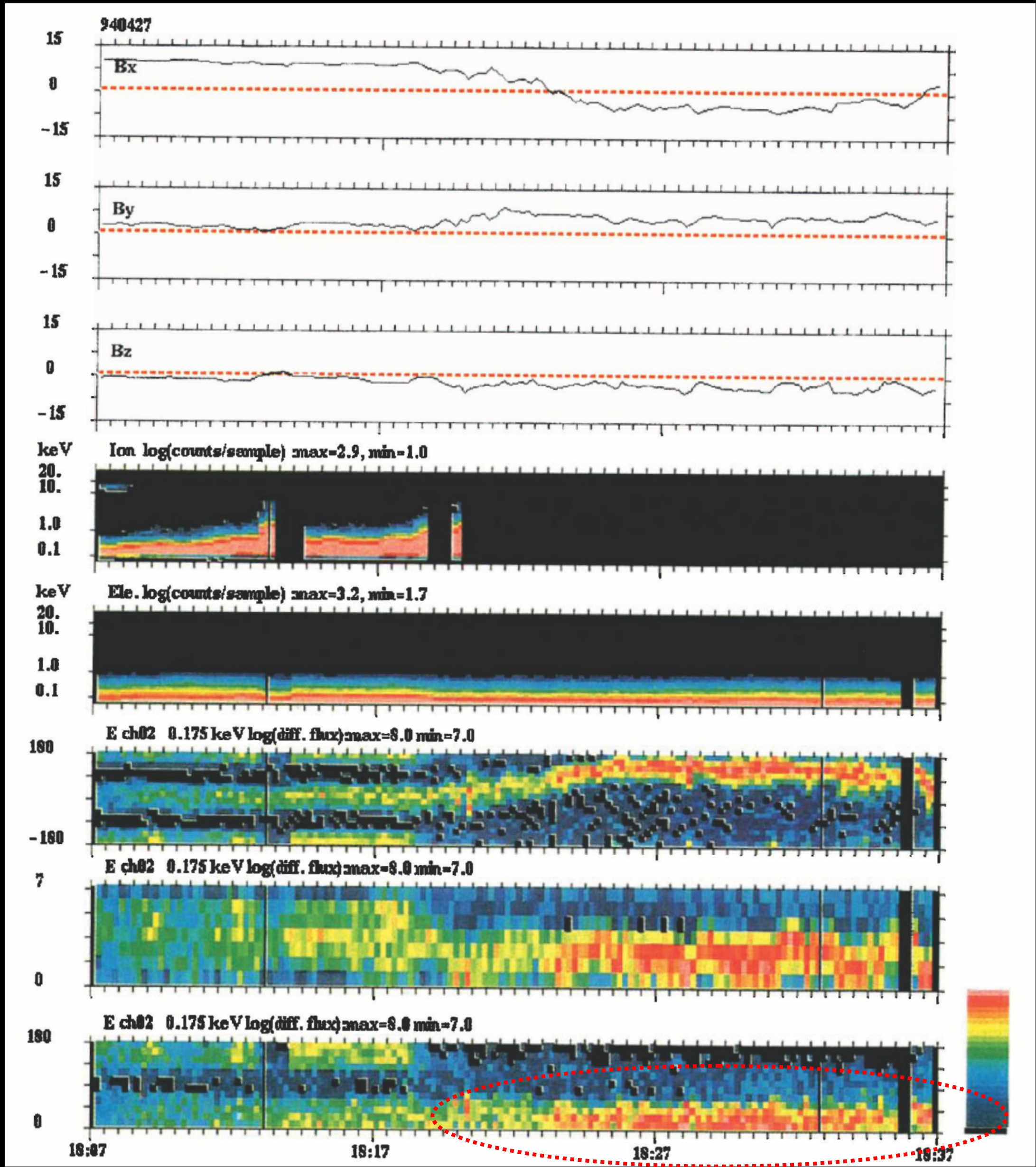
☞ *Ion acceleration through low-altitude inverted Vs*

Electron measurements



Shirai et al. [1998]

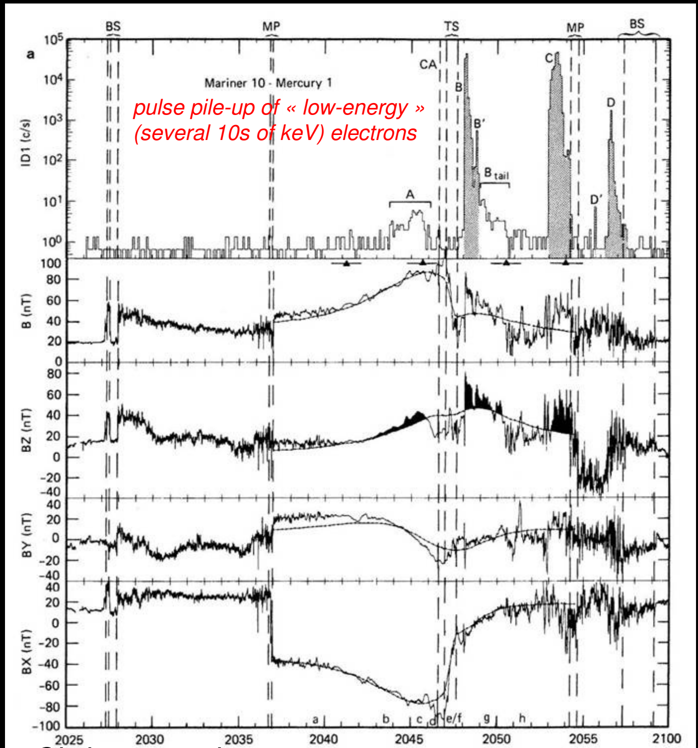
Electron measurements



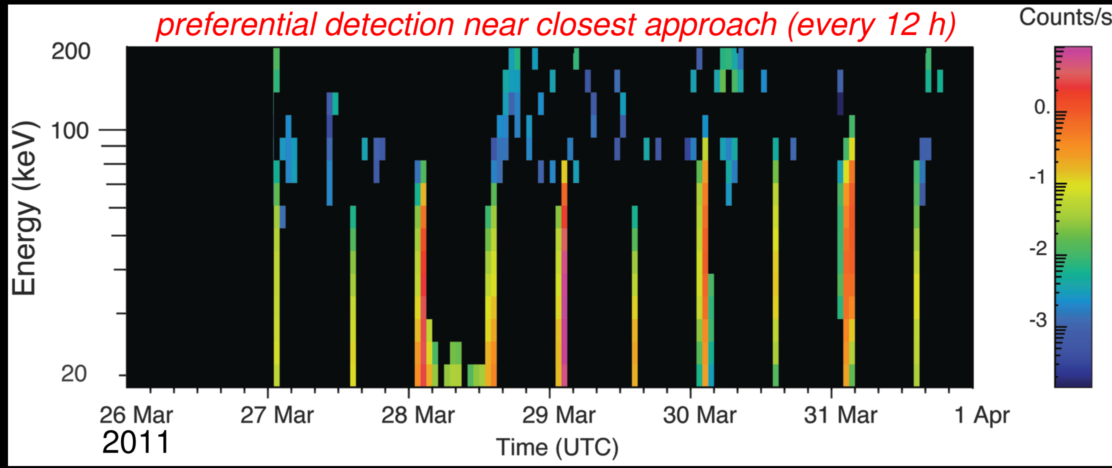
Shirai et al. [1998]

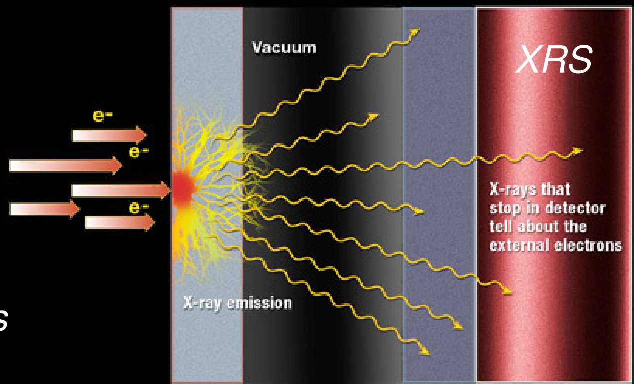
☞ « Polar rain » observed in distant tail (X = -200 RE)

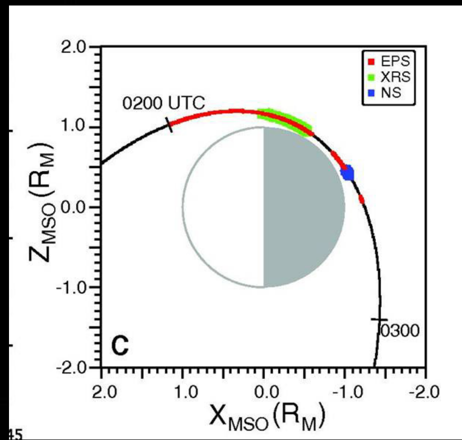
Electron measurements / Energetic particles



Christon et al., 1987







Ho et al. [2011]

☞ *Indirect evidences of energetic electrons from XRS (caused by bremsstrahlung of ~10 keV electrons).*

☞ *EPS (25 keV-1 MeV) measures only the high-energy tail of energetic electron bursts.*

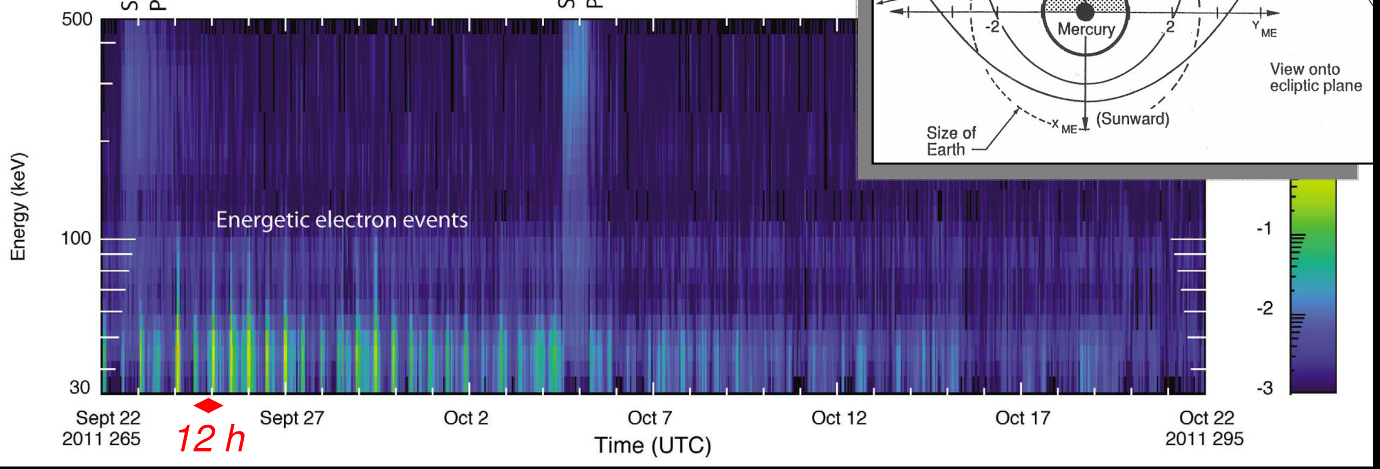
Onboard MMO, 3D distributions obtained in 1 s
- electrons from MEA 1-2 (3 eV/q - 30 keV/q)
- ions from MIA (5 eV/q – 30 keV/q)
and MSA (1 eV/q – 38 keV/q ; mass : 1-60)

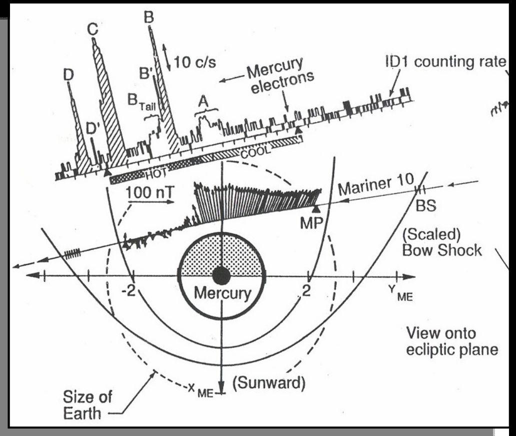
Energetic particles

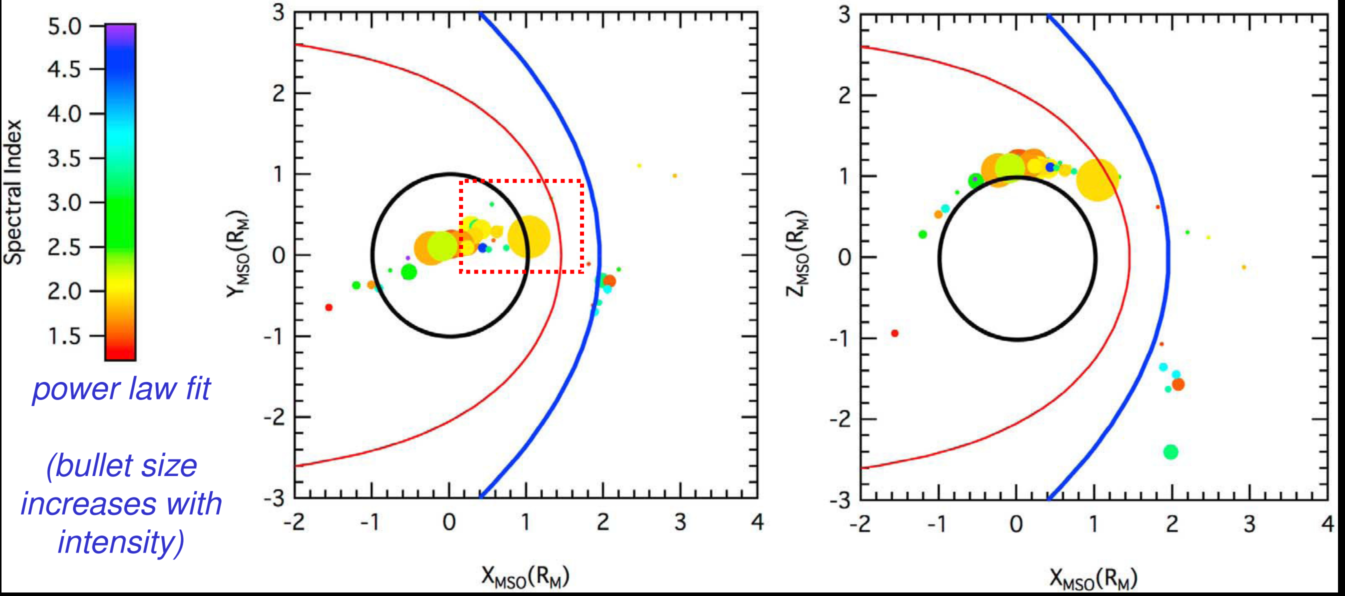
Onboard MMO :

- *HEP-electrons : 30-700 keV (FOV : 20°x130°)*
- *HEP-ions : 30-1500 keV (FOV : 11°x110°)*

One month of energetic electron data characteristic of other periods in noon-midnight configuration (few events in dawn-dusk configuration)







☞ *Most intense energetic electron events near northern dayside cusp*

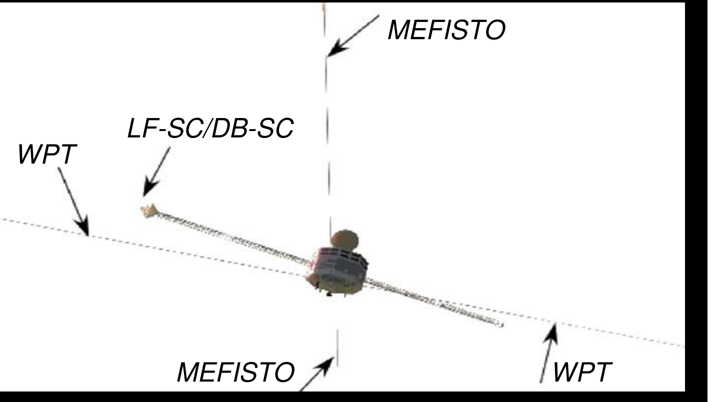
☞ *Some moderate-size events near local midnight*

Ho et al. [2012]

Plasma Wave Investigation (PWI) onboard MMO

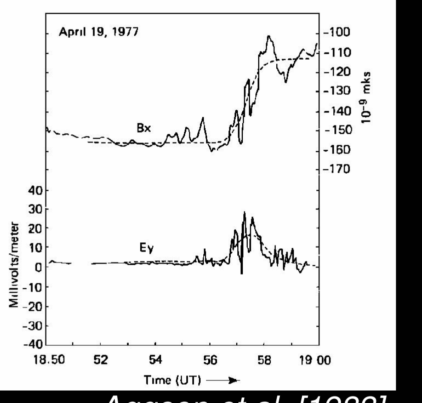
☞ **NEW wrt MESSENGER payload**

☞ two sets of E field sensors : MEFISTO, WPT
[DC-10 MHz]
two sets of B field sensors : LF-SC, DB-SC
[1 Hz-20 kHz, 10 kHz-640 kHz]
three sets of receivers : SORBET, AM2P, EWO



☞ MEFISTO, WPT (spin plane) :

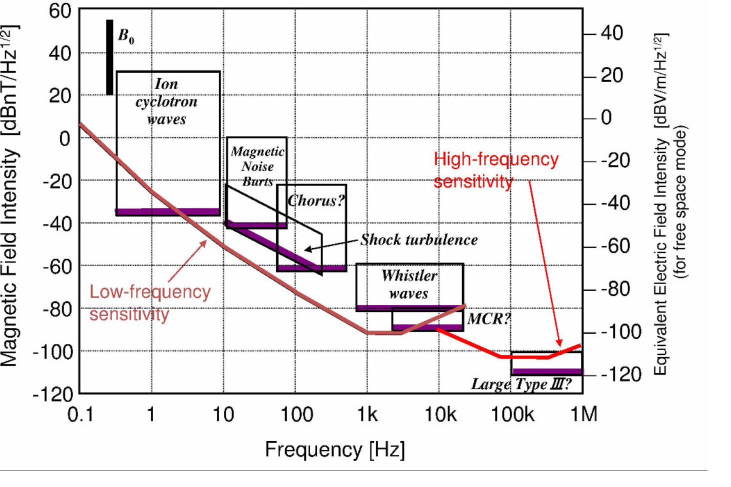
- first in situ E-field measurements in specific environment (lack of conducting ionosphere that limits potential drop, dipole offset leading to precipitation asymetry…)
- plasma convection (DC), ULF wave, substorm phenomena (induced E-field), field-aligned currents (current closure), coupling with solar wind and characterization of upstream electron populations, Hermean Kilometric Radiation (trapped below 80 kHz)…



Aggson et al. [1983]

☞ LF-SC (spin plane), DB-SC (spin axis) :

- many scientific goals (identification of magnetospheric regions and boundaries, substorms, wave-particle interactions, solar wind monitoring, turbulence…) that all include wave mode analysis (e.g., whistlers, KAWs, EMIC…)



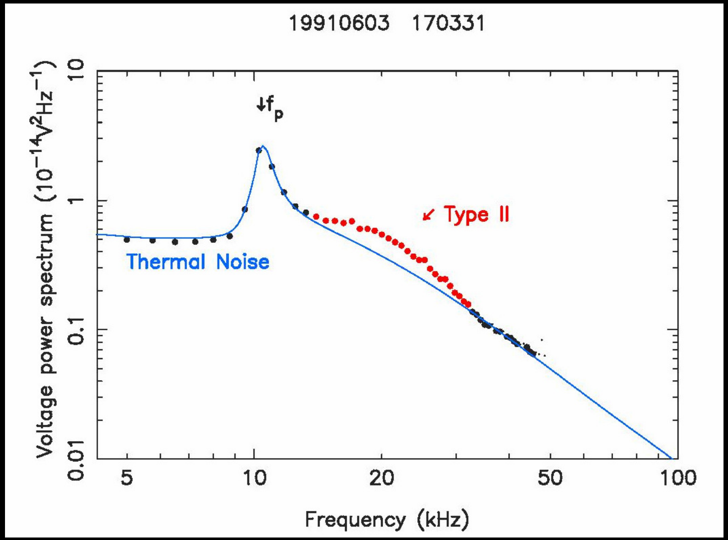
Plasma Wave Investigation (PWI) onboard MMO

Fundamental frequency of magnetized plasma :
☞ plasma frequency

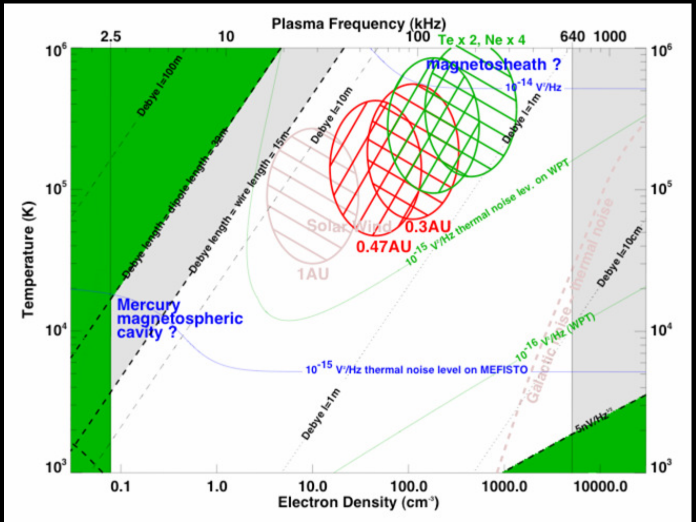
SORBET :
Continuous spectral power survey along MMO orbit with
- *☞ Thermal Noise Receiver (2.5 kHz - 640 kHz)*
  - *quasi-thermal noise spectroscopy (mapping of electron density and temperature, both core and halo)*
  - *radio wave detection (trapped cyclotron waves, direction finding and polarisation)*
- *☞ High Frequency Receiver (500 kHz - 10.2 MHz)*
  - *solar activity monitoring (emissions of type II, III, CMEs)*
  - *synchroton emission of radiation belts (?)*

AM2P :
Active experiment using mutual impedance principle that provides electron density and temperature (128 Hz-143 kHz)

EWO :
Detector and frequency analyzer
E-field (DC-32 Hz and 10 Hz - 20 kHz)
B-field (0.1 Hz – 20 kHz)

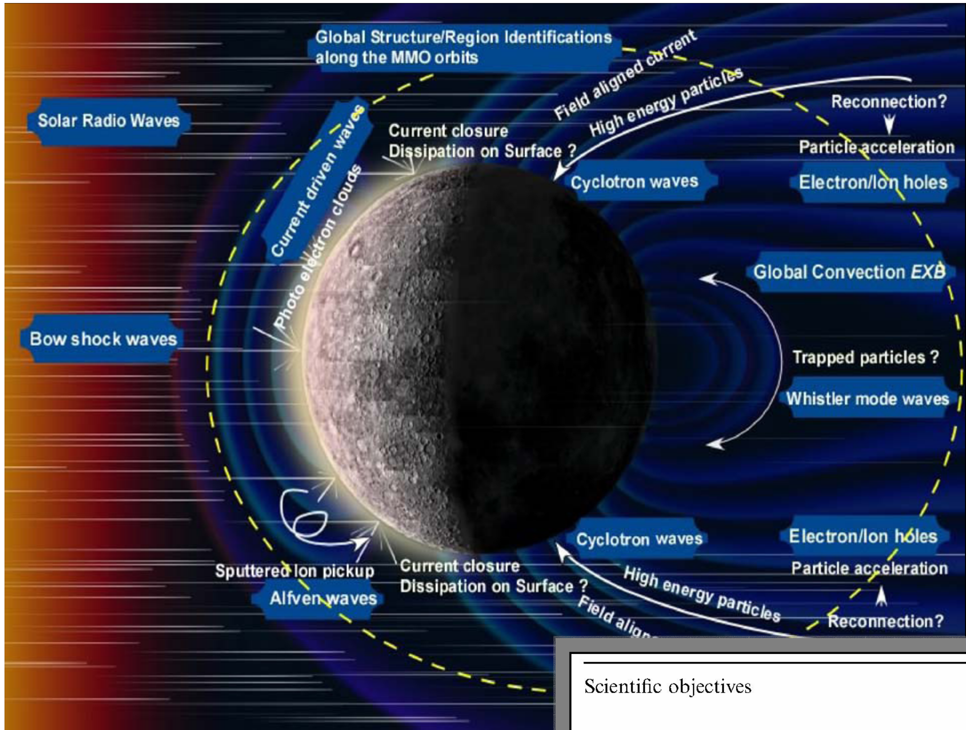


Meyer-Vernet et al. [2000]



Moncuquet et al. [2006]

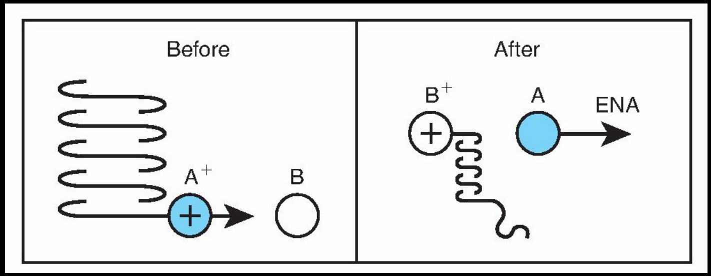
Plasma Wave Investigation (PWI) onboard MMO

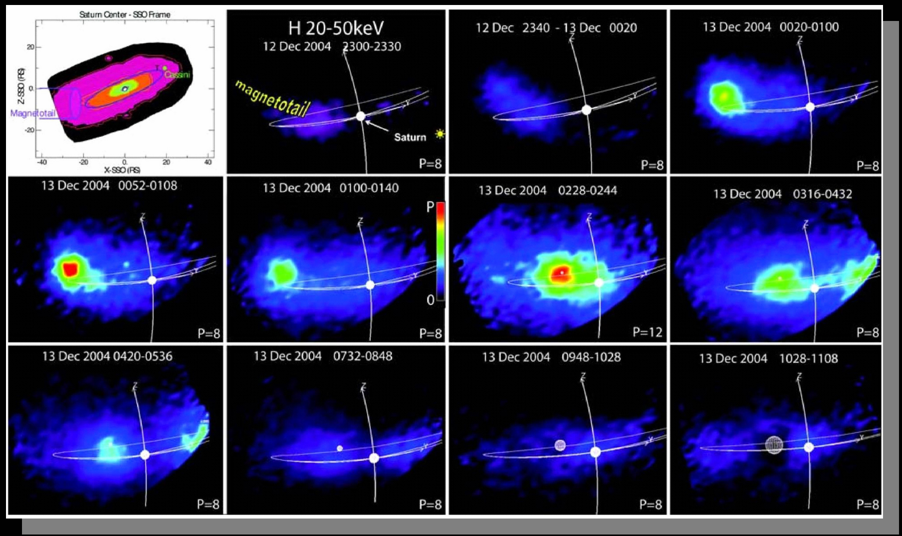


Scientific objectives	Receivers			Sensors			
	EWO	SORBET	AM^{2}P	WPT	MEFISTO	LF-SC	DB-SC
Structure of the magnetosphere							
Identification of regions and boundaries of the magnetosphere	x	x	x	x	x	x	x
Global plasma convection	x			x	x		
Global profile of plasma density and temperature	x	x	x	x	x		
Current closure/dissipation at low altitude	x			x	x		
Plasma wave propagation	x	x	x	x	x	x	x
Dynamics of the magnetosphere							
Solar wind–magnetosphere coupling	x	x	x	x	x	x	x
Response of the magnetosphere to large-scale solar wind structures	x	x	x	x	x	x	x
Nature of Herman substorms	x	x	x	x	x	x	x
Magnetosphere–exosphere coupling	x	x	x	x	x	x	x
Search for transient radiation belts	x	x		x	x	x	x
Energy transfer and scale coupling							
Reconnection	x			x	x	x	x
Identification of auroral processes	x	x		x	x	x	x
Wave–particle interactions							
Nonlinear kinetic processes	x	x		x	x	x	x
Non-gyrotropic effects	x	x		x	x	x	x
Solar radio emissions and diagnostics							
Space weather/observation of key parameters	x	x	x	x	x		x
Opportunity of stereoscopic observation		x		x	x		
Characterization of solar radiations (interplanetary shocks and electron beams)	x	x		x	x	x	x
Dust impact measurement	x	x		x			

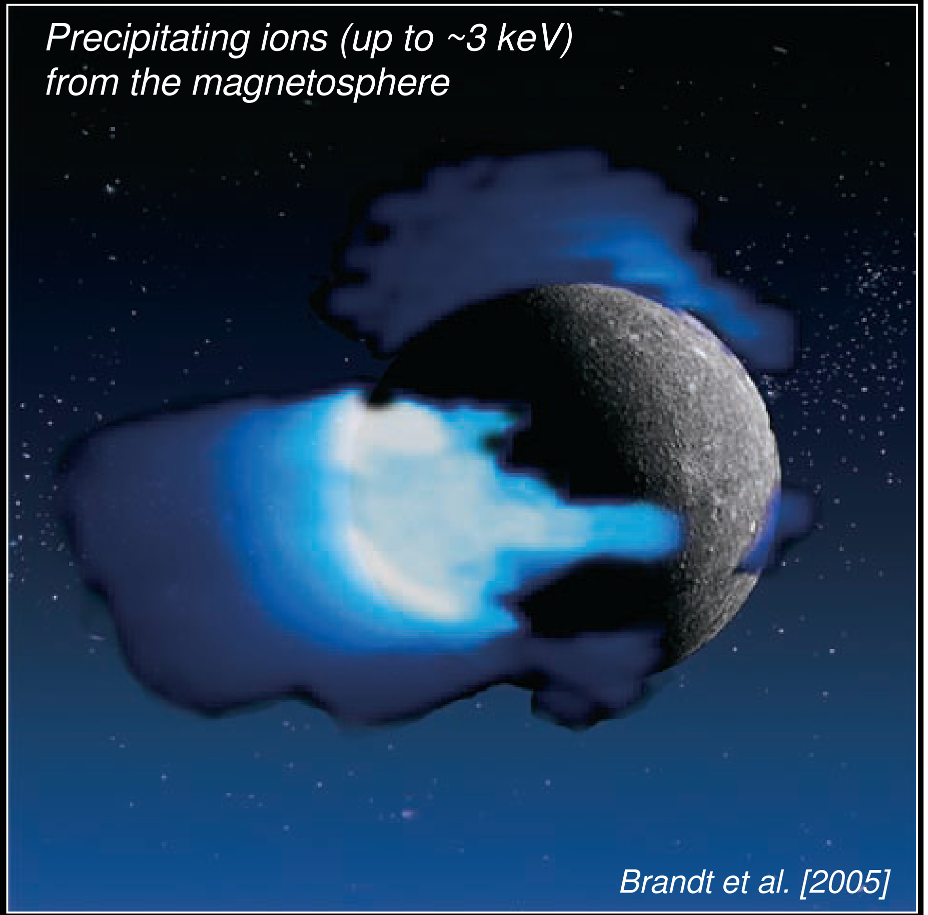
Kasaba et al. [2010]

ENA imaging





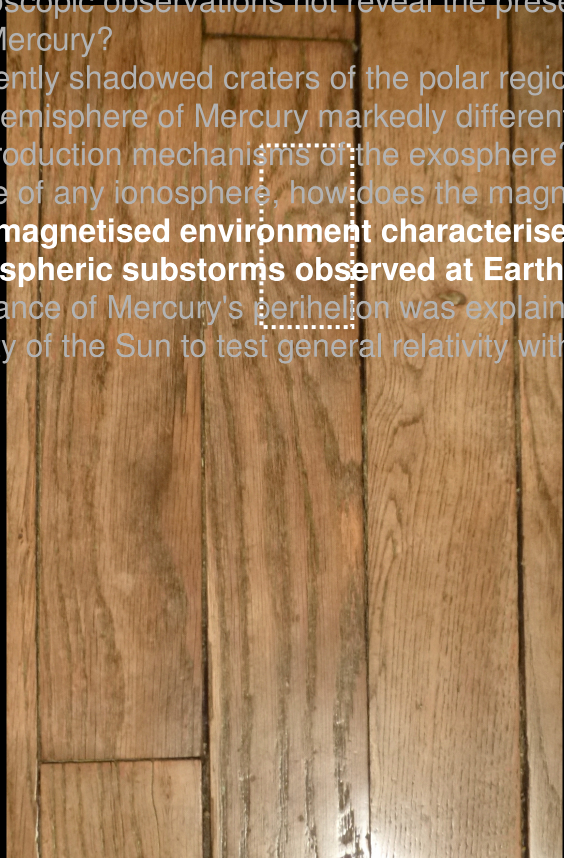
Brandt et al. [2008]

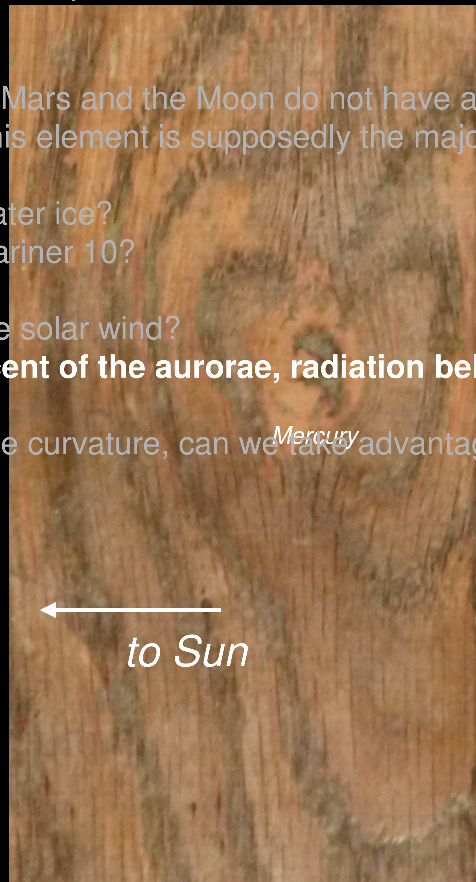


Nature's original patterns are reproduced on various scales and in various contexts

The scientific objectives behind BepiColombo can be viewed by considering the following 12 questions :

1. What can we learn from Mercury about the composition of the solar nebula and the formation of the planetary system?
2. Why is Mercury's normalized density markedly higher than that of all other terrestrial planets, Moon included?
3. Is the core of Mercury liquid or solid?
4. Is Mercury tectonically active today?
5. Why such a small planet does possess an intrinsic magnetic field, while Venus, Mars and the Moon do not have any?
6. Why do spectroscopic observations not reveal the presence of any iron, while this element is supposedly the major constituent of Mercury?
7. Do the permanently shadowed craters of the polar regions contain sulphur or water ice?
8. Is the unseen hemisphere of Mercury markedly different from that imaged by Mariner 10?
9. What are the production mechanisms of the exosphere?
10. In the absence of any ionosphere, how does the magnetic field interact with the solar wind?
11. **Is Mercury's magnetised environment characterised by features reminiscent of the aurorae, radiation belts and magnetospheric substorms observed at Earth?**
12. Since the advance of Mercury's perihelion was explained in terms of space-time curvature, can we take advantage of the proximity of the Sun to test general relativity with improved accuracy?





Nature's original patterns are reproduced on various scales and in various contexts

1. For properties of its own (« end member magnetosphere ») :

How are these « original » patterns reproduced at Mercury ?

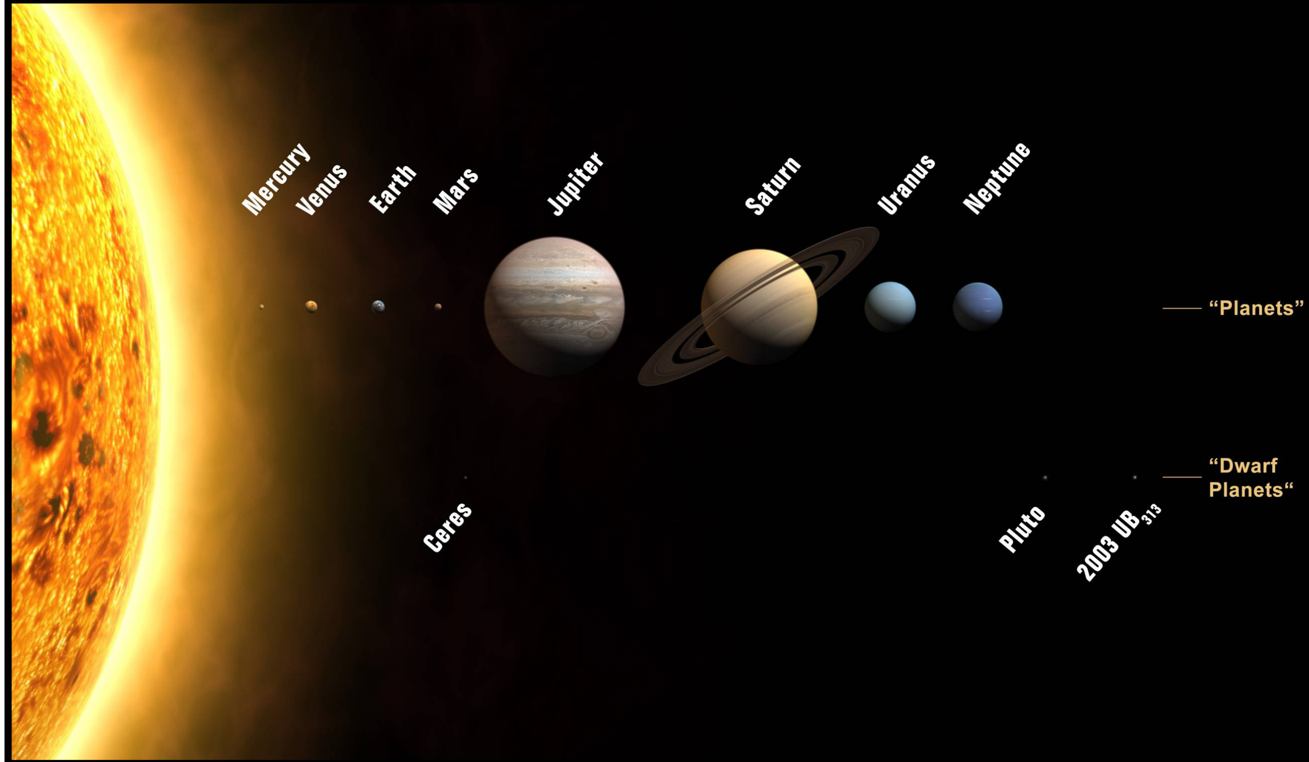
Nature's original patterns are reproduced on various scales and in various contexts

- ☞ *intense solar wind forcing*
- ☞ *consequence of planetary dipole offset*
- ☞ *plasma supply from exosphere*
- ☞ *(partially) trapped region*
- ☞ *production of energetic particles*

...

2. <u>For comparison with Earth's magnetosphere ?</u>

What can we learn from the dynamics of other planetary magnetospheres ?

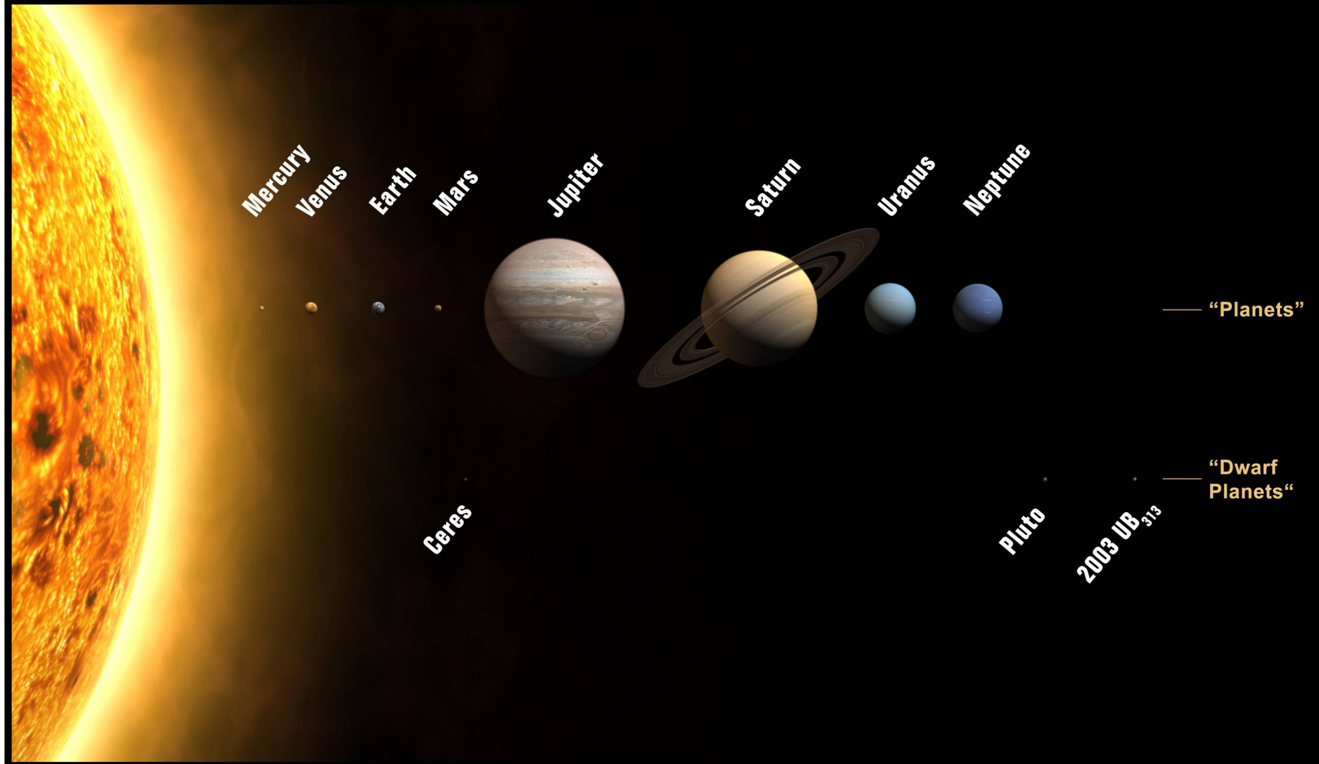


ILWS

International Living With a Star

2. <u>For comparison with Earth's magnetosphere ?</u>

What can we learn from the dynamics of other planetary magnetospheres ?



ILWS

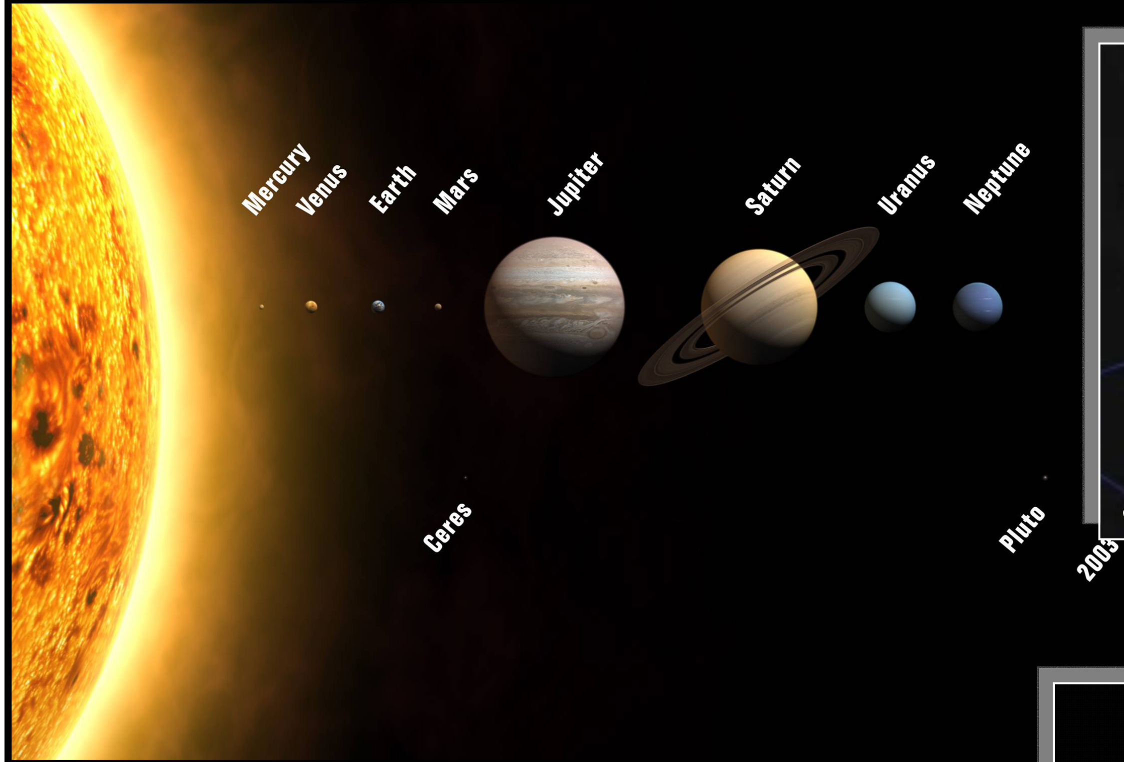
International Living With a Star

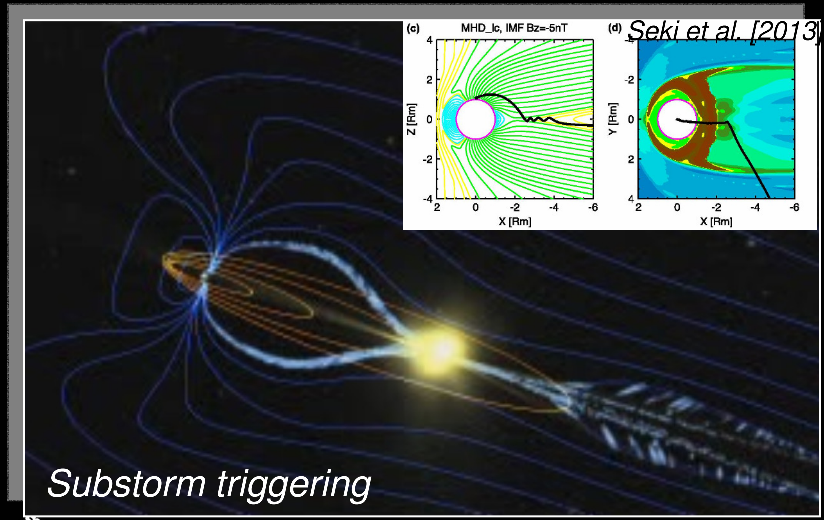
ILWOP

International Living With Other Planets

2. <u>For comparison with Earth's magnetosphere ?</u>

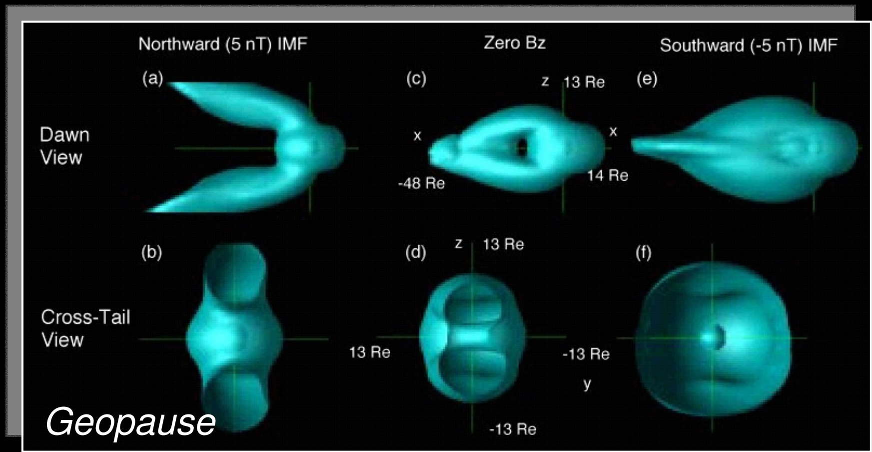
What can we learn from the dynamics of other planetary magnetospheres ?





ILWS
International Living With a Star

ILWOP
International Living With Other Planets



Winglee et al. [1998]

MESSENGER Mission News
April 16, 2015
http://messenger.jhuapl.edu

NASA Celebrates MESSENGER Mission Prior to Surface Impact of Mercury

NASA's highly successful MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft is coming to the end of its operations. Mission engineers predict that the probe — out of fuel and under gravity's spell — will impact Mercury on April 30 at more than 8,750 miles per hour (3.91 kilometers per second).

The spacecraft launched on August 3, 2004, and travelled more than six and a half years before it was inserted into orbit about Mercury on March 18, 2011. The original plan was to orbit the planet for one Earth year, collecting data to answer six critical questions. But new questions raised by early findings motivated two extensions of orbital operations for a total of three more years. Moreover, through a series of technological innovations, MESSENGER's engineers devised a way to save fuel early on and leverage helium gas later, paving the way for a final one-month extension that enabled mission scientists to continue to acquired novel, low-altitude measurements of the planet closest to the Sun.

"MESSENGER had to survive heating from the Sun, heating from the dayside of Mercury, and the harsh radiation environment in the inner heliosphere, and the clearest demonstration that our innovative engineers were up to the task has been the spacecraft's longevity in one of the toughest neighborhoods in our Solar System," said MESSENGER Principal Investigator Sean Solomon, director of Columbia University's Lamont-Doherty Earth Observatory. "Moreover, all of the instruments that we selected nearly two decades ago have proven their worth and have yielded an amazing series of discoveries about the innermost planet."

"Although Mercury is one of Earth's nearest planetary neighbors, astonishingly little was known when we set out," Solomon continued. "MESSENGER has at last brought Mercury up to the level of understanding of its sister planets in the inner Solar System. Of course, the more we learn, the more new questions we can ask, and there are ample reasons to return to Mercury with new missions."

In a briefing at NASA Headquarters today, MESSENGER scientists and engineers ticked off the top science findings and technological innovations from the mission. Near the top of the list of science accomplishments is having provided compelling support for the hypothesis that Mercury harbors abundant water ice and other frozen volatile materials in its permanently shadowed polar craters.

"The water now stored in ice deposits in the permanently shadowed floors of impact craters at Mercury's poles most likely was delivered to the innermost planet by the impacts of comets and volatile-rich asteroids," says Solomon. "Those same impacts also likely delivered the material in the dark layer discovered by MESSENGER to cover most polar deposits and interpreted, on the basis of its sublimation temperature and low reflectance, to be carbonaceous. By this interpretation, Mercury's polar regions serve as a witness plate to the delivery to the inner solar system of water and organic compounds from the outer solar