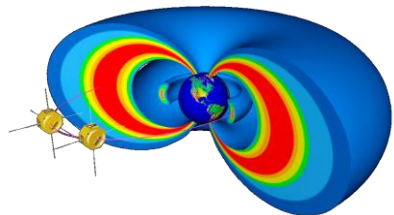
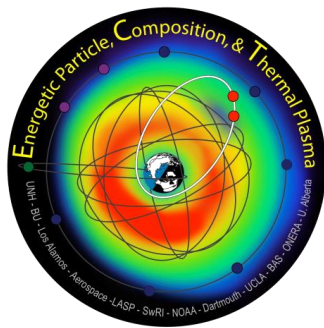


Truths and Consequences of Ionizing Radiation: New Science Results from Van Allen Probes and LRO

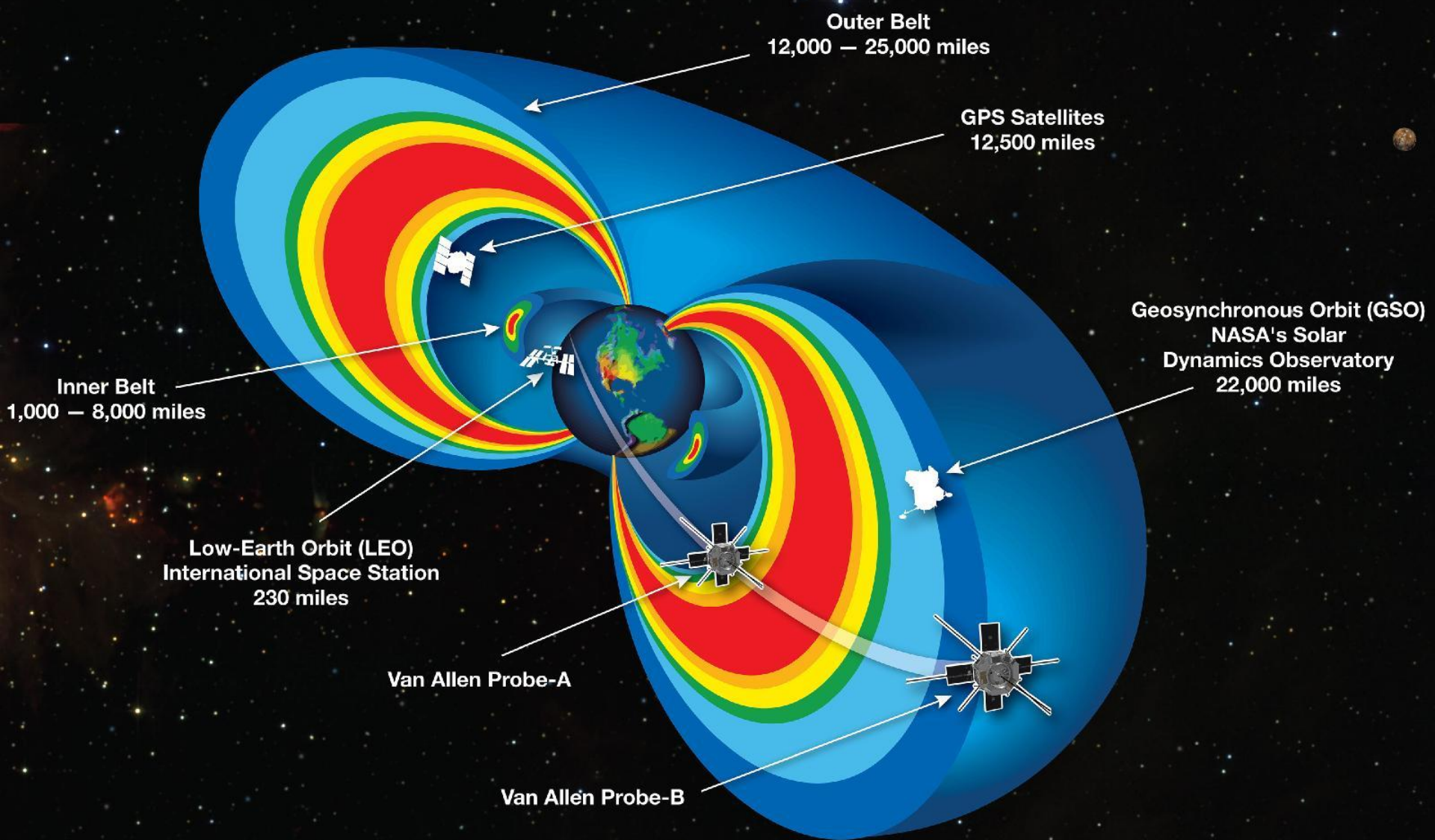
Harlan E. Spence

University of New Hampshire

And Extended RBSP-ECT and CRaTER Teams



NAC Science Committee Meeting
8 April 2015



Outer Belt
12,000 – 25,000 miles

GPS Satellites
12,500 miles

Geosynchronous Orbit (GSO)
NASA's Solar
Dynamics Observatory
22,000 miles

Inner Belt
1,000 – 8,000 miles

Low-Earth Orbit (LEO)
International Space Station
230 miles

Van Allen Probe-A

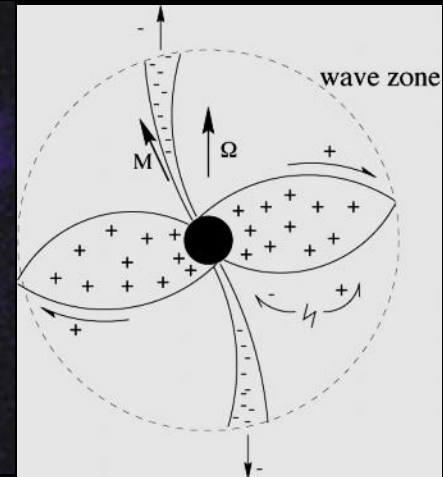
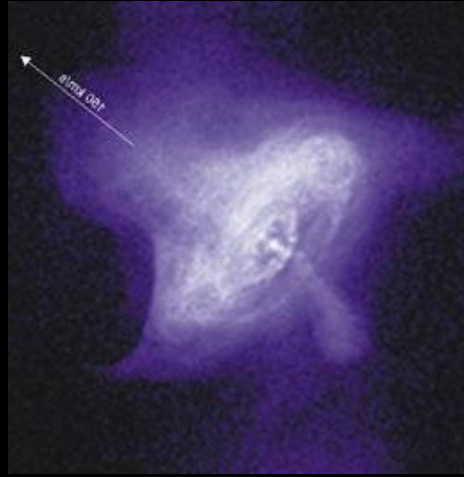
Van Allen Probe-B

Motivation #1: Discover Our Own Cosmic Particle Accelerator

Cas A Supernova Remnant



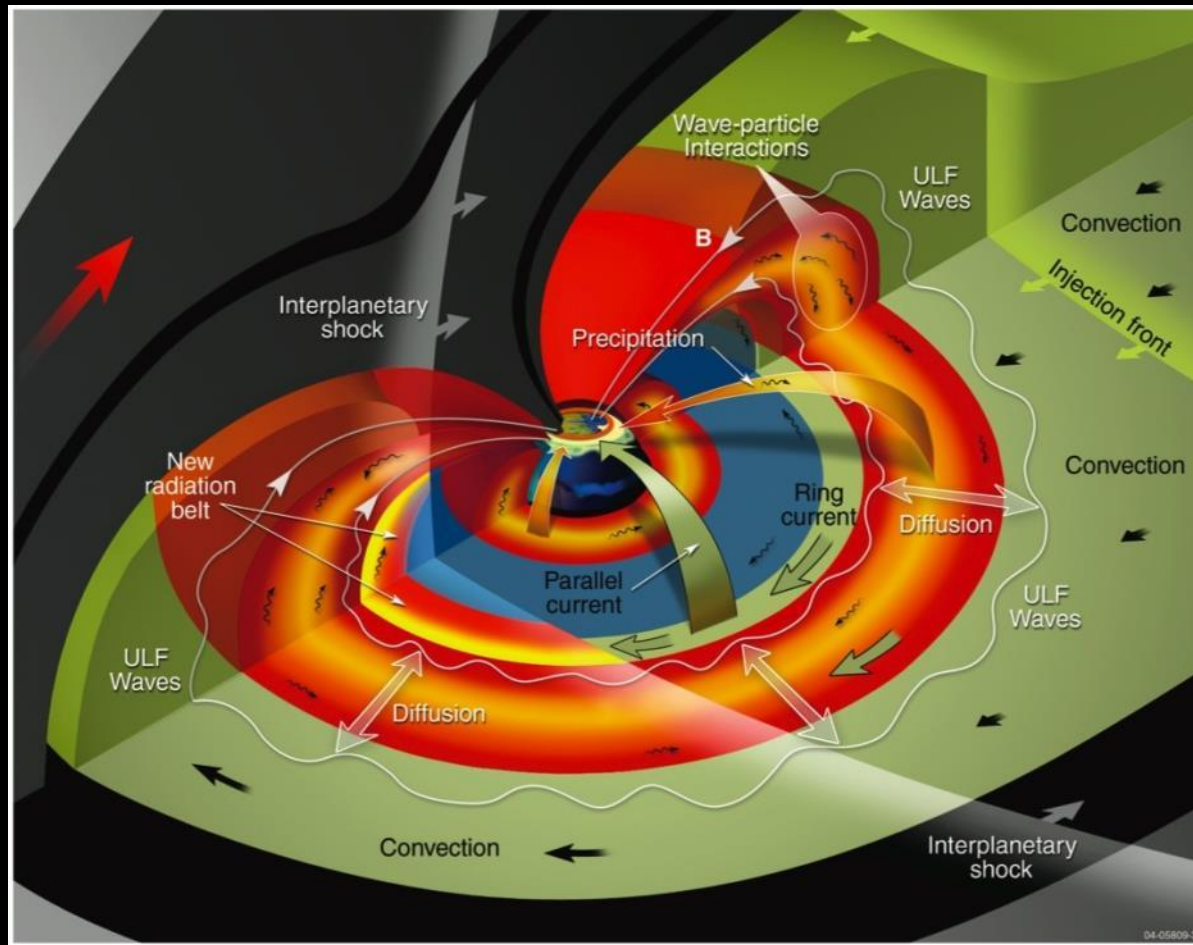
(Credit: NASA/CXC/UMass Amherst/M.D.Stage et al.)



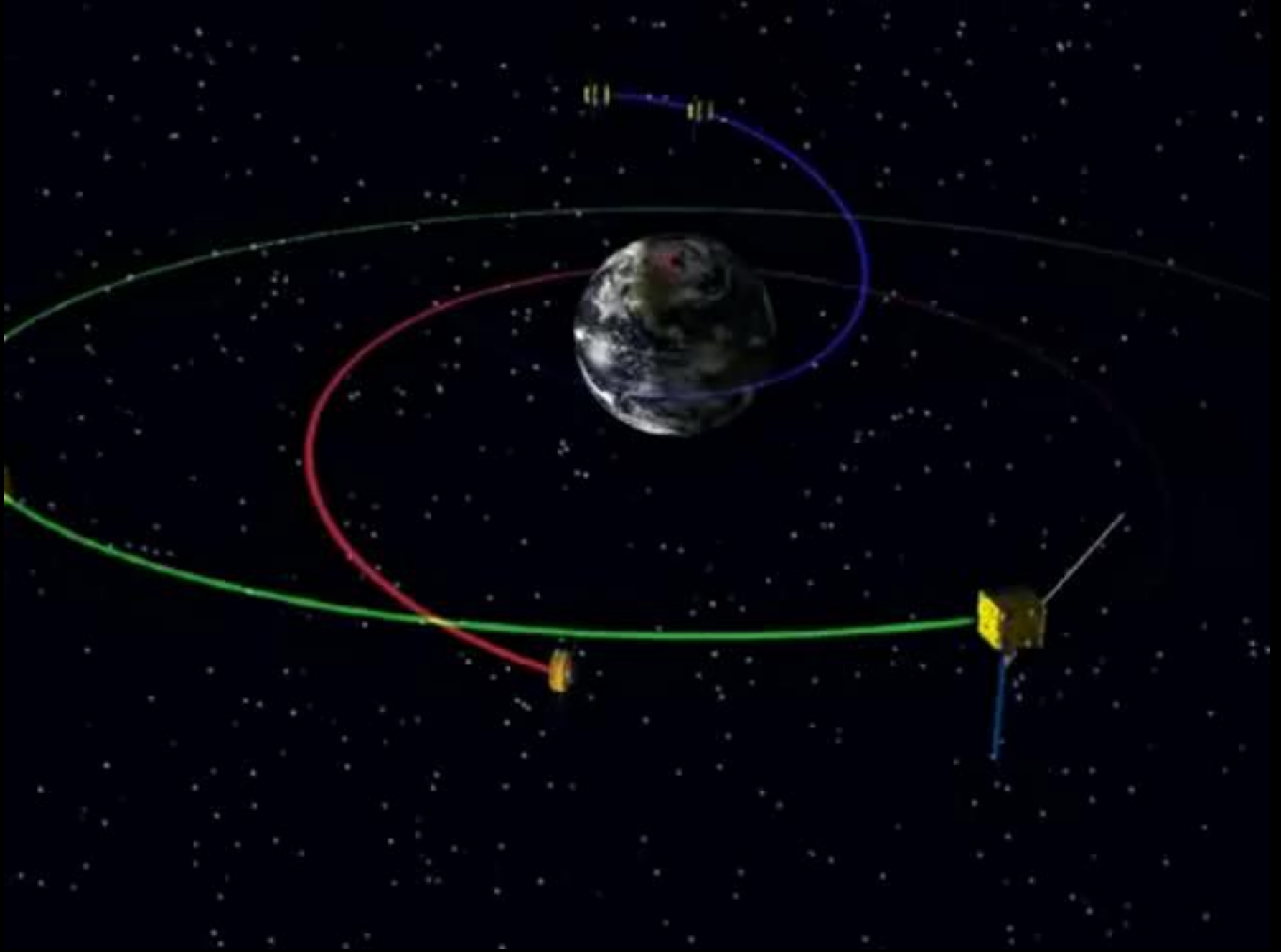
Pulsar magnetospheric physics (F.C. Michel, 1998)

- Ironically, we view through our own invisible radiation belts when viewing exotic, high energy, astrophysical objects, places where the same universal processes occur but where key observations are highly limited
- Our own cosmic particle accelerator exists literally just above our heads where we can witness the universal physics *in situ*

Motivation #2: Differentiate Between Competing Mechanisms and Theories



- Many acceleration, transport, and loss mechanisms theorized, however earlier observations insufficient to differentiate uniquely between them and to establish relative importance

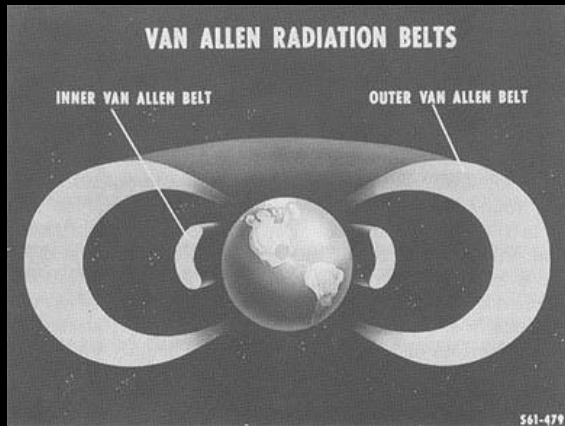
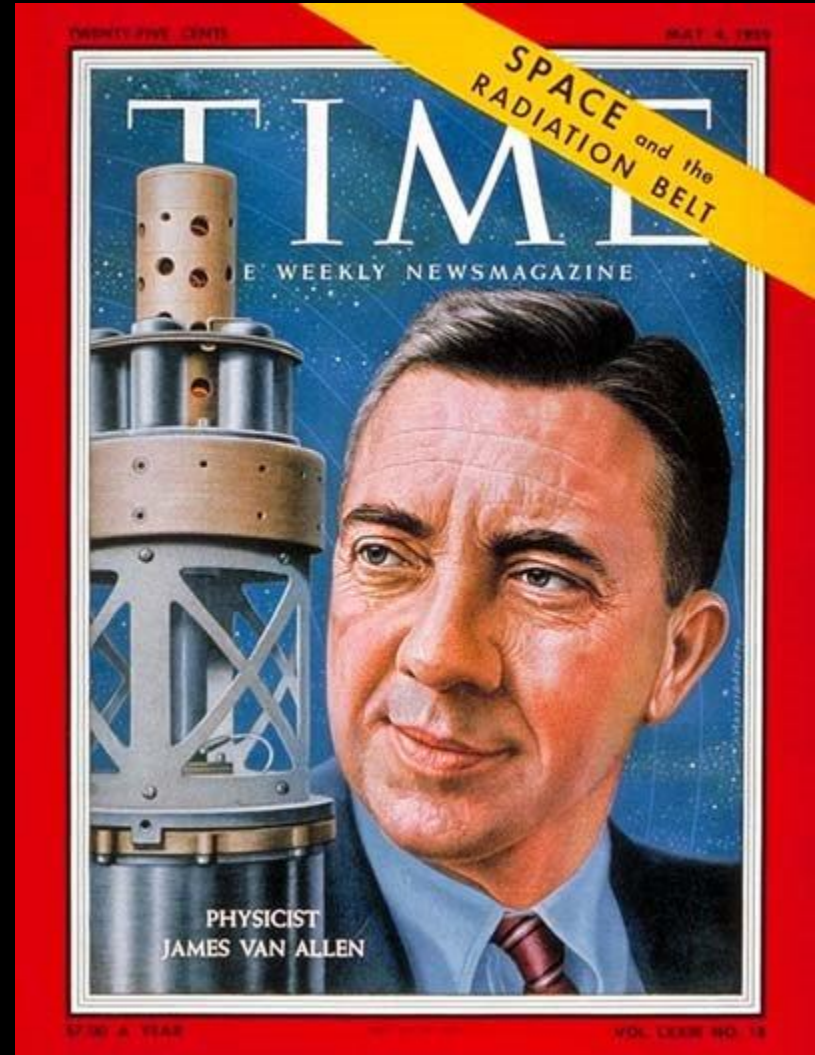
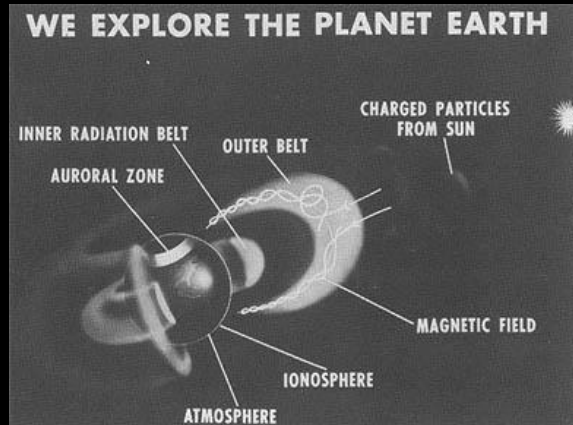


Movie courtesy of A. Kale and I. Mann, University of Calgary

James Van Allen's Discovery

- Thrust space physics into American culture with discovery on Explorer 1 in 1958
- "Static" belts

Artistic images of Van Allen belts, NASA/Langley, circa 1961

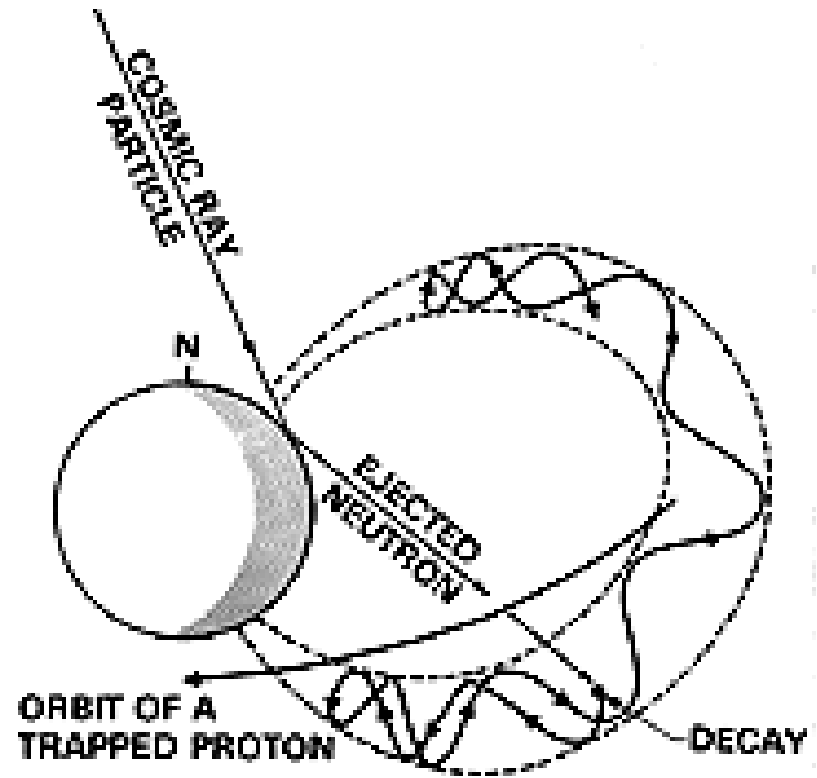


Cover of TIME in '59 and '64

Inner Belt – Dominated by
Relativistic Protons

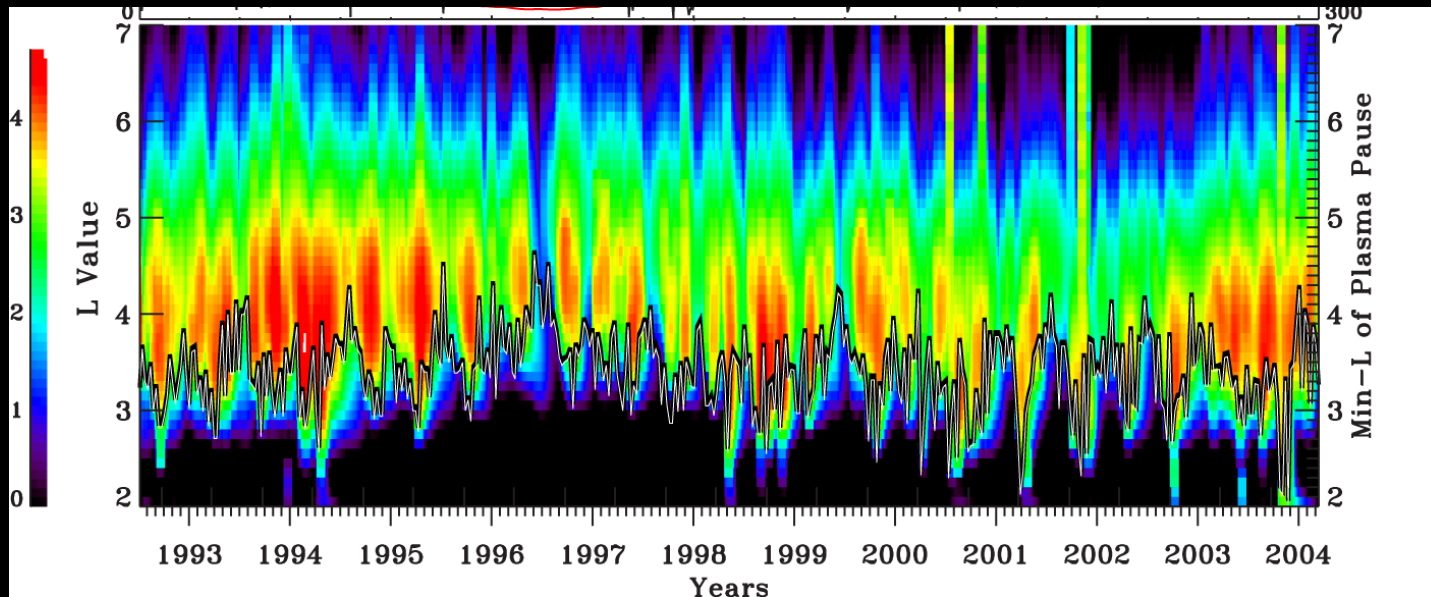
Formed by CRAND
(**Cosmic Ray Albedo**
Neutron Decay) and
SPAND mechanisms

Reasonably well
understood process, now
quantified exceptionally
by Van Allen Probes



The Outer Belt? And yet it moves...

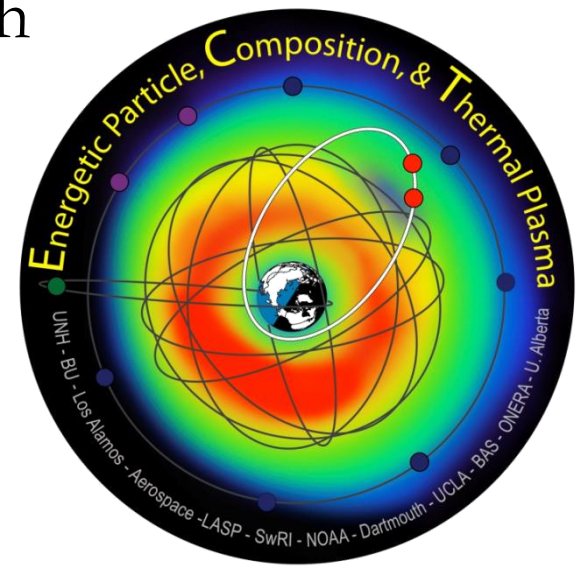
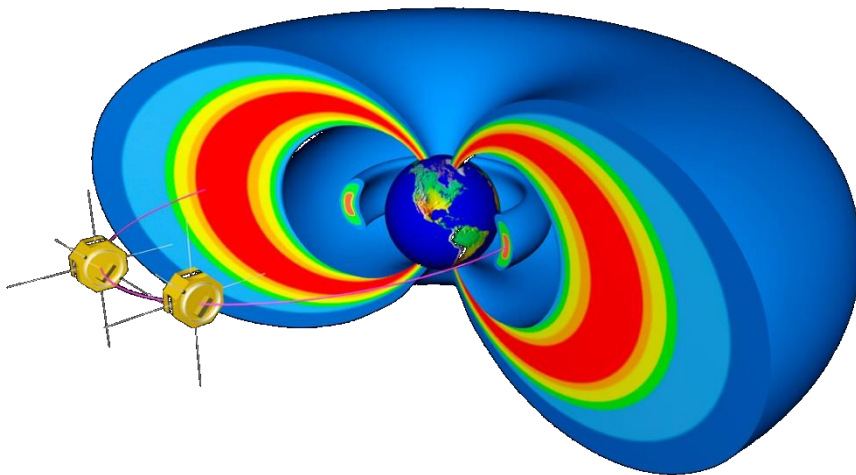
- **CRRES** (1990-91), a joint NASA/USAF equatorial mission, targets radiation belt physics ~30 years after discovery
- CRRES confirmed basic structure but revealed unanticipatedly rich dynamics and structure



- **SAMPEX** (1992 - 2013) was the first NASA Small Explorer; sampled radiation belts at their low altitude “horns”
- SAMPEX revealed incessant creation/destruction/evolution of radiation belts driven by impulsive and persistent factors

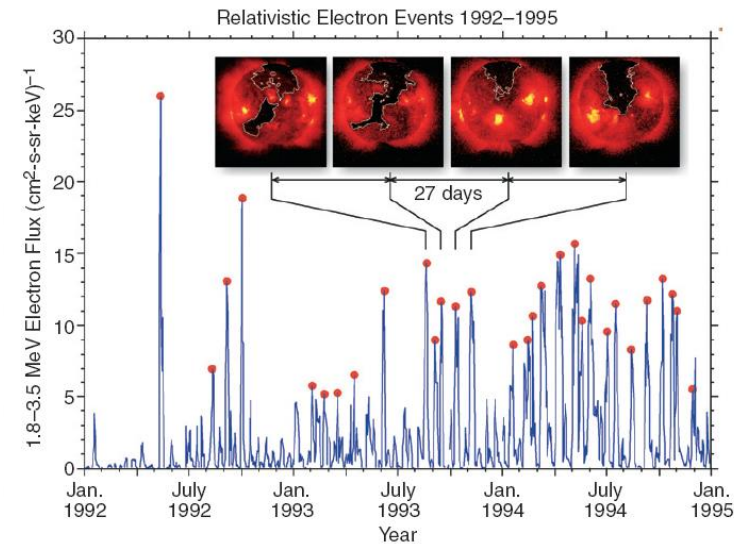
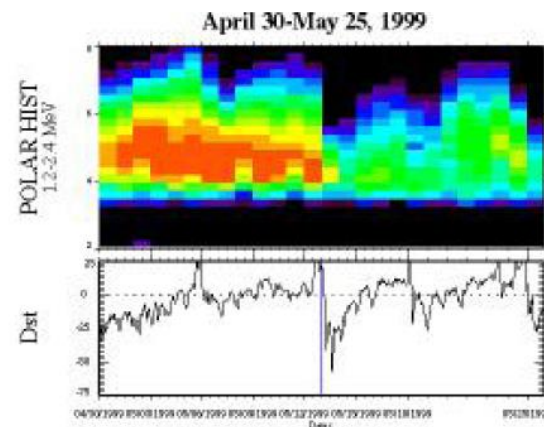
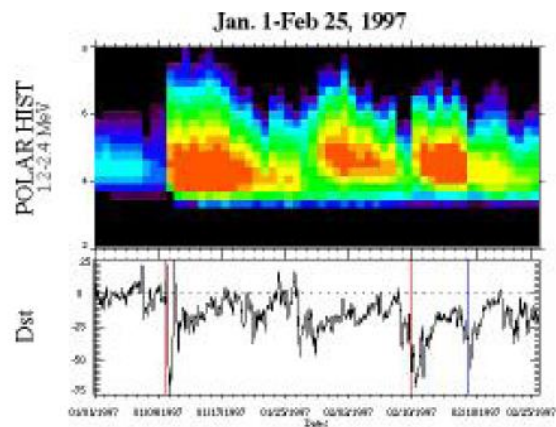
The NASA Van Allen Probes (“RBSP”) Mission

- Instrument proposals due in Fall 2005
- Instrument science teams were selected in summer 2006
- Launched September 2012 from Cape Canaveral
- Two identical spacecraft in elliptical, near-equatorial orbits provide crucial observations to resolve radiation belt physics
- Full particles (low to ultra-relativistic energies; composition) and fields (magnetic and electric DC and waves) on both s/c
- Mission renamed from Radiation Belt Storm Probes (RBSP) to Van Allen Probes shortly after launch



Van Allen Probes Mission Objective

- To understand, ideally to the point of predictability, how populations of relativistic electrons and ions in space are formed or changed in response to the variable inputs of energy from the Sun.

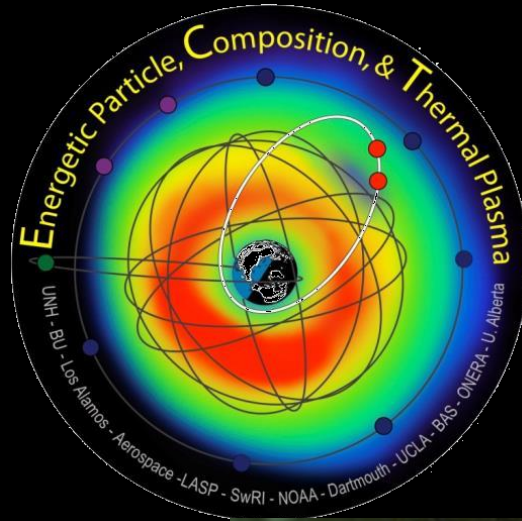


- While connections to high speed streams are well established, response to storms is presently not predictable! Why?
- Subtle but powerful tug-of-war between acceleration, transport, and loss processes

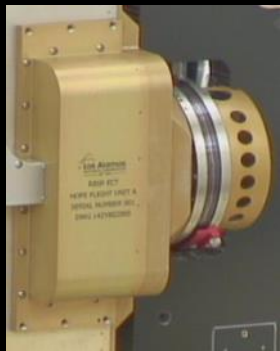
(Figures from Reeves ; 2003, 1998)

RBSP-ECT: Radiation Belt Storm Probes – Energetic Particle, Composition and Thermal Plasma Suite

Baker et al., 2013
Blake et al., 2013
Funsten et al., 2013
Spence et al., 2013



- HOPE – Helium, Oxygen, Protons, Electrons (1 eV to 40 keV)
- MagEIS – Magnetic Electron Ion Spectrometer (10's keV to few MeV)
- REPT – Relativistic Electron Proton Telescope (> few MeV)
- Background rejection techniques successful on all instruments



HOPE



MagEIS



REPT

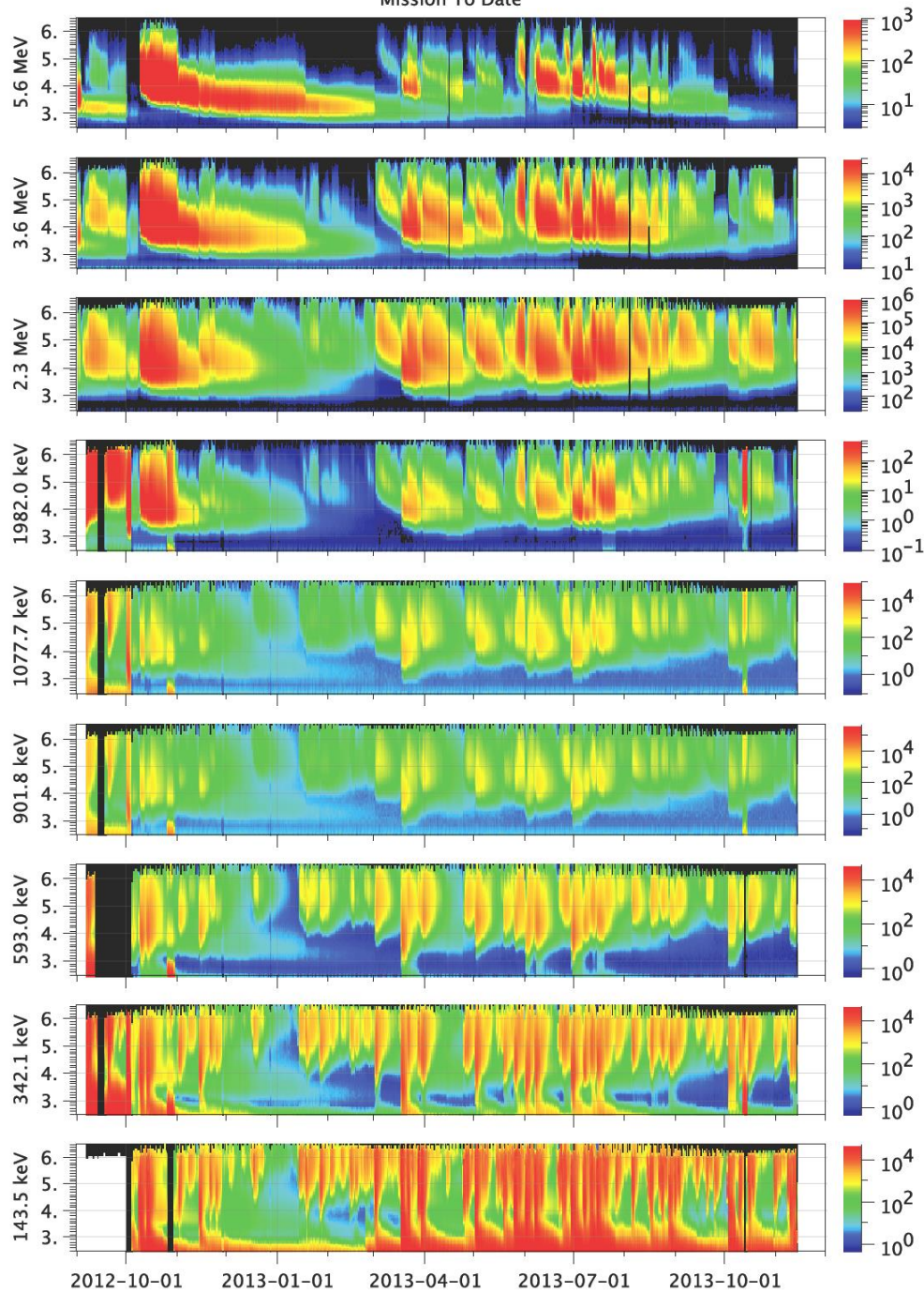
Van Allen Probes – A Brief Summary of Remarkable Scientific Accomplishments

- Tremendous scientific discovery and understanding obtained during prime mission phase
 - Discovery of mechanisms for creation of “third” belt
 - Definitive observations of acceleration mechanism affirming that “local” acceleration is powerfully efficient and rapid; implicates wave modes operative to accelerate electrons from a lower energy seed population to relativistic and ultra-relativistic energies
 - Roles that interplanetary shocks play in prompt acceleration as they plow through Earth’s inner magnetosphere
 - Understanding of how seed and accelerated particles are transported both diffusively and advectively
 - Will focus today on one loss mechanism – “precipitation”

Precipitation Loss: Motivation

- Understanding the relative importance of radiation belt enhancements and decreases relies on a quantitative assessment of the state of the belts before and after an event
- For instance, estimates of belt loss through precipitation only become meaningful when compared to the total belt population; regardless of radiation belt loss, what impacts are there to the atmosphere?

RBSP-ECT L-Sorted Electron Fluxes
Mission To Date



- L-sort plots spanning the full mission show the sort of energy dependence and variability of the outer zone electron populations

Overview and Motivation

- Understanding the relative importance of radiation belt enhancements and decreases relies on a quantitative assessment of the state of the belts before and after an event
- For instance, estimates of belt loss through precipitation only become meaningful when compared to the total belt population
- Previous studies have used observations to quantify the total number of energetic electrons in the Van Allen belts
 - Baker et al. (2004) used measurements from the low altitude SAMPEX mission to estimate the radiation belt content
 - Selesnick and Kanekal (2009) used high altitude NASA/Polar measurements

Overview and Motivation

- Understanding the relative importance of radiation belt enhancements and decreases relies on a quantitative assessment of the just prior state of the belts
- For instance, estimates of belt loss through precipitation only become meaningful when compared to the total belt population
- Previous studies have used observations to quantify the total number of energetic electrons in the Van Allen belts
 - Baker et al. (2004) used measurements from the low altitude SAMPEX mission to estimate the radiation belt content
 - Selesnick and Kanekal (2009) used high altitude NASA/Polar measurements
- **Our work extends these pioneering studies by taking advantage of measurements from the Radiation Belt Storm Probes (RBSP) Energetic Particle, Composition, and Thermal Plasma (ECT), providing full coverage of particle energy, pitch angle, and near the magnetic equator with relatively high time cadence**

“The Bucket List”: #1 – Tail Source

- Impulsive transport during substorms directly injects accelerated electrons into the radiation belt from the near magnetotail
- Time scale for injections can be ~1 hour
- *Analogous to faucet being turned on and introducing new water into the system*



“The Bucket List”: #2 – Local Source

- Wave-Particle Interactions can resonantly accelerate seed electrons from lower energy into core RB electrons
- Time scale for acceleration can be ~12 hours

- *Analogous to water created within the bucket by a water wizard (aka, plumber), magically combining hydrogen and oxygen into water and filling the bucket from thin air*



“The Bucket List”: #3 – M’pause **Loss**

- Impulsive loss of previously trapped RB electrons to magnetosheath when drift paths cross magnetopause during sudden compressions
- Electron reservoir decreases impulsively by many orders of magnitude over large range of L-shells over several hours
- *Analogous to height of bucket momentarily shrinking, water emptying to new height level, then bucket returning to normal height*



“The Bucket List”: #4 – Precip. **Loss**

- Electrons experience pitch angle scattering into the loss cone and are lost from the system when they collide with the atmosphere
- Scattering can happen slowly (at diffusive timescales) or impulsively (such as in microbursts)
- *Analogous to bucket have a leaky bottom, with a myriad of tiny holes of various sizes, constantly weeping and dripping at different rates*



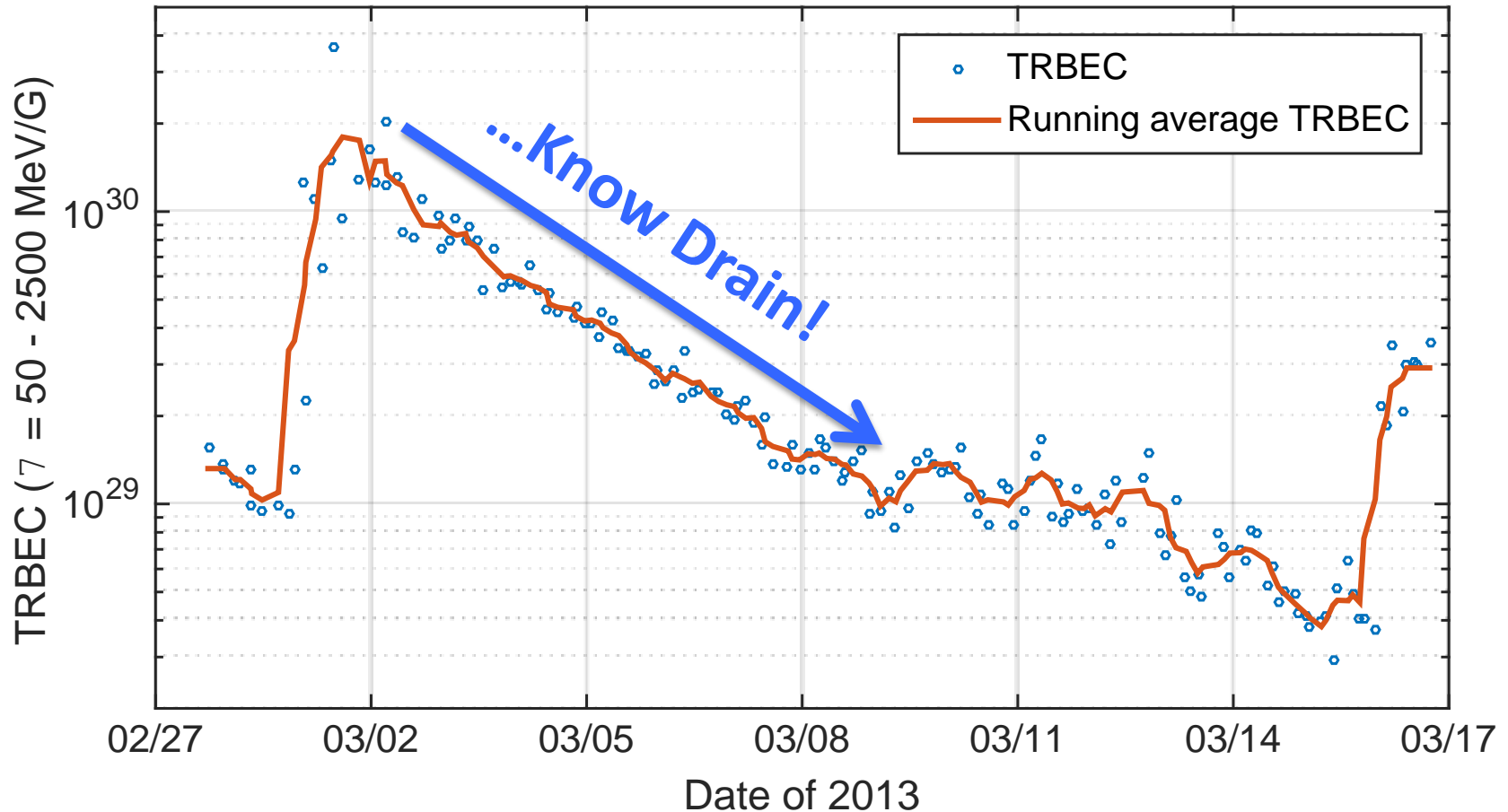
“No Gain, Know Drain”

- Measuring precipitation locally at high or low altitudes extremely difficult
- Measuring local precipitation globally essentially impossible
- Instead, find time when sources are off (**NO GAIN**) and no magnetopause losses, then measure total radiation belt electron content (TRBEC) loss to quantify precipitation (**KNOW DRAIN**)
- *Analogous to inferring cumulative loss through leaky bucket by watching drop in height of water over time*



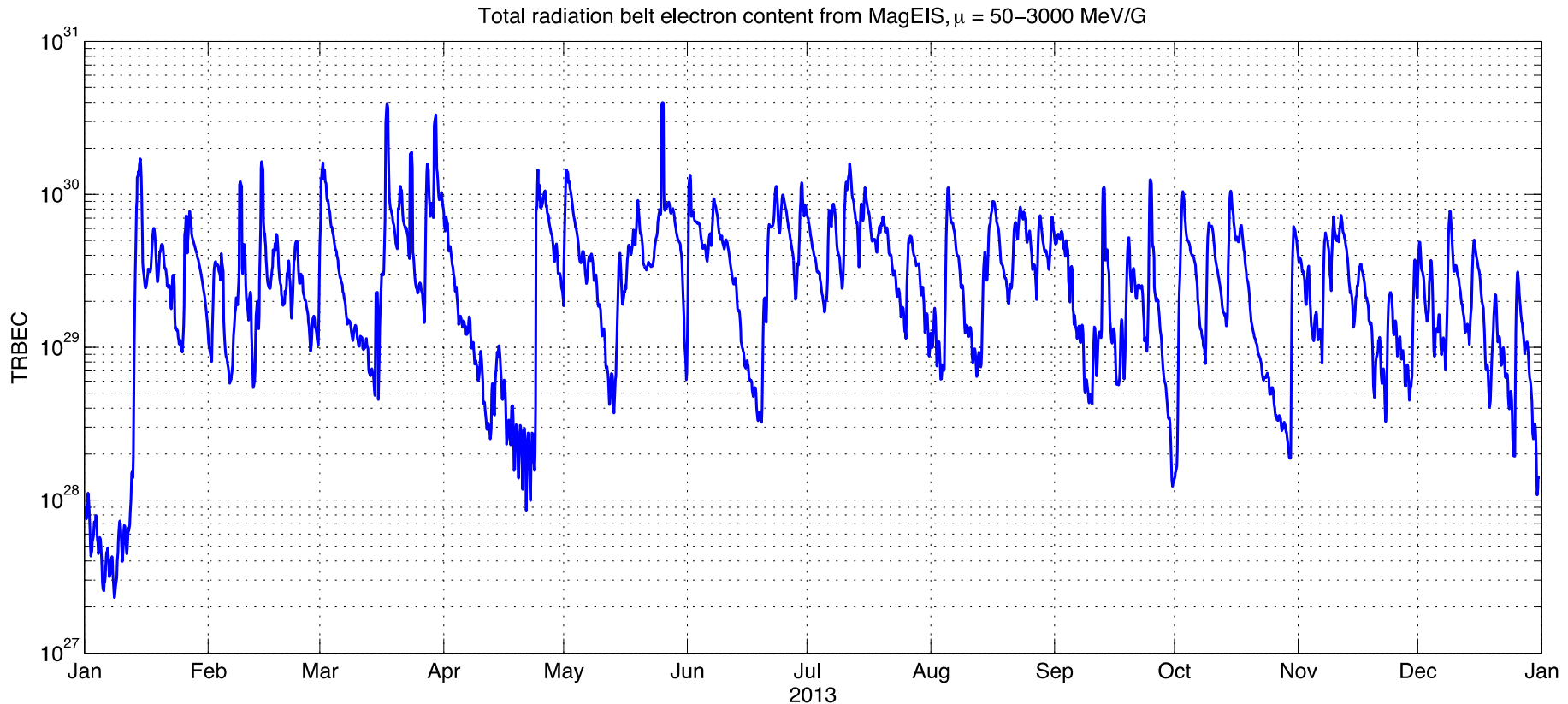
Time Evolution of TRBEC During March 2013: Event with “No Gain...”

TRBEC of 2013 March Event



Note – even though total mass of electrons in radiation belts is comparable to that of a bagel energy per particle is high hence their importance to space weather

Hemispheric Power Estimates = Energy into the Atmosphere

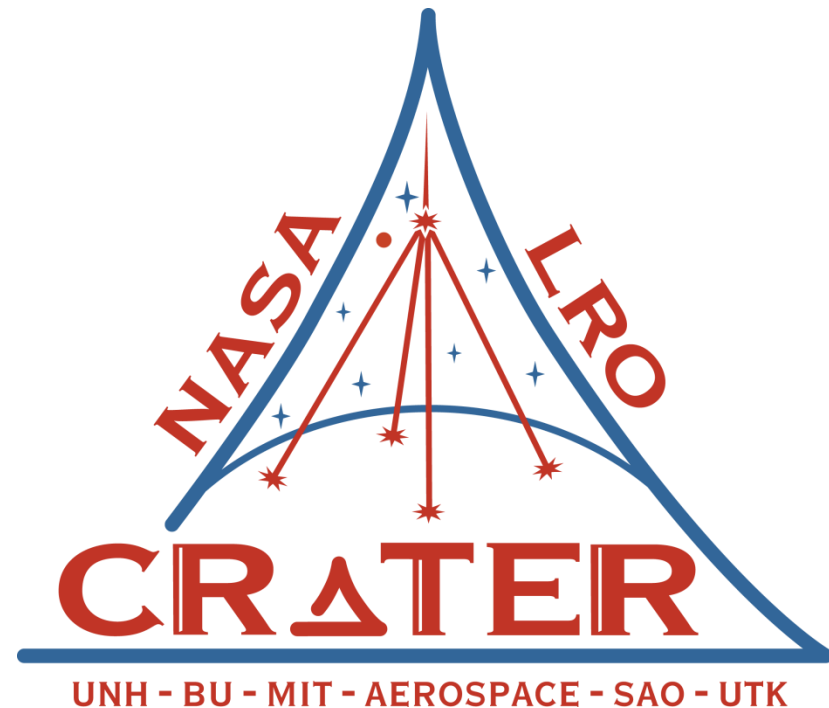
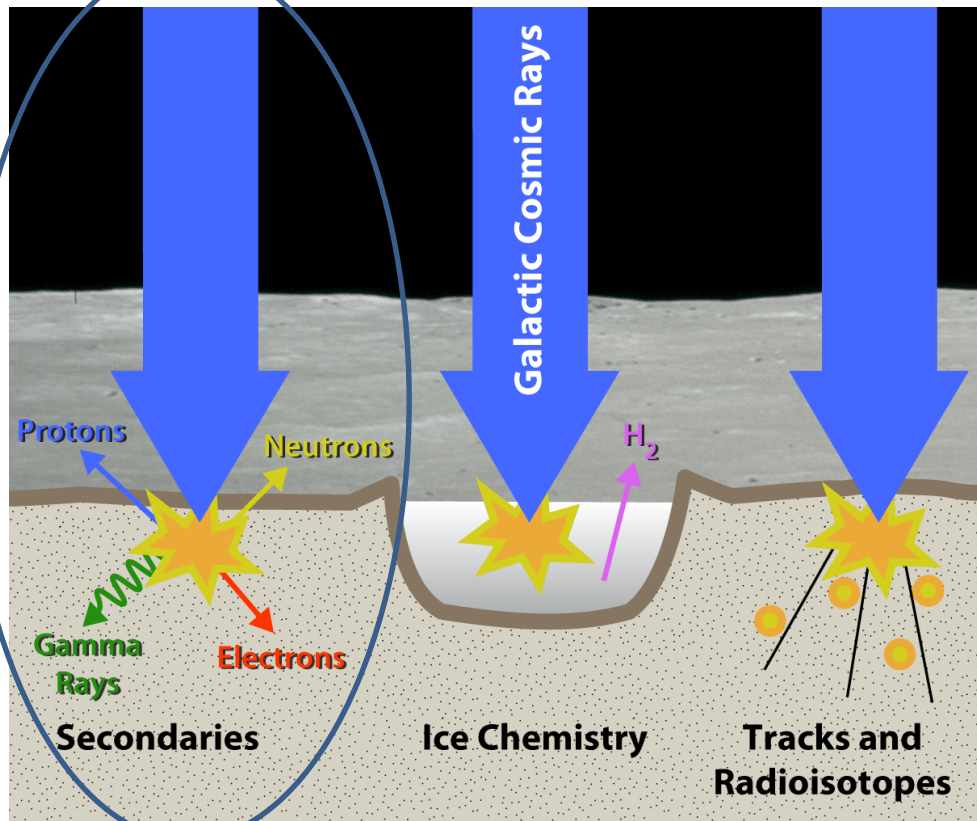


- ~ 100 GW of hemispheric power over \sim two week period in March 2013 when conditions were favorable to estimate precipitation loss
- This represents typical precipitation flux from dynamic belts even during unremarkable periods (such as during this anemic solar maximum)
- Power is $\sim x10$ greater than a typical auroral substorm

Science Summary #1 – Important e-Precipitation Impacts to Upper and Middle Atmosphere

- Improved TRBEC estimate using ECT observations quantifies variability of belt content
- Precipitation loss is sometimes dominant loss process; other times it is small in comparison to catastrophic losses to magnetopause – both are important
- Regardless of relative importance of precipitation loss to radiation belt, impact of loss on upper atmosphere is comparable to or greater than that from typical substorm precipitation; modeling underway to quantify that impact
 - Medium energy electrons deposit energy in middle atmosphere where they participate in ozone chemistry – potentially as important as solar EUV
 - Connections with Schumann resonance effects?

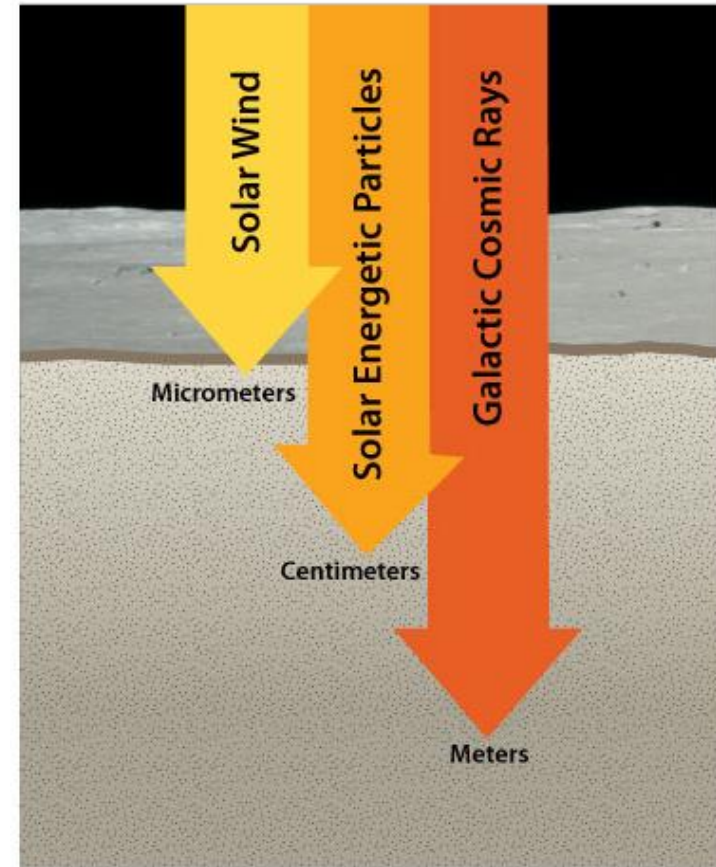
Consequences of Lunar Energetic Particle Albedo from LRO



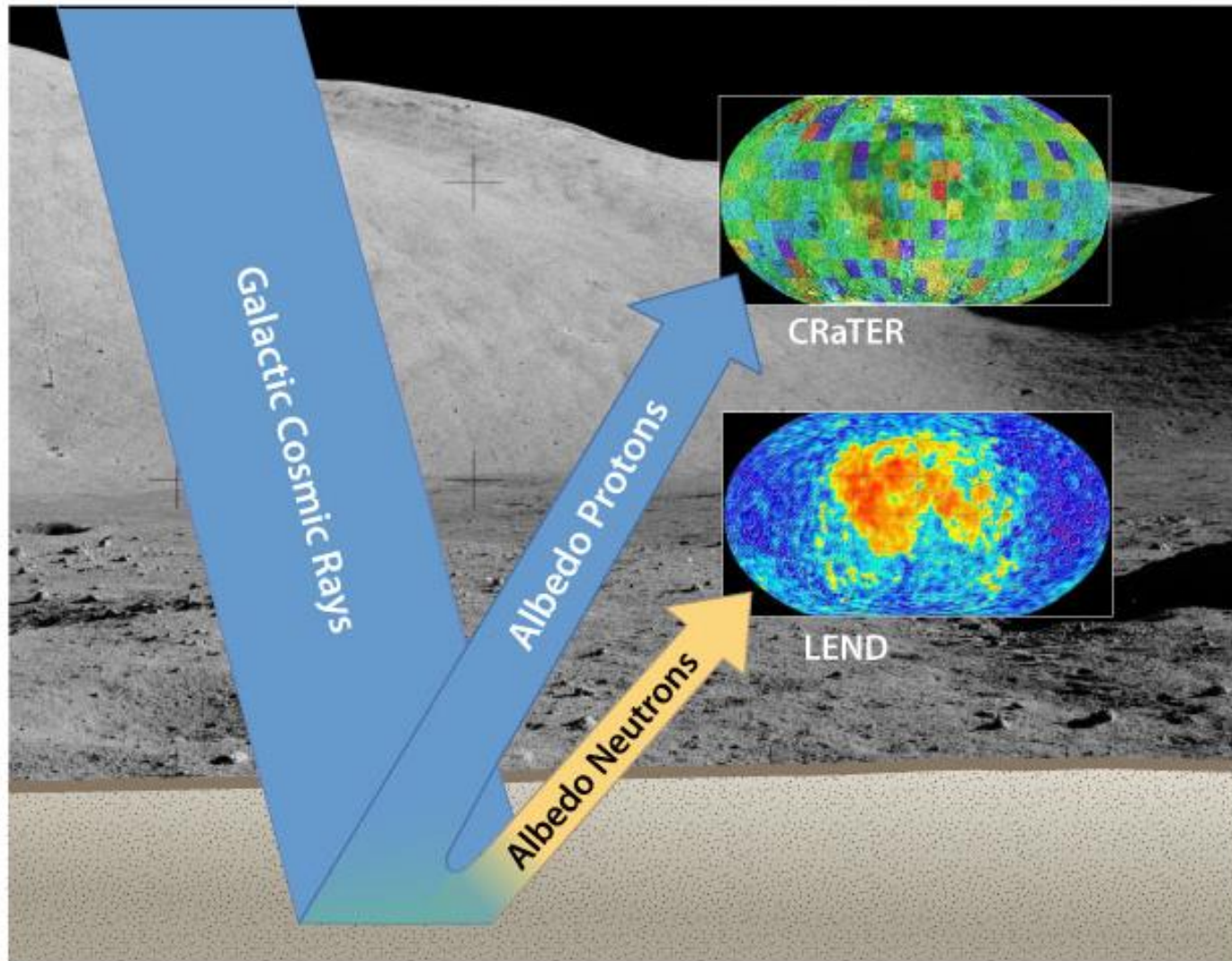


What do we mean by Energetic Particle Albedo?

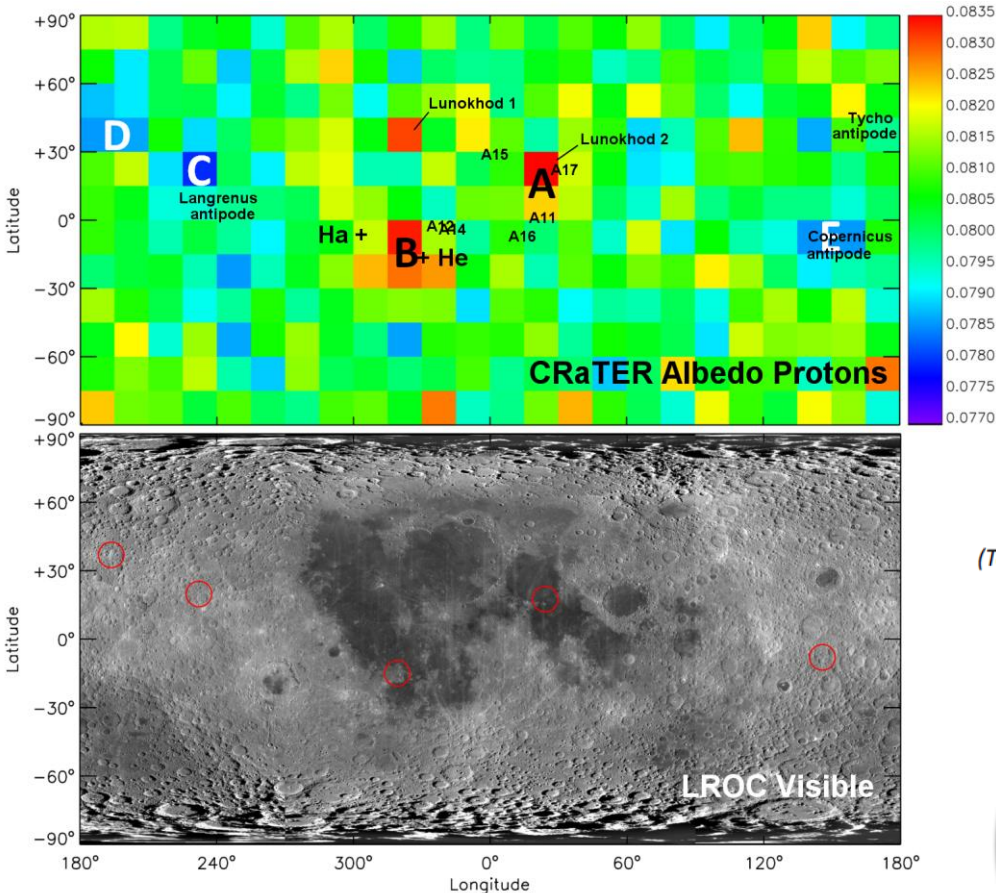
- The term “albedo” borrowed loosely from optical physics
- Particle “albedo” refers to particles released from Moon owing to processes occurring within lunar regolith
- Specifically here, focus on albedo particles produced through nuclear reactions when solar energetic particles and galactic cosmic rays interact with material in outer layers of regolith – requires HIGH impact energies to get nuclear interactions
- Albedo particles are **energetic secondary** particles created and released after primary cosmic ray particles strike surface down to a few meters



Energetic Particle Albedo Allows for Remote Sensing of Regolith



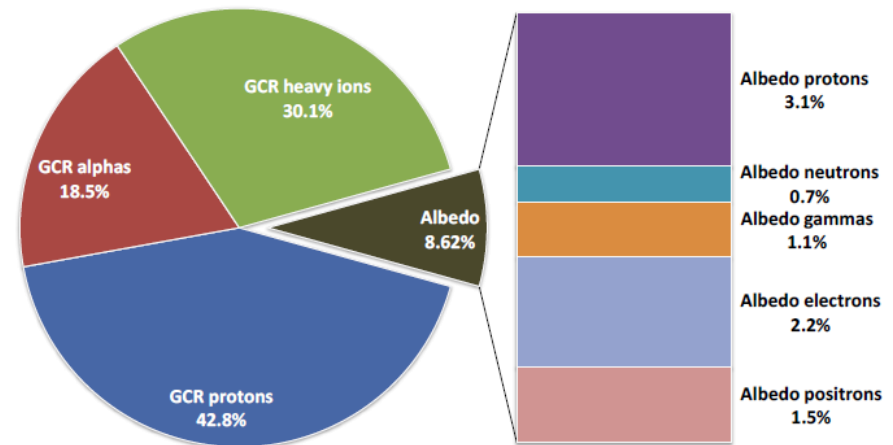
How the Moon looks through the lens of proton albedo from GCR source



From Wilson et al., 2013; 2015

- Yield from mare statistically greater than from highlands
- High/low albedo spots still not well understood
- Primary GCR radiation dose at surface reduced by factor of two, but secondaries add back

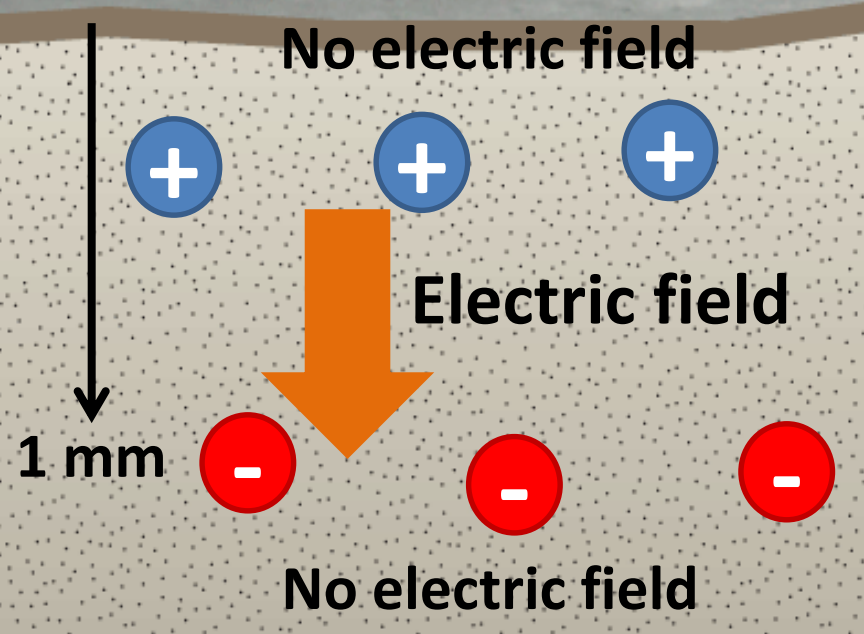
D5-D6 absorbed dose rate percentages by species
(Total absorbed dose rate in Silicon = 0.0037 cGy/d; annual dose = 0.14 Gy)



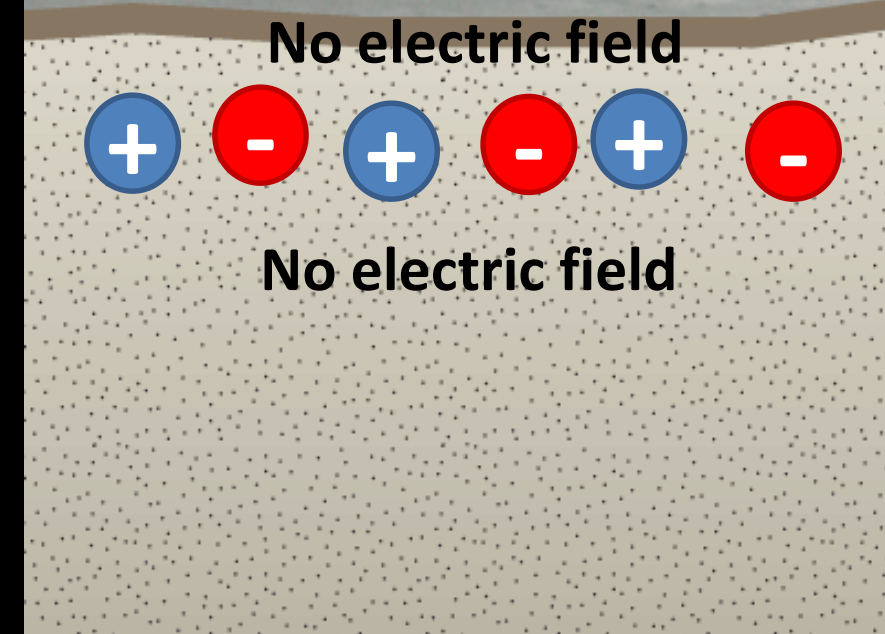
From Spence et al., 2014

Solar Particle Events – A second source of ionizing radiation at the Moon

1) SEPs charge the subsurface, setting up a capacitor-like situation



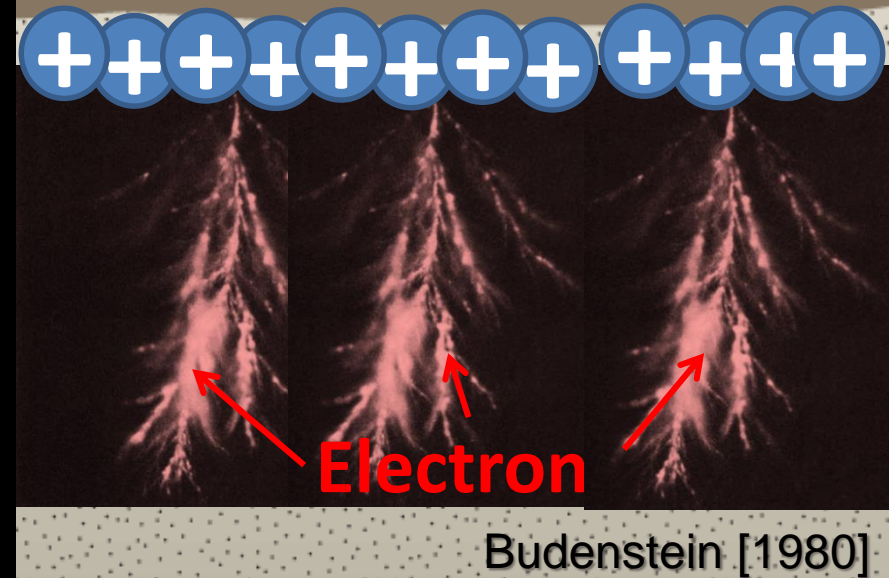
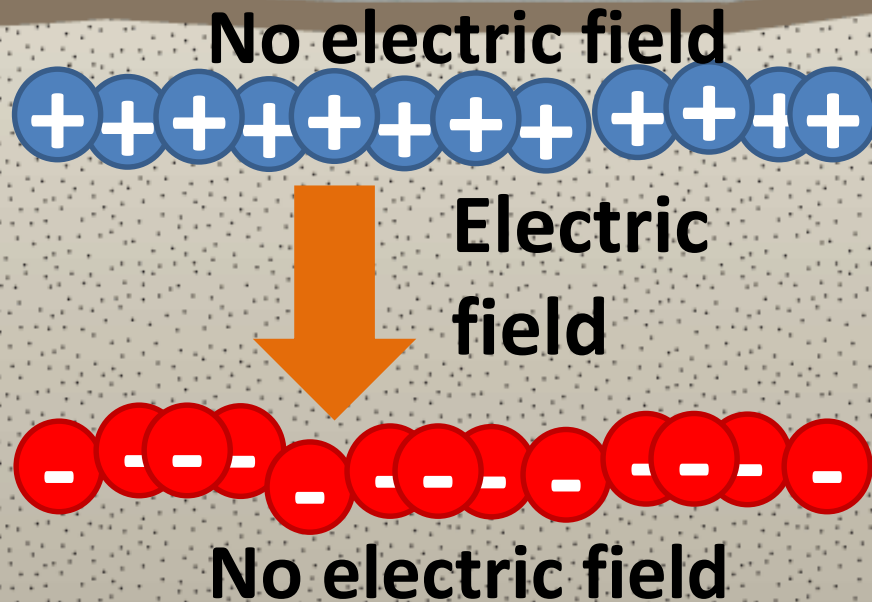
2) Charging dissipates as in a capacitor



If SEPs charge regolith faster than it can discharge (fluence of 10^{10} - 10^{11} cm^{-2})...

... electric field can increase to threshold for dielectric breakdown (10^6 - 10^7 V/m)

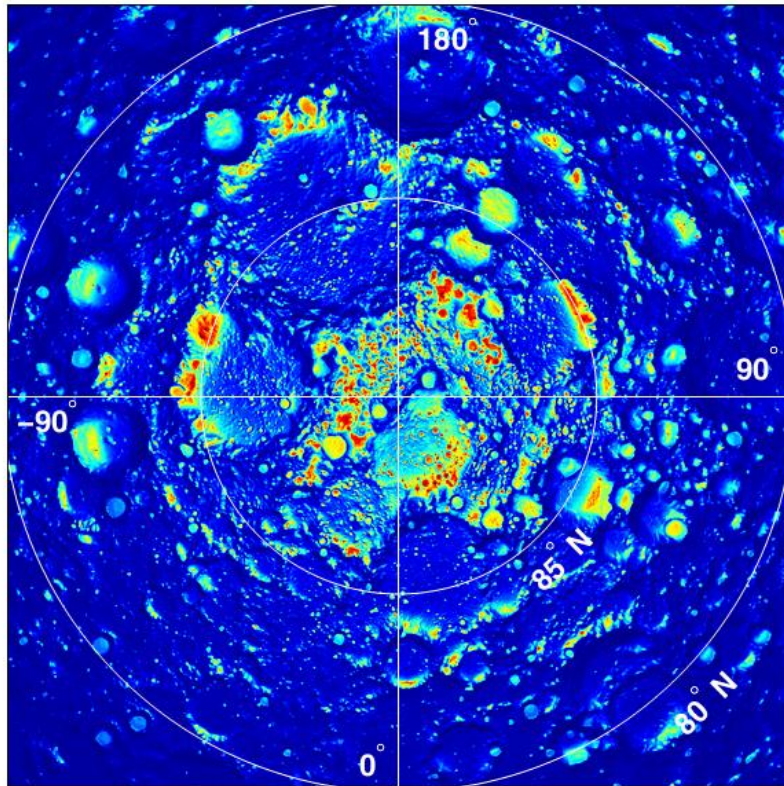
Colder regolith \rightarrow lower conductivity
 \rightarrow more charging



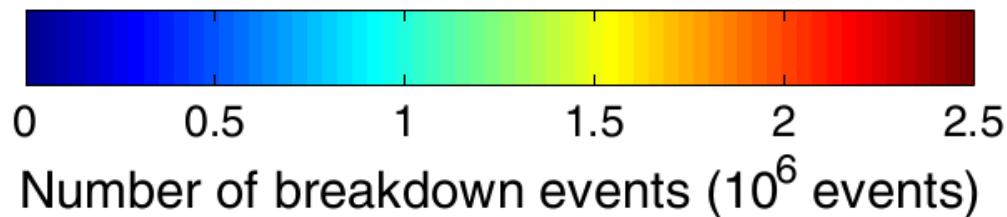
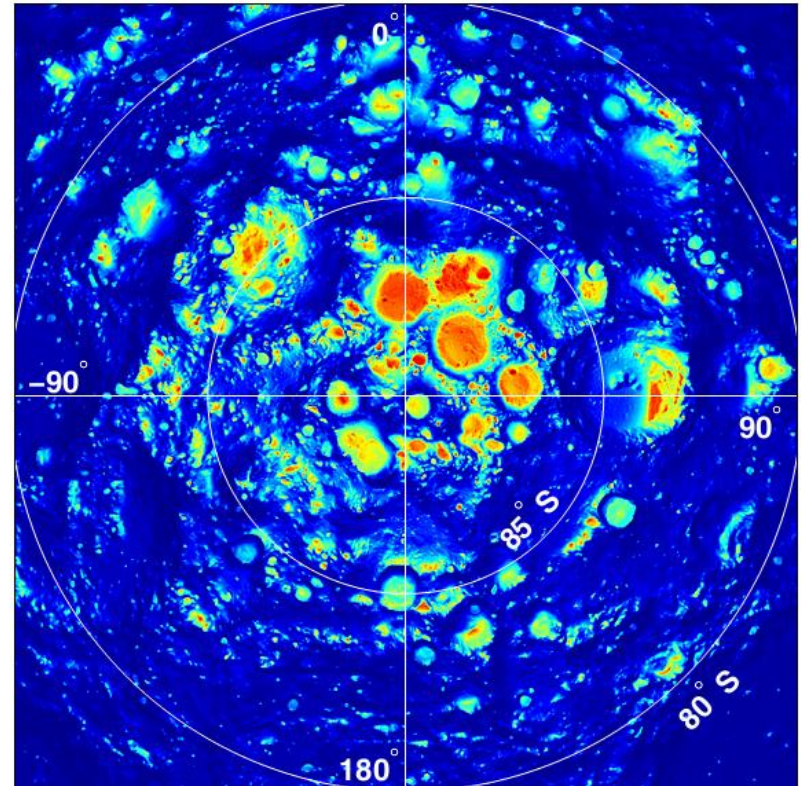


All gardened soil within PSRs has likely experienced $\sim 10^6$ SEP events capable of causing breakdown

North Pole



South Pole



What can breakdown weathering do?

- E-field energy density due to large SEP event:
 $u_E \approx 880 \text{ J m}^{-3}$ (assuming 10^7 V/m)
- Energy density needed to vaporize all regolith:
 $u_{\text{reg}} = \rho_{\text{reg}} c_p (T_{\text{vapor}} - T_{\text{PSR}}) = 7.3 \times 10^9 \text{ J m}^{-3}$
- Fraction of top 1 mm vaporized each event:
 $u_E / u_{\text{reg}} = 1.2 \times 10^{-7}$
- After 10^6 yr (10^6 events), percentage vaporized:
~12%

How does breakdown weathering compare to meteorite weathering?

- **Meteorite weathering**

- Energy flux:

$$F_m = 12 \text{ J m}^{-2} \text{ yr}^{-1} \text{ (Grün et al., 1985)}$$

- Meteoritic vapor/melt production:

$$P_m = 1.8 \times 10^{-7} \text{ kg m}^{-2} \text{ yr}^{-1} \text{ (Cintala, 1992)}$$

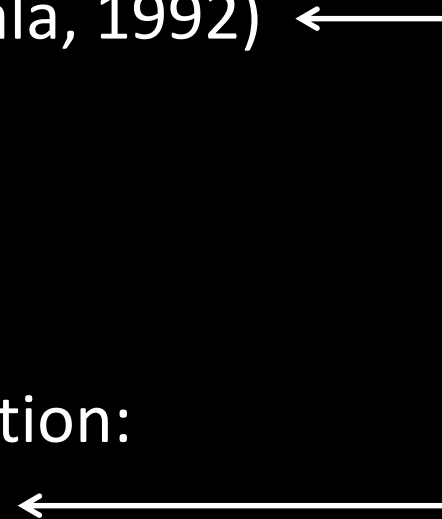
- **Breakdown weathering**

- Breakdown energy flux:

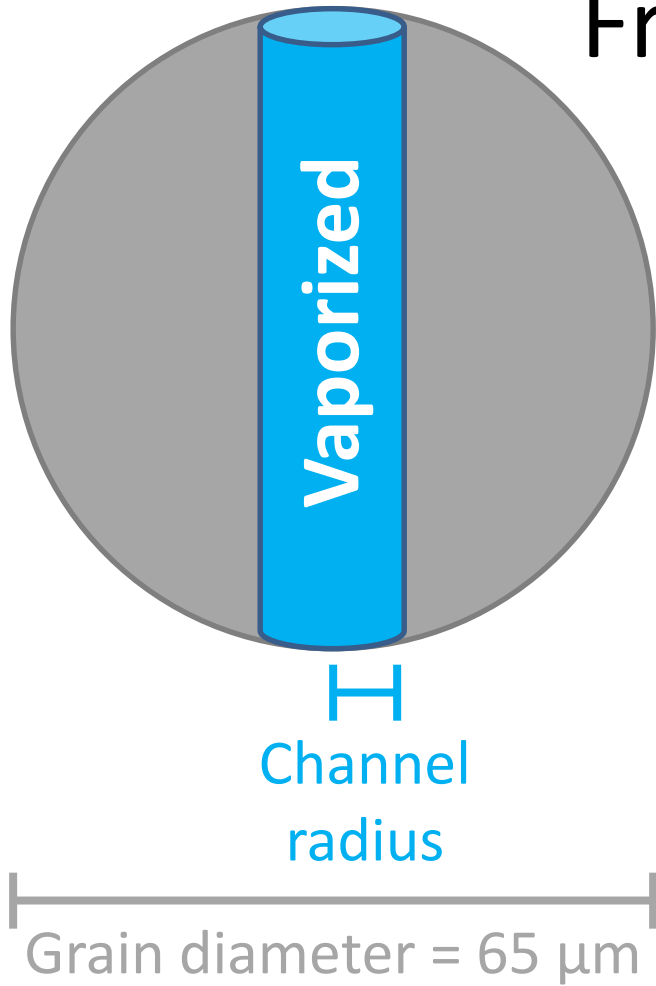
$$F_E \approx 0.88 \text{ J m}^{-2} \text{ yr}^{-1}$$

- Breakdown vapor/melt production:

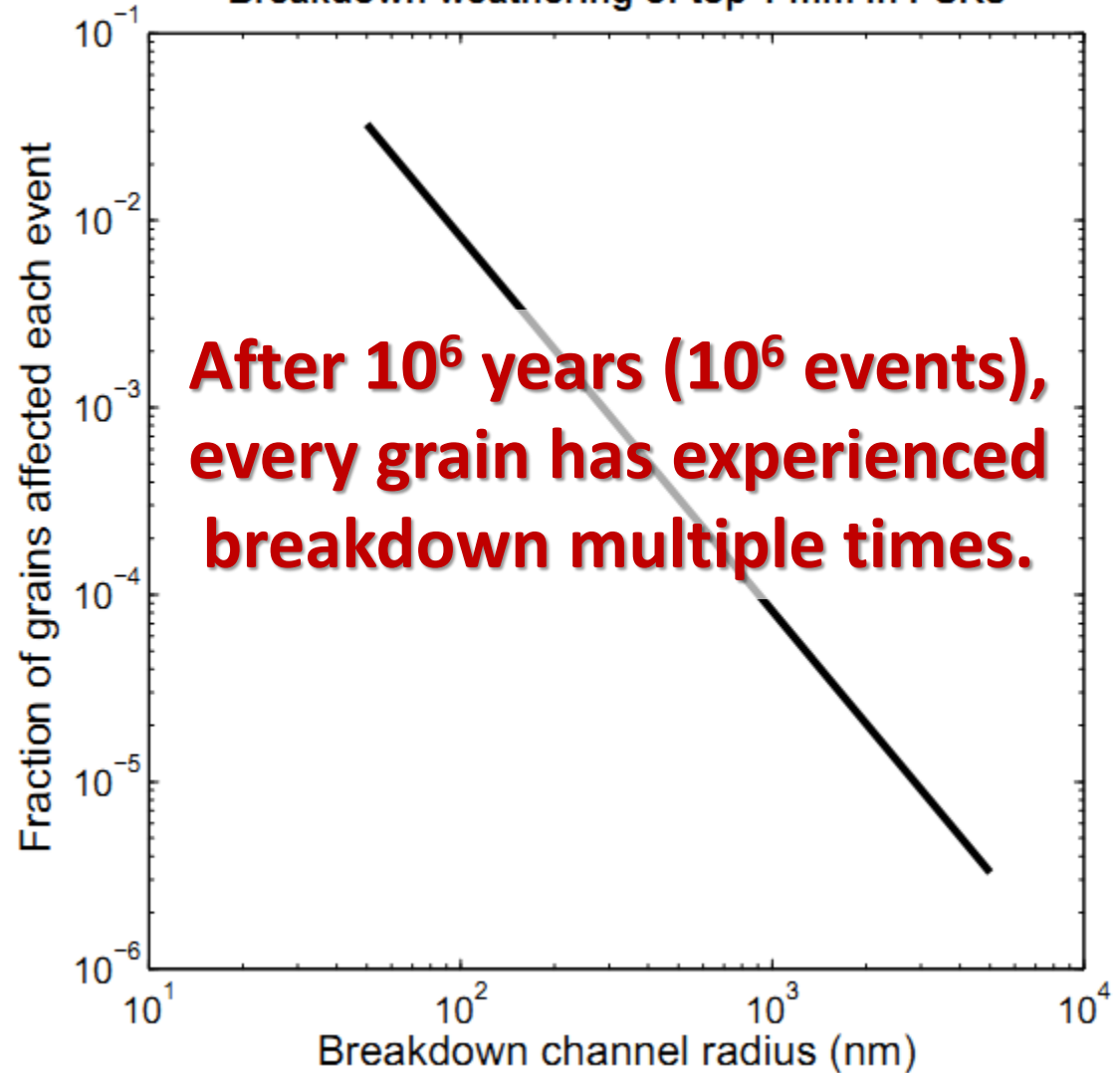
$$P_E \approx 1.8 \times 10^{-7} \text{ kg m}^{-2} \text{ yr}^{-1}$$



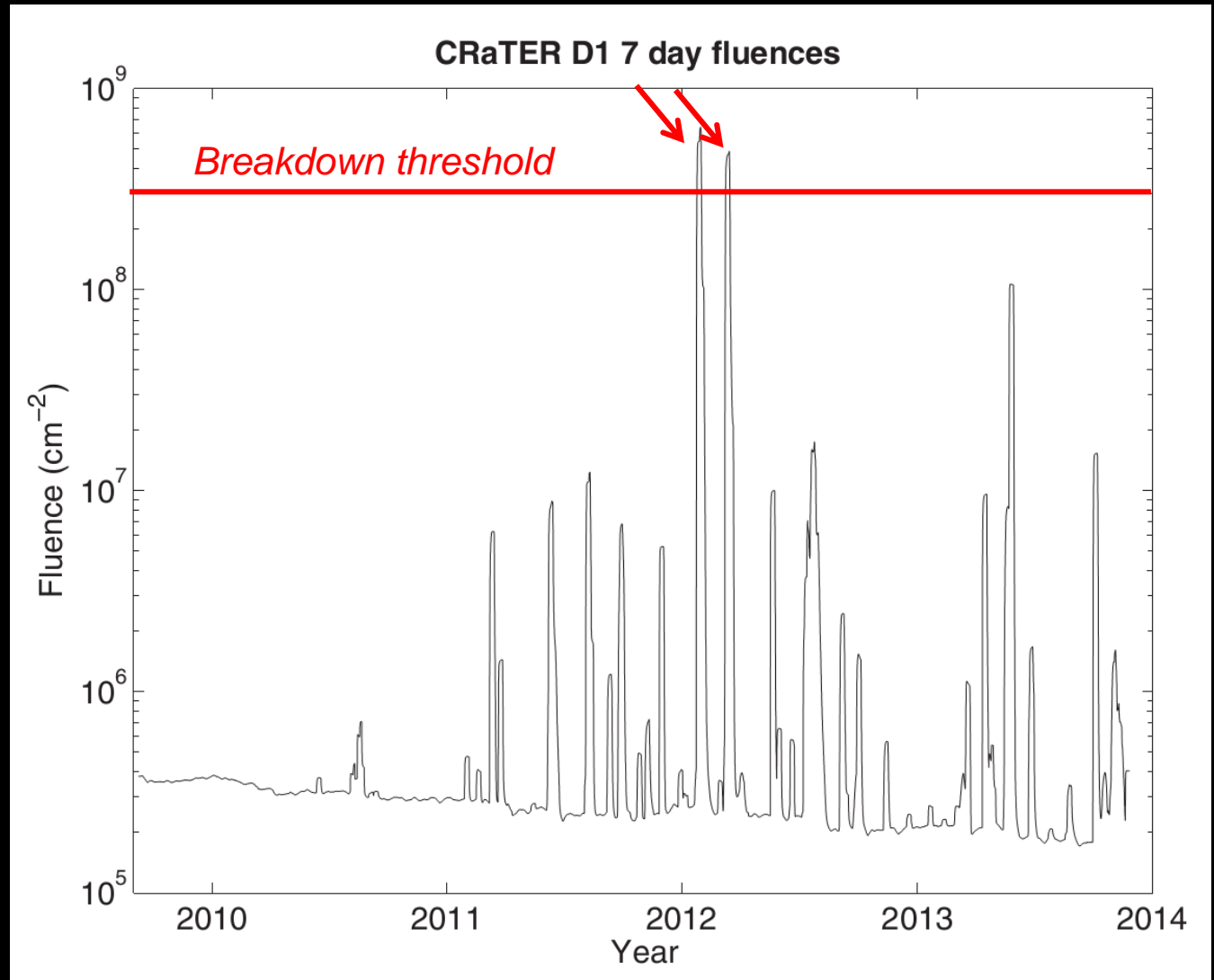
Fraction of grains affected by breakdown weathering



Breakdown weathering of top 1 mm in PSRs



LRO/CRaTER data indicates two breakdown-causing SEP events occurred during mission.



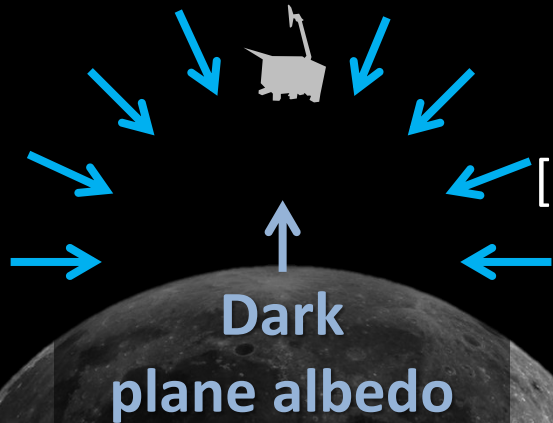
(Jordan et al., 2015)

→ Up to 8% of PSR regolith grains in top 1 mm have received a breakdown channel during LRO's mission.

Instrument	Observation of PSR regolith
LCROSS	Increased porosity in Cabeus (Schultz et al., 2010)
LRO/LAMP	Darker plane albedo / increased porosity (Gladstone et al., 2012)
LRO/LOLA	Brighter normal albedo (Lucey et al., 2014)

LRO/LAMP:

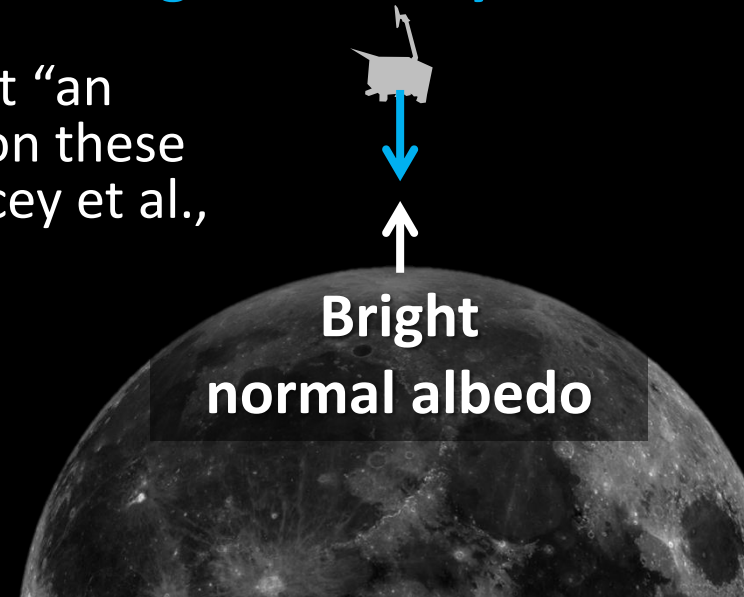
Light incident from 2π sr



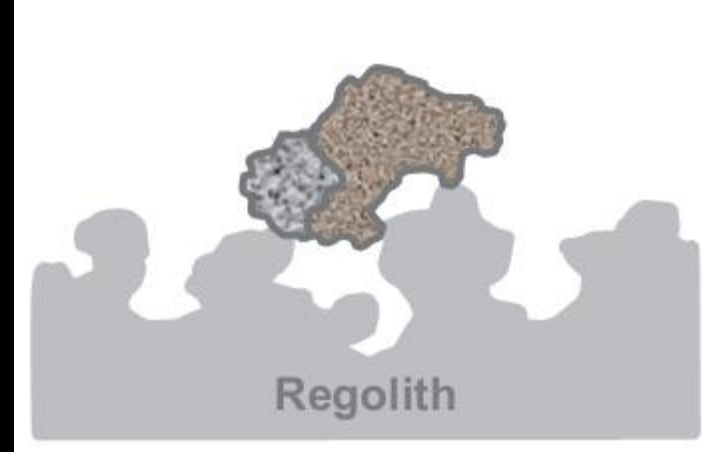
Observations suggest "an environmental control on these [optical] properties" (Lucey et al., 2014)

LRO/LOLA:

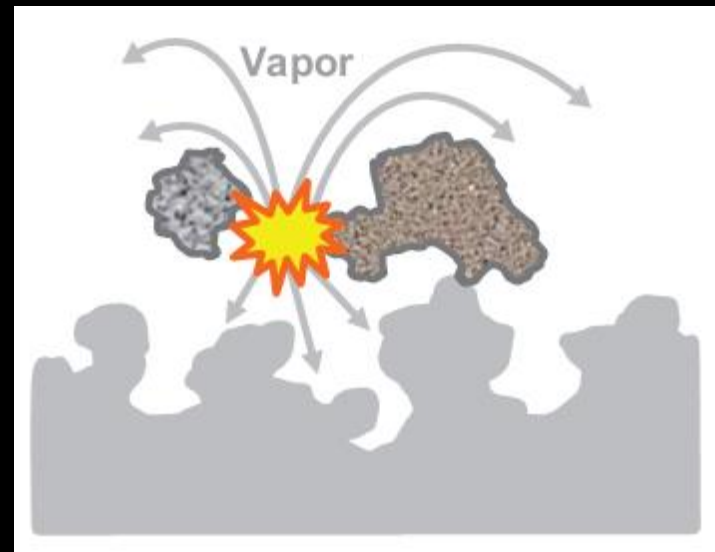
Light normally incident



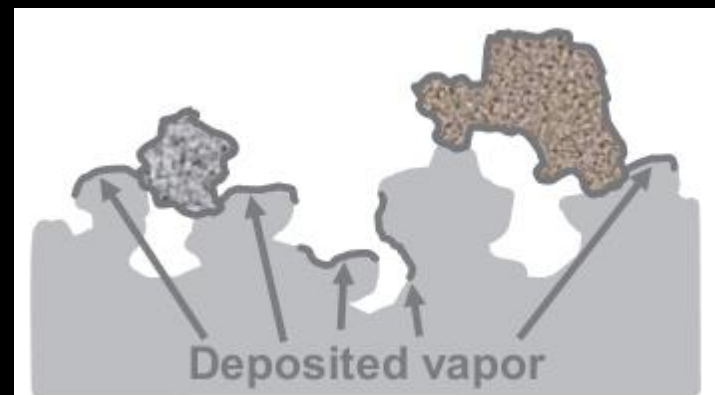
Grain at regolith's surface



**Breakdown vaporizes
some of grain's material
and splits grain**



**Deposited vapor increases
nanophase iron, and
regolith's porosity changes**



Science summary #2 – Significant radiation impacts to lunar regolith

Breakdown weathering in PSRs

- may produce vapor/melt comparable to meteoritic weathering
- affects ~12% of gardened regolith
- may help explain PSR observations

Instrument	Observation of PSR regolith
LCROSS	Increased porosity in Cabeus (Schultz et al., 2010)
LRO/LAMP	Darker plane albedo / increased porosity (Gladstone et al., 2012)
LRO/LOLA	Brighter normal albedo (Lucey et al., 2014)

Summary

- Ionizing radiation throughout the heliosphere and at planets has both intrinsic science value (“truths”) and space weather applications (“consequences”)
 - Van Allen Probes differentiating between and quantifying physical mechanisms responsible for particle acceleration, transport, and loss in radiation belts
 - **Precipitation loss critical mechanism for radiation belt dynamics AND as energy input coupling to atmosphere**
 - Lunar Reconnaissance Orbiter discovering the roles that ionizing radiation plays in modifying planetary surfaces
 - **Solar particle events may be as important as meteoritic weathering at Moon, particularly in PSRs**
- Examples underscore how science topics often connect seamlessly across SMD and with application to HEO