James Van Allen and the quest for the discovery of Radiation Belts: from Mercury to the Heliosphere

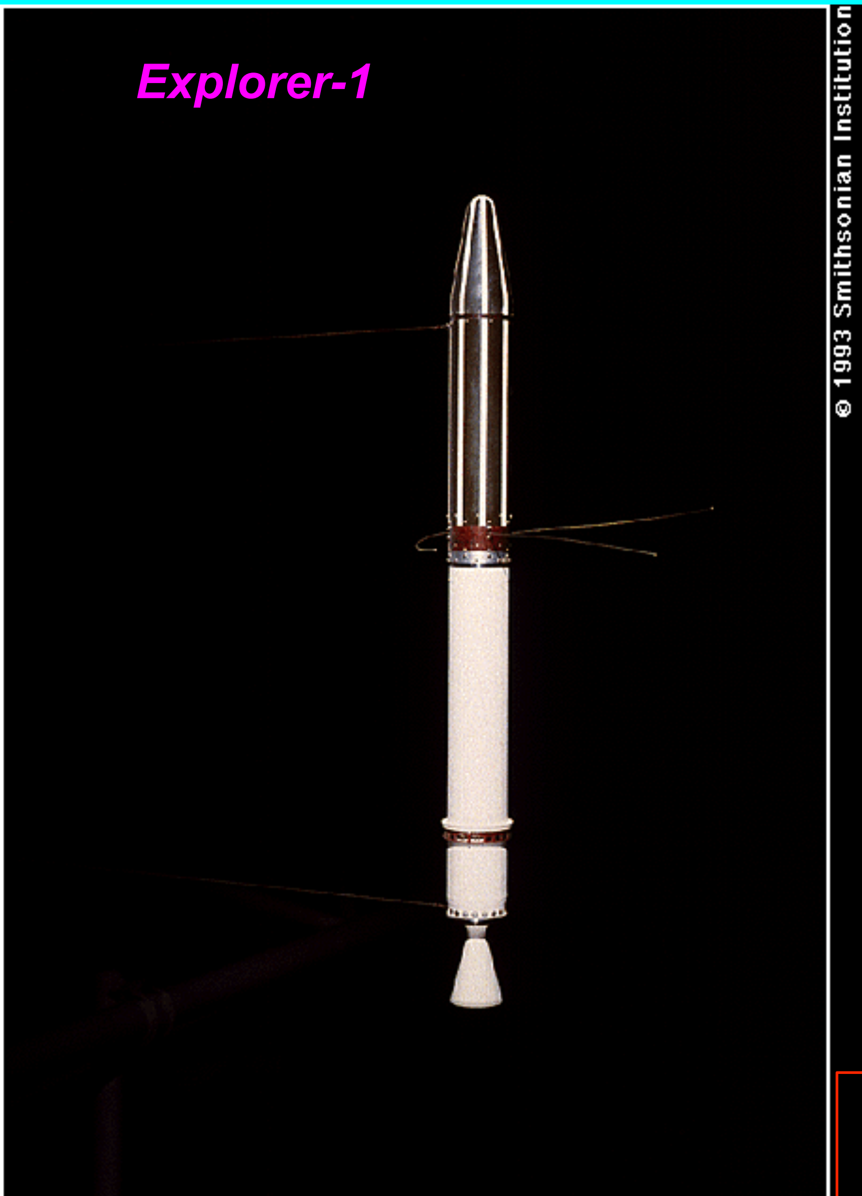
Stamatios M. Krimigis

Johns Hopkins University
Applied Physics Laboratory
And
Academy of Athens

Some early history based on “Opening Space Research: Dreams, Technology, and Scientific Discovery” George H. Ludwig, published by AGU in 2011 and Krimigis’ association with the University of Iowa (1961-1968) and the Applied Physics Laboratory of Johns Hopkins University (1968-present)

CLUSTER / MAARBLE / VAN ALLEN PROBES Conference
Rhodes, Greece-September 15-19, 2014

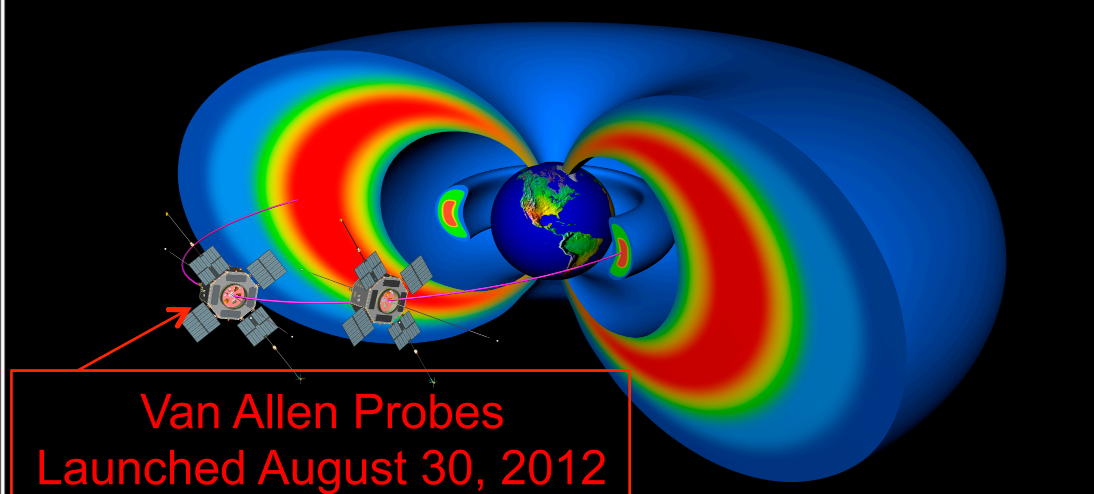
Explorer 1 was the first US satellite, launched on January 31, 1958 with James Van Allen, University of Iowa as Principal Investigator



May 4, 1959

James A. Van Allen (1914-2006)

Van Allen Belts, rings of radiation encircling Earth at high altitudes



Van Allen's Background and Education

- **Born on 7 September 1914, Mount Pleasant, Iowa**
- **Valedictorian of Mount Pleasant High School, June, 1931**
- **Iowa Wesleyan College, Mount Pleasant, majoring in physics and graduating *summa cum laude* in a class of 38 in June 1935 (mentored by Professor Thomas C. Poulter, geophysicist).**
- **Graduate work at State University of Iowa (M.S. 1936, PhD 1939) both in Physics, where he built a Cockroft-Walton accelerator and measured nuclear cross-sections for his dissertation**

September 15, 2014

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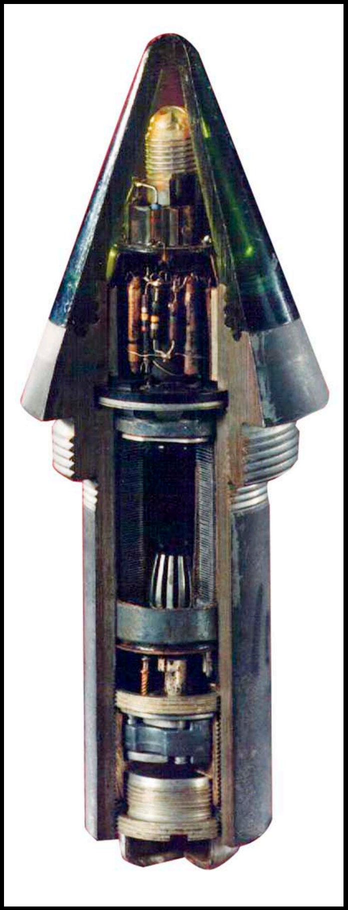
Post-Doctoral Work and the War Years

- Carnegie Research Fellow at the Department of Terrestrial Magnetism (DTM), 1939-40, in Merle A. Tuve's nuclear physics laboratory
- Contact with DTM colleagues Scott Forbush, Harry Vestine, John Fleming, Alvin McNish, and Bill Rooney and visiting European geophysicists Sydney Chapman and Julius Bartels
- In 1940 DTM director Tuve converted much of the institution's effort to the development of the proximity fuse to increase the effectiveness of naval anti-aircraft fire, and Van Allen joined the National Defense Research Council/Office of Scientific Research and Development
- In April, 1942, Johns Hopkins University established the Applied Physics Laboratory (APL) for the purpose of advancing the work on the proximity fuse with Merle Tuve as its first Director, and Van Allen on the staff
- Van Allen's principal focus in the proximity fuse work was development of rugged miniature vacuum tubes that could withstand the shock (~20000 g) and acceleration of gun-fired projectiles
- In November 1942, Van Allen was commissioned Navy Lieutenant and dispatched to the Pacific to teach Navy crews how to use the fuse

Van Allen at APL as a Navy Lieutenant, and the Proximity Fuse

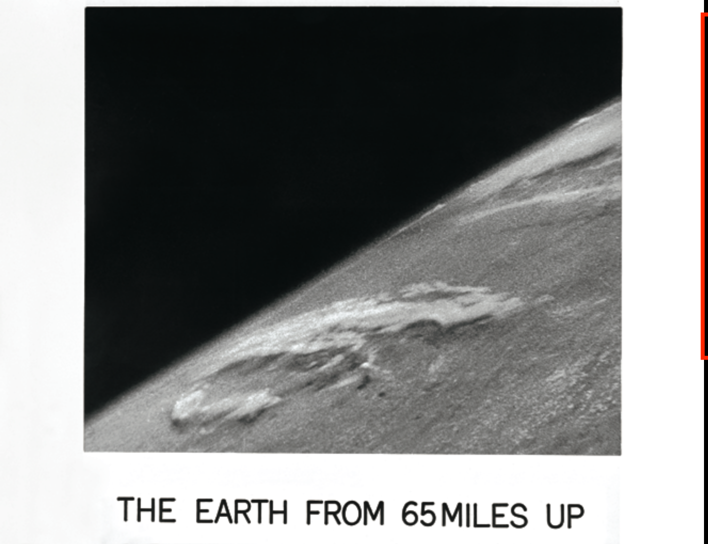


The Years Leading up to the International Geophysical Year (IGY)

- Established and led the High Altitude Research Group at APL (forerunner of today's Space Department)
- Instrumented V-2 rockets with cosmic ray detectors, UV spectrometers, magnetometers, ozone sensors, and IR and visible cameras
- Oversaw the development of the Aerobee high altitude research rocket (1037 fired through 1985)
- Was a participant in the establishment in 1946, and eventually chairman of the "V-2 Rocket Panel", "V-2 Upper Atmosphere Panel", "V-2 Upper Atmosphere Research Panel" in September 1946, the "Upper Atmosphere Rocket Research Panel" in March 1948, and the "Rocket and Satellite Research Panel" in April 1957 that, although unofficial, organized and run US efforts in this field until the establishment of NASA in October, 1958
- Moved to the State University of Iowa in 1951 and established a most capable group to continue and advance high altitude research.
- Research from 1946-1957 by Van Allen and collaborators had resulted in many new and important findings, including the variation of cosmic rays with altitude and latitude, measurements of solar UV lines, partial sampling of the equatorial electrojet, ionospheric structure, imaging of cloud cover from high altitude, and the auroral "soft radiation"

Work with V-2 at APL, 1946-1949

High Altitude Research Group at APL with V-2



V-2 readied for launch at White Sands Proving Grounds, New Mexico

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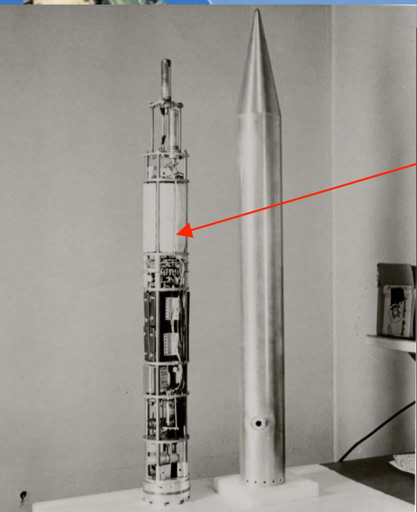
Balloons and Rockoons at State University of Iowa (SUI)



Loki-rockoon cosmic ray payload with GM-tubes

Preparing Loki II rocket for launch from a balloon from USS Glacier, 1957
Larry Cahill and Van Allen, center

Holding the rocket as the balloon lifts up off the deck

Balloon launch in Antarctic, November, 1957

Discovery of “soft radiation” and its mapping to the Auroral zone *(Van Allen, 1957)*

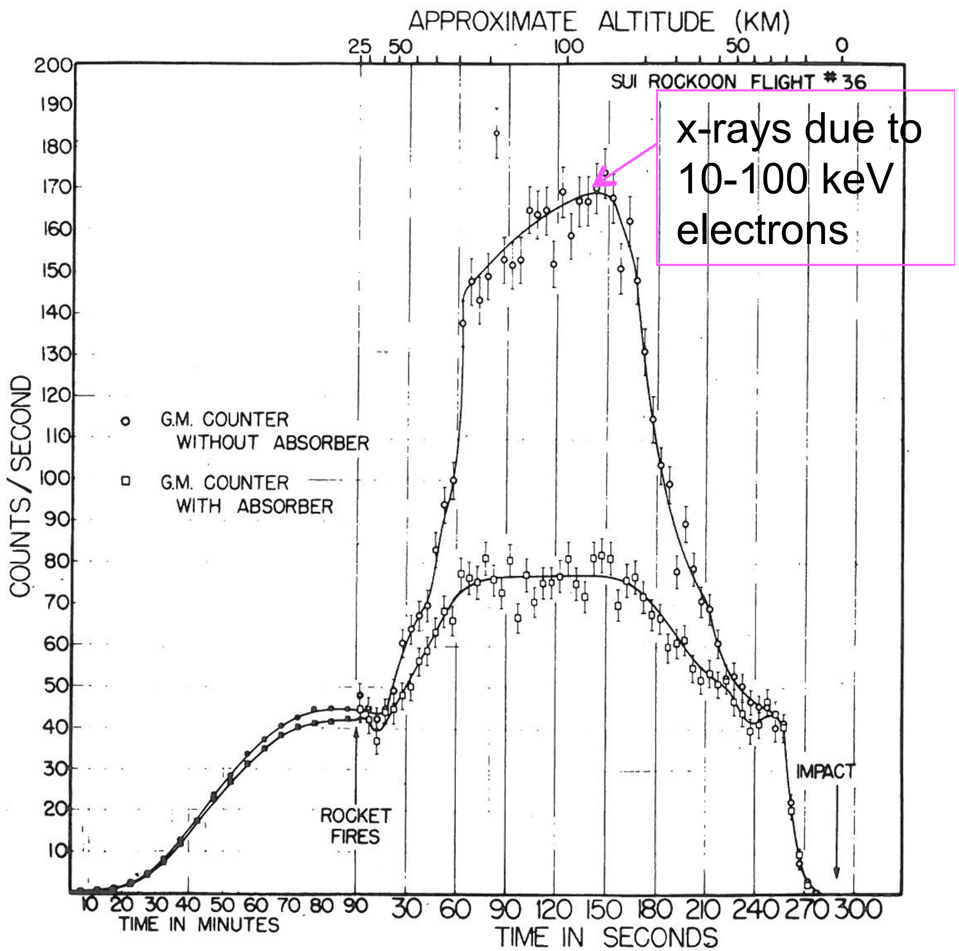


Fig. 10. An example of the detection of the auroral soft radiation with a rockoon flight off the southwestern coast of Greenland. Note that the time scale is in minutes during the ascent of the balloon and in seconds during the flight of the rocket [Van Allen 1957].

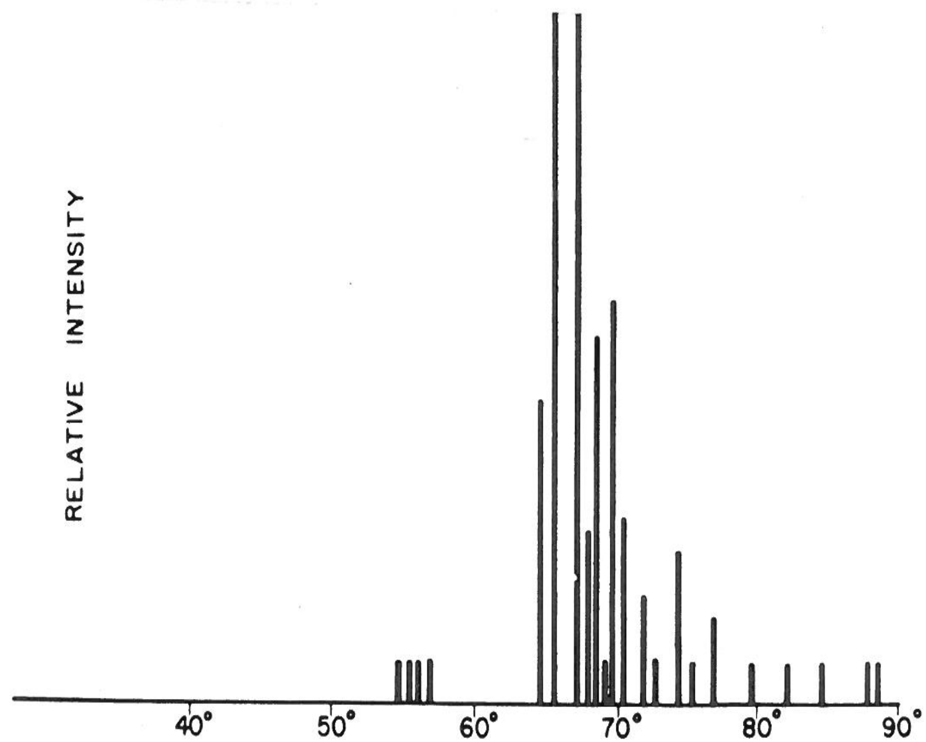
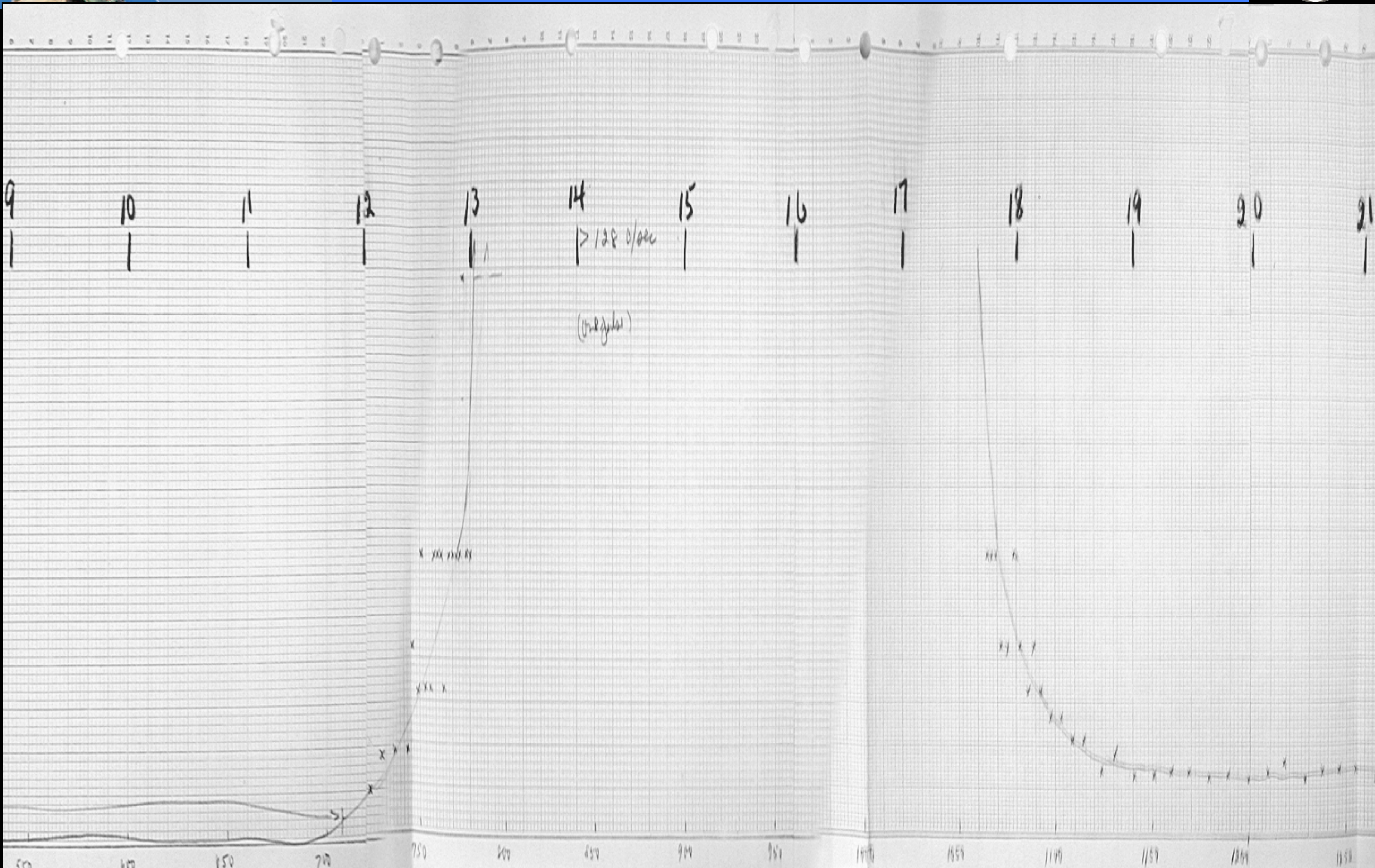


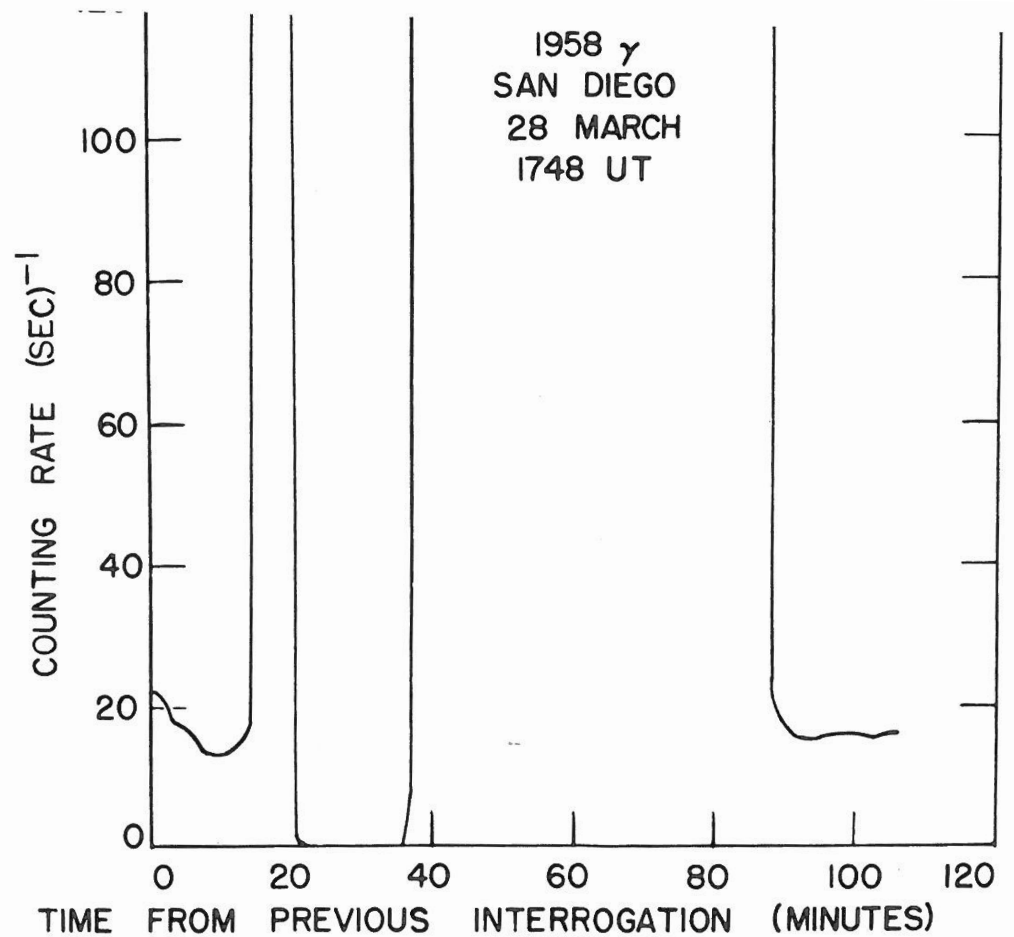
Fig. 11. The geomagnetic latitude dependence of the maximum counting rate of lightly shielded Geiger-Mueller tubes flown in the Arctic to high altitudes by balloon-launched rockets on twenty-two occasions during the summers of 1953, 1954, and 1955. The great intensity peak centered at about 68° is attributed to primary auroral electrons having energies of $E_e \sim 10$ kiloelectron volts (the auroral soft radiation) [Van Allen 1957].

Van Allen's plot in a hotel room on April 2-3, 1958 of an Explorer 3 pass



Lugwig's digital recorder on Explorer 3 was key to the discovery of the Belts

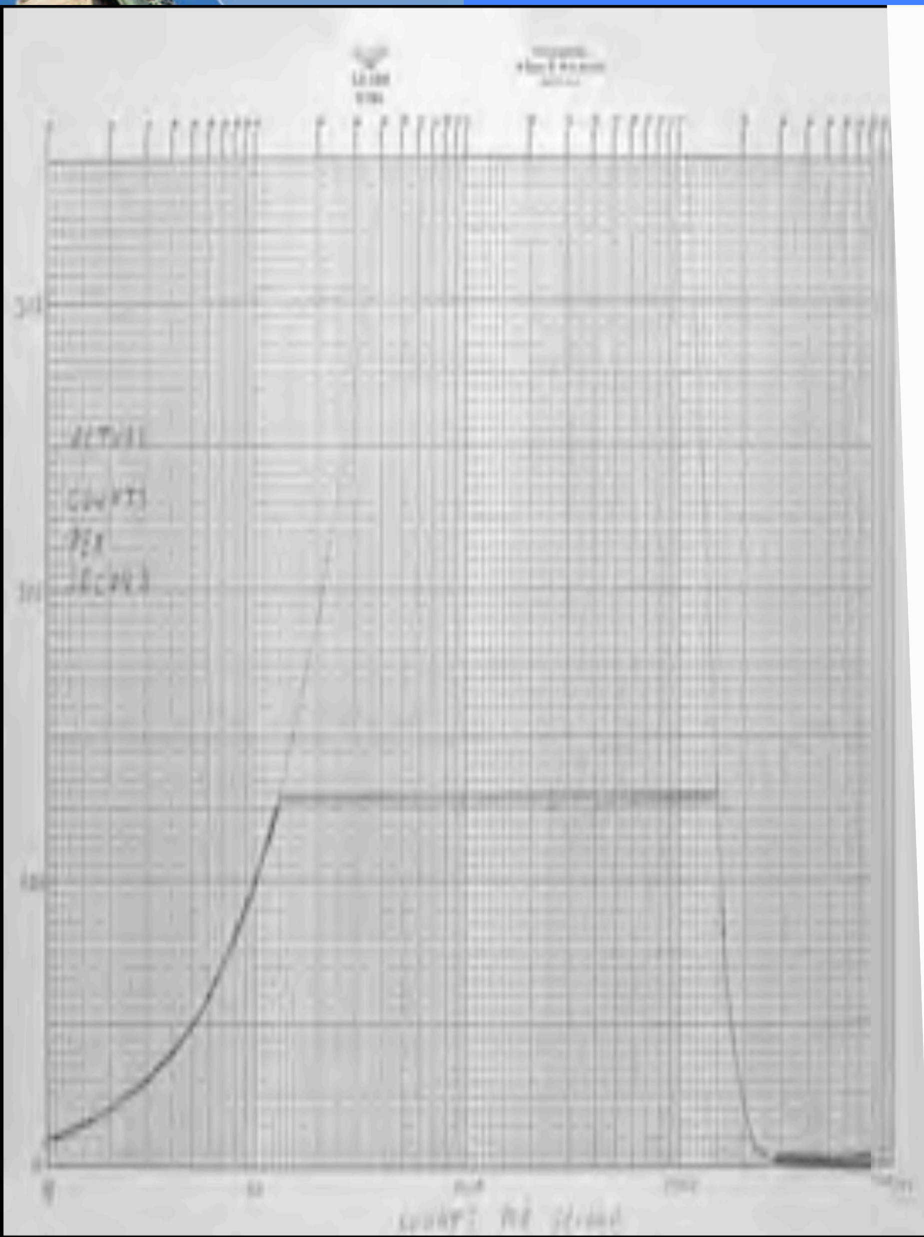
Inexplicable behavior of count rate with altitude/time-Explorer III

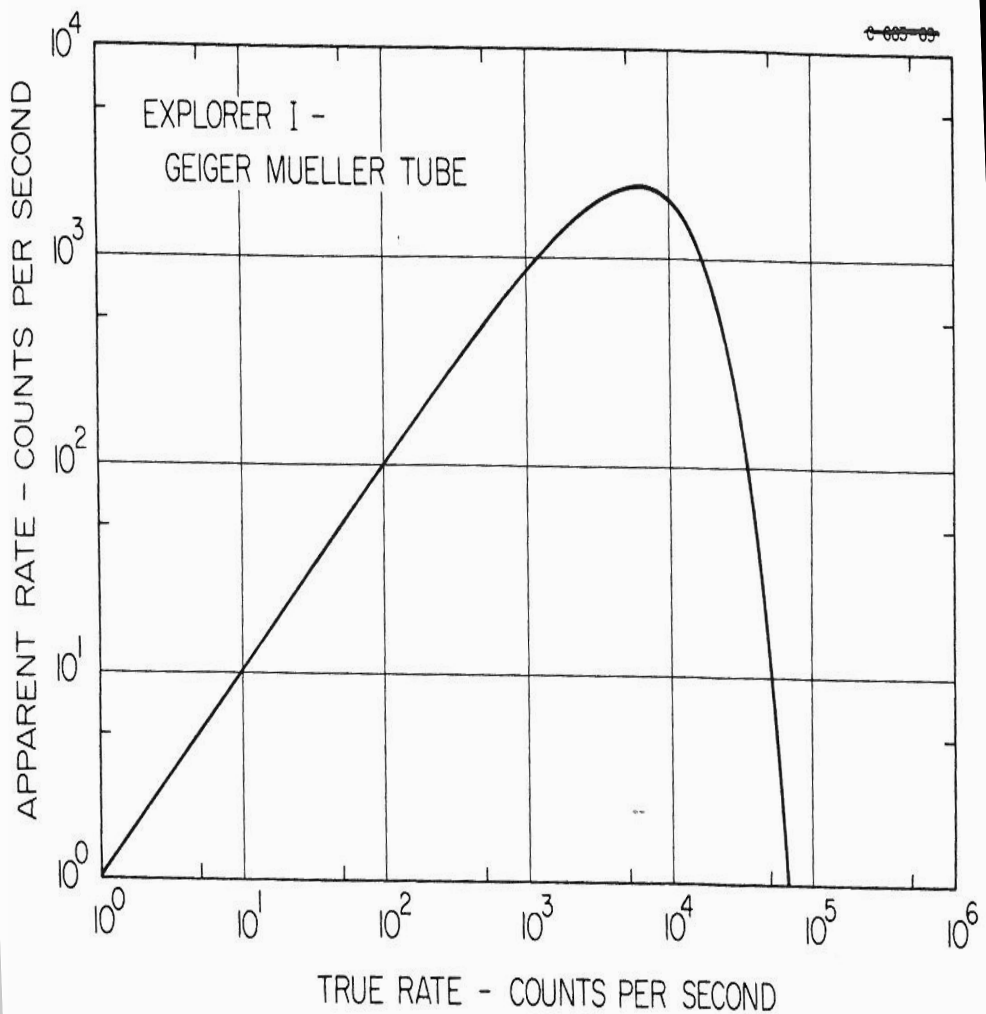


Courtesy of J. A. Van Allen.

Fig. 21. The first available full orbital set of radiation data from the tape recorder on Explorer III, *obtained from an interrogation over San Diego. The horizontal dashed line at 128 counts per second is the upper counting rate limit of the tape recorder system.*

Explorer 1 GM counter exposed to x-ray beam
What happens to an over-driven G-M tube?





Courtesy of J. A. Van Allen.

Fig. 24. Relationship of the apparent (observed) counting rate to the true counting rate of the Geiger-Mueller tube on Explorer I.

Ernie Ray's famous note


Ernie Ray 4/5/58

NOTE:

1958 γ

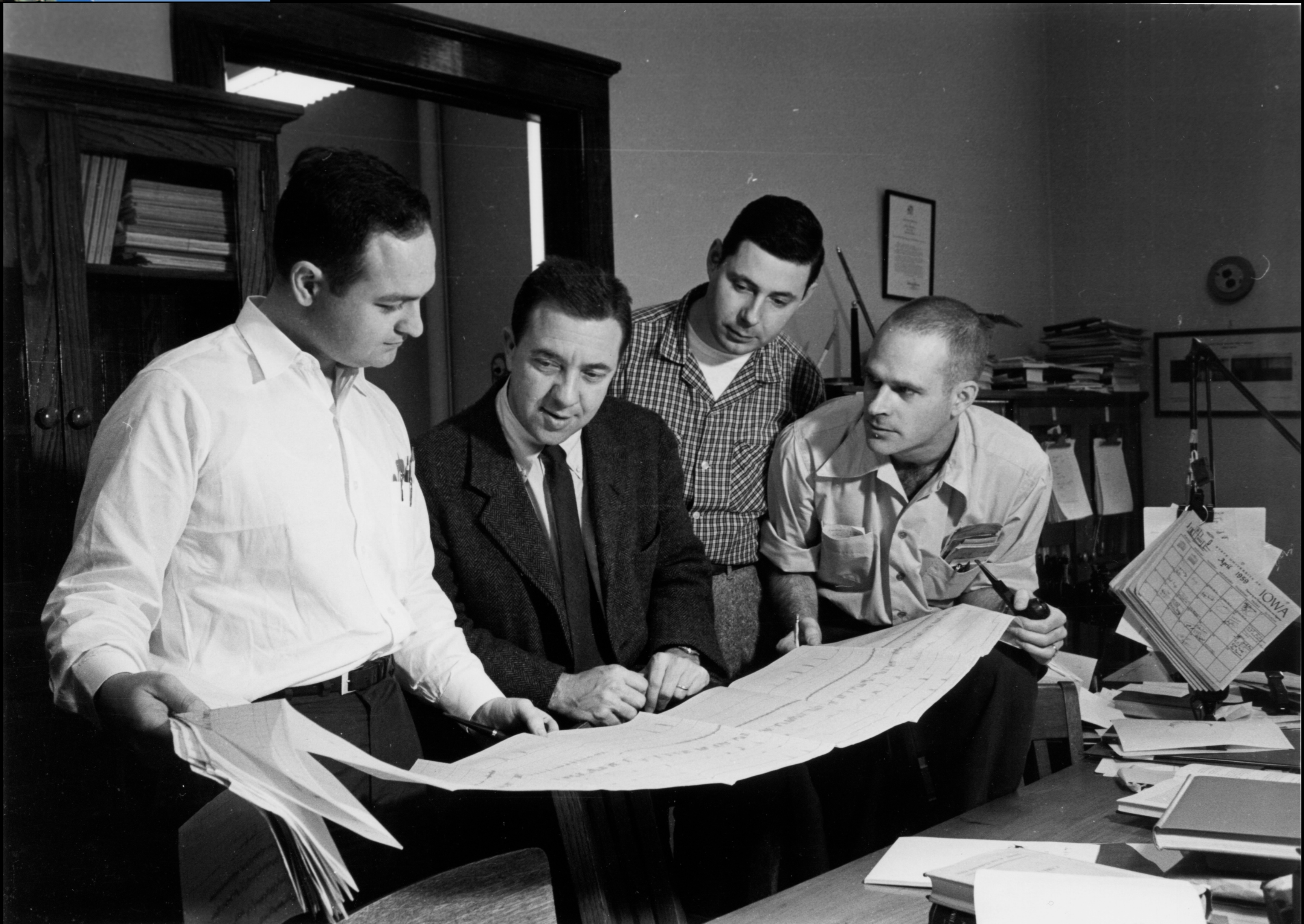
DATA

SPACE IS
RADIOACTIVE

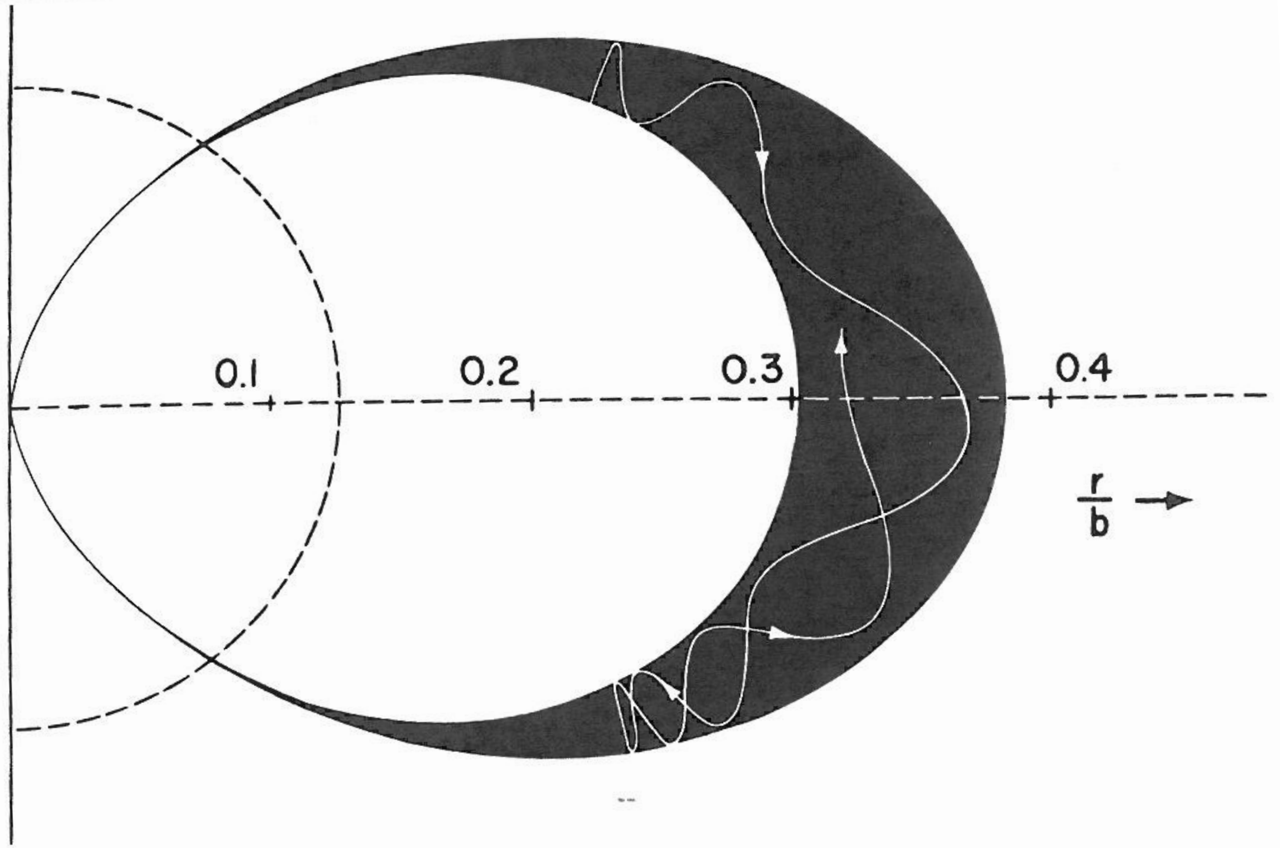
64
107 } ~ 60%

Protagonists of Radiation Belts Discovery

(Left to right) Carl McIlwain, James Van Allen, George Ludwig, Ernie Ray



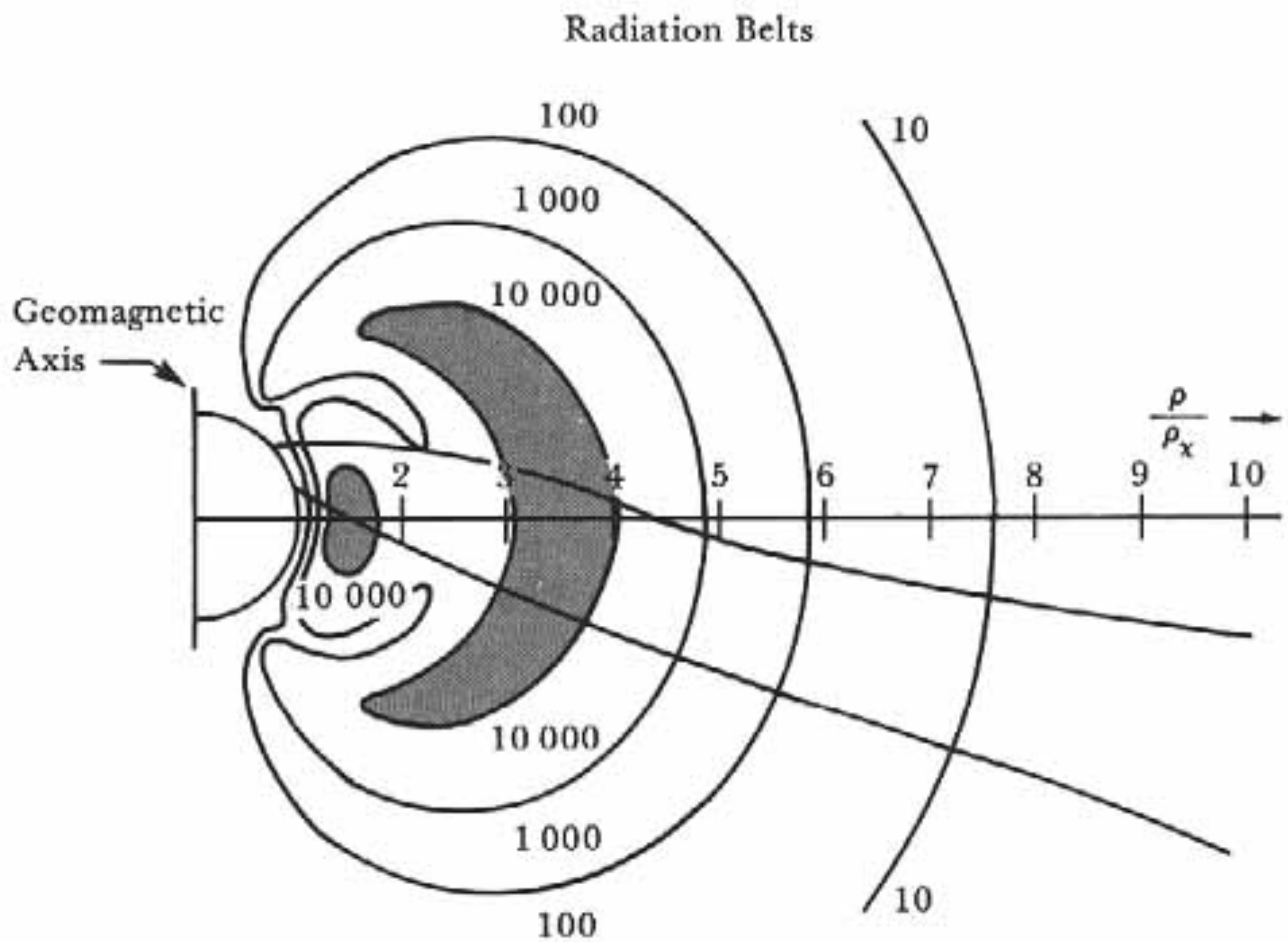
Van Allen's favorite figure in conceptualizing particle trapping in a dipole field (Stormer, 1907)



Courtesy of Archives des Sciences, Muséum d'Histoire Naturelle, Geneva.

Fig. 4. A diagram, after Størmer [1907], illustrating the meridian projection of the spatial trajectory of an energetic, electrically charged particle in the field of a magnetic dipole and the boundaries of the theoretically rigorous trapping region. The quantity r/b *is the dimensionless ratio of the radial distance to a parameter of Størmer's theory of this motion. The earth is represented by the dashed semicircle.*

Van Allen et al initial sketch of Earth's radiation belts



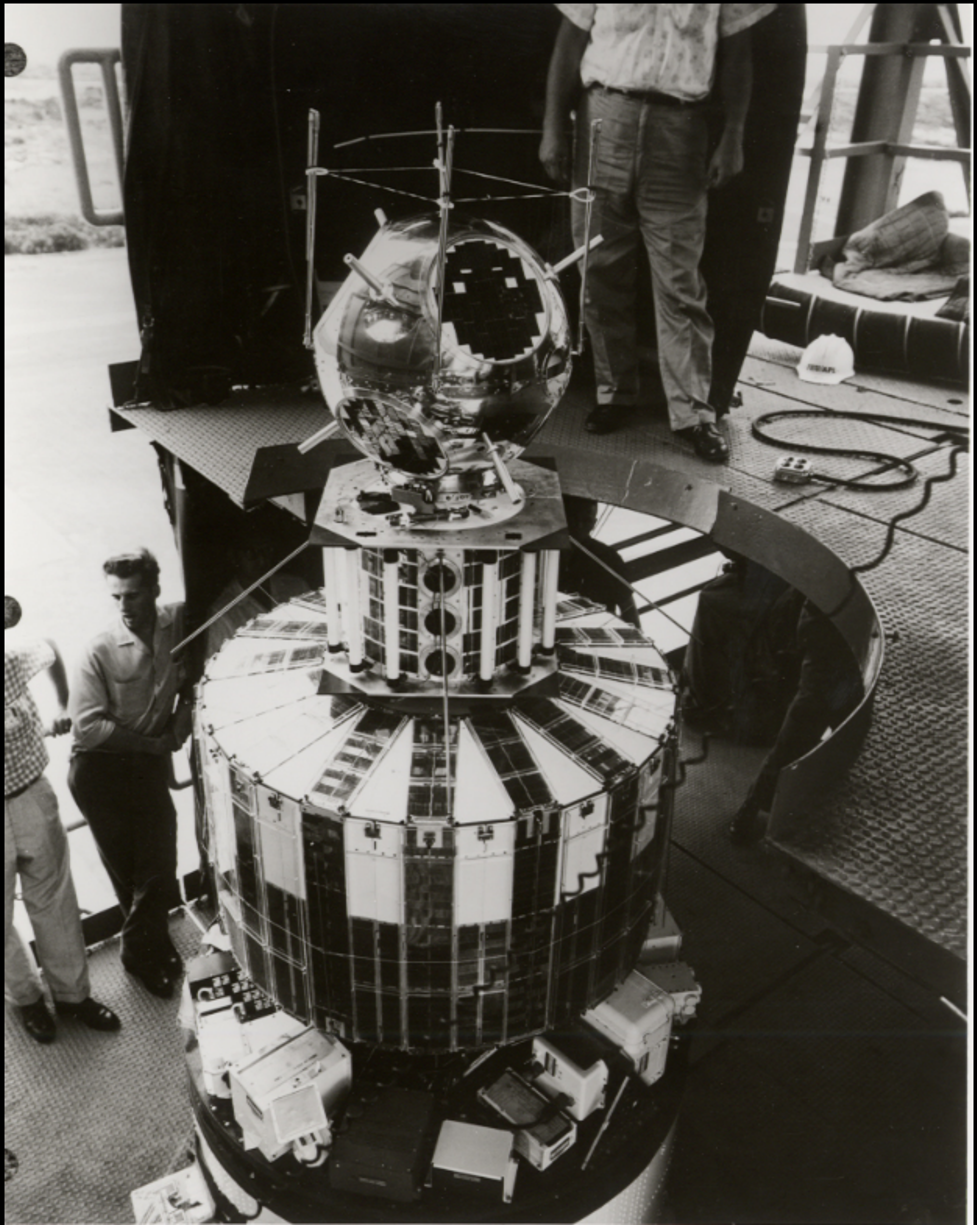
The first artificial radiation belt

Nicholas Christofilos, a Greek scientist who migrated in the US in 1953, had proposed in October 1957 in an unpublished memorandum [mentioned by Van Allen, in 1959] that charged particles could be trapped around the Earth and he had proposed that an artificial radiation belt, due to beta decay, could be created by exploding one or more small nuclear fission bombs at high altitude (~200 km)

Christofilos' proposal evolved into Argus - the first active experiment in space, which was successfully performed in 1958

N. Christofilos, The Argus Experiment, *J. Geophys. Res.*, *64*, 869-875, 1959

Transit 4A (APL), Injun 1 (1st University-built satellite), and Greb 3(NRL), 6/29/61

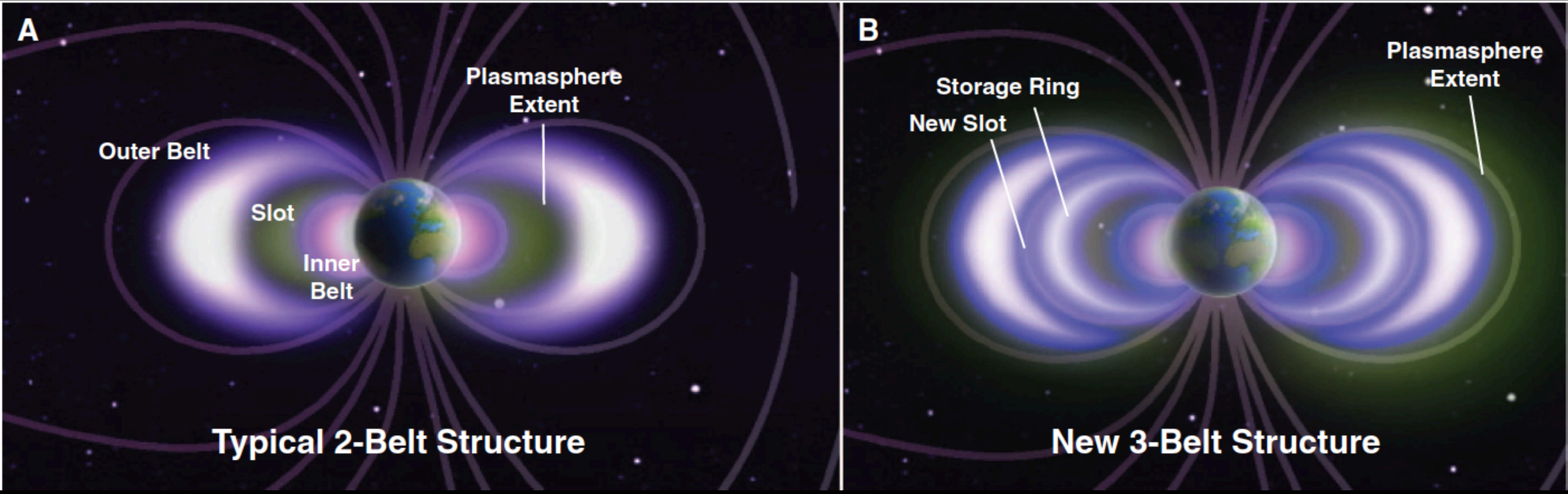


J. A. Van Allen, T. P. Armstrong, and S. M. Krimigis

with Explorer 33 (anchored IMP) instrument, 1965

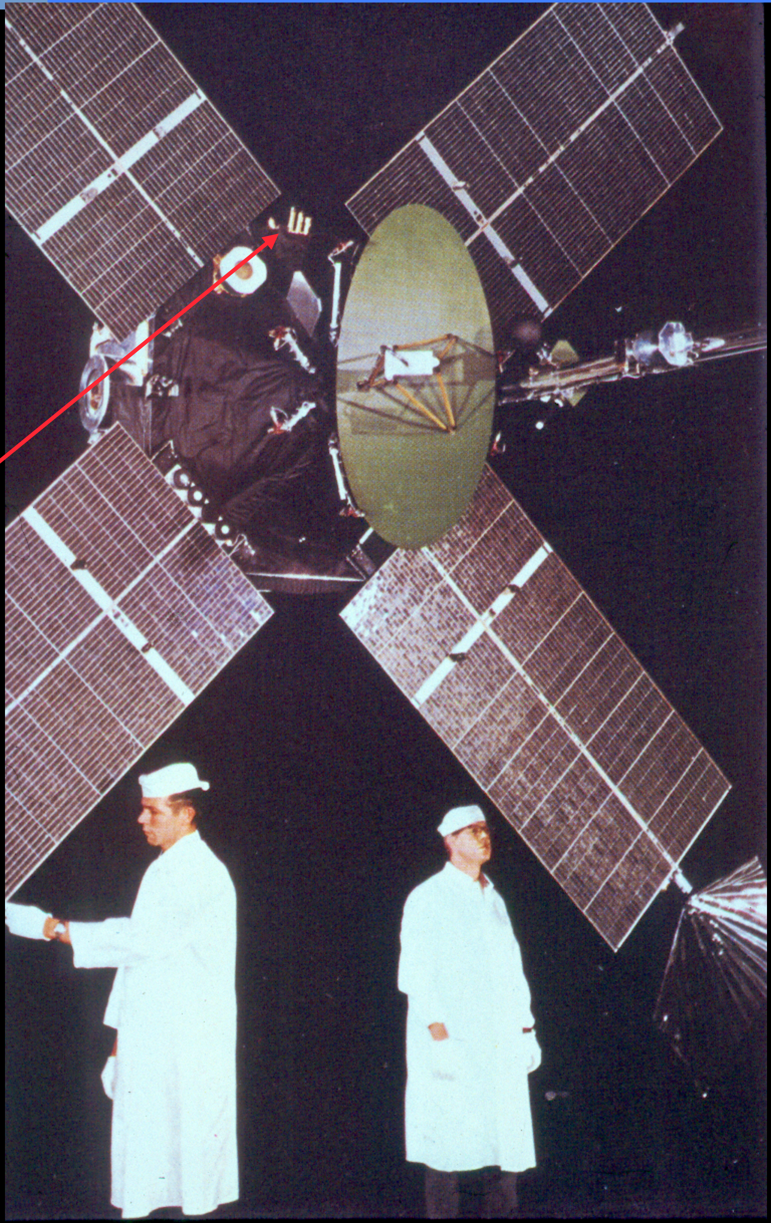
Relativistic Electron Storage Ring Embedded in Earth's Outer Van Allen Belt

(from Van Allen Probes, Baker et al*, Science, 340, 186, 2013)*



The first mission to Mars, Mariner 4 (Mariner 3) was launched on November 30,1964

The U of Iowa Trapped Radiation Detector (TRD)



Mariner 4, flew by Mars on August 15, 1965

Observing incoming data at JPL during Mariner 4 flyby of Mars 15 July, 1965

Mars flyby data on July 14-15, 1965 were disappointing! (Van Allen et al, 1965)

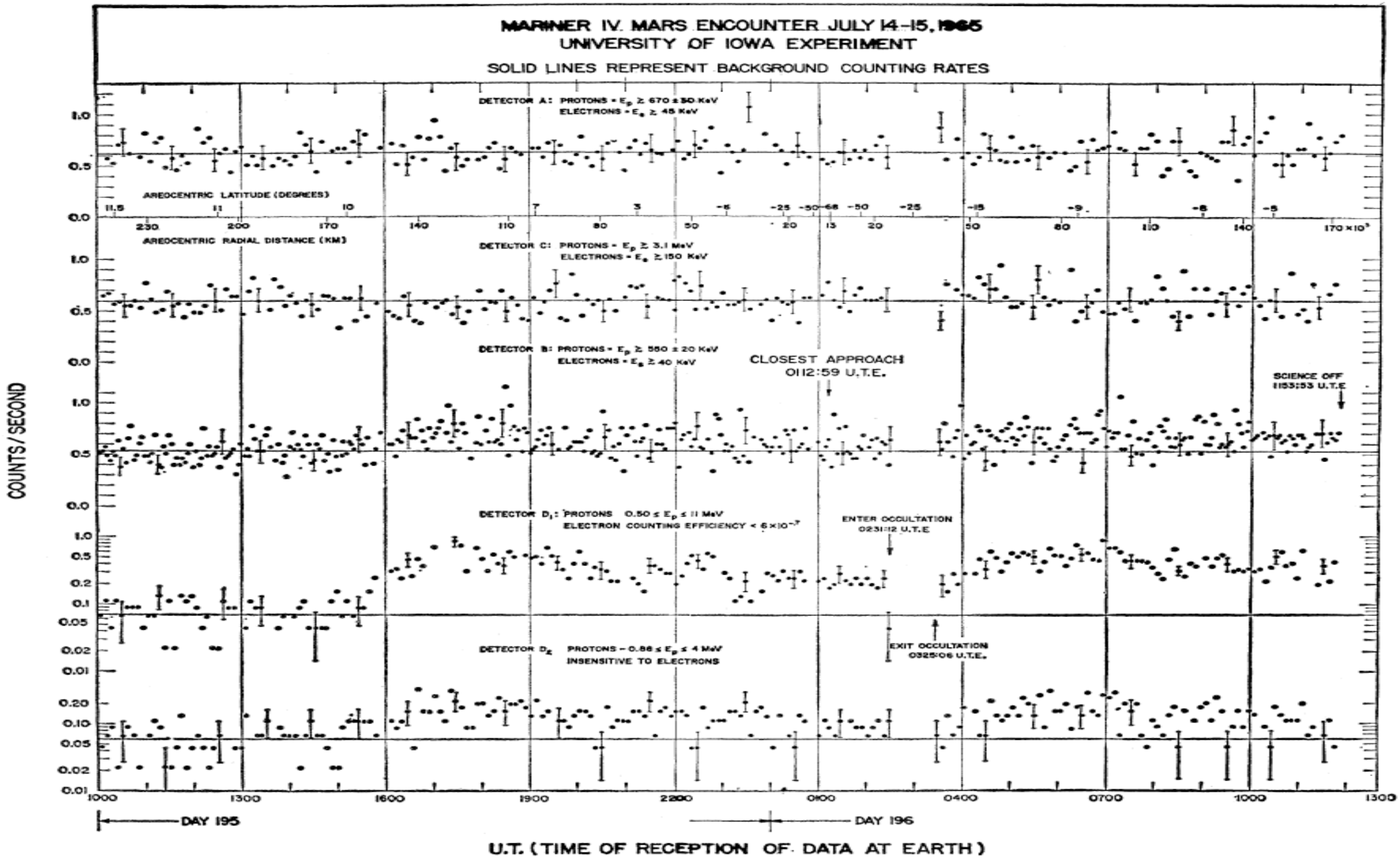
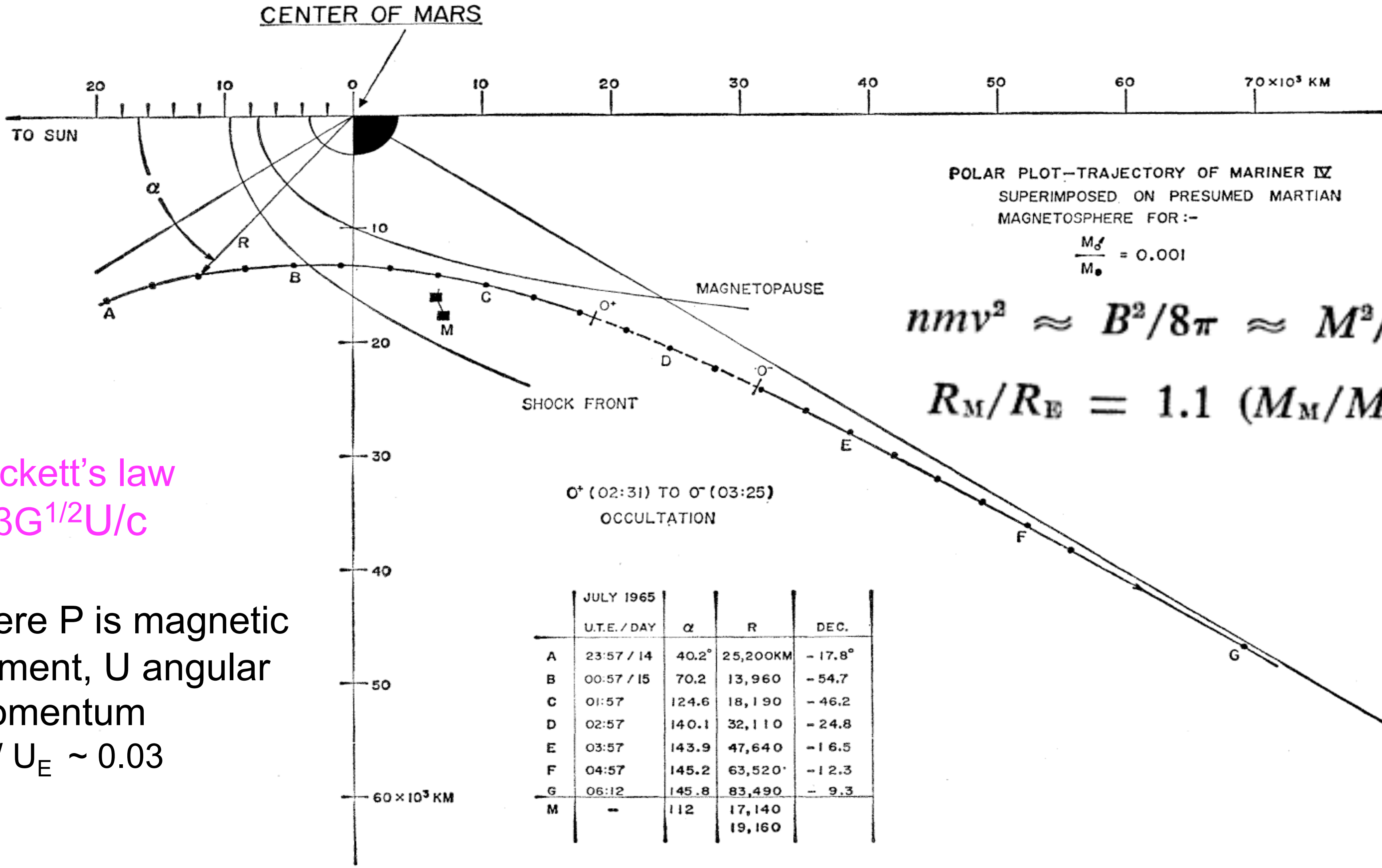


Fig. 2. A comprehensive plot of the counting rates of detectors A, C, B, D_1, and D_2 before, during, and after the encounter with Mars on 14–15 July 1965. Note scale of positional coordinates of the spacecraft in upper part of the figure.

Estimate of Magnetic Moment of Mars
(Van Allen, Frank, Krimigis, Hills, Science, 149, 1965)



JULY 1965 U.T.E./DAY		α	R	DEC.
A	23:57 / 14	40.2°	25,200KM	-17.8°
B	00:57 / 15	70.2	13,960	-54.7
C	01:57	124.6	18,190	-46.2
D	02:57	140.1	32,110	-24.8
E	03:57	143.9	47,640	-16.5
F	04:57	145.2	63,520	-12.3
G	06:12	145.8	83,490	- 9.3
M	–	112	17,140 19,160	

$$nmv^2 \approx B^2/8\pi \approx M^2/R^6.$$

$$R_M/R_E = 1.1\ (M_M/M_E)^{1/3}.$$

Blackett's law
$P=\beta G^{1/2}U/c$

where P is magnetic moment, U angular momentum
$U_M / U_E \sim 0.03$

Fig. 3. An analytical diagram used for inferring an upper limit to the ratio of the magnetic dipole moment of Mars to that of the earth. Successive black dots on the trajectory are at 15-minute intervals.

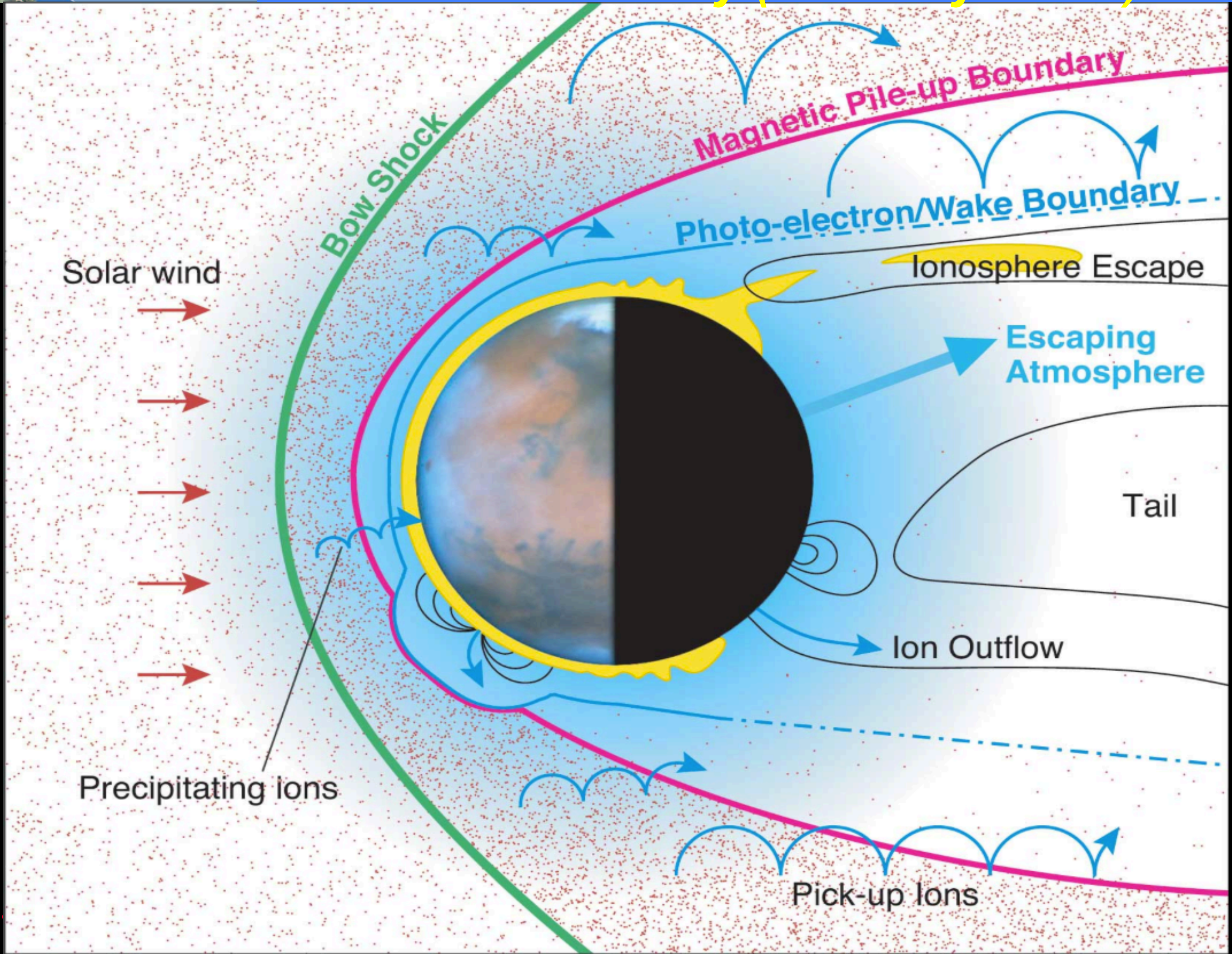
Quote from paper on Mars magnetic moment

Absence of Martian Radiation Belts and Implications Thereof
J. A. Van Allen, L. A. Frank, S. M. Krimigis, H. K. Hills
Science, Vol. 149, No. 3689 (Sep. 10, 1965), pp. 1228-1233

"The foregoing results mean that the equatorial surface magnetic field of Mars is less than 200 (and perhaps 100) gammas (radius = 3417 km), and hence they suggest that the solar wind will, on occasion and perhaps usually, have a direct interaction with the Martian atmosphere. This interaction may be of essential importance in determining the physical state of the atmosphere.

Also, it is evident that the Martian atmosphere and surface are exposed to the full effects of solar and galactic cosmic radiation irrespective of latitude."

Conceptual model of the magnetosphere of Mars due to remanent crustal fields as known today (courtesy LASP)



Flyby of Venus by Mariner 5 in 1967 showed that it did not possess a measurable magnetic field
(Van Allen, Krimigis, Frank, Armstrong, Science, 158, 1967)

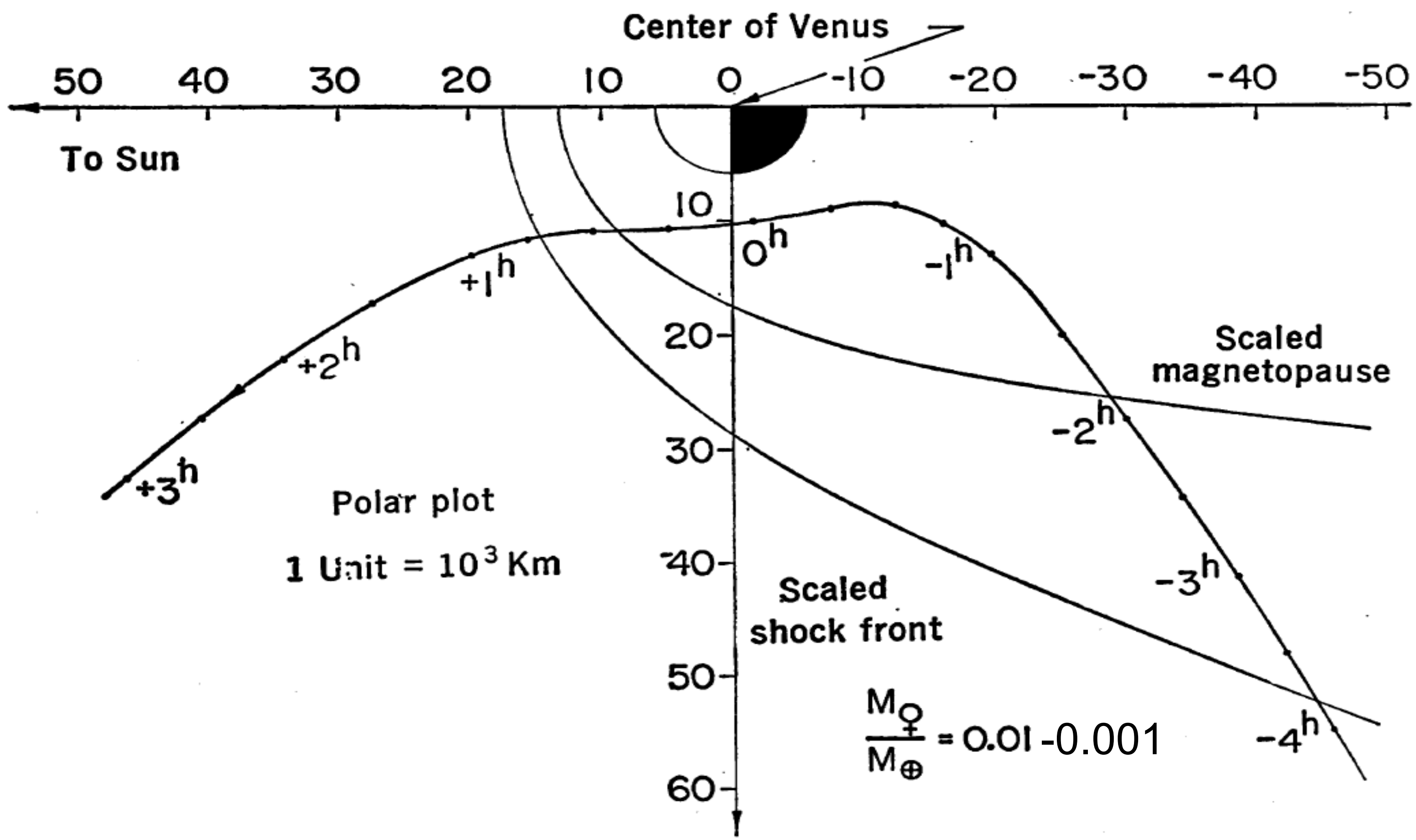
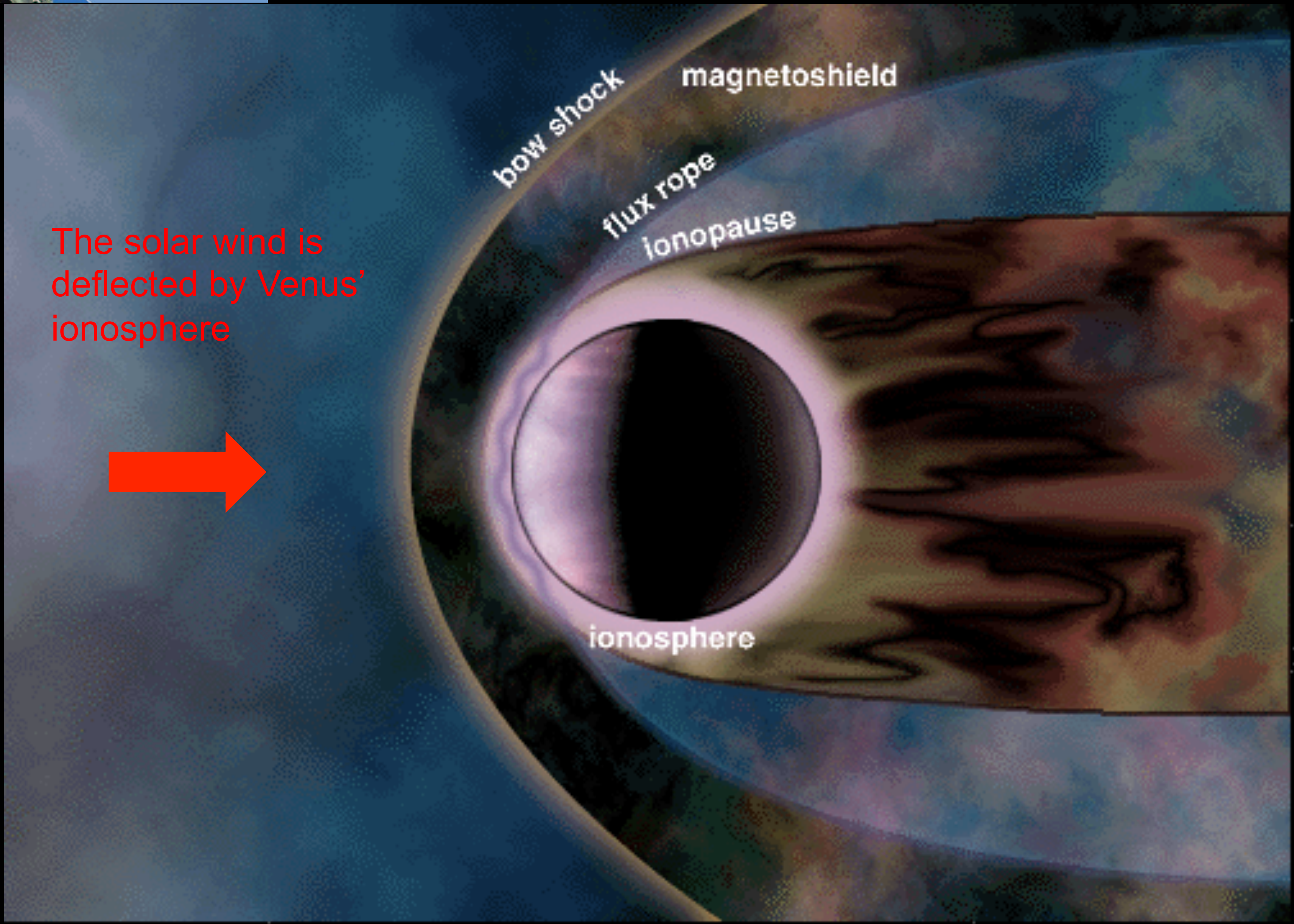
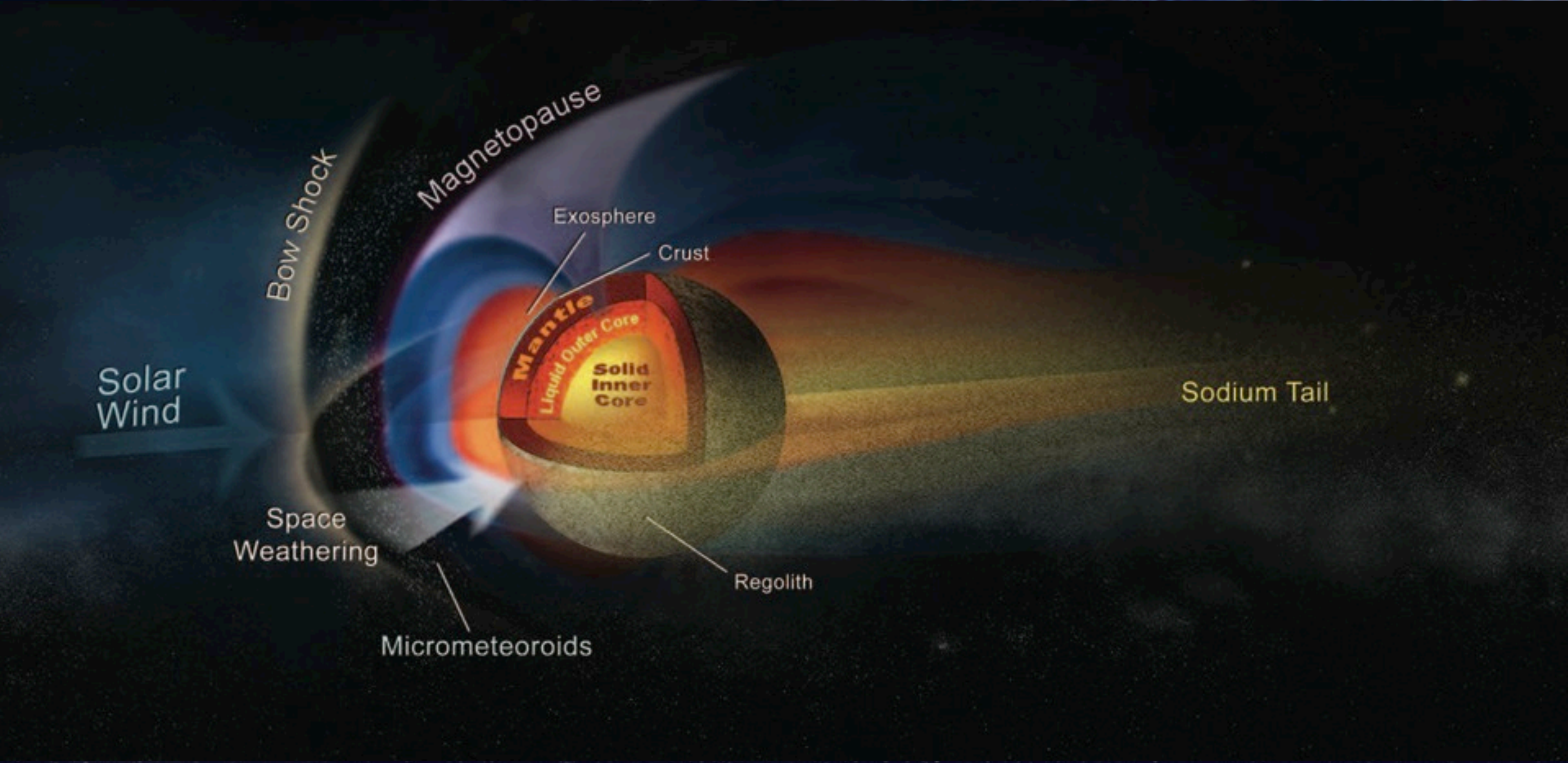


Fig. 2. Encounter trajectory of Mariner V with Venus in the rotating plane which contains Sun, the center of the planet, and the spacecraft. The coordinates are the Sun-Venus-spacecraft angle and the radial distance from the center of the planet to the spacecraft. Blackened circles on the trajectory are at 15-minute intervals from − 1 hour to + 1 hour, and at 30-minute intervals elsewhere. One unit equals 10^3 km. Also shown are traces of the magnetopause and shock front to be expected if the intrinsic magnetic dipole moment of Venus were 0.01 of that of Earth.

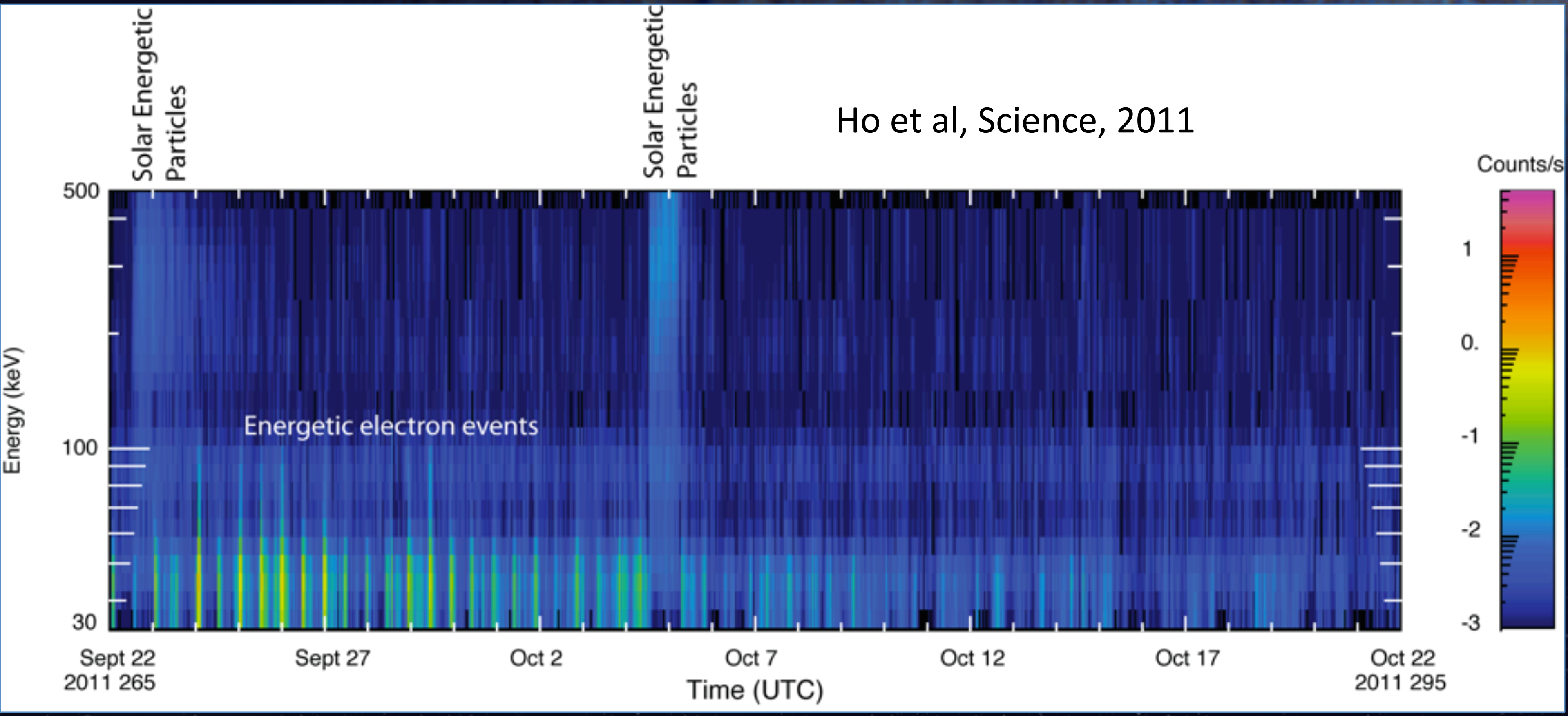
Current view of Venus SW interaction



Mercury's magnetosphere is truly unique

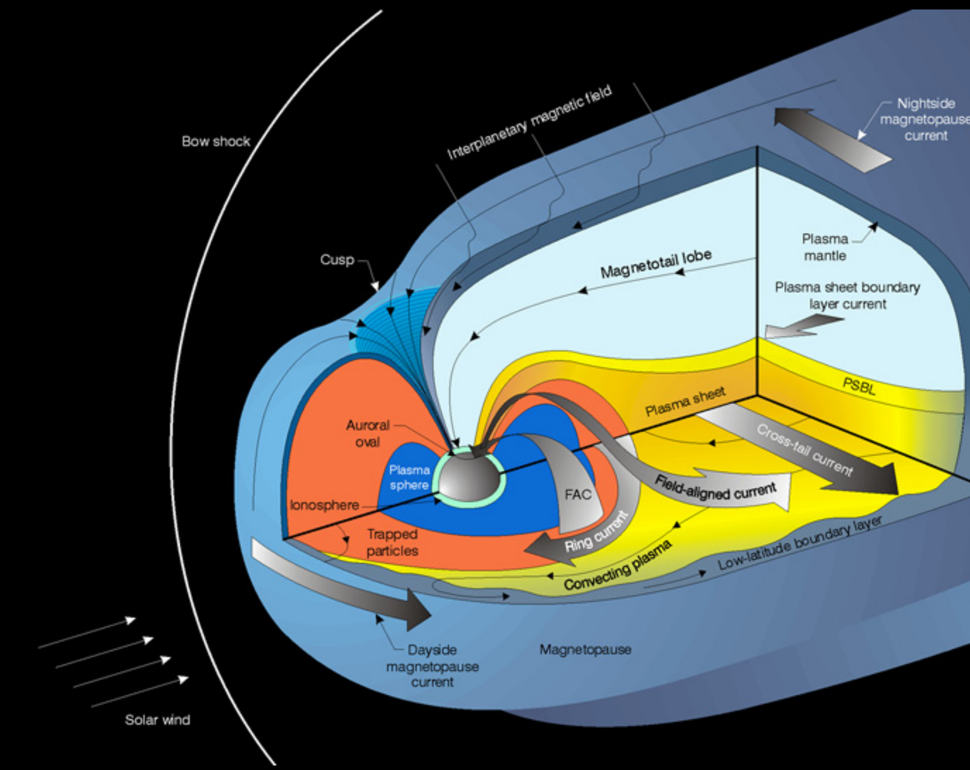


Occurrence of Electron Events

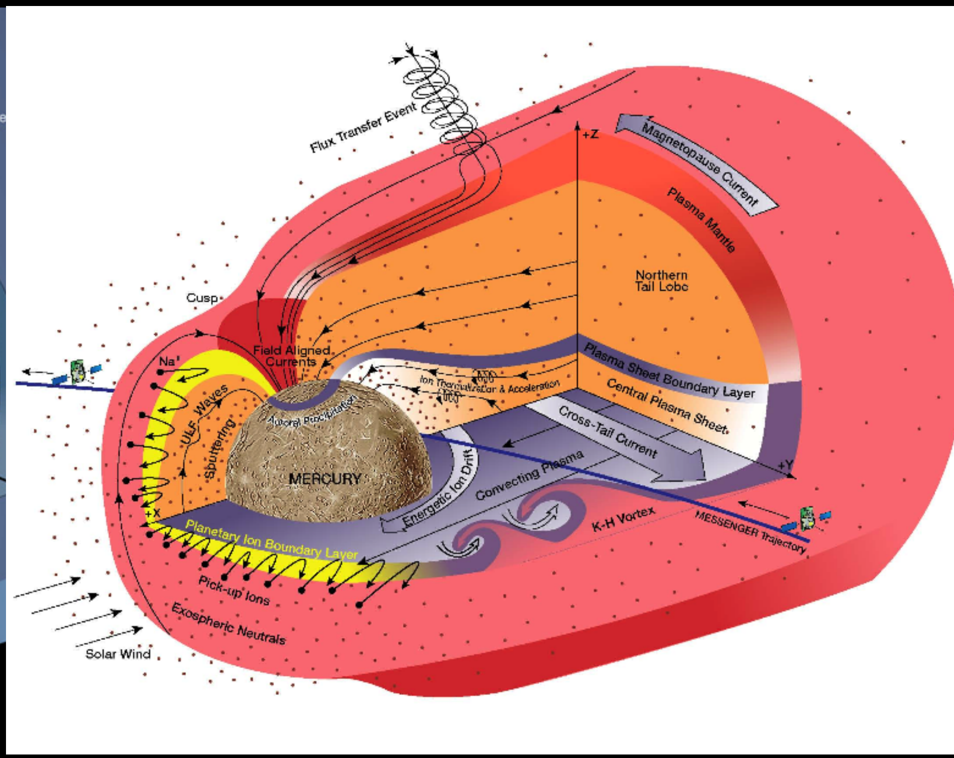


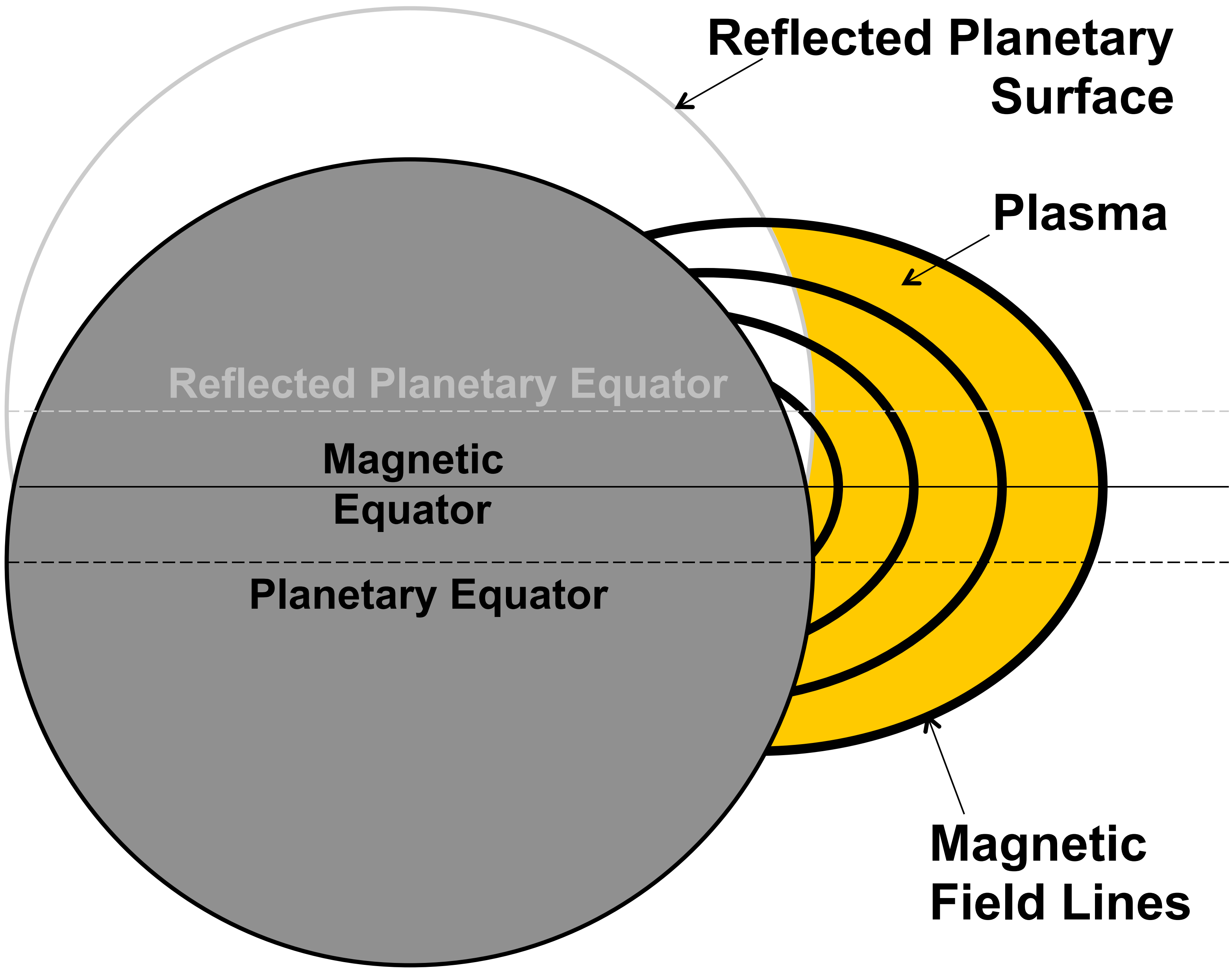
Earth's magnetosphere is the paradigm we use everywhere!

Earth's model



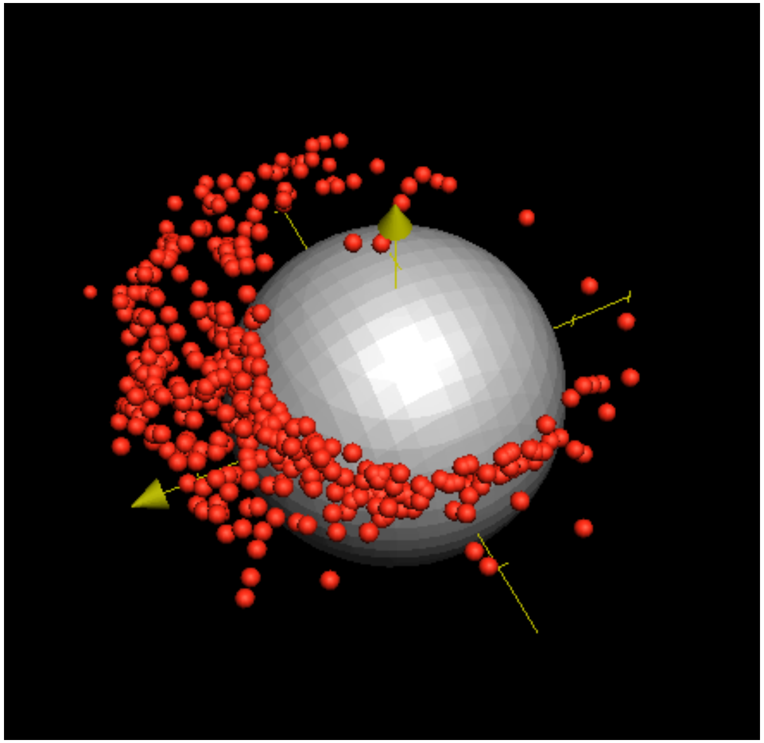
Mercury's model

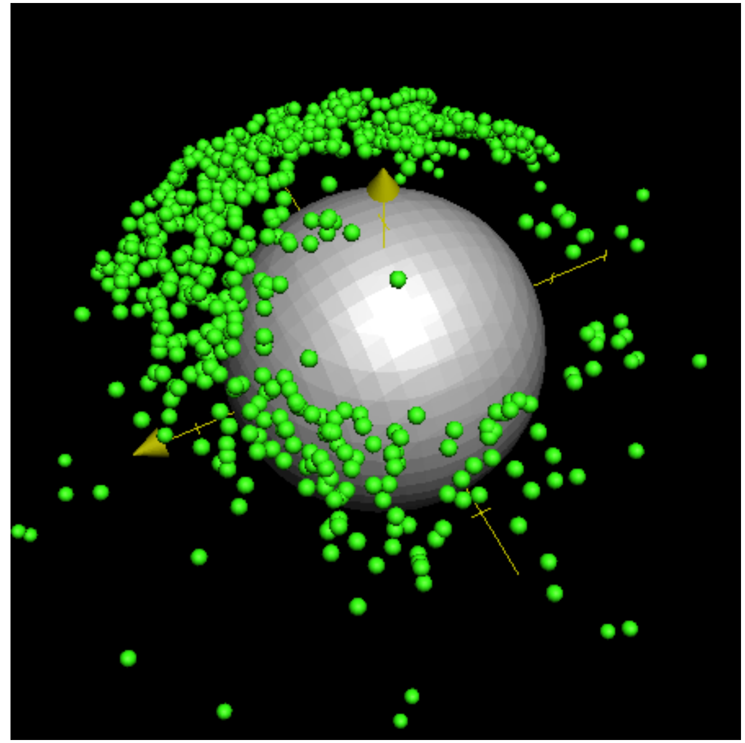




Reflected Planetary Surface
Plasma
Reflected Planetary Equator
Magnetic Equator
Planetary Equator
Magnetic Field Lines

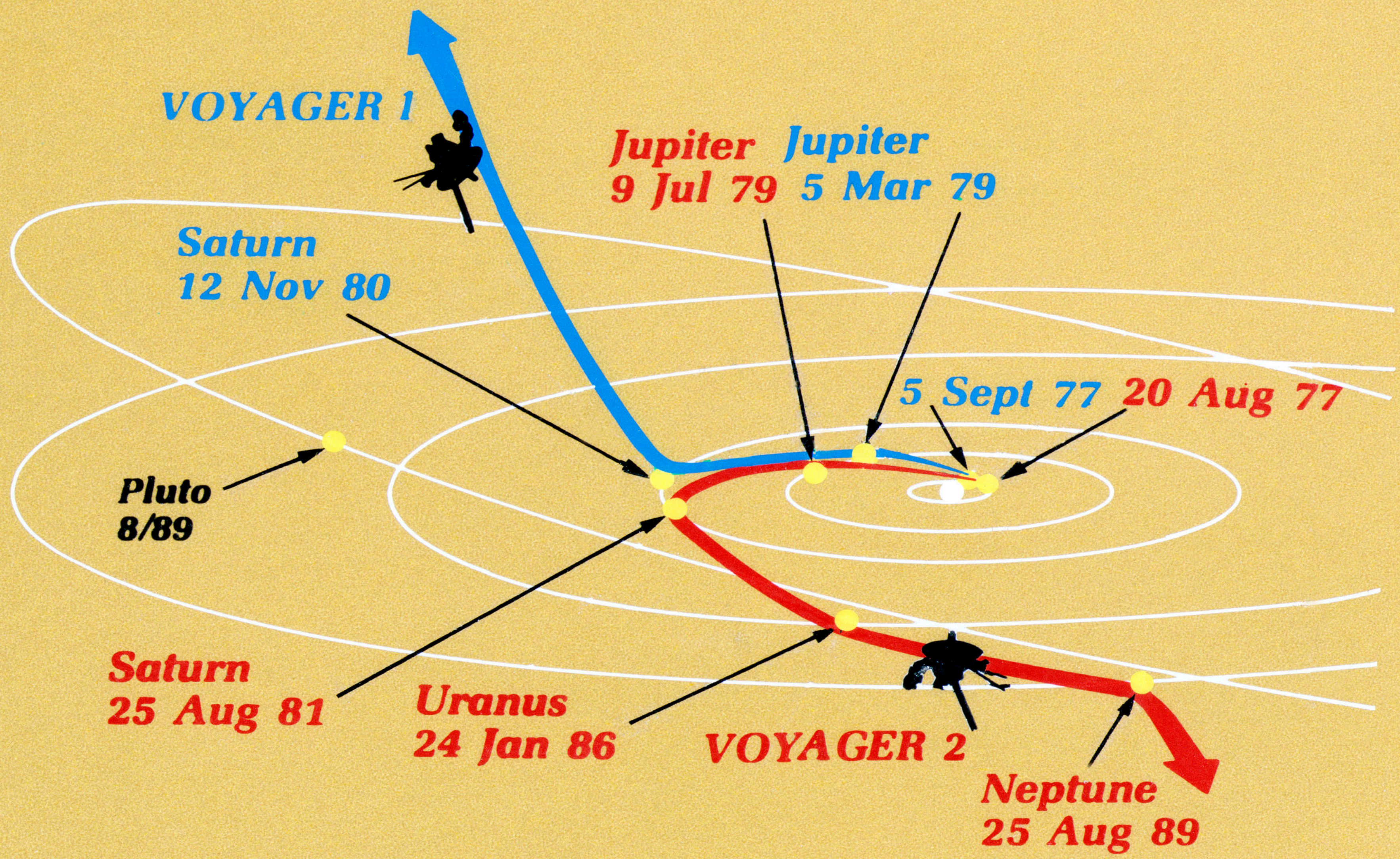
Three dimensional view of electron events from MESSENGER



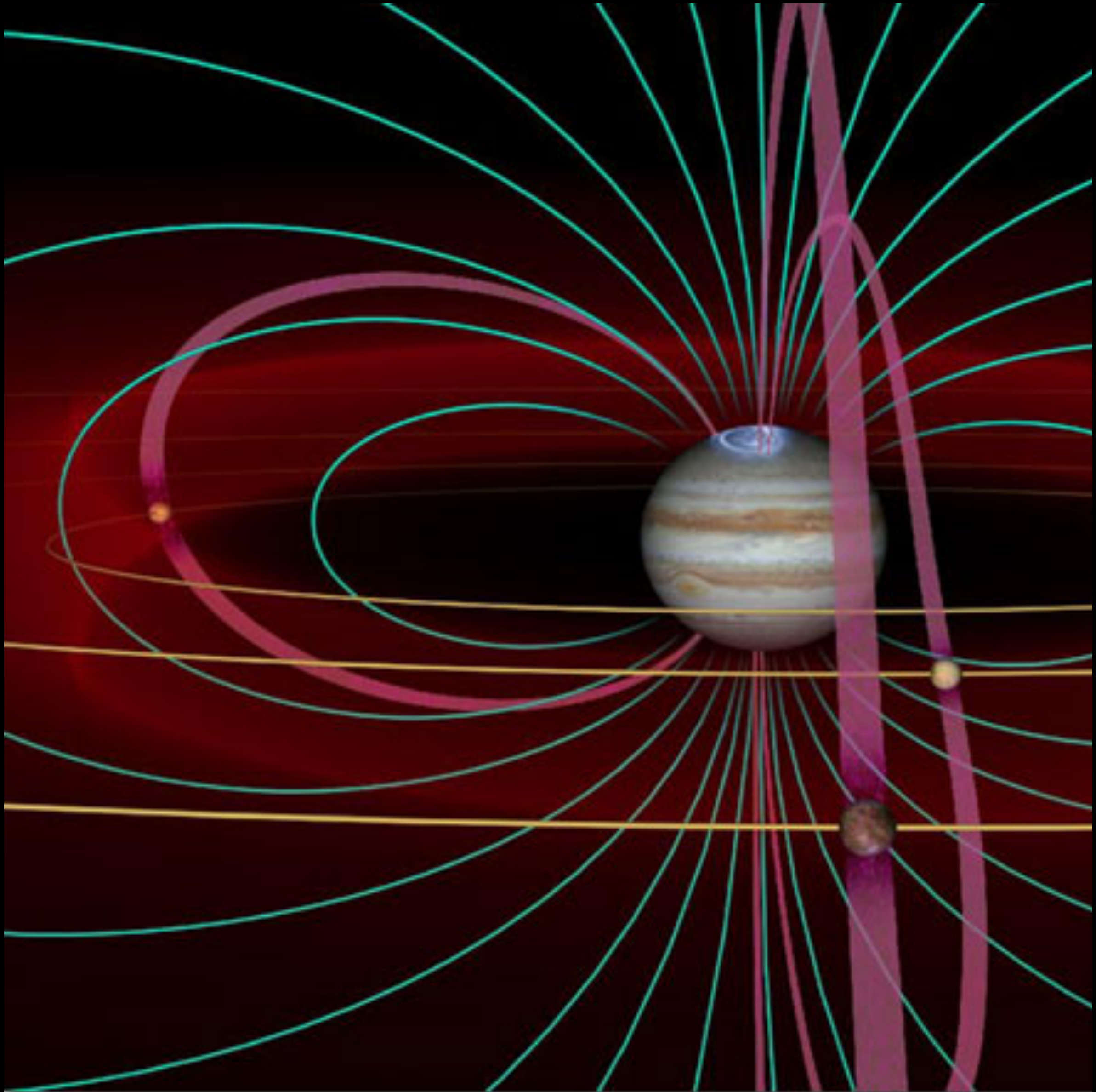


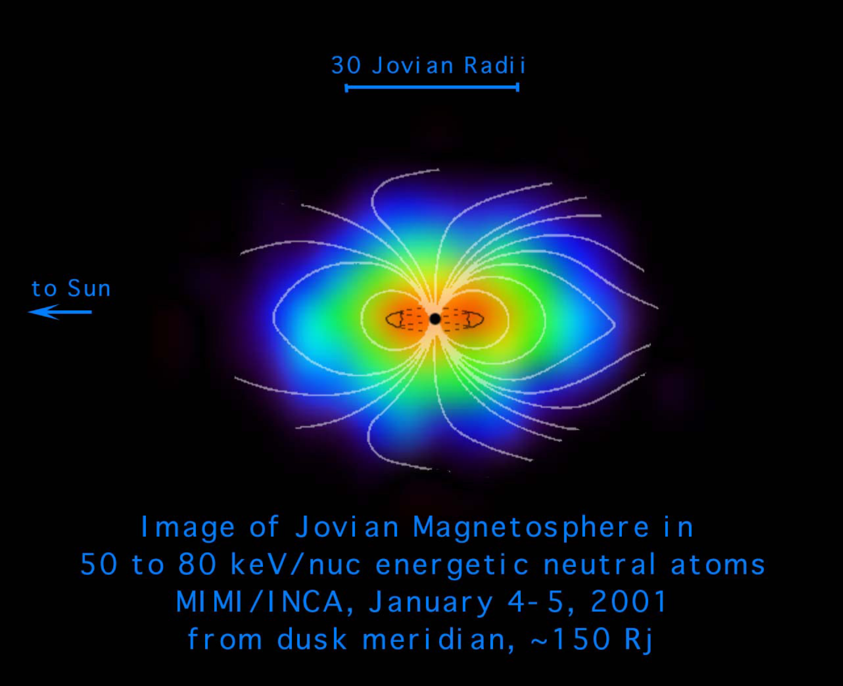
- 8 hour orbit shows different locations for smooth and bursty events.

Pioneer 10,11 and Voyager completed the exploration of magnetospheres of the Outer Planets

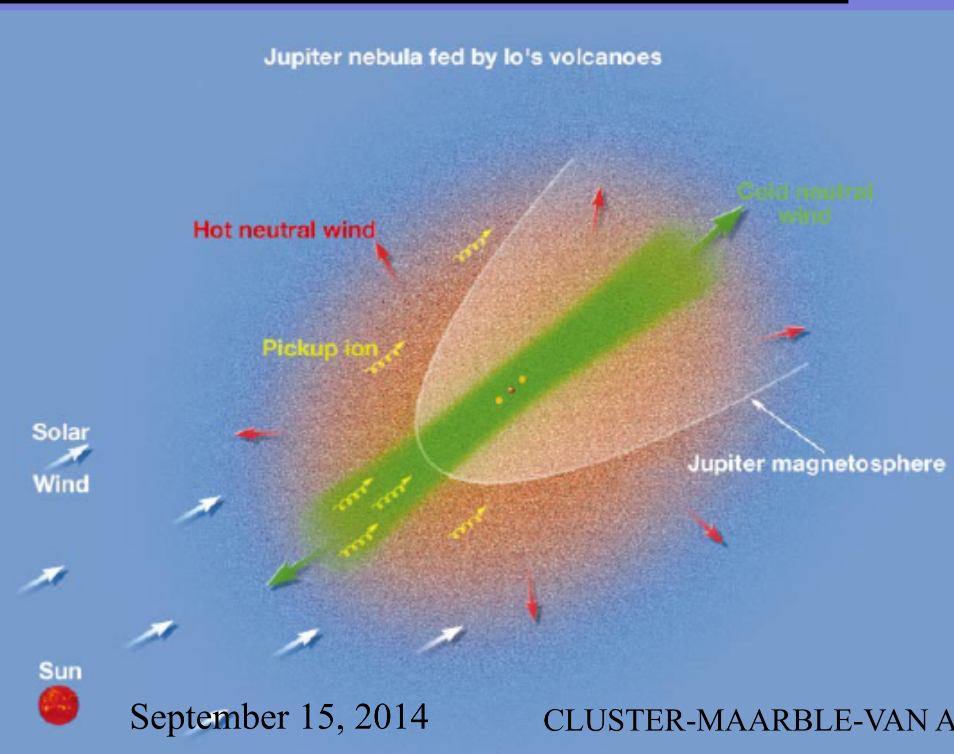


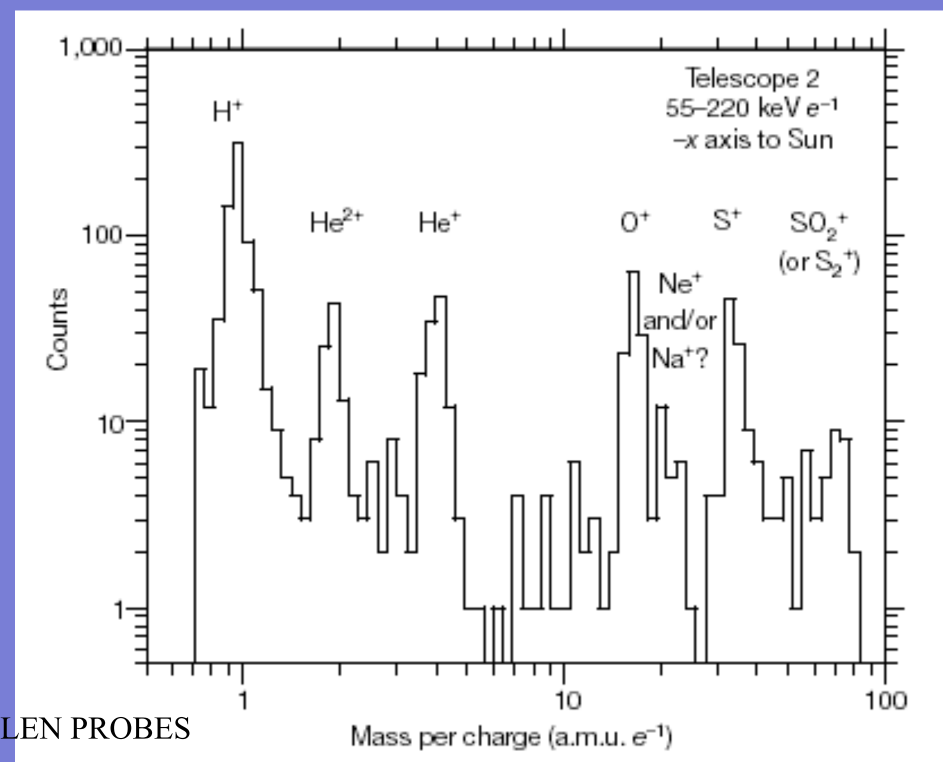
Jupiter's Magnetic Field and Aurora





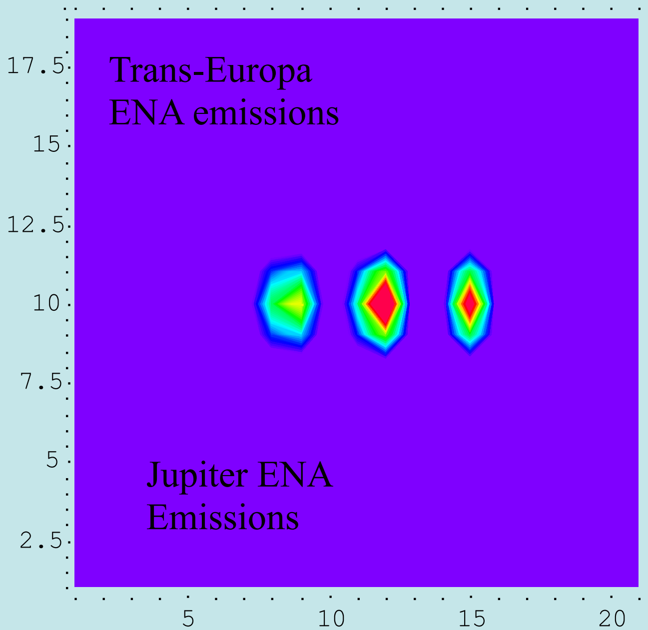
Cassini/MIMI discovery of planetary nebula of Iogenic gases populating huge volume of space around Jupiter (*Krimigis et al, Nature, 415, 994, 2002*)



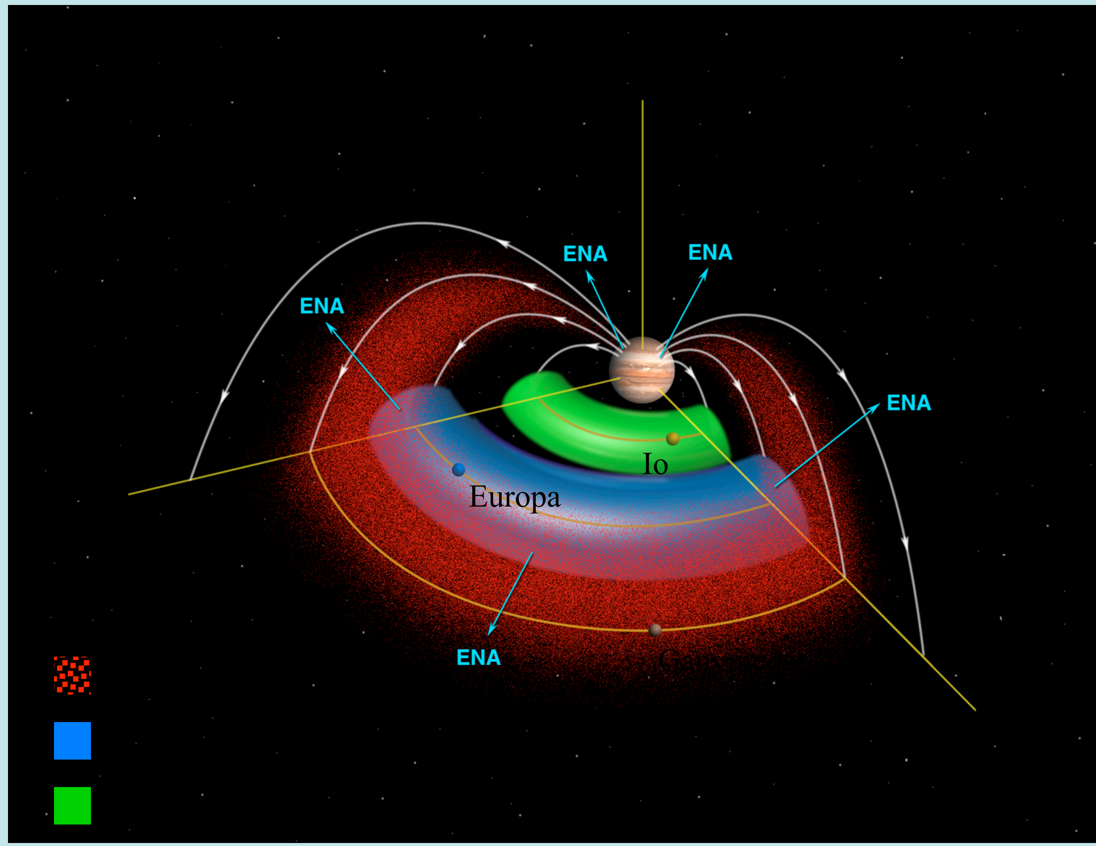


Cassini Ion and Neutral Camera (INCA) Discovers Massive Gas Cloud Encircling Jupiter

Planetary space environments glow with Energetic Neutral Atoms (ENAs) from interactions between magnetically trapped hot ions and cold neutral gas



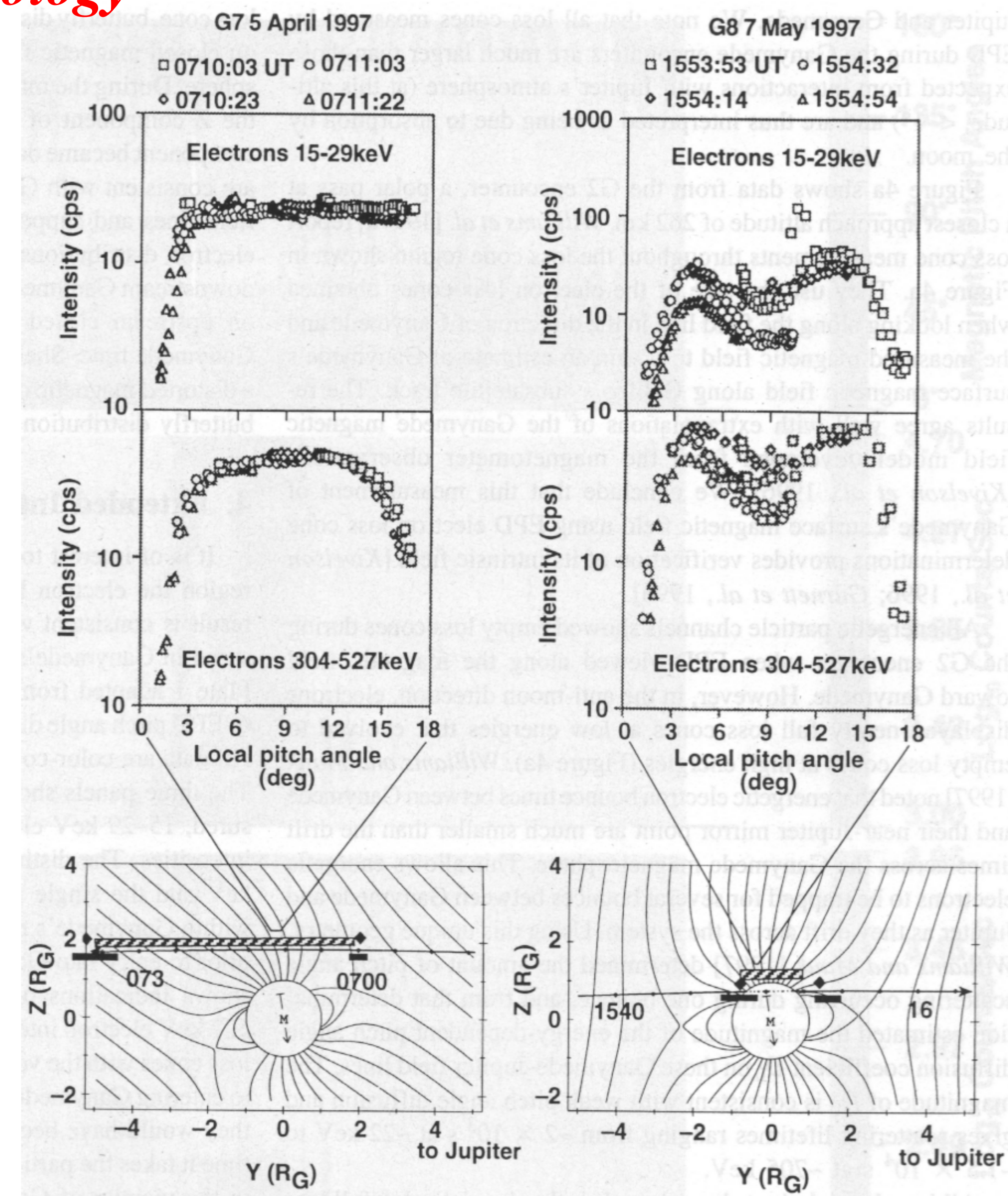
INCA ENA Image of Jupiter reveals torus of gas just outside the orbit of Jupiter's moon Europa ***(Mauk, Mitchell, Krimigis, and Roelof, Nature, 421, 920-922, 2003)***



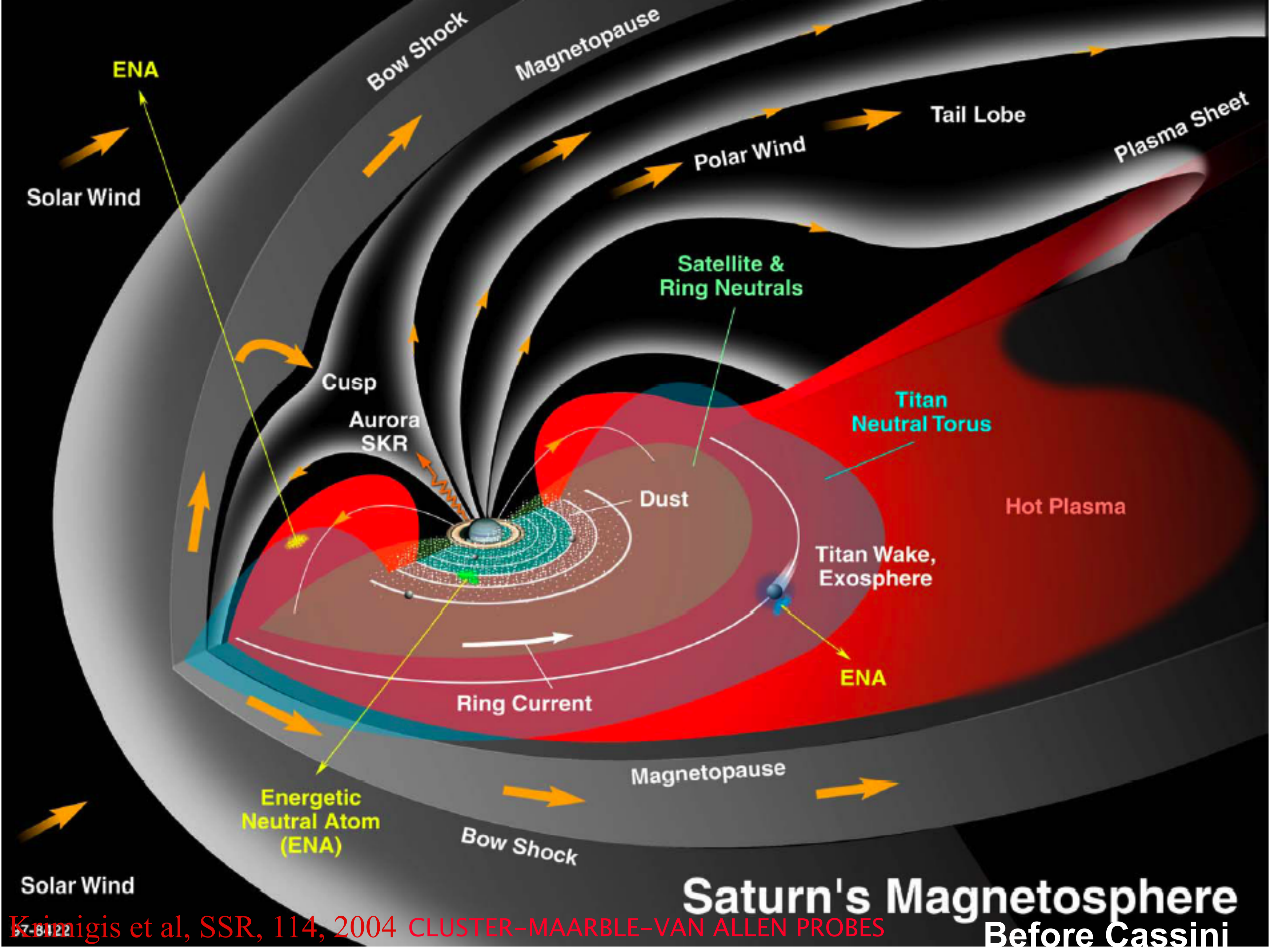
Configuration of Jupiter's space environment as inferred from the INCA image. The new component is the blue gas torus

Ganymede's Magnetic Topology

Energetic electron measurements remotely diagnose magnetic topology, boundary geometry and surface magnetic field strengths of icy moons.



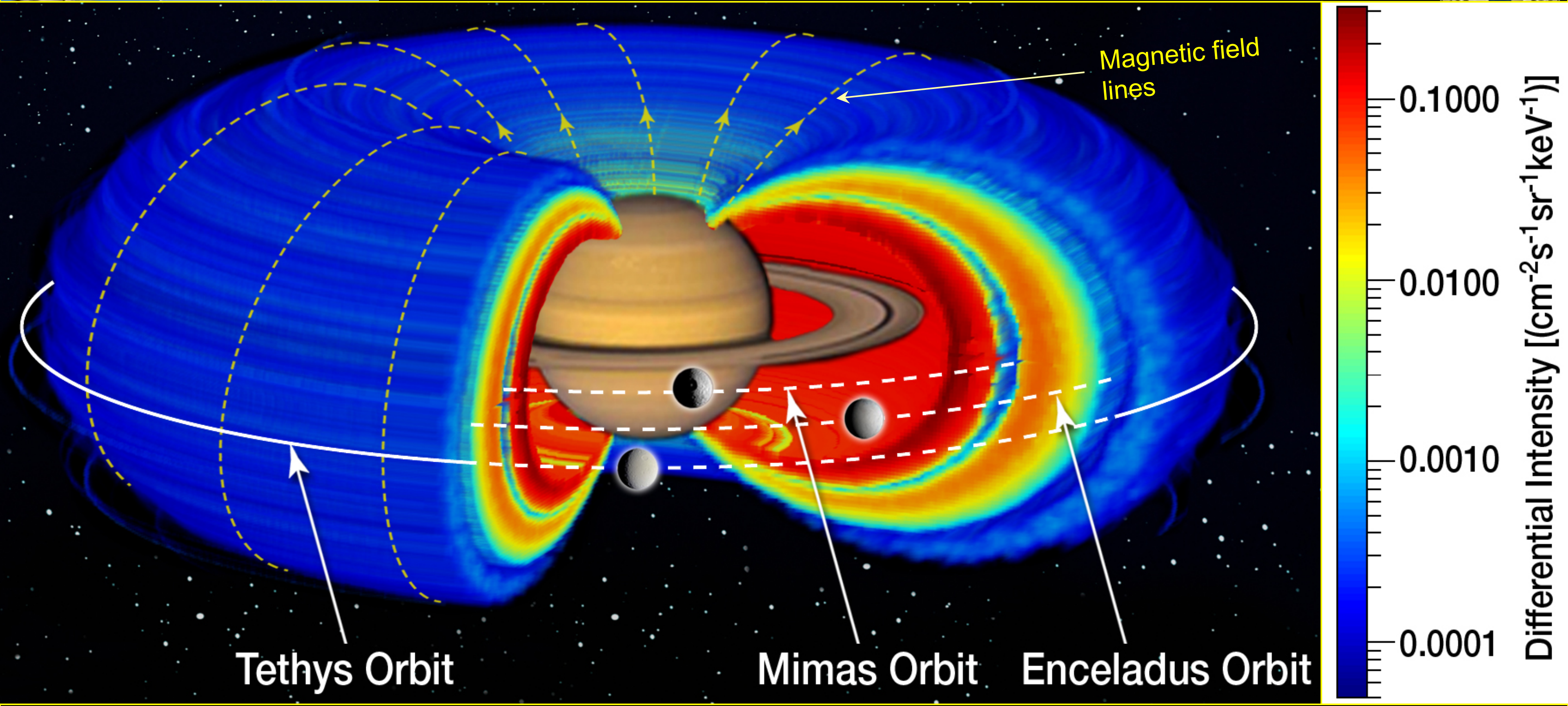
Williams et al., GRL, 1998



Krimigis et al, SSR, 114, 2004 CLUSTER-MAARBLE-VAN ALLEN PROBES

Saturn's Ion Radiation Belts
Cassini measures their solar-cycle modulation

MPS APL Fundamental Technologies, LLC



- Saturn's ion radiation belts extend between the main rings and the orbit of Tethys.
- Energetic ions are absorbed from all inner Saturnian moons, resulting in a "sectorized" belt structure, isolated from the outer Saturnian magnetosphere.
- Only Galactic Cosmic Rays (GCRs) can propagate across the moon orbits and impact Saturn and its rings
- Impacts of GCRs on Saturn's rings and atmosphere produce energetic ions that populate the radiation belts.
- The intensity of GCRs in our solar system varies during the 11-year cycle of the solar activity.
- This modulation, which should then be "reflected" in the intensity of Saturn's ionic belts, has now been resolved using a 6-year dataset of Cassini's MIMI/ LEMMS energetic charged particle detector.

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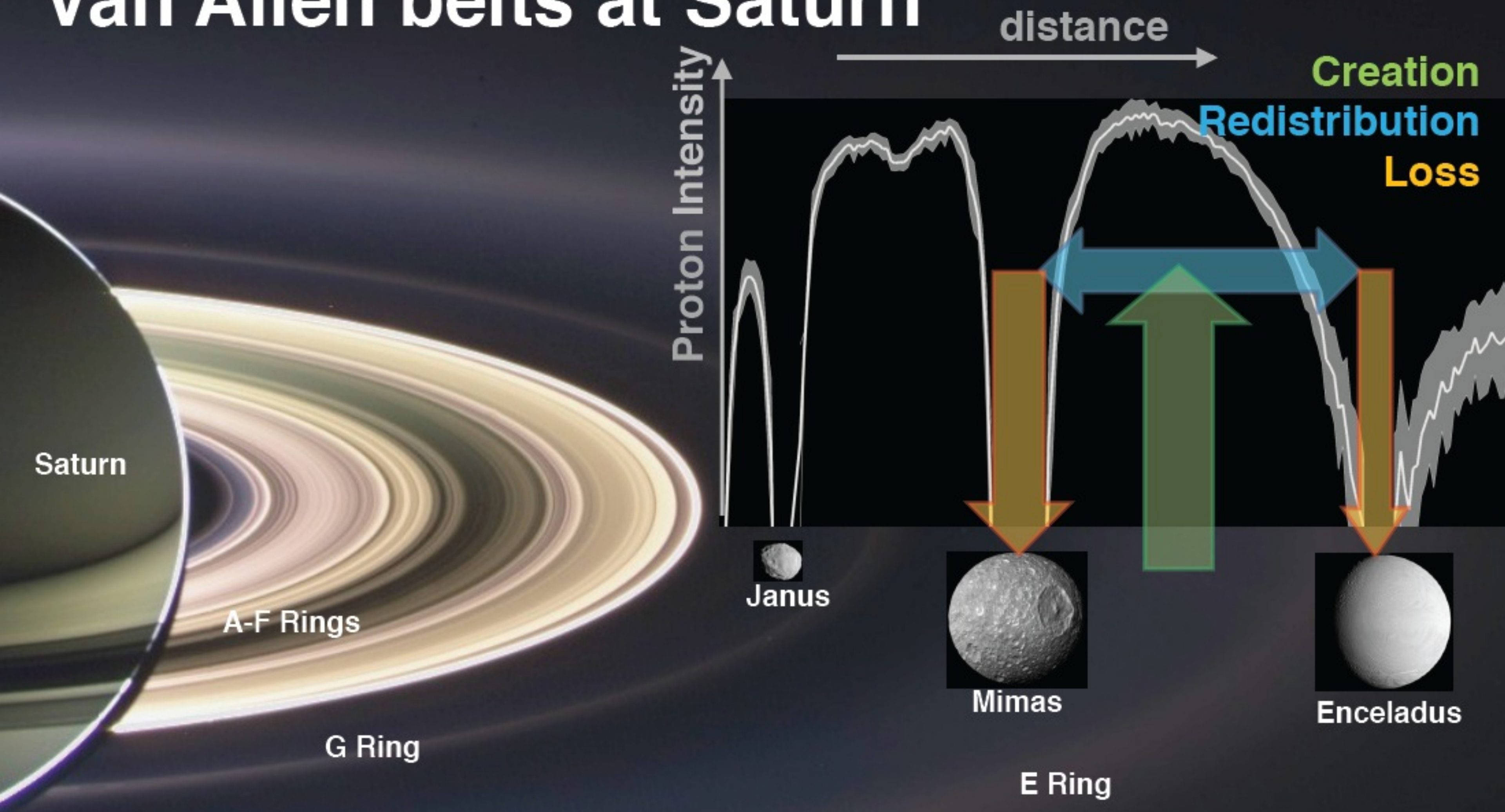
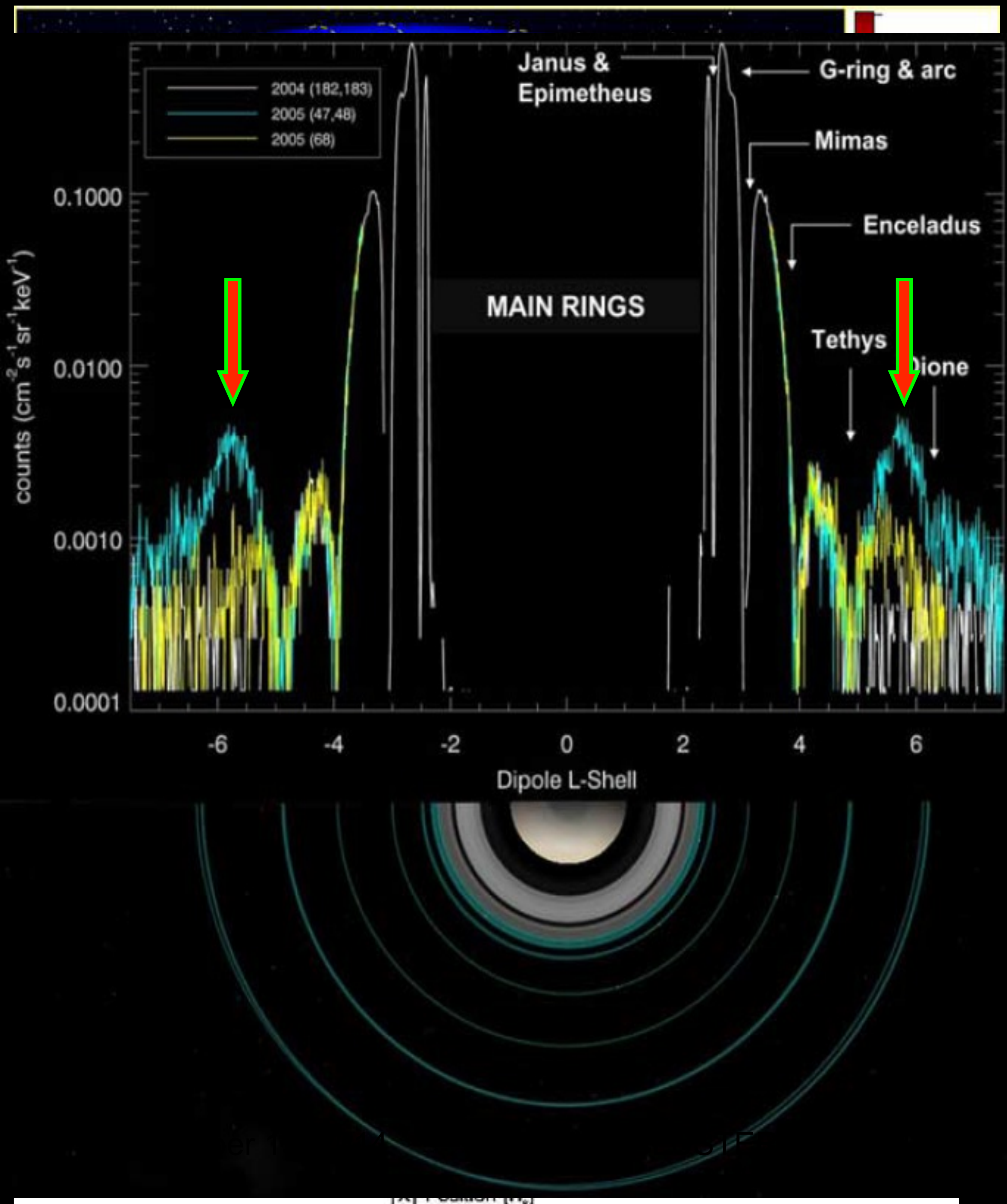
Van Allen belts at Saturn



- Curves show proton radiation belts of Saturn. Protons have MeV energies
- Protons are created from neutrons produced by cosmic partices hitting Saturn
- They redistribute due to diffusion...
- ...until they reach the orbits of the icy moons or rings and get lost there. The E ring has no effect.



Saturn's radiation belts

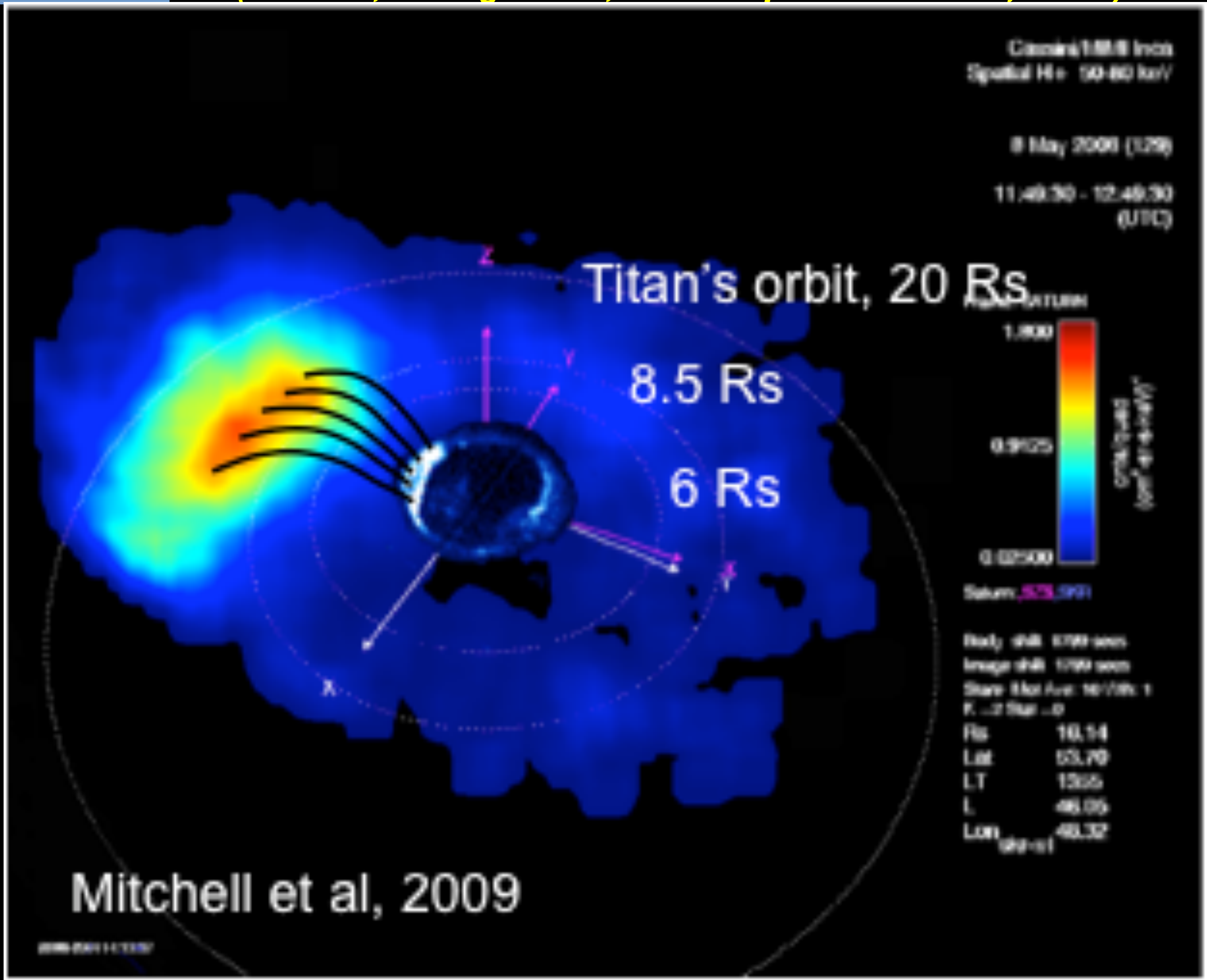
MeV ions, symmetrically distributed in Local Time, are separated by the orbits of the moons and form 4 stable belts inside L=5 (orbit of Tethys).

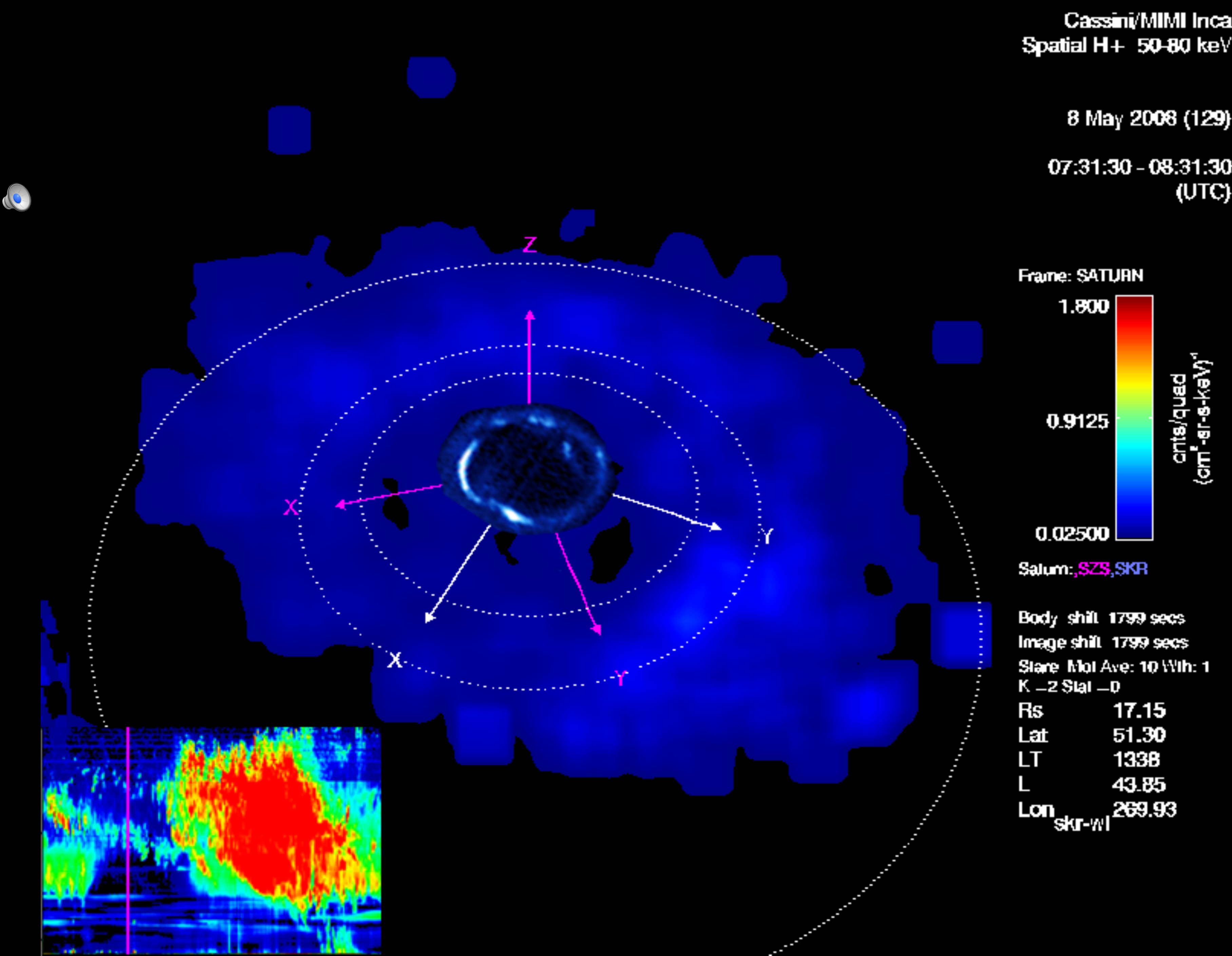
On 2005, Cassini discovered a new transient radiation belt between the orbits of Tethys and Dione that remained observable for several weeks as a result of 3 intense solar energetic particle events that hit the magnetosphere of Saturn during that period.

Roussos et al., 2008

Imaging of Acceleration at Equator and Connection to UV Aurora

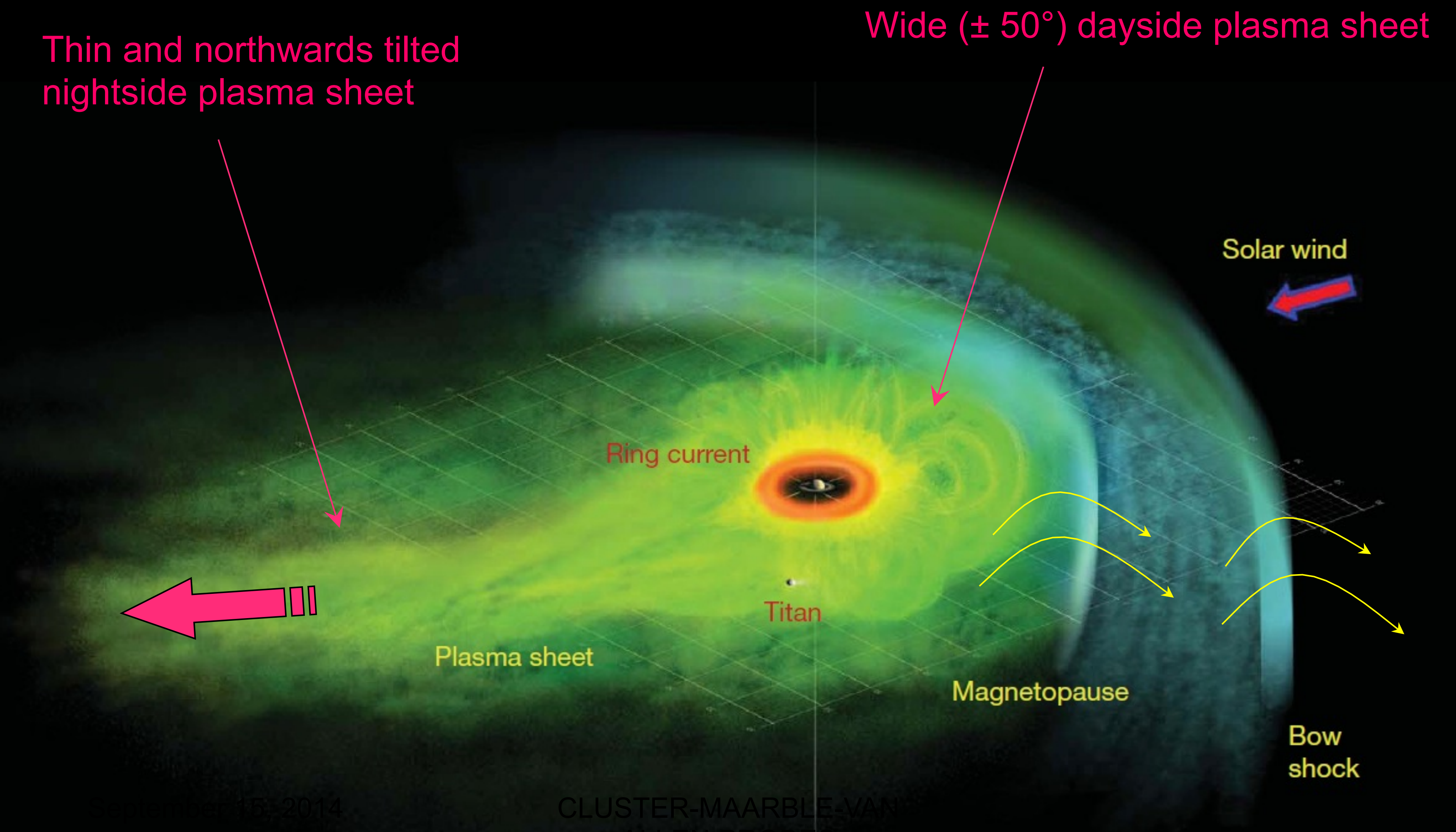
(Mitchell, Krimigis et al, Planet. Space Science, 2009)





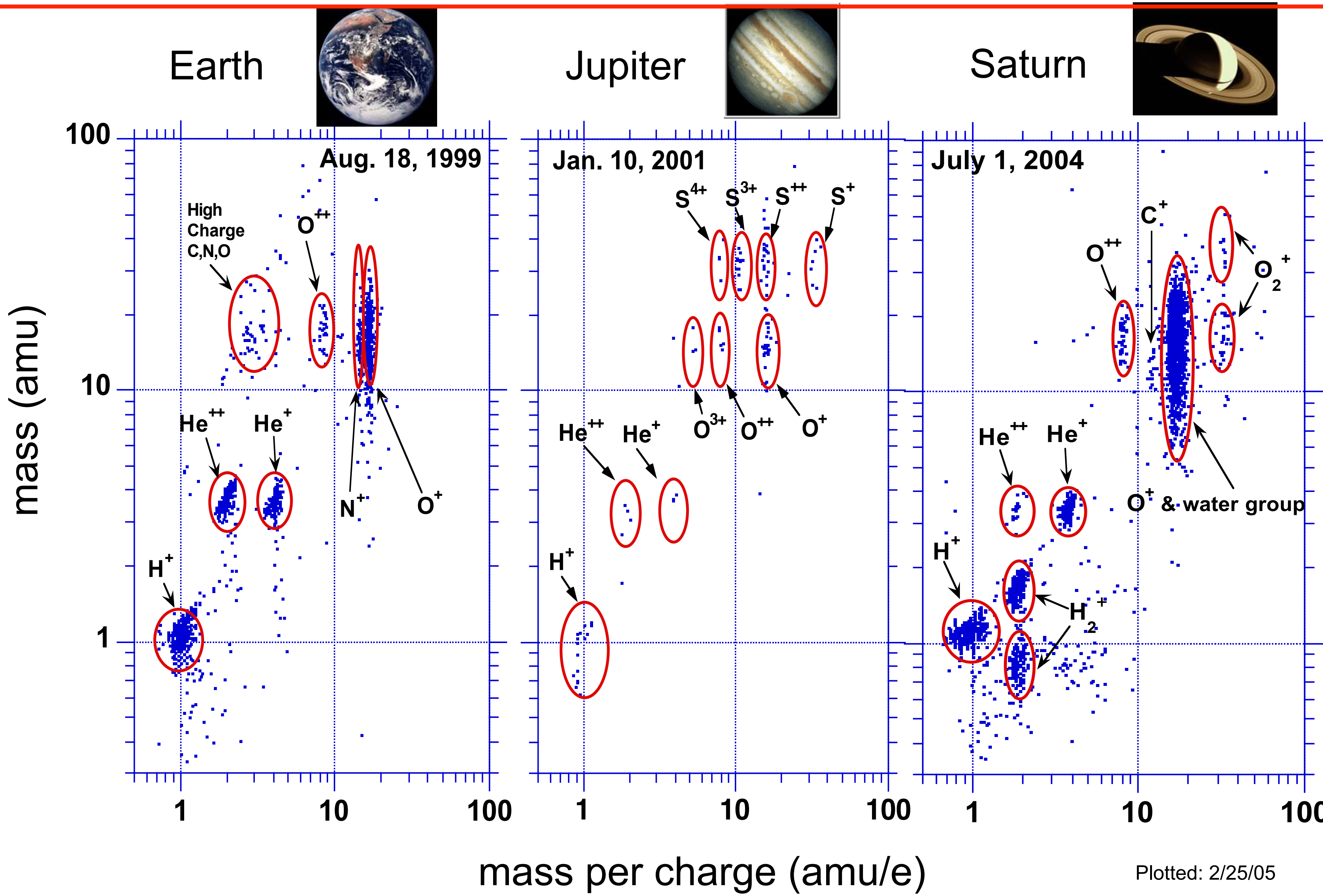
Cassini/MIMI Inca
Spatial H+ 50-80 keV
8 May 2008 (129)
07:31:30 - 08:31:30
(UTC)
Frame: SATURN
1.800
0.9125
0.02500
cnts/quad
(cm²-sr-s-keV)⁻¹
Saturn:,SZS,SKR
Body shift 1799 secs
Image shift 1799 secs
Stare Mot Ave: 10 Wth: 1
K =2 Stat =0
Rs 17.15
Lat 51.30
LT 1338
L 43.85
Lon skr-wl 269.93
Z
X
Y
X
Y

A **data based**, 3D artist's concept of the **>3 keV** energetic particle distribution in the Saturnian magnetosphere, as measured by Cassini/MIMI between SOI and mid 2007.

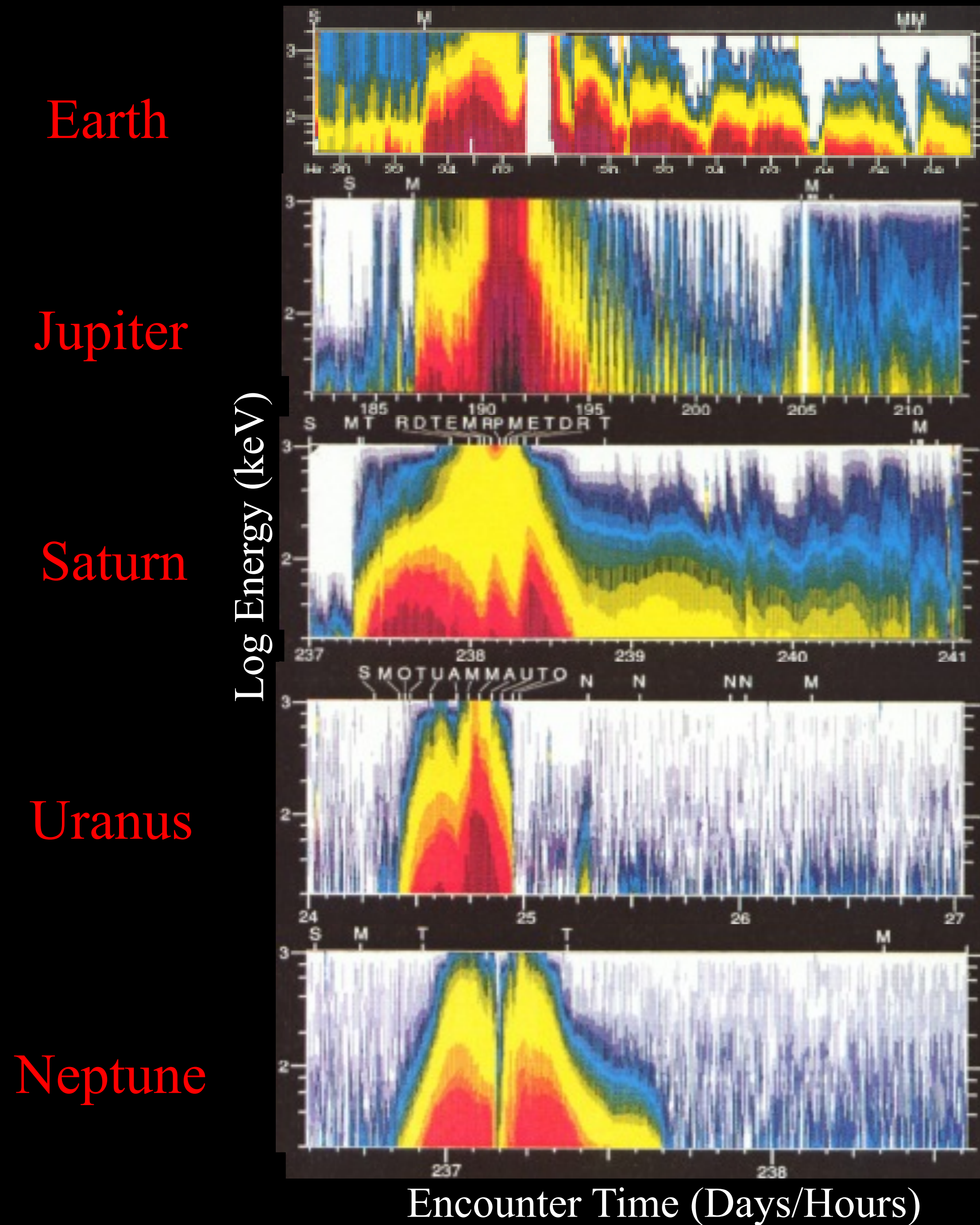


Krimigis et al., Nature, 2007

Charge Energy Mass Spectrometer (CHEMS) on Cassini records "fingerprints" of ion composition at Earth, Jupiter, and Saturn (Hamilton et al, 2005)

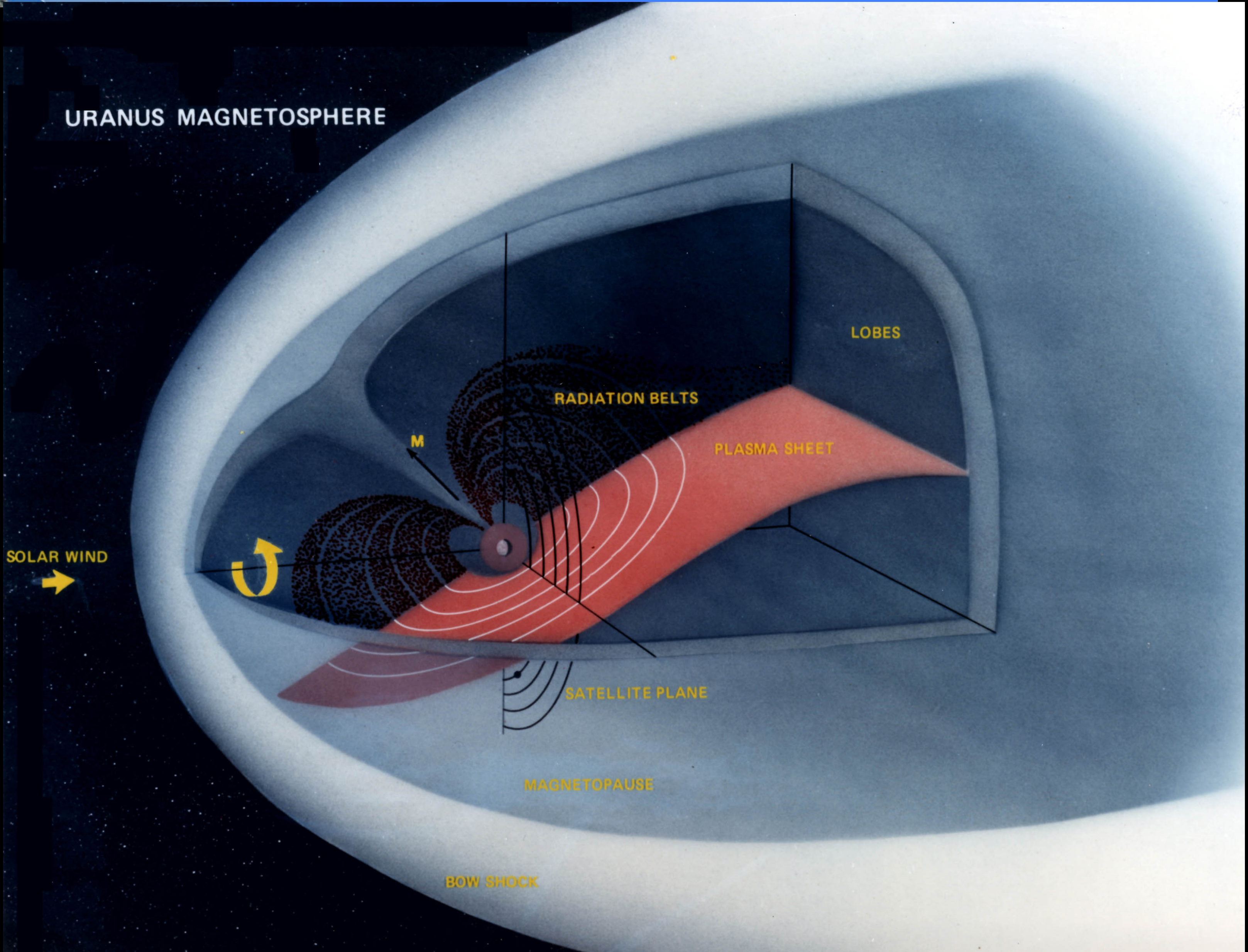


Energetic particle intensities (Low Energy Charged Particle-LECP) from Voyager flybys of all outer planets compared to Earth,
but on different time axis



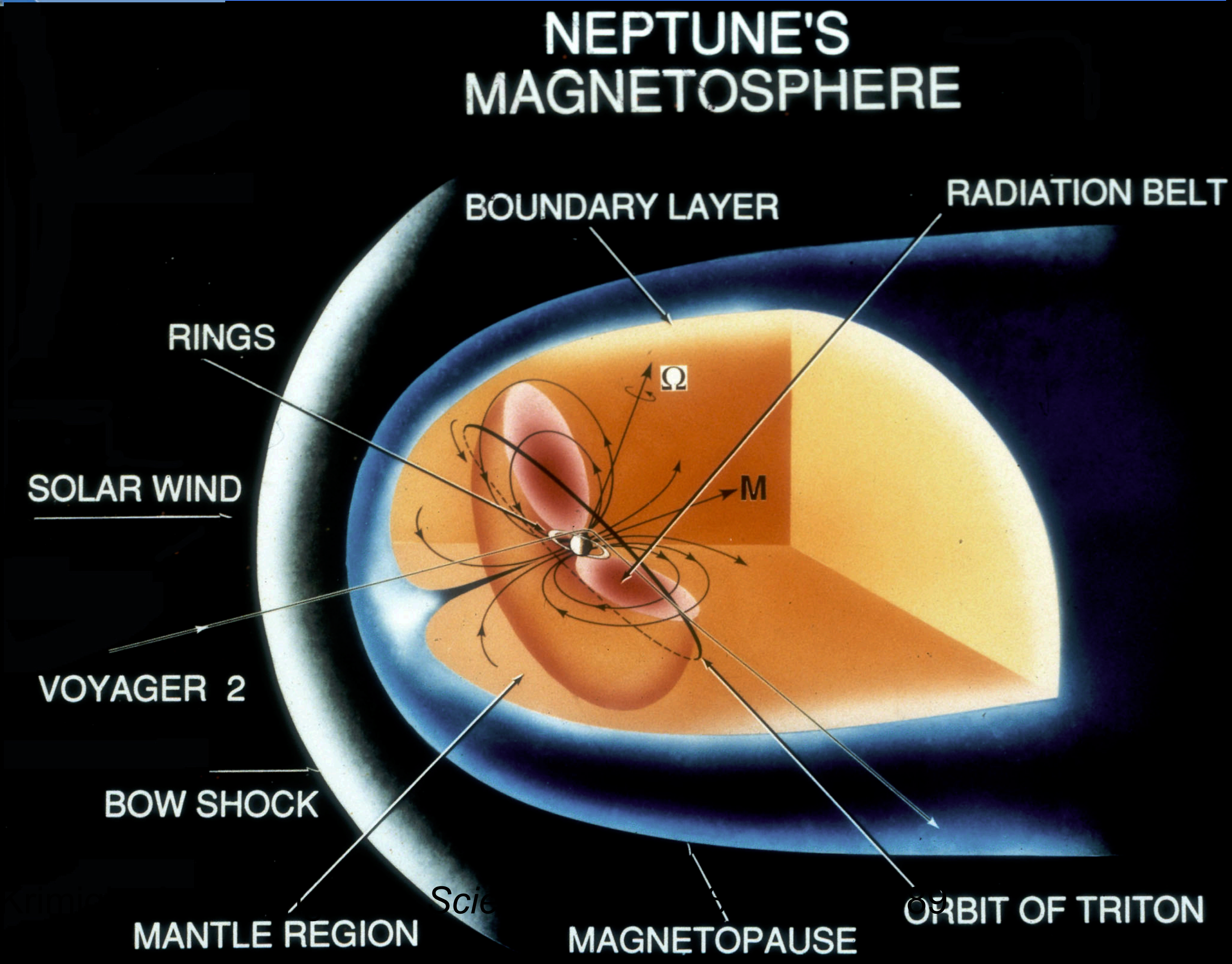
Radiation Belts at Uranus

(Krimigis et al, Science, 233, 1986)



Radiation Belts in Neptune's magnetosphere

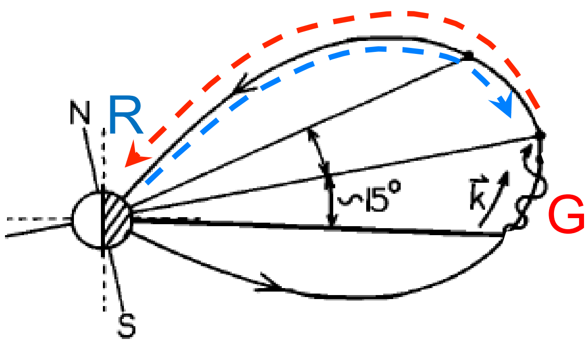
(Krimigis et al, Science, 246, 1989)



What is the Kennel Petschek Limit?
(Mauk, JGR, in press, 2014)

- Kennel and Petschek (KP, 1966) proposed that electron and ion integral fluxes are limited by a non-linear upper limit, now called the Kennel Petschek Limit.

Whistler Wave Growth



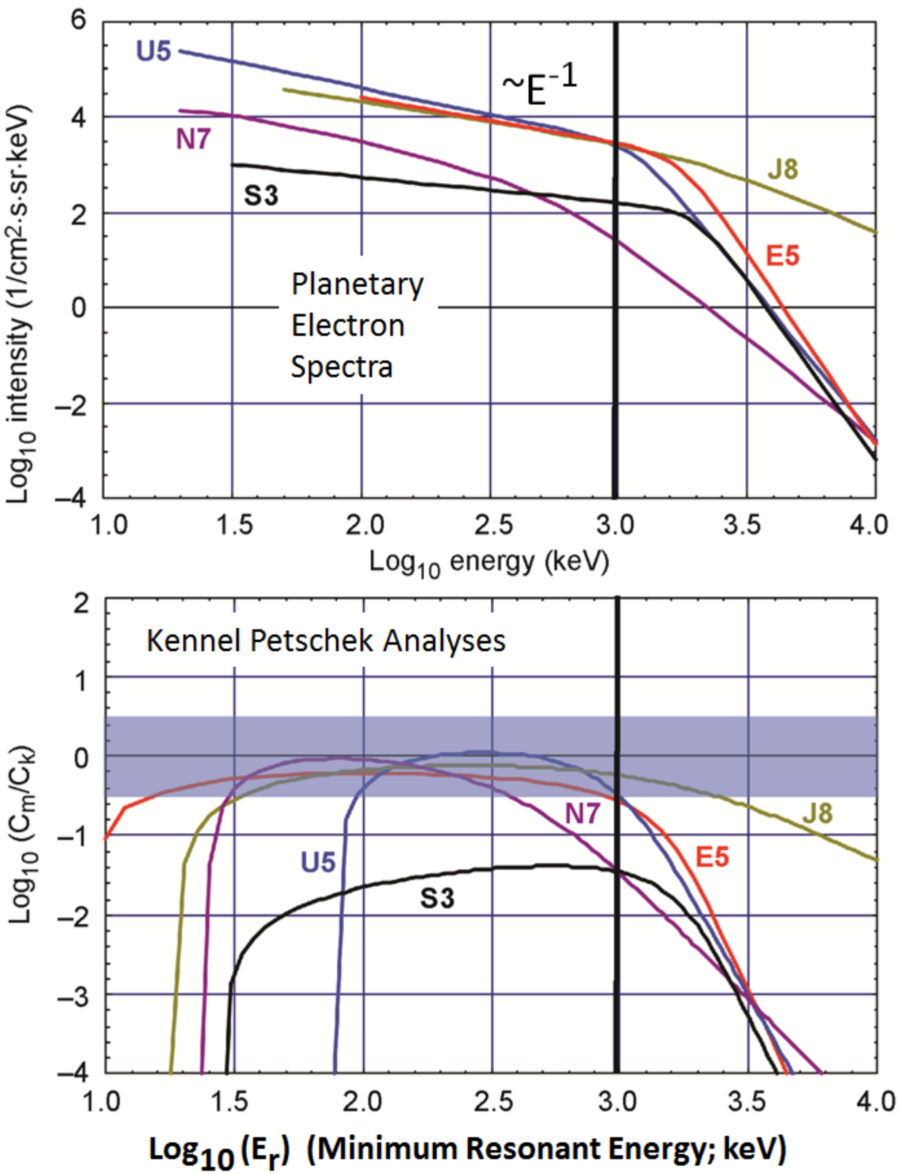
$$G \approx Exp[\frac{\gamma}{V_g} \cdot S \cdot R_P]$$

G	= Wave gain
γ	= Temporal growth rate
R_P	= Planetary radius (cm)
R	= Reflection coefficient
S	= Growth spatial scale (R_E) (“L” is commonly used)
V_g	= Wave group speed (cm/s)
	= Down-going wave
	= Up-going reflected wave

The big idea:

- **A flux tube is populated by some strong acceleration process.**
- **If wave growth (G) and ionospheric wave reflection (R) have G·R > 1 , electrons are lost at the very fast, strong diffusion limit from wave scattering.**
- **When acceleration is fast (but still slower than the strong diffusion limit), particles adjust themselves so that G·R ~ 1**

The Differential KP Limit was found to greatly order the most intense radiation belt electrons in planetary magnetosphere

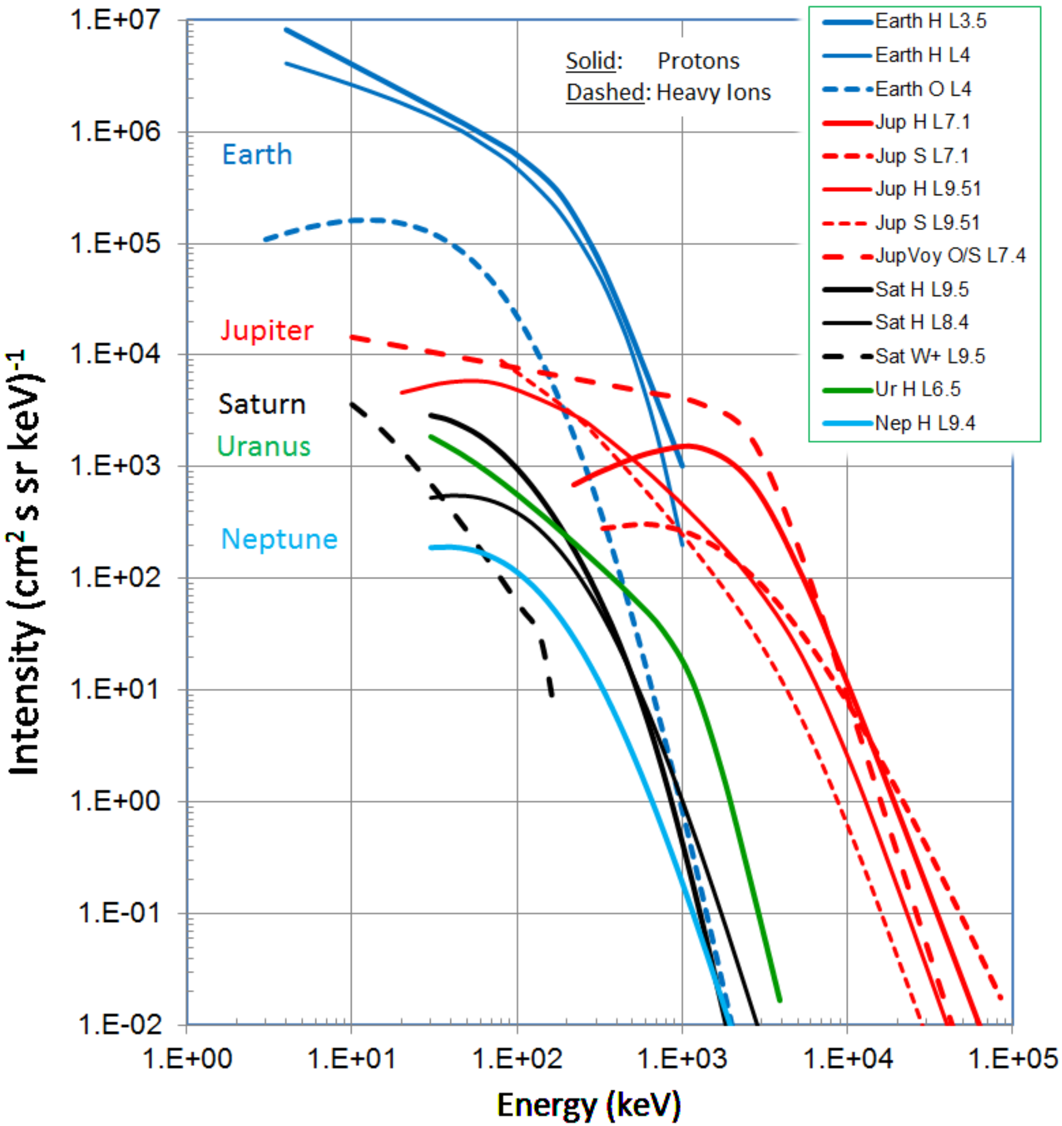


The most intense electron radiation belt electrons at 5 planets (most intense at 1 MeV; Mauk and Fox, 2010)

All of the sample spectra except that of Saturn are apparently affected by the KP limit (with $C_m/C_K \sim 1$ for a broad range of energies).

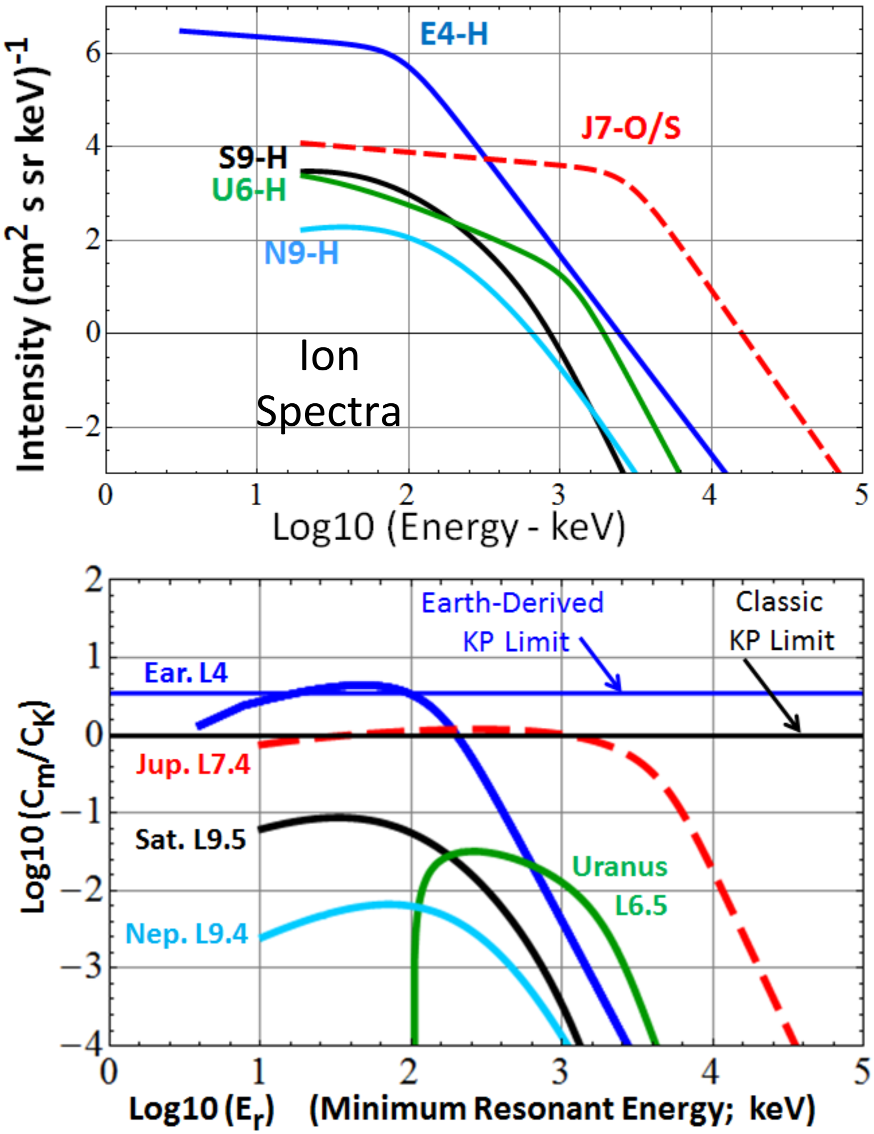
The result is a characteristic "flat" spectrum, and specifically $\sim E^{-1}$ spectral shapes at the lower energies.

Planetary Energetic Ion Populations throughout the Solar System are exceedingly diverse. (Mauk, JGR, in press, 2014)



- Shown are the most intense ion spectra observed throughout these systems, at 100 keV and 1 MeV.
- The question is: By what standard do we compare particle populations of diverse planetary magnetospheres?
- One proposal is to use updated versions of the classical Kennel-Petschek Limit Theory.

When all 5 planets are examined together, we see that <u>only</u> Earth and Jupiter appear to have KP limited ion spectra (Mauk, JGR, in press, 2014)



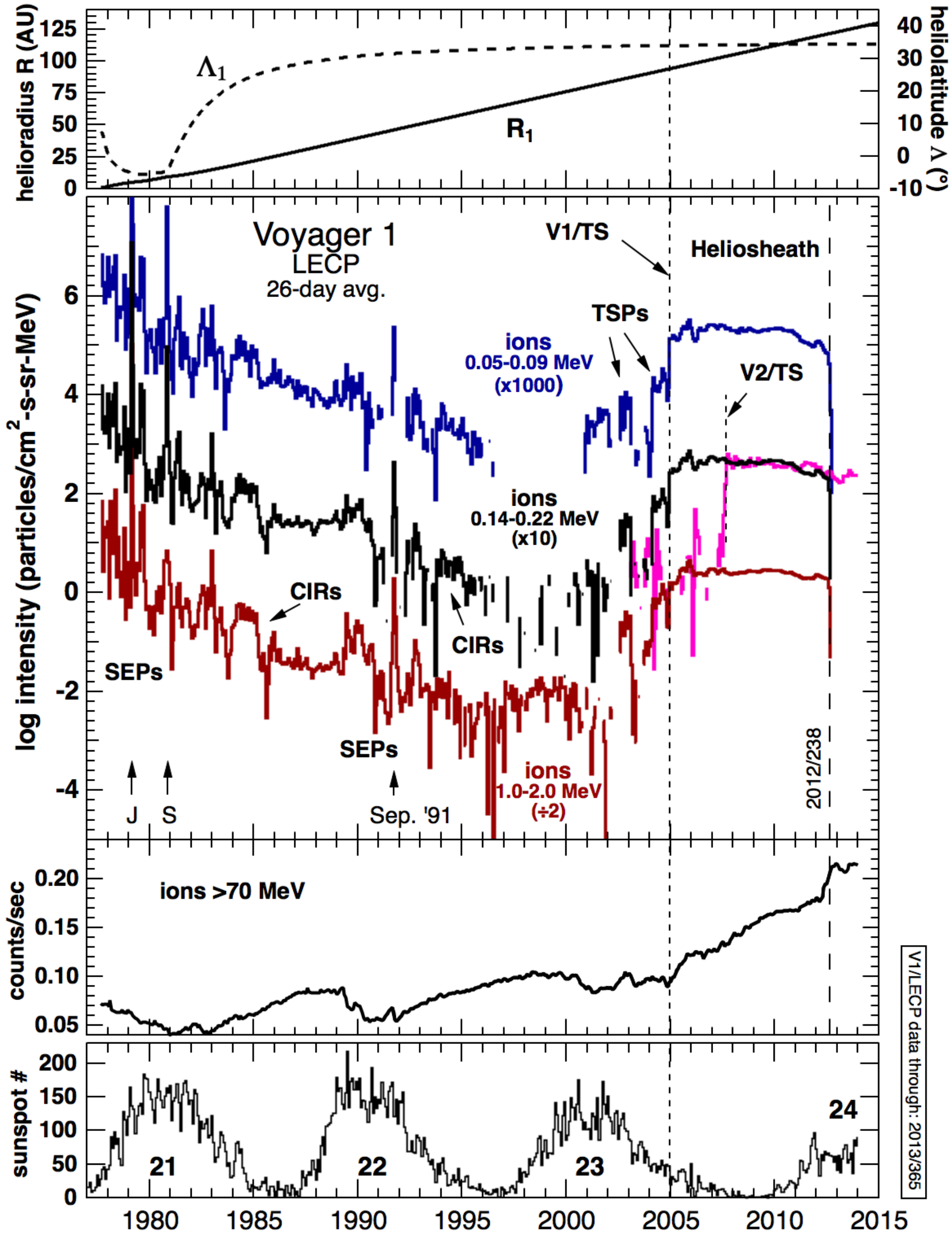
- This result is different than that found for radiation belt electrons.
- For electrons the KP limit appears to play a role for Earth, Jupiter, and Uranus, and somewhat for Neptune (only Saturn is excluded).

Magnetospheres are accessible laboratories for astrophysical processes in space plasmas (not discussed in this talk)

- **Sources of plasma for magnetospheres**
- **Acceleration of particles to high energies**
- **Particle motion and adiabatic invariants**
- **Current flow and how it's routed**
- **Generation of waves**
- **Transfer of magnetic flux and Magnetic reconnection**
- **Plasma instabilities at boundaries and elsewhere**
- **Triggering and development of storms and sub-storms**
- **Convection and diffusion processes**
- **MHD simulations and applicability**
- **Auroral processes and electrostatic double layers**
- **Plasma motions and electric fields**
- **Importance of embedded moons and particle absorption**
- **Etc., etc., etc.**

Voyager Mission:

37-year cruise through heliosphere



- Voyager 1: 1977.7-2014.3
  - Ions 53-85 keV &140-220 keV, protons 1.0-2.0 MeV & >70 MeV
  - * **Note**: *Very low intensities during 1995-2000*

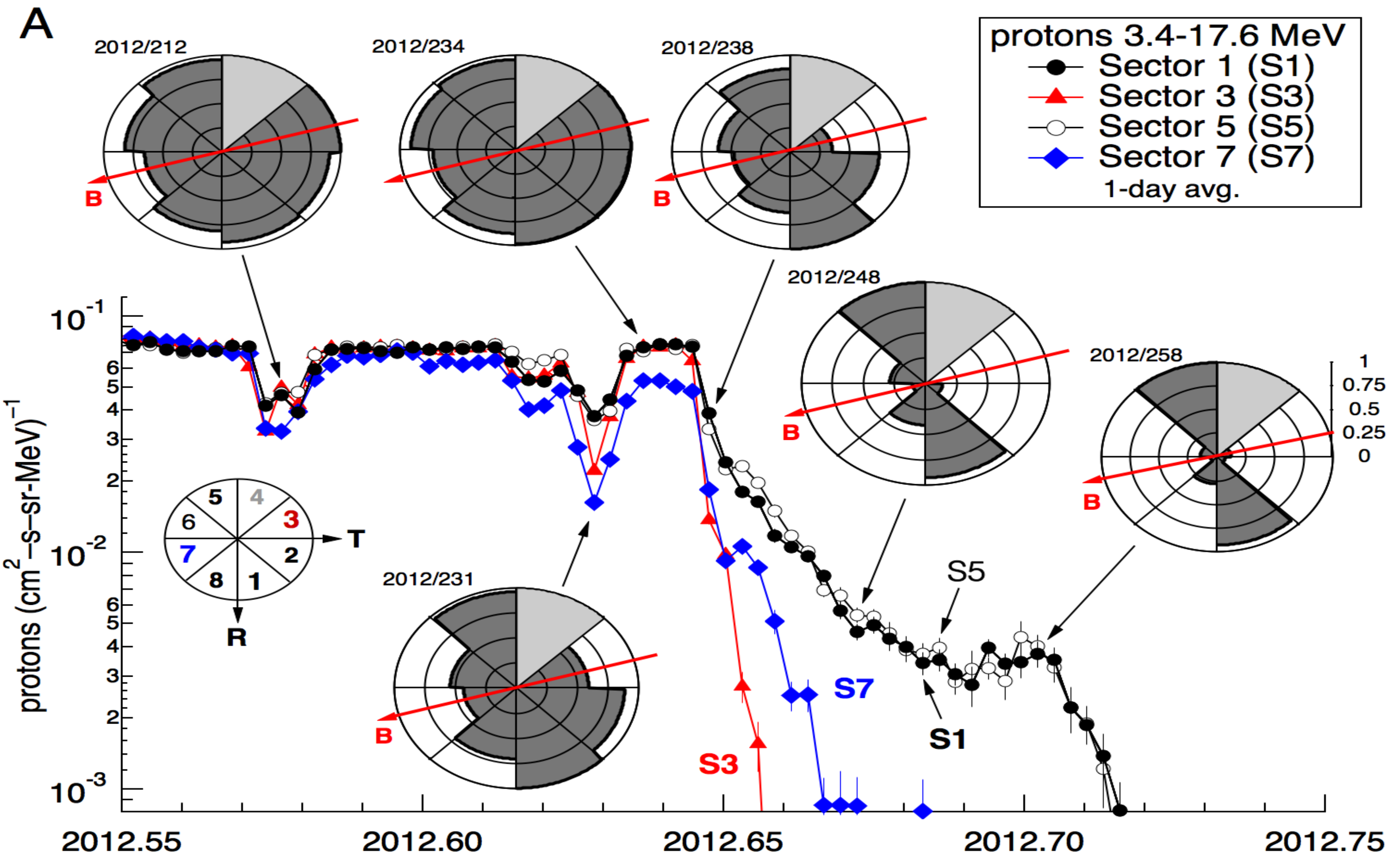
Relatively slow S/C speed ≈0.01 AU/day gives in-depth view of solar-interplanetary phenomena

ICMEs, SEPs, CIRs, CMIRs, MIRs, GMIRs, TSPs, TS, HSH, ACRs, GCRs …

Voyager 1 at the Heliopause

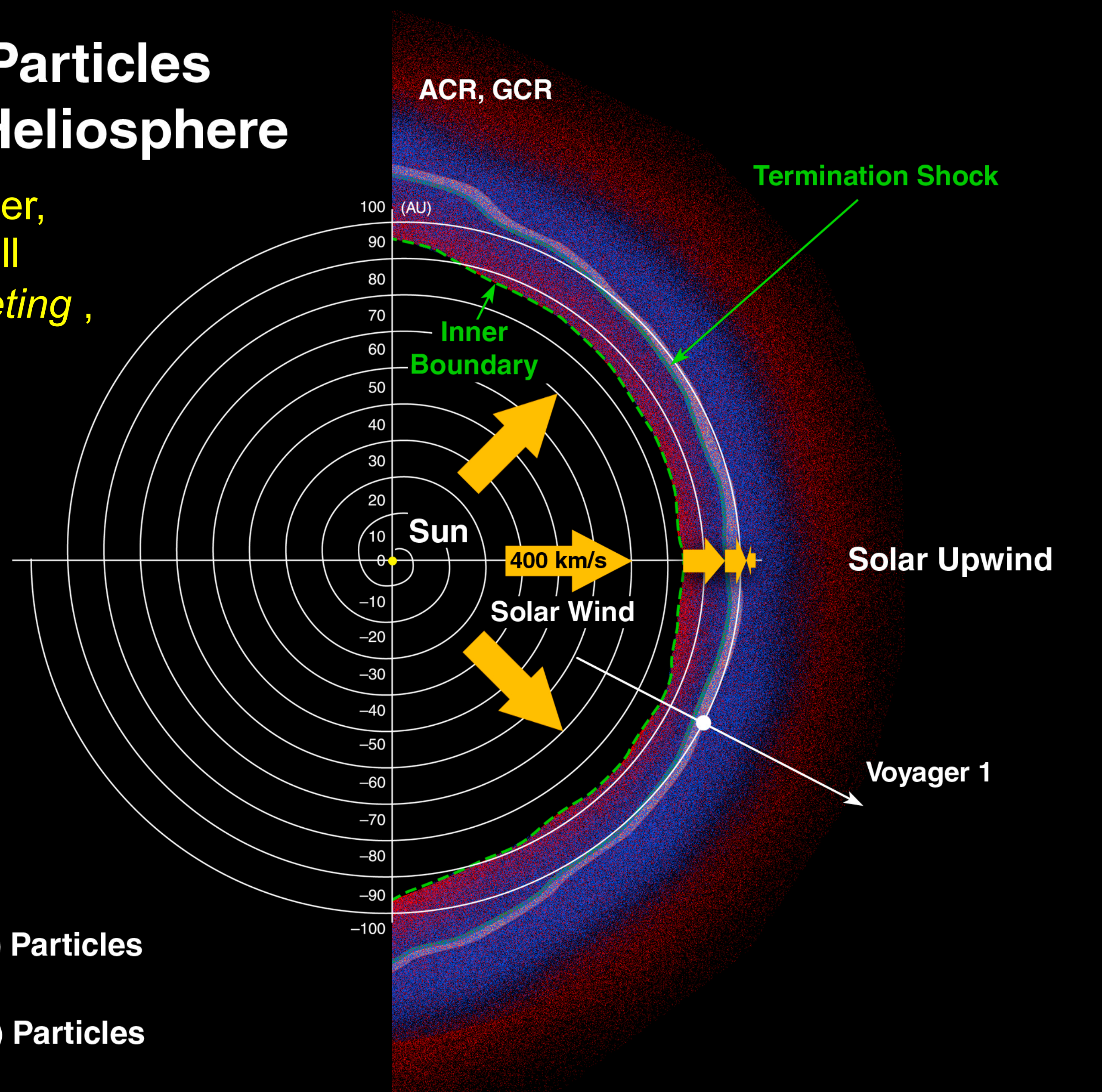
Intensity decreases depend on pitch angle

(**Krimigis, S. M. et al.**, Search for the Exit: Voyager 1 at Heliosphere's Border with the Galaxy, *Science, 341, 144*, DOI: 10.1126/science.1235721, 2013)



Belt of Energetic Particles Surrounding the Heliosphere

Krimigis, S. M., R. B. Decker,
E. C. Roelof and M. E. Hill
Solar Wind 11/SOHO 16 Meeting ,
ESA SP-592, 2005

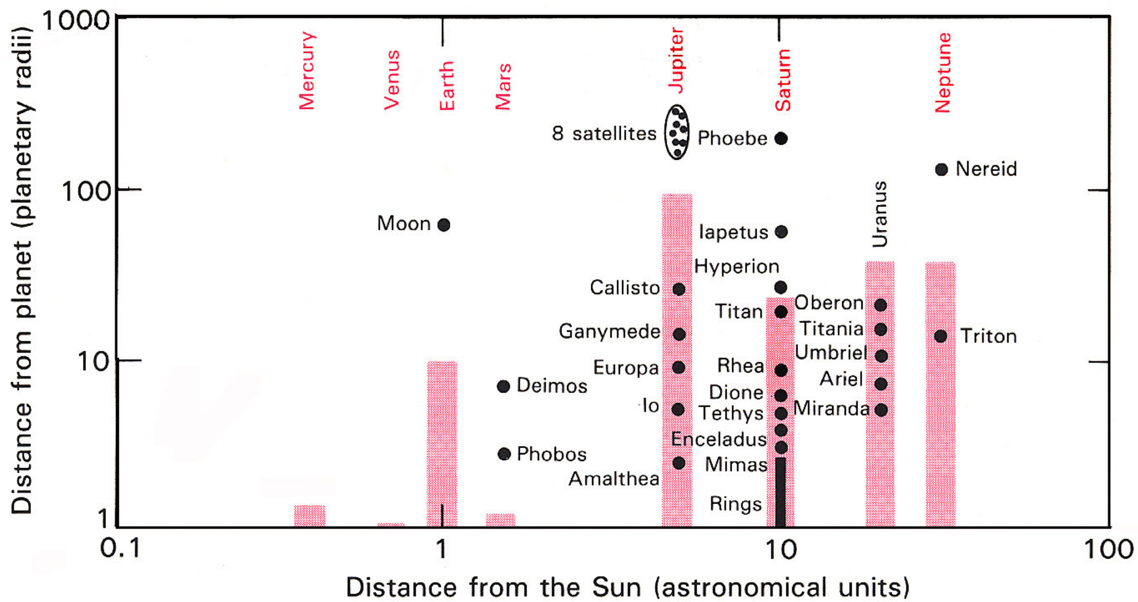


High Energy (> 1 Mev) Particles

Low Energy (> 40 kev) Particles

September 15, 2014

Figure 4—Magnetosphere sizes, satellite locations, and planetary orbital radii. Each vertical bar represents the distance from the center of a planet to the Sunward boundary of its magnetosphere, in units of the planet's radius. The magnetosphere size for Neptune is an estimate. (Adapted from Ref. 5.)



Lanzerotti, L. J. and S. M. Krimigis, Comparative magnetospheres, *Physics Today, 38*, 25-34, 1985.

Van Allen Radiation Belts in the Solar System

- Five planets with intrinsic magnetic fields (Earth, Jupiter, Saturn, Uranus, Neptune) have belts
- One planet (Mercury) with intrinsic field has transient electron bursts, but no durable belt. Also, Ganymede has intrinsic magnetic field, but no belts
- Venus and Mars do not have radiation belts
- Pluto is unlikely to have belt(s)--must wait for New Horizons encounter in 2015!
- Voyagers have found a belt surrounding the Heliosphere from ~90 to ~122 AU

"Van Allen Day" in Iowa City on the Occasion of his 90th Birthday, October 9, 2004 (outside Van Allen Hall, University of Iowa)

THANK YOU