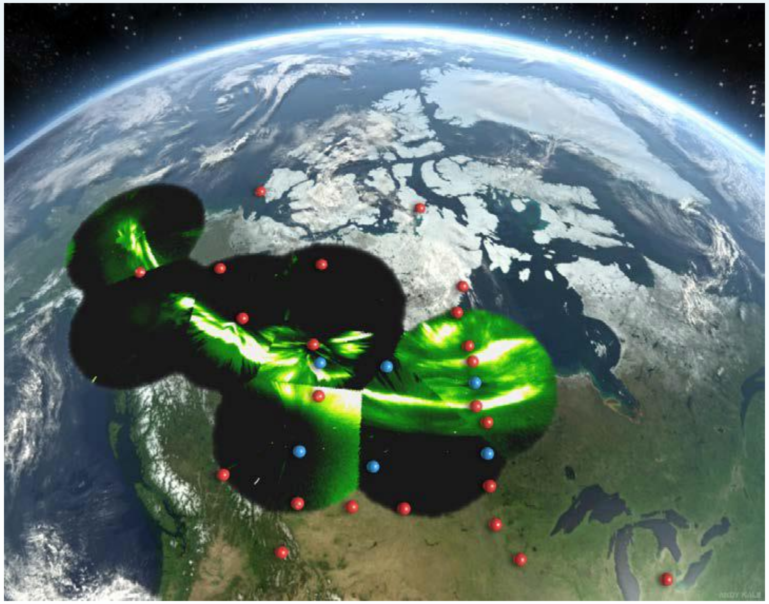
Bead Evolution and Development of Substorms (BEADS)

A mission to discover the key that unlocks massive energy release in the magnetosphere

Prof. Jinbin Cao, Beihang University, China

Dr. I. Jonathan Rae, Mullard Space Science Laboratory, UCL, UK

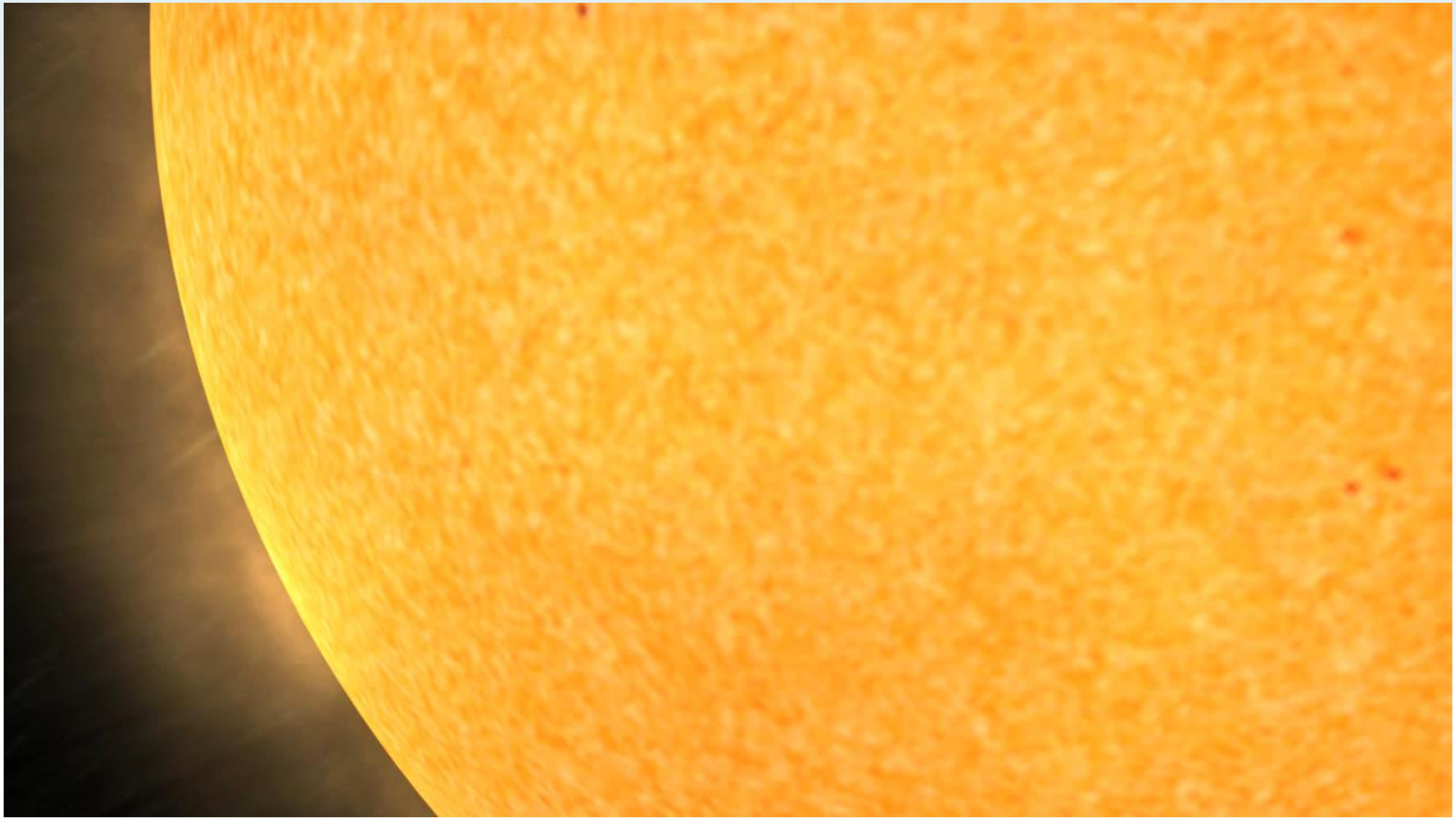


And the BEADS Science Working team, including: Andrew Fazakerley, Chi Wang, Zhongyi Chu, Malcolm Dunlop, Zuyin Pu, Yong Liu, Clare Watt, Qiugang Zong, Hong Zou, Ian Mann, Ping Zhu, Chris Owen, William Liu, Steve Milan, Zhonghua Yao, Craig Rodger, Jianyong Lu, Tielong Zhang, Kyle Murphy

北京航空航天大學 BEIHANG UNIVERSITY

UCL

Targeting the Science behind Space Weather: Geomagnetic Storms and Substorms



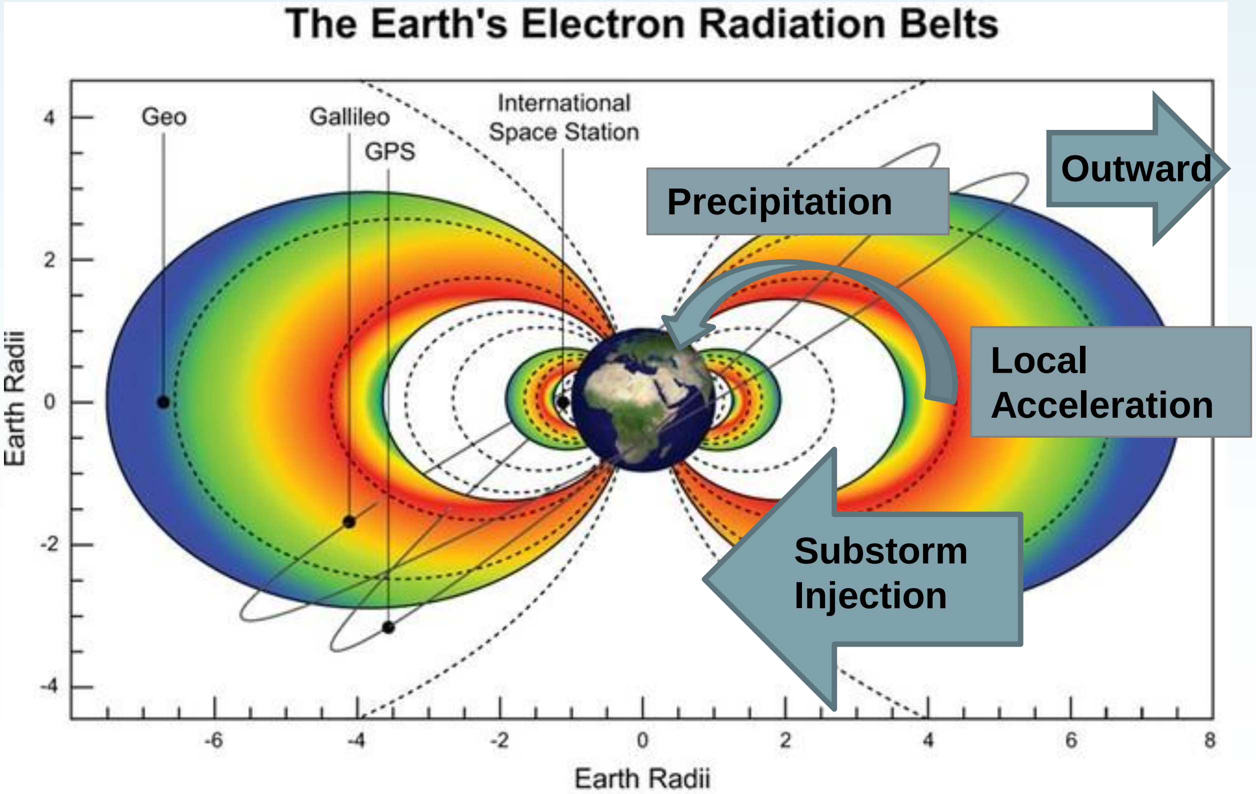
Credit: NASA

BEADS Primary Science Goal

- To discover the plasma instability responsible for the detonation of the magnetospheric substorm

BEADS Secondary Science Goal

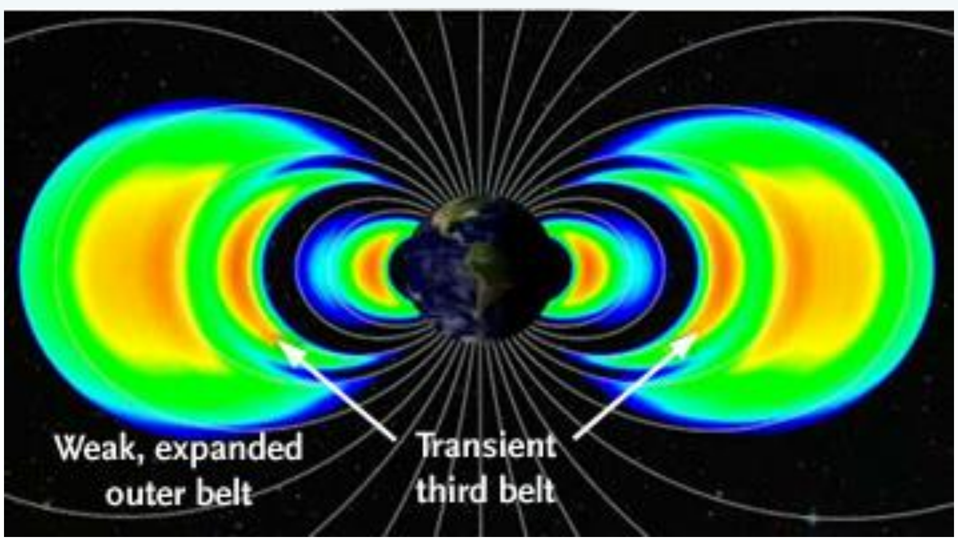
- To determine the causes of radiation belt precipitation and quantify their loss into the upper atmosphere
  - By measuring the true precipitating population

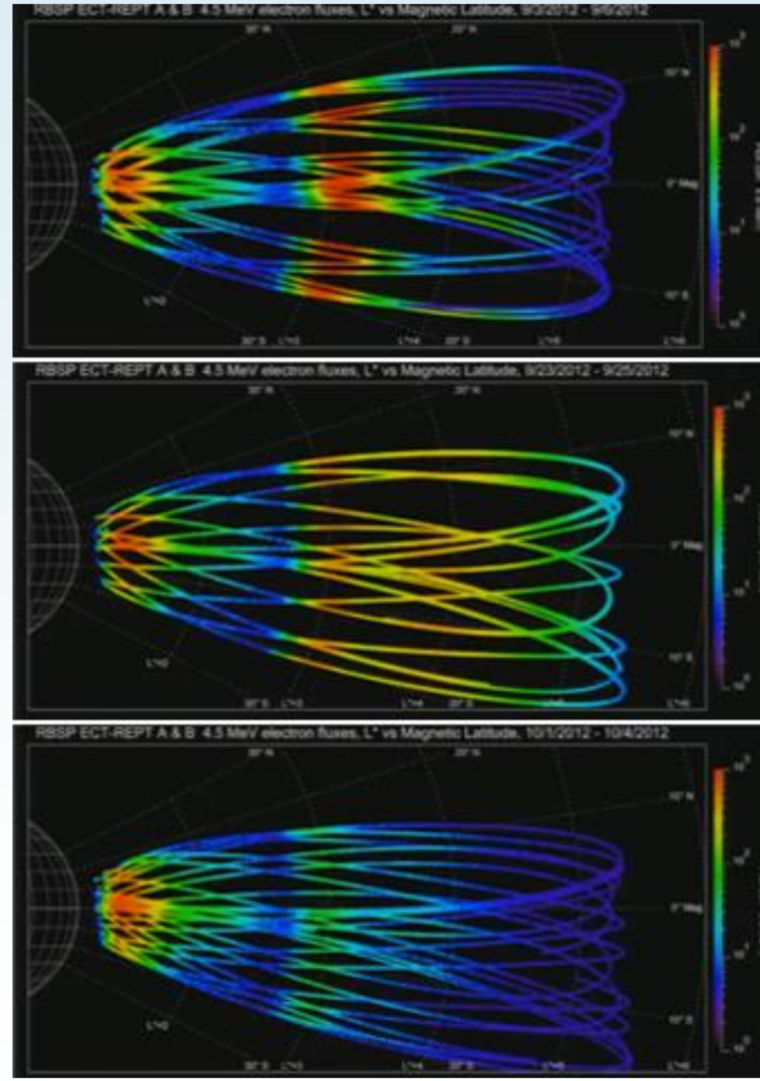


Horne [2007], *Nature Physics*

BEADS Tertiary Science Goal

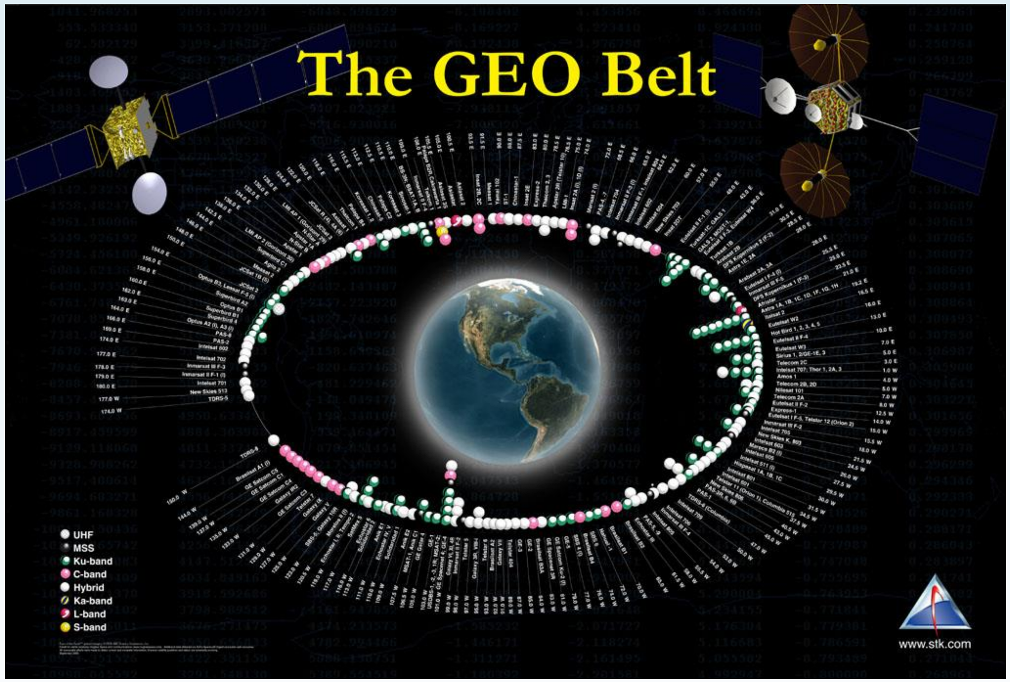
- To understand the dynamics of the Van Allen Radiation Belts
  - By monitoring the trapped radiation





Baker et al., [2013], *Science*

Consequences of Space Weather



Courtesy: Craig Rodger

- Roughly 450 operational satellites currently in GEO Orbit.
- Examples of Losses: Intelsat K, Anik E1 & E2, Telstar 401, Galaxy-4, Galaxy-15
- Costs: ~€200M build, ~ €100M launch to GEO,
  3%-5%/yr to insure; e.g., in 1998 €1.6B in claims, €850M in premiums

Primary: What is a substorm?

- 50th Anniversary of science problem [Akasofu, 1964]
- Physically: An explosive energy release of stored magnetic energy from solar wind-magnetosphere interaction
- Substorm Phase timescales
  - Growth Phase ~10s minutes
  - **Expansion Phase ~10s seconds**
  - Recovery Phase ~100s minutes

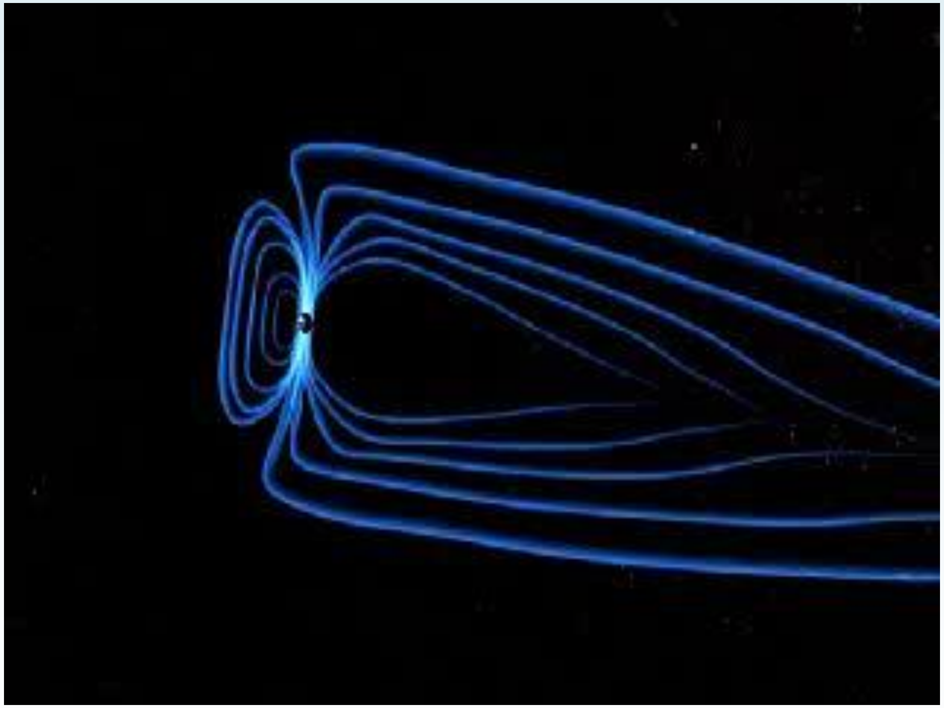
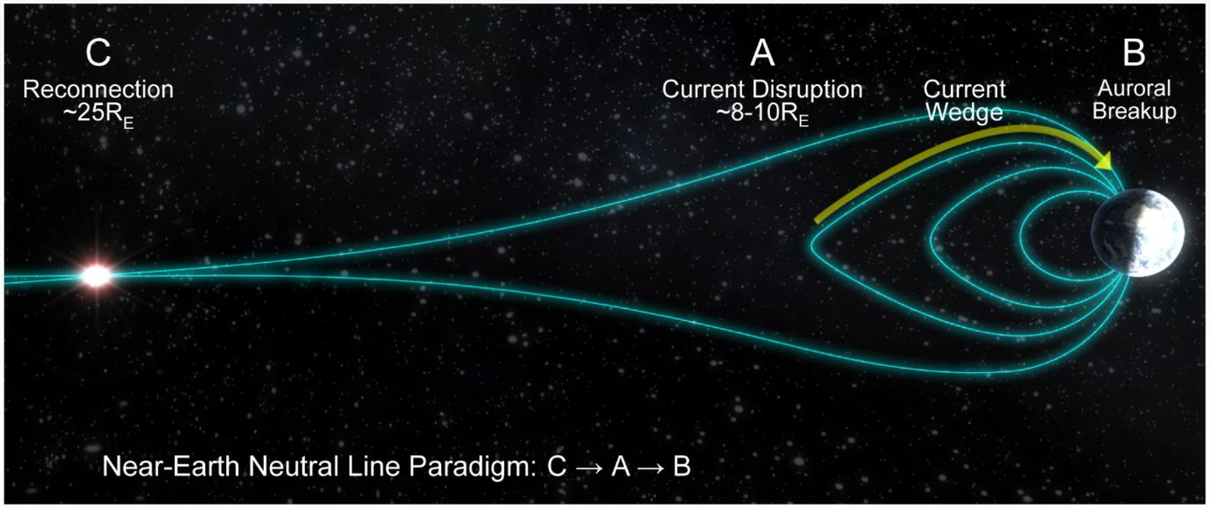


Image Credit: NASA

Primary: Putting BEADS into context

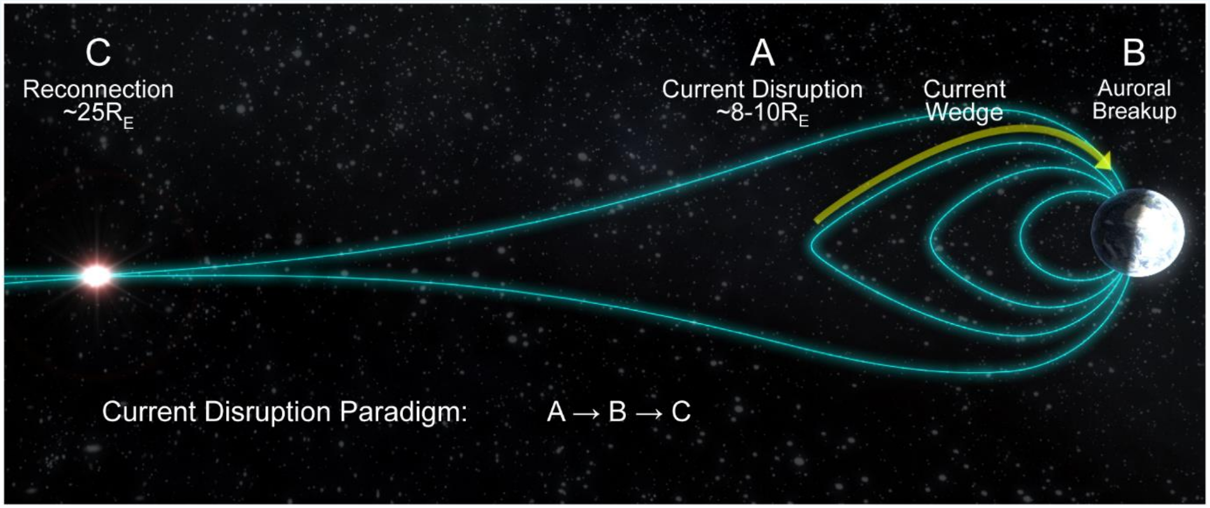
- NASA THEMIS mission designed to determine the relative timing of substorm related phenomena to distinguish between substorm models
- New science results revealed on timing of substorm phenomena



Rae et al. [2009]

Primary: Putting BEADS into context

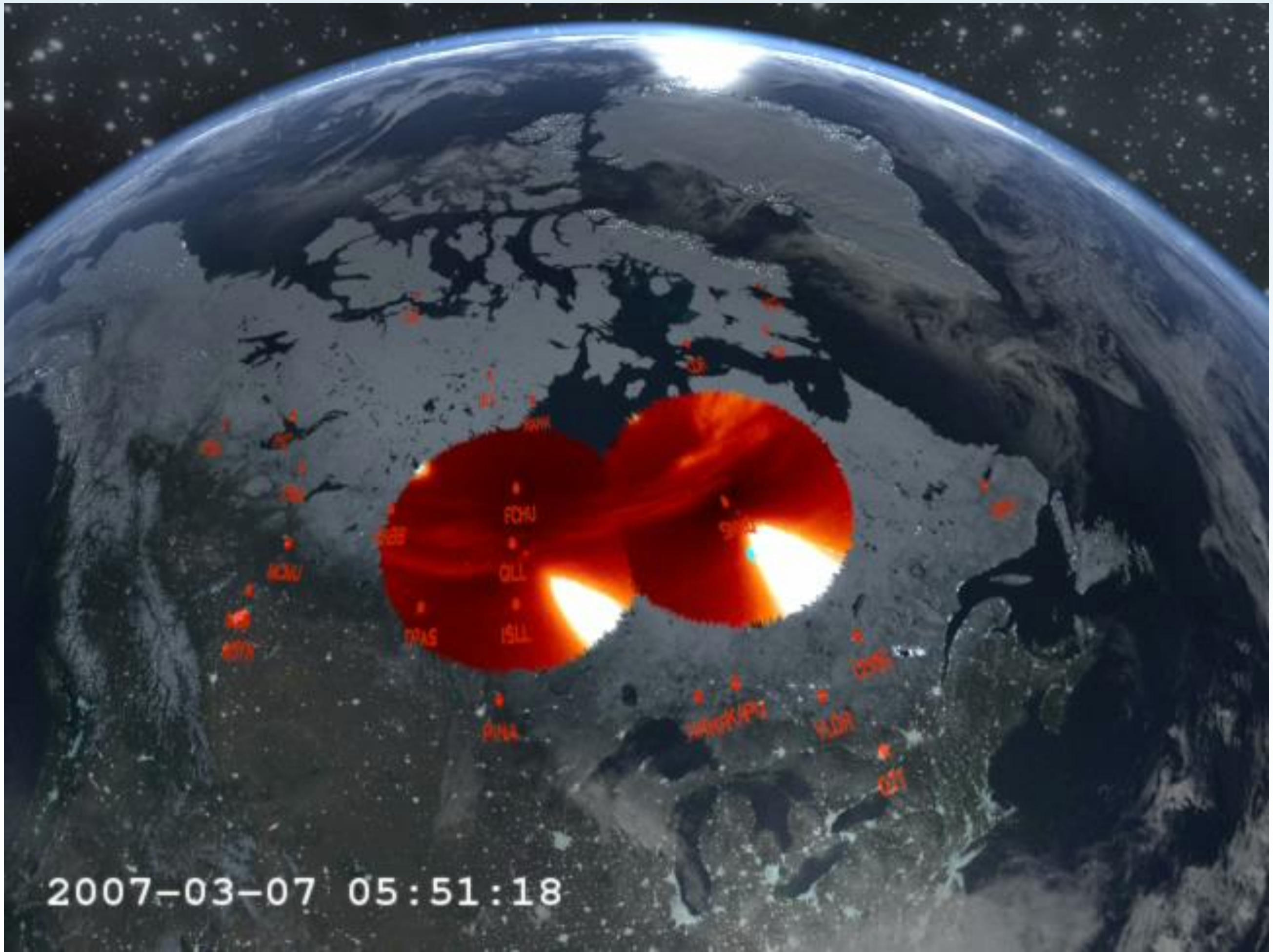
- NASA THEMIS mission designed to determine the relative timing of substorm related phenomena to distinguish between substorm models
- New science results revealed on timing of substorm phenomena



Rae et al. [2009]

Primary: The Discovery of Auroral Beads and Magnetic Wave Epicentre

- Auroral and magnetic waves mark substorm onset



Rae et al. [2009]

Primary: THEMIS Discoveries inspire BEADS science

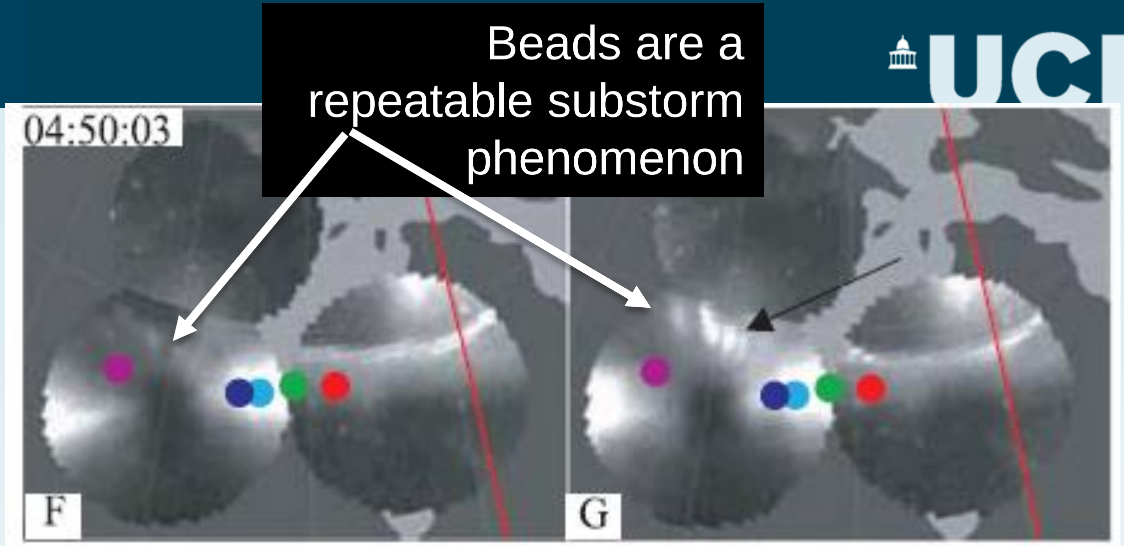


Figure 2 Angelopoulos et al., Science 2008

- NASA THEMIS provided many important substorm breakthroughs, *including* discovering BEADS science
  - e.g. Rae et al., JGR, 2009 using ground-based THEMIS ASI
- Auroral beads provide crucial new information regarding the physics of the substorm in the magnetotail to drive science significantly beyond the “substorm timing” problem.
  - Beads are clearly signature of an instability – is free energy from reconnection or from local plasma?

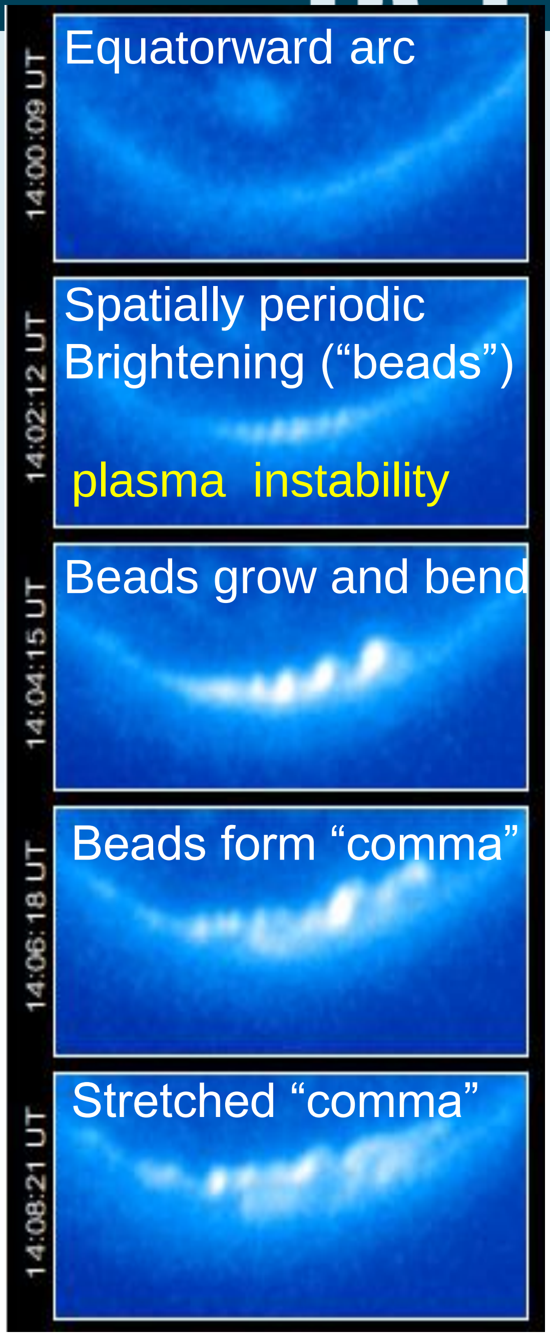
Primary: THEMIS Discoveries inspire BEADS science

- Explosive magnetic reconnection linked to auroral intensification
  - The timing of this connection is very fast (6s in Angelopoulos Science paper)
  - Unexplained by any current theory or simulation
  - Physics of auroral formation and intensification itself not understood

Primary: Diagnosing substorm auroral acceleration

- From ground measurements, we have shown that substorm onset starts with auroral and magnetic waves
  - Same time, same place,same frequency, same characteristics
- We know the particle characteristics of wave-driven auroral acceleration

- BEADS targeted to match optical space-based observations of aurora with simultaneous particle measurements of the precipitating electrons (and ions) that cause it



Henderson et al. [2009]

Primary: BEADS science questions directly follow on from THEMIS mission goals

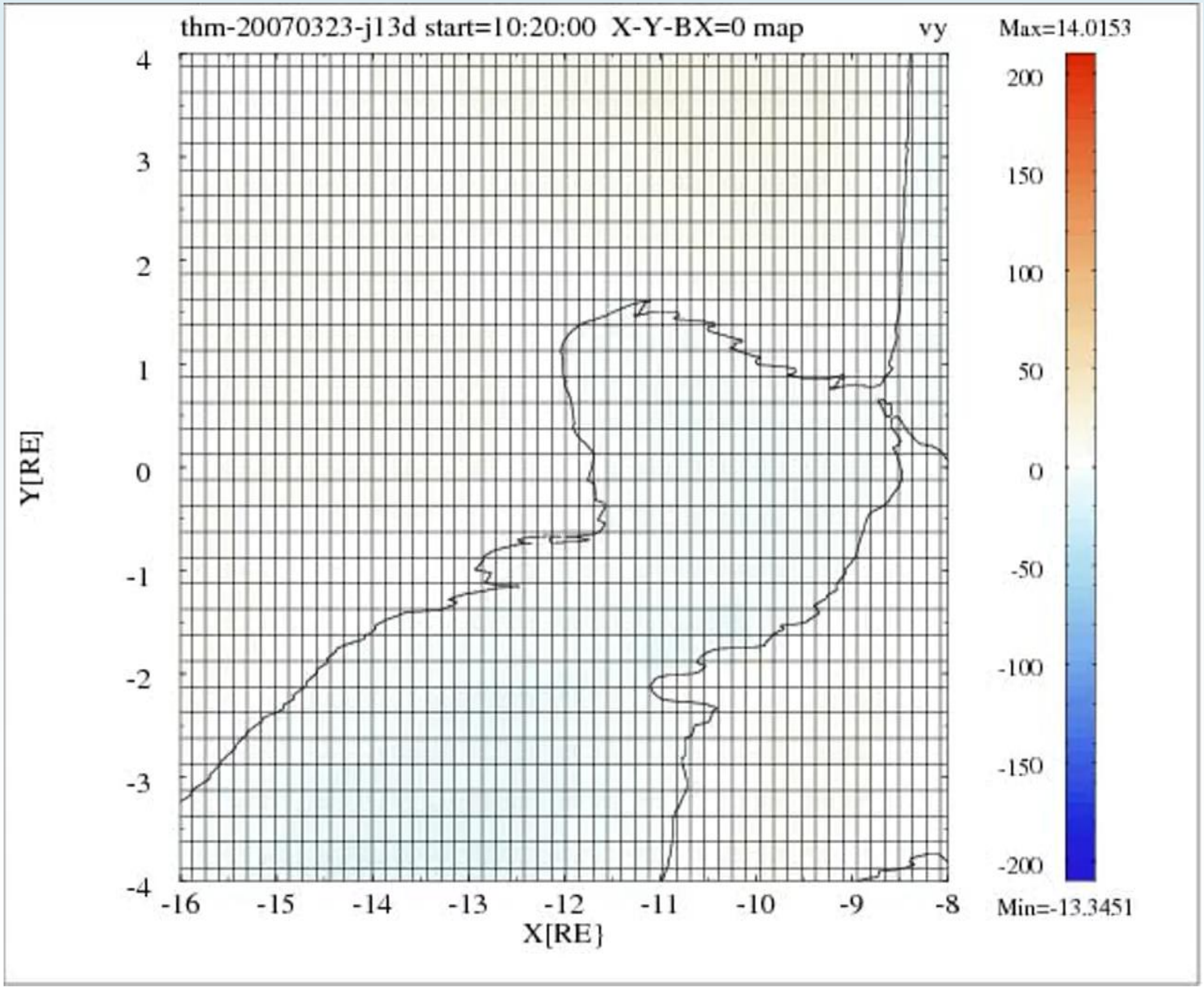
- Auroral beads are an important, repeatable phenomena of substorm physics
- Wave signatures in aurora and magnetic fields are a sign of a plasma instability

P1.1 What is this plasma instability?

P1.2 What is the source of the plasma instability?

P1.3 How does this instability related to magnetotail reconnection?

Primary: Simulations of magnetospheric instability

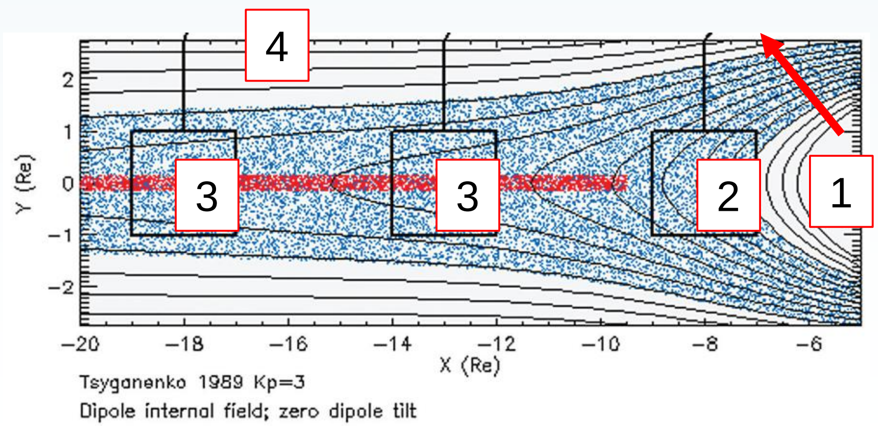


Courtesy: Ping Zhu and Joachim Raeder

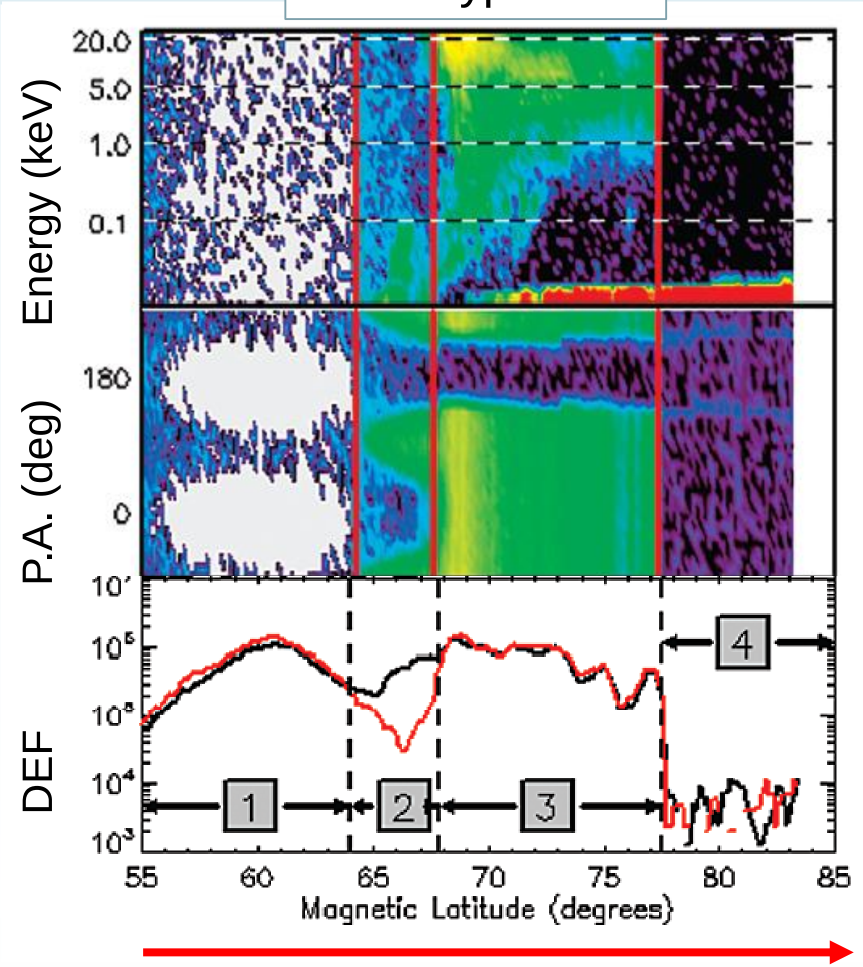
Where does the substorm arc map to?

Plasma boundaries mark crucial regions in space

1. equatorward of the inner edge of the ion plasmsheet
2. stably bounce trapped plasmasheet ions
3. isotropic fluxes outside the upgoing loss cone, due to strong pitch angle diffusion
4. poleward of the ion plasmasheet



I-ESA-type data

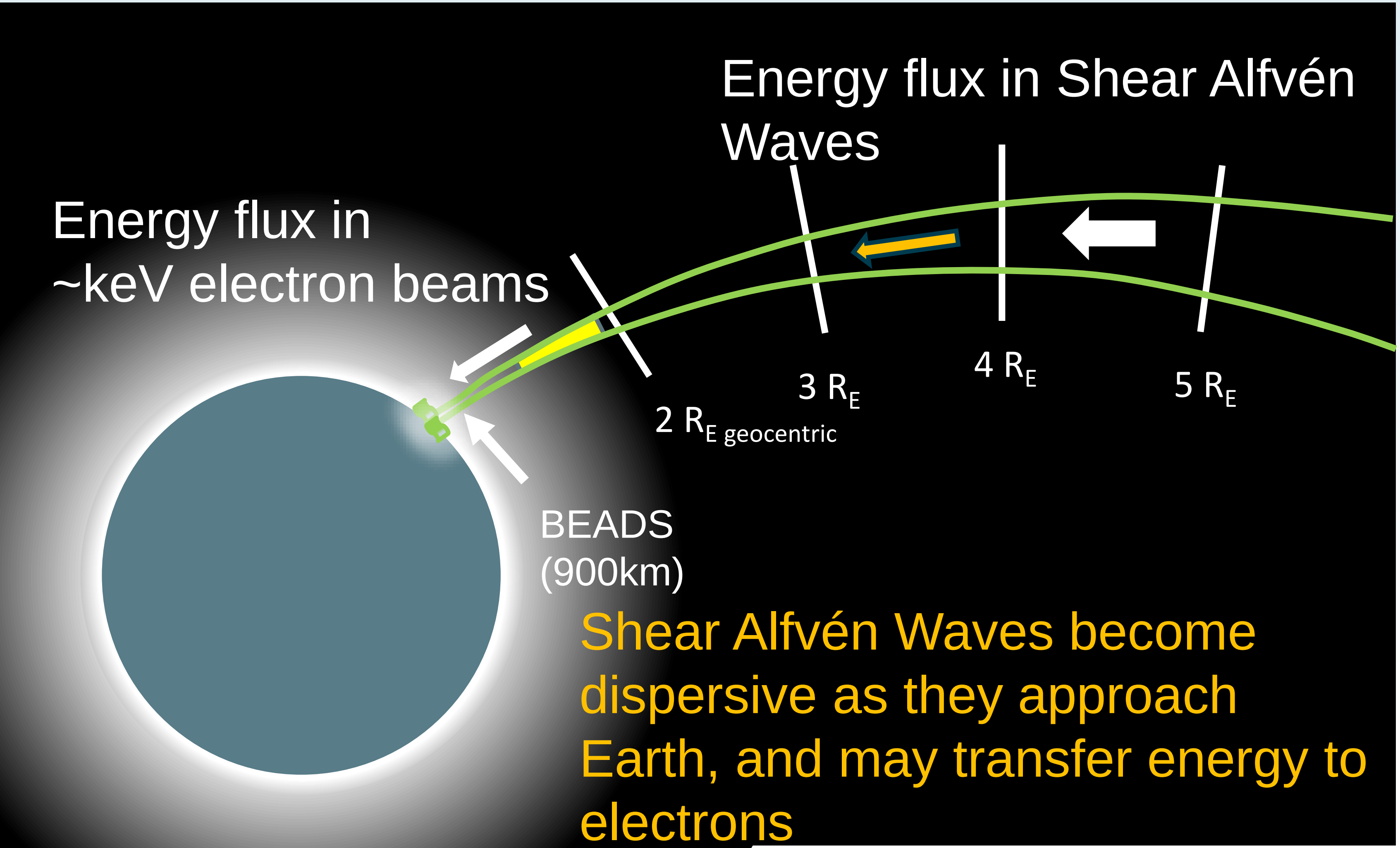


Magnetotail mapping: Donovan et al [2012]

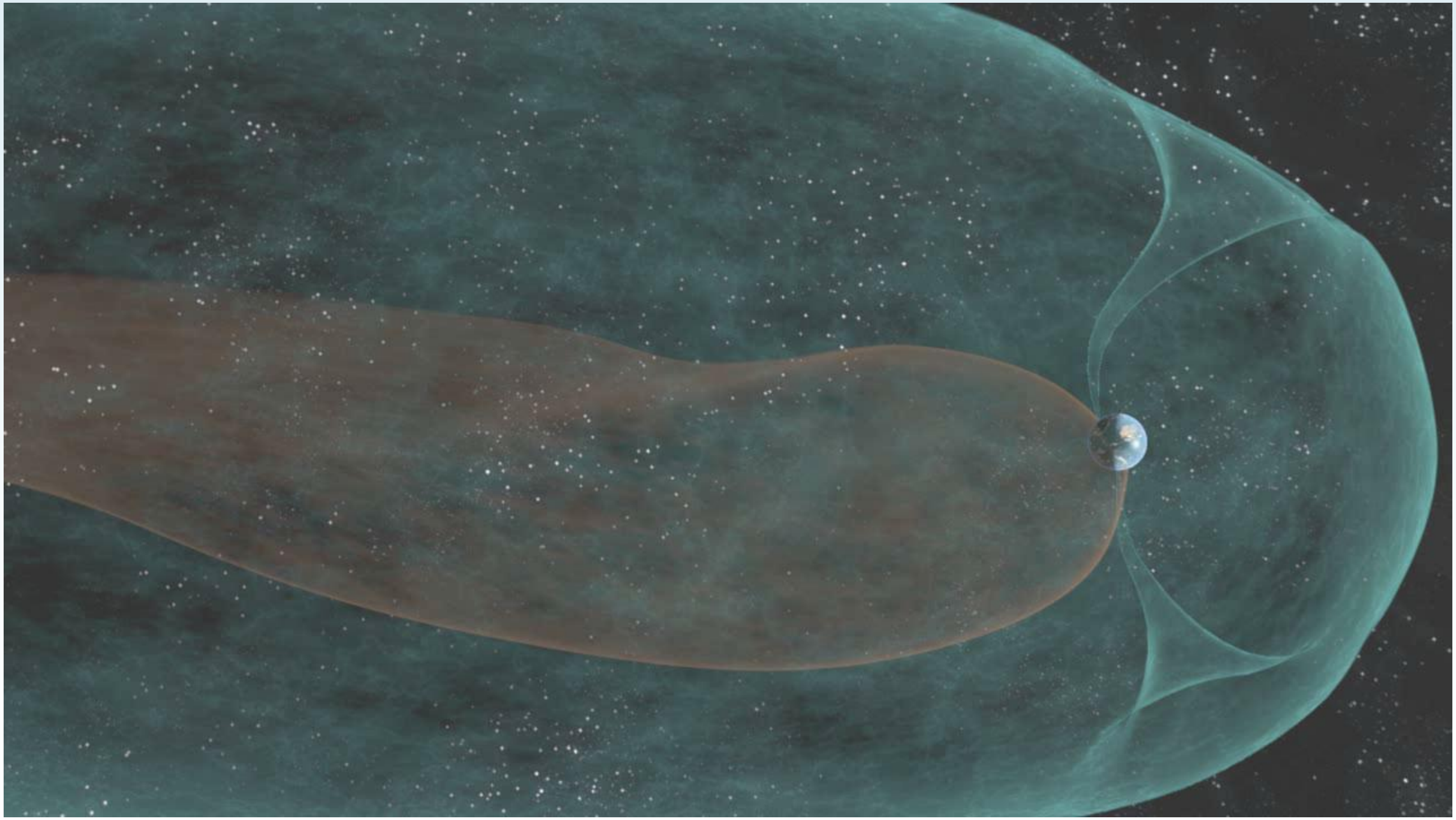
Primary: Distinguishing between instabilities through observational and theoretical tests

Plasma Instability	Frequency	Spatial Scales	Growth Rates	Auroral Signature
Cross-field Current Instability (CCI)	25mHz	10 km	0.1/s	Electron aurora
Ballooning Instability	25 mHz	10km	0.1/s	Electron and proton precipitation
Current-driven Alfvenic instability	100s mHz	Variable	1/s	Electron aurora monoenergetic
Tearing	1-100mHz	Variable	0.01/s	Unknown
Drift Kink/Sausage	1-100mHz	Variable	0.01/s	Unknown
Lower-hybrid drift	Hz	Variable	1/s	Unknown

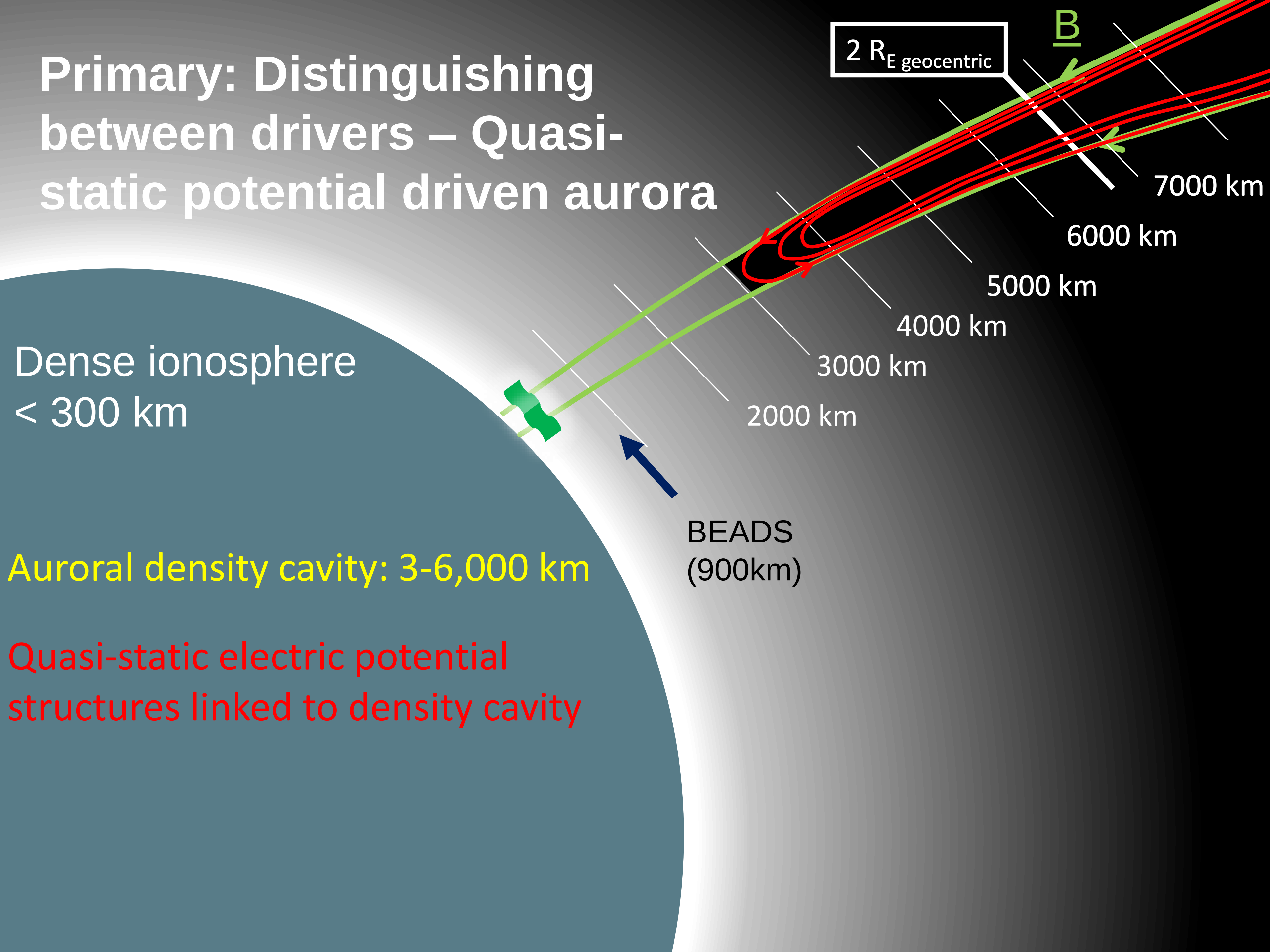
Primary: Distinguishing between drivers - Alfvén wave driven aurora



Primary: Wave-driven acceleration

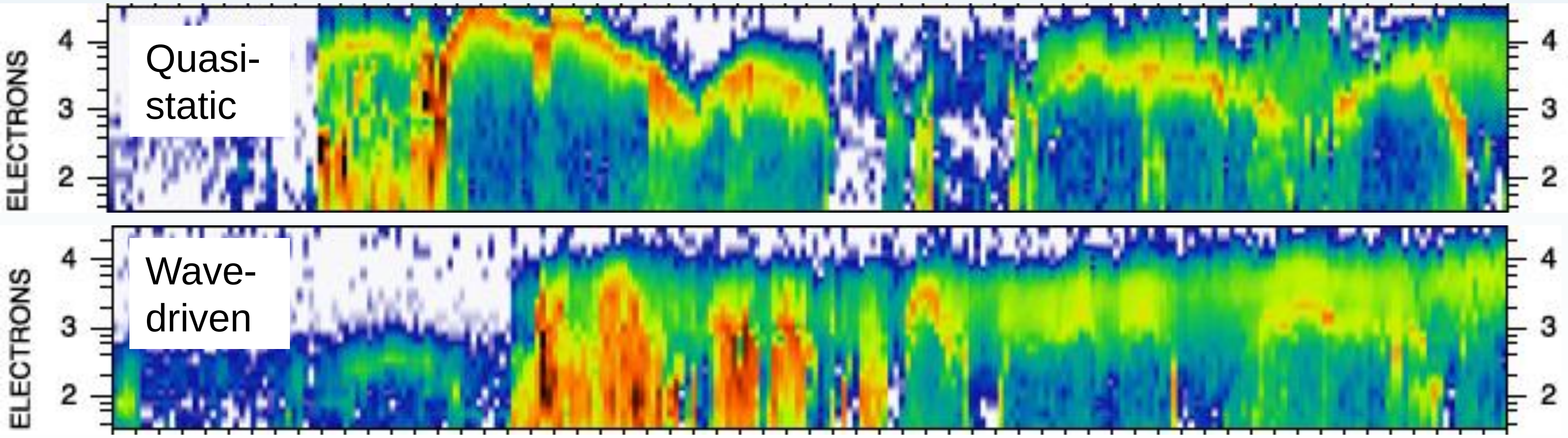


Courtesy: Andy Kale and Clare Watt


Primary: Distinguishing between drivers – Quasi-static potential driven aurora
2 R_{E} geocentric
B
7000 km
6000 km
5000 km
4000 km
3000 km
2000 km
Dense ionosphere
< 300 km
BEADS
(900km)
Auroral density cavity: 3-6,000 km
Quasi-static electric potential
structures linked to density cavity

Primary: Distinguishing between auroral drivers

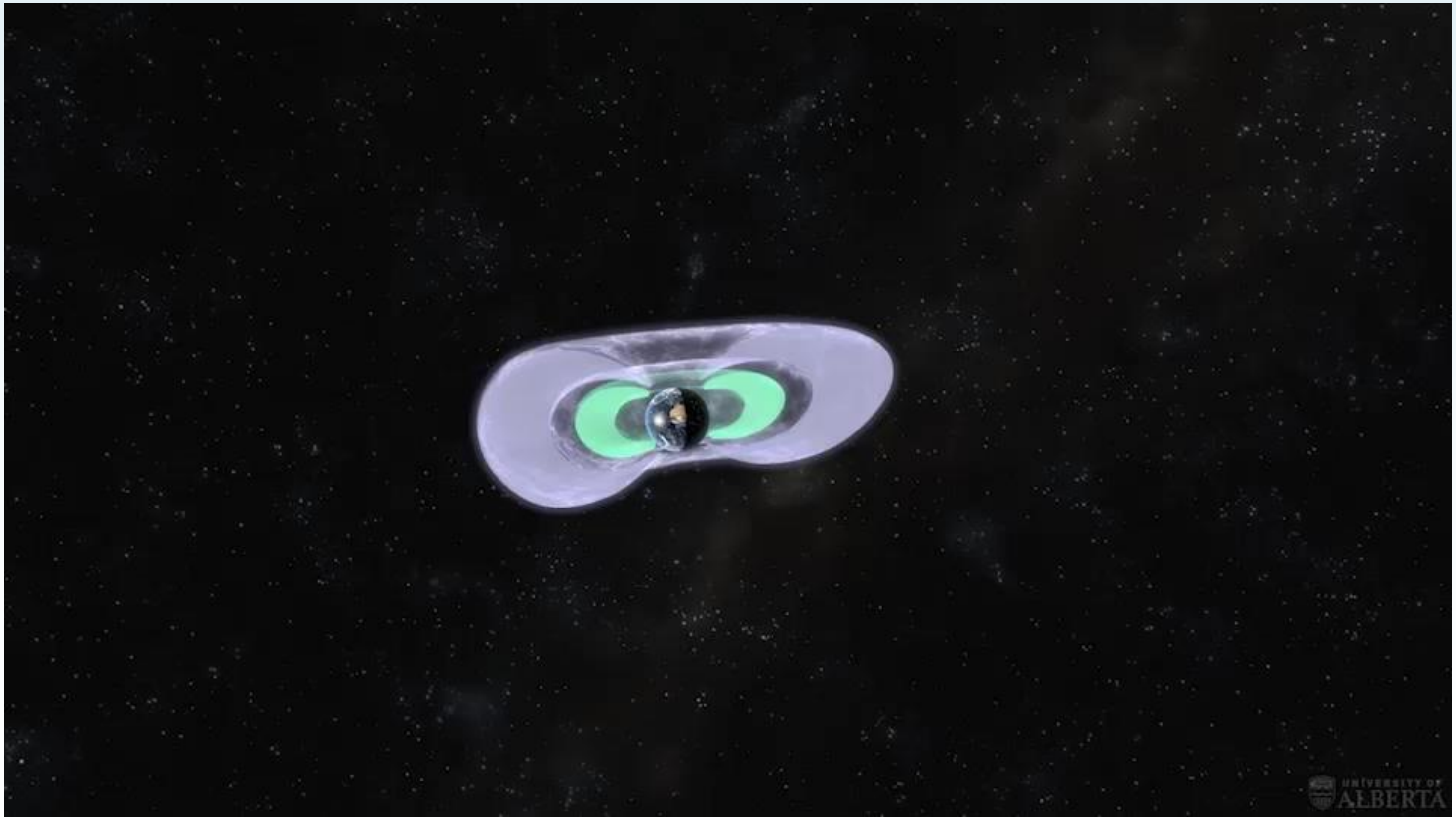
- Quasi-static potential drops
  - mono-energetic electron acceleration
- Shear Alfven Waves
  - broadband electron acceleration



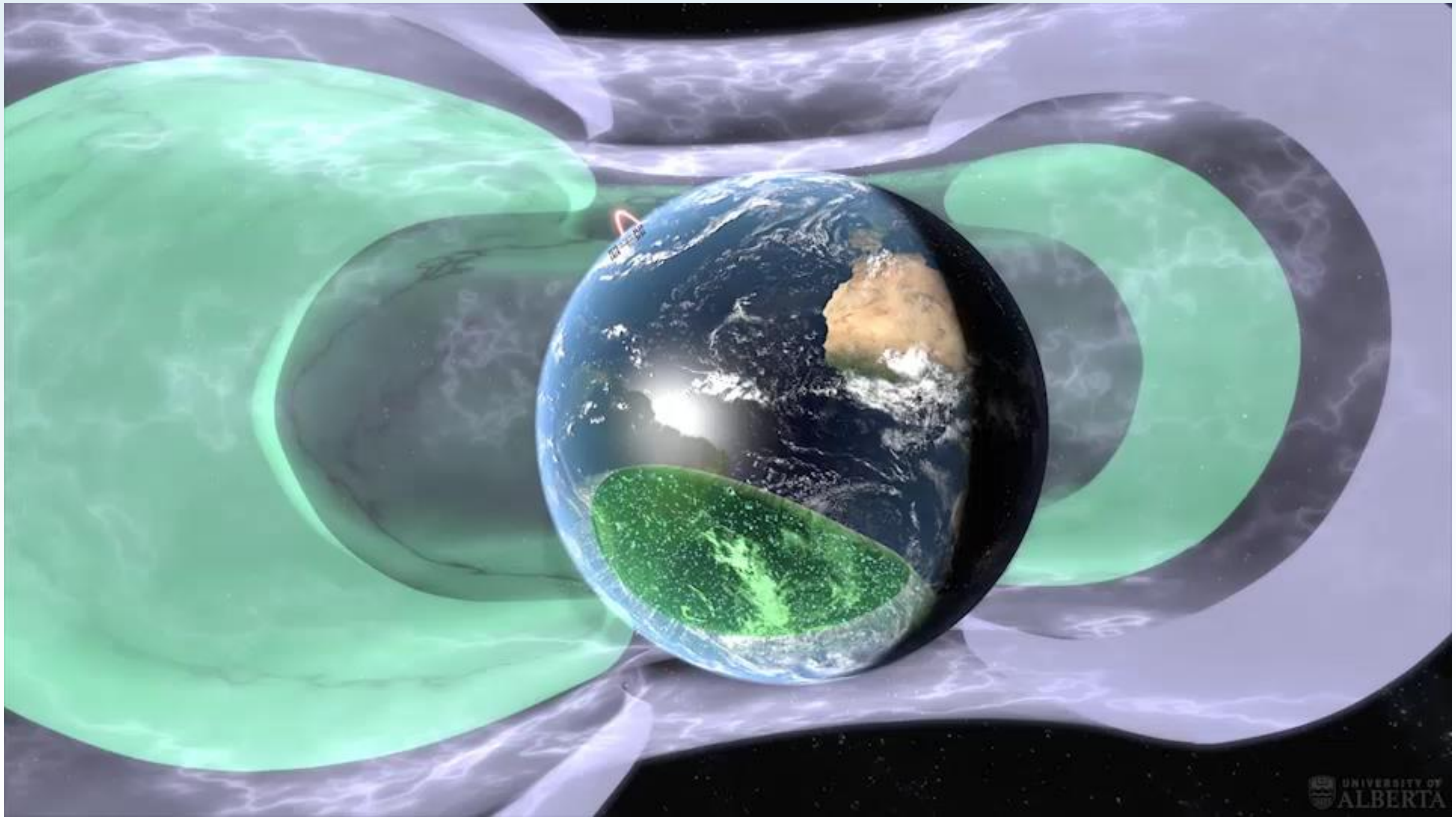
Newell et al. [2009]

Secondary Science Goal: To determine the causes of radiation belt precipitation and quantify their loss into the upper atmosphere

Secondary: Energetic Particle Dynamics in the Radiation Belts

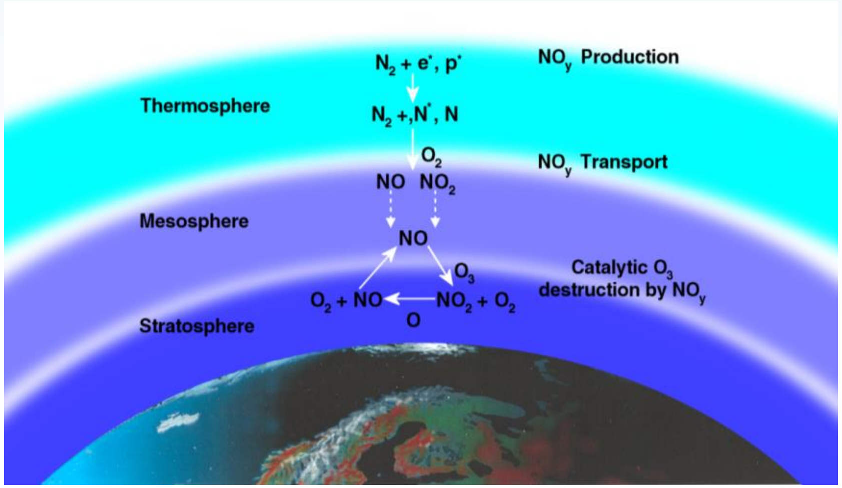


Secondary: Energetic Particle Precipitation from the Radiation Belts



Secondary: The importance of energetic particle (EPP) precipitation on atmospheric chemistry

- Understanding a 60 year physics problem
- Understanding the natural variation in global temperatures
- Understanding the role of EPP in the destruction of ozone



Particle precipitation

↓

Production of NO_x and HO_x

↓

Destruction of mesospheric and upper stratospheric O_3

↓

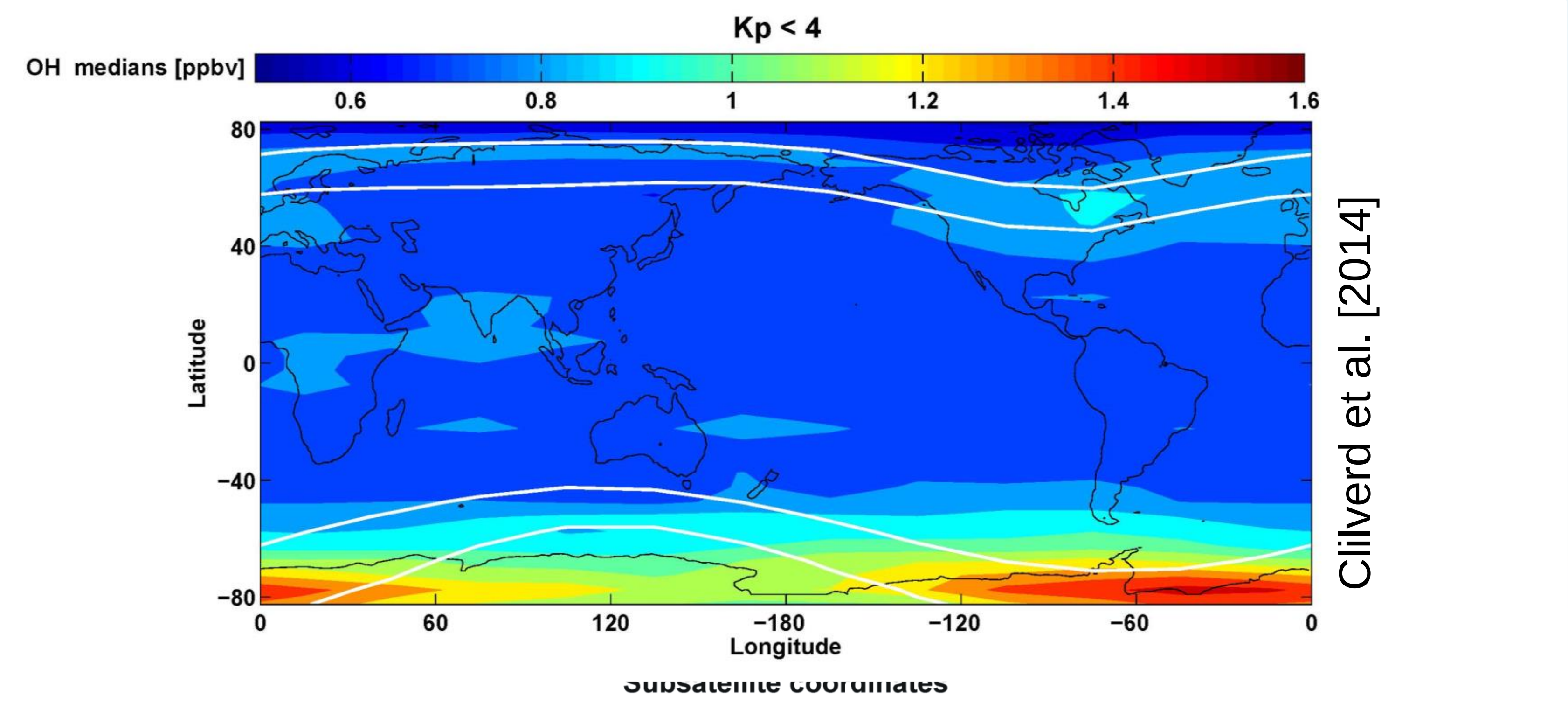
Change in dynamics mesosphere & stratosphere

↓

Implications for Climate

Secondary: In-situ EPP and HOx measurements

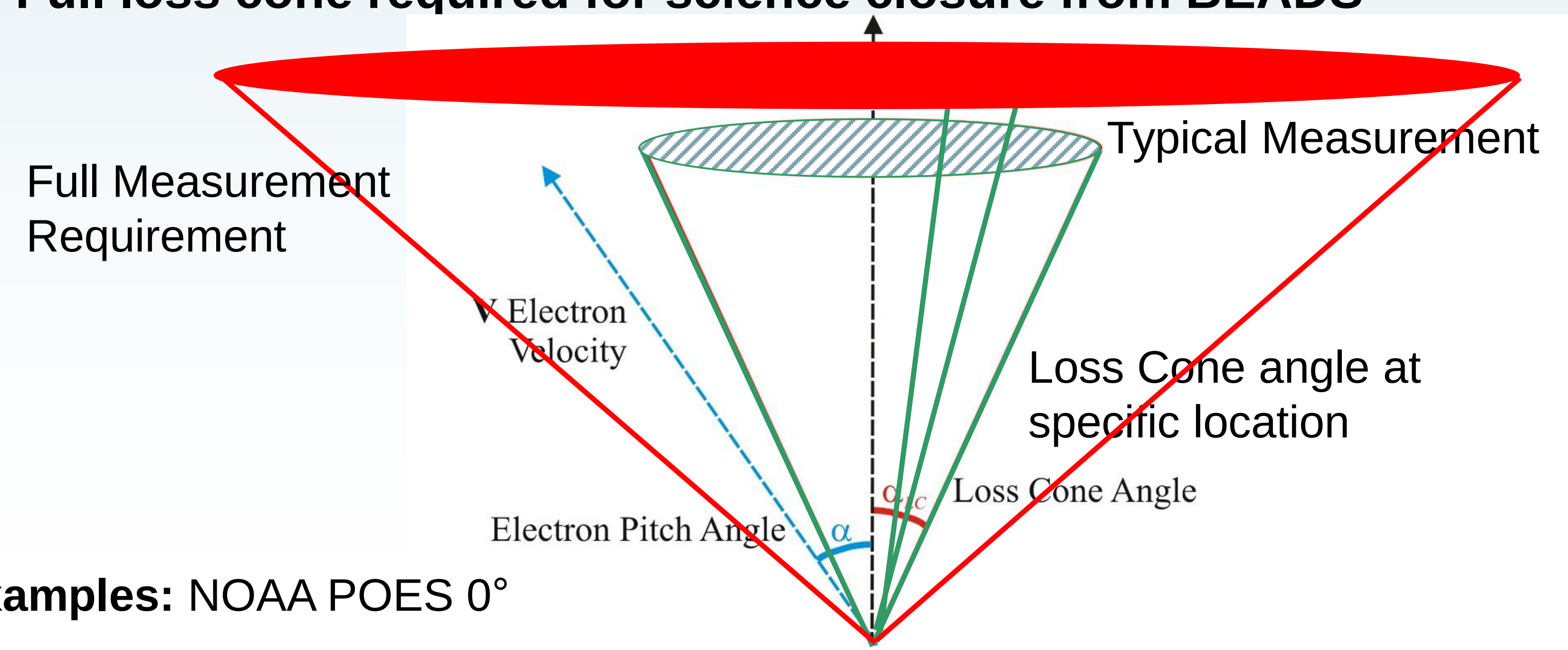
- NOAA POES measurements usually used to estimate particle precipitation
- ~835 km Sun synchronous orbit (c.f., BEADS)
- Numerous approximations required for scientifically useful data
- Close relationship between EPP and HOx
- Input into chemistry climate models reveal surface temperature redistribution through EPP



Clilverd et al. [2014]

Secondary: Particles inside the loss cone

- All currently flying instruments measure only a small fraction of precipitation, and assume symmetry
- Able to only measure ***strong*** precipitation events
- Weak precipitation thought to be ***crucial***
- **Full loss cone required for science closure from BEADS**

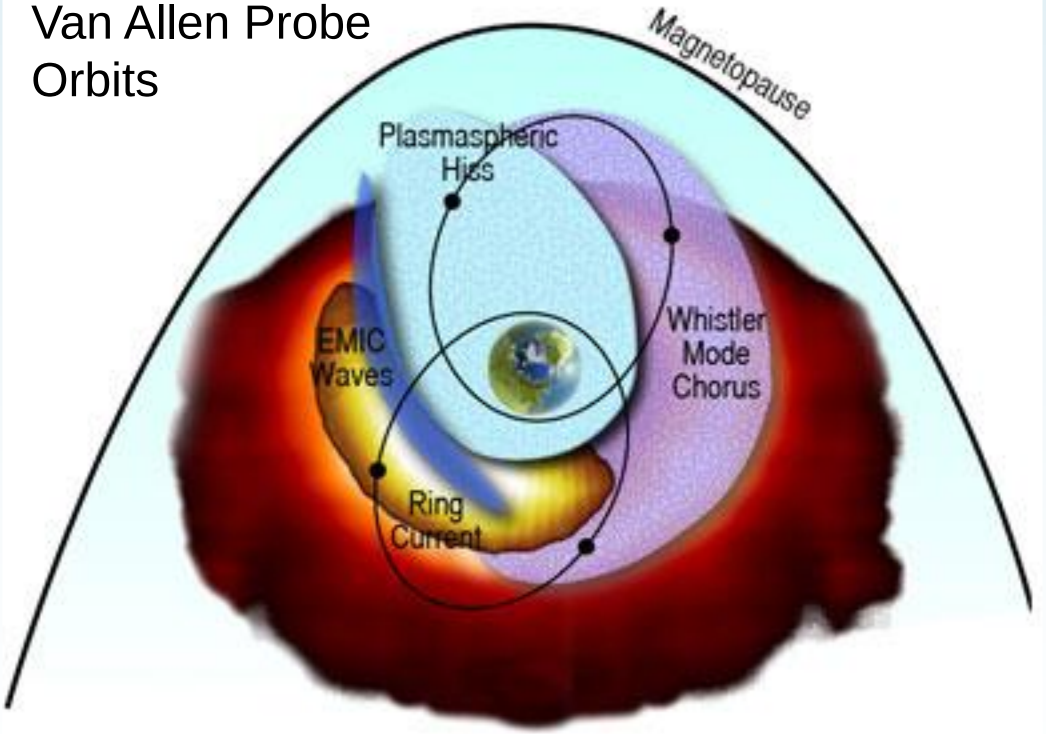


Examples: NOAA POES 0°

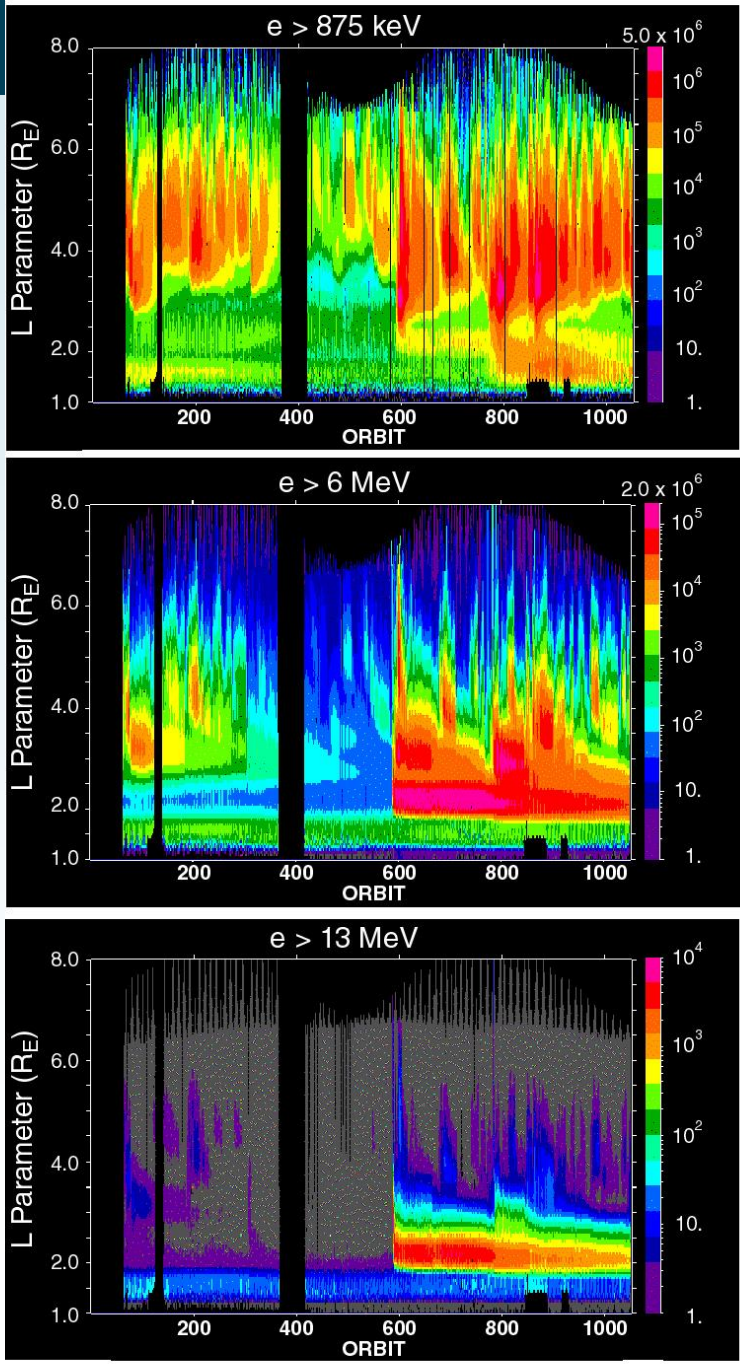
Courtesy: Craig Rodger

Tertiary Science Objective : Understanding Radiation Belt dynamics

Van Allen Probe Orbits



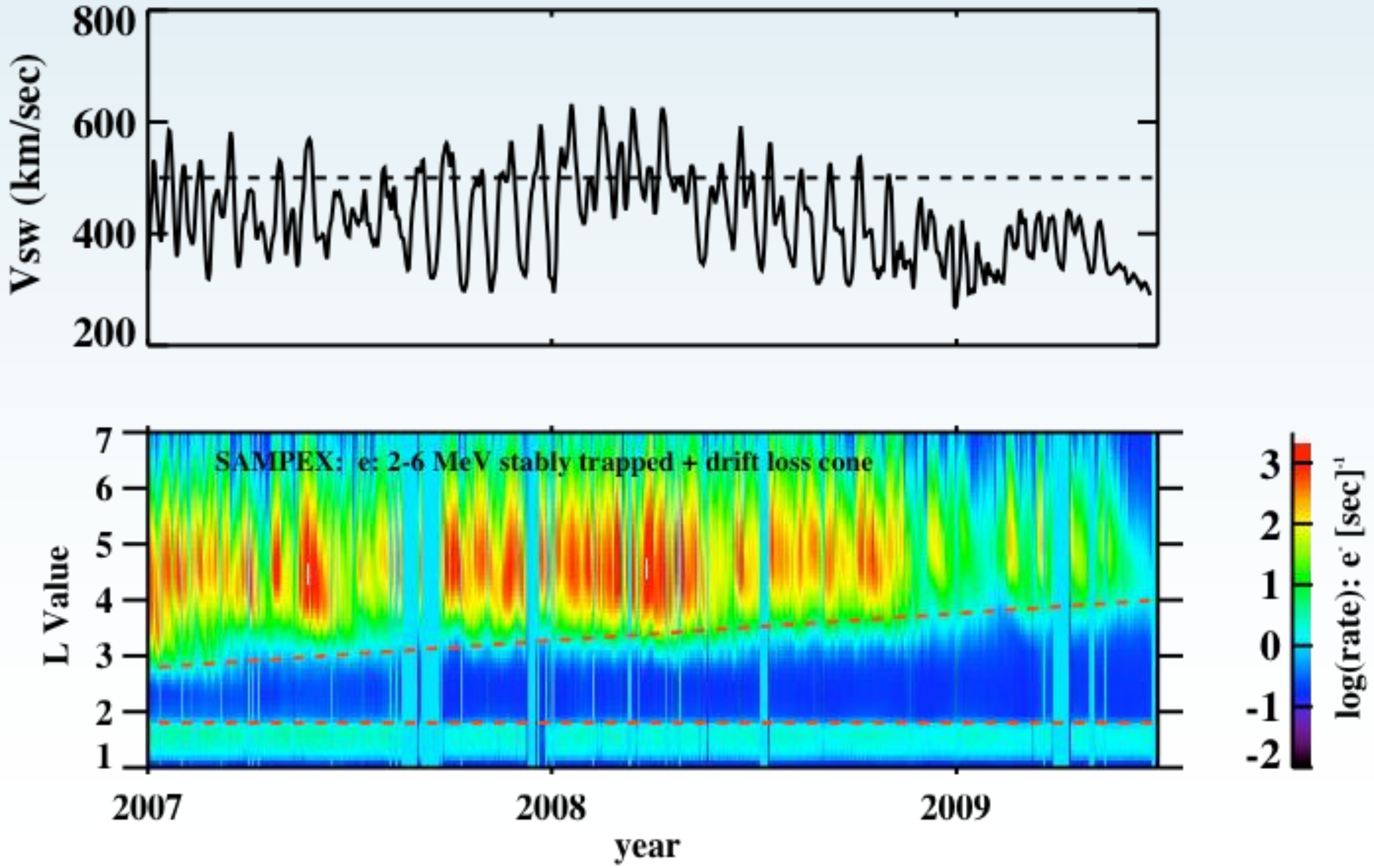
Energetic electrons during the CRRES mission



北京航空航天大學 BEIHANG UNIVERSITY

UCL

Tertiary: Radiation Belt Dynamics in response to Solar Driving

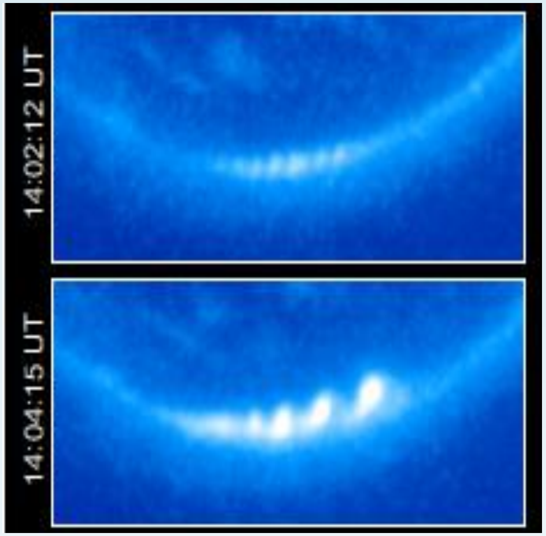


Courtesy: Dan Baker

BEADS Science Goals

Primary

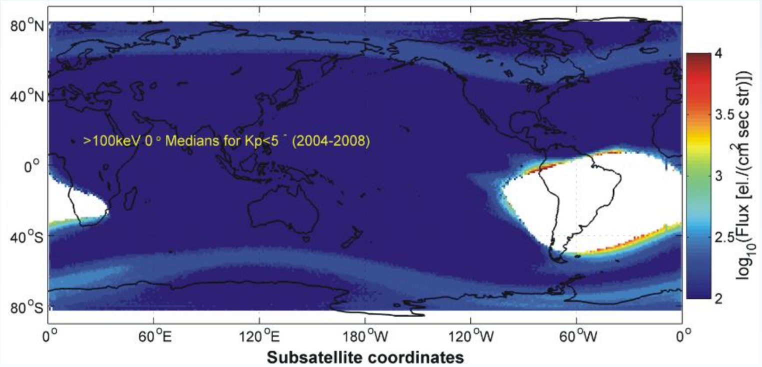
To discover the plasma instability responsible for the detonation of the magnetospheric substorm



Henderson [2009]

Secondary

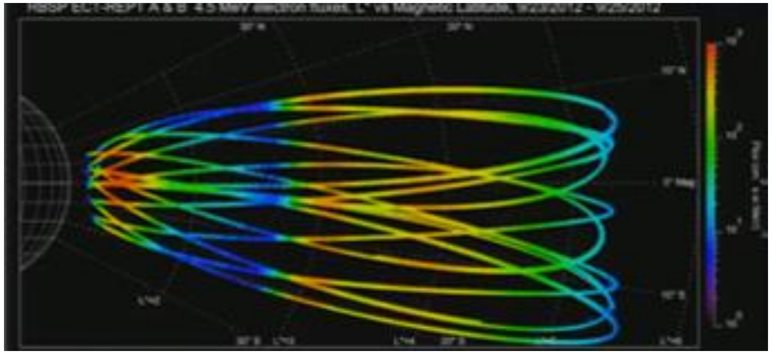
To understand the physics controlling Van Allen Radiation Belt Precipitation



Rodger et al. [2013]

Tertiary

To understand Radiation Belt dynamics



Baker et al. [2013]

BEADS Mission Design

- Proposed orbit
- Mission scenario
- Payload
- Spacecraft
- Scenario vs Boundary Conditions
- Launcher capabilities

BEADS Mission Design

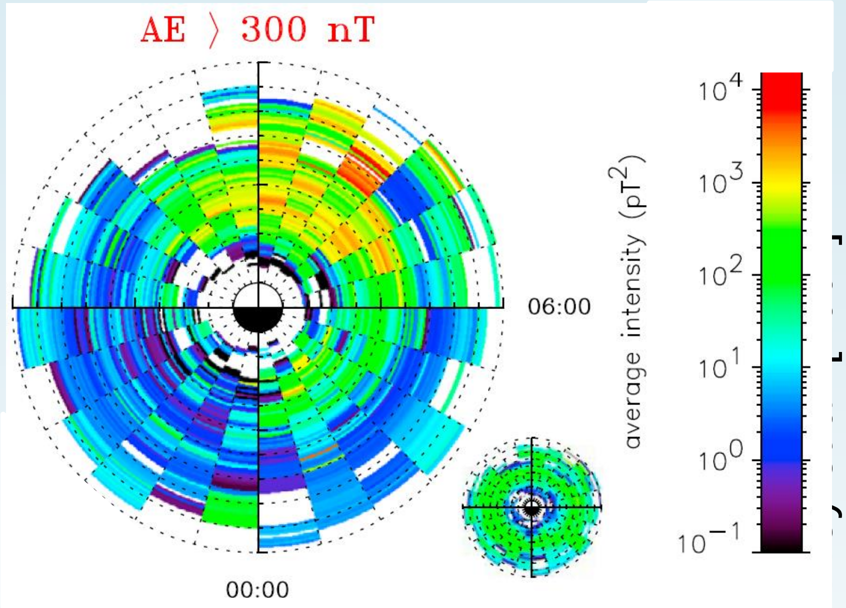
- Proposed orbit
- Mission scenario
- Payload
- Spacecraft
- Scenario vs Boundary Conditions
- Launcher capabilities

Proposed BEADS Orbit:

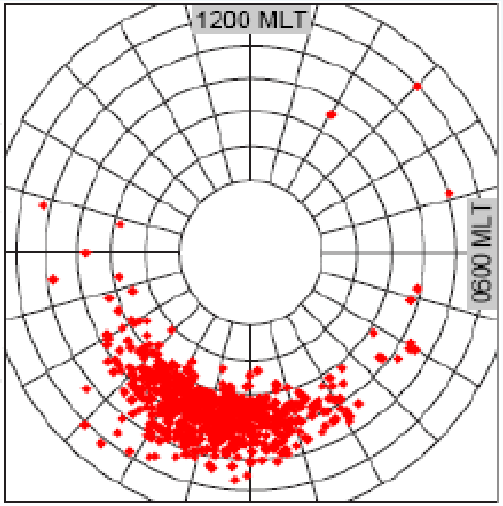
Science Drivers:

- *Radiation Belt:* whistler-mode lower-band chorus wave distribution for high geomagnetic activity
  - 45°- 70° Magnetic Latitude
  - 14 to 08 h Magnetic Local Time

- *Beads:* auroral substorm onset statistics from IMAGE
  - 63°- 70° Magnetic Latitude
  - 22 to 00 h Magnetic Local Time



Meredith et al. [2012]



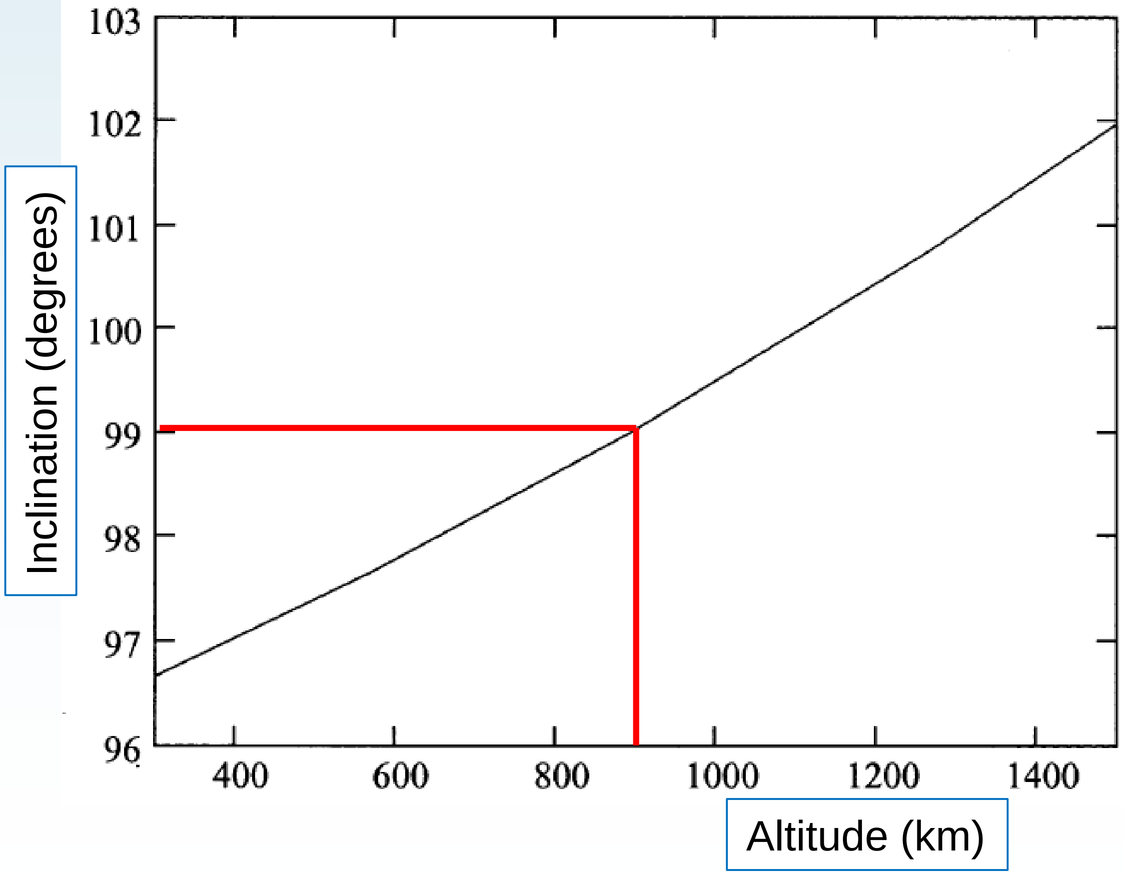
Frey et al. [2004]

Proposed BEADS Orbit:

Sun-Synchronous orbit: fixed in Sun-Earth frame

Proposed orbit

- Circular
- Inclination ~ 99°
- 894 km altitude
- period 103m
- 14 revs per day (easy downlink)

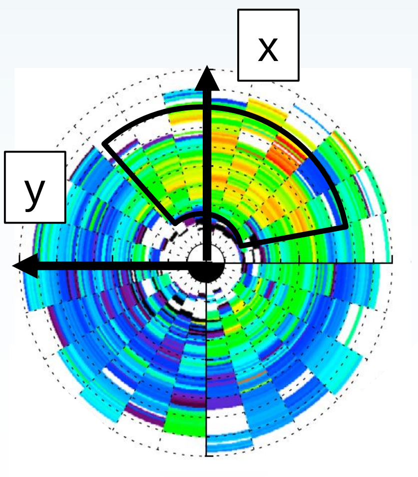


Proposed BEADS Orbit:

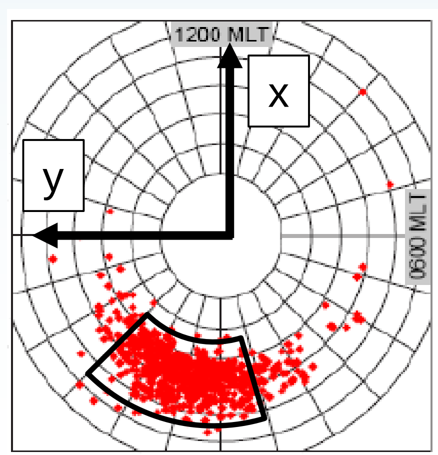
Sun-Synchronous orbit:

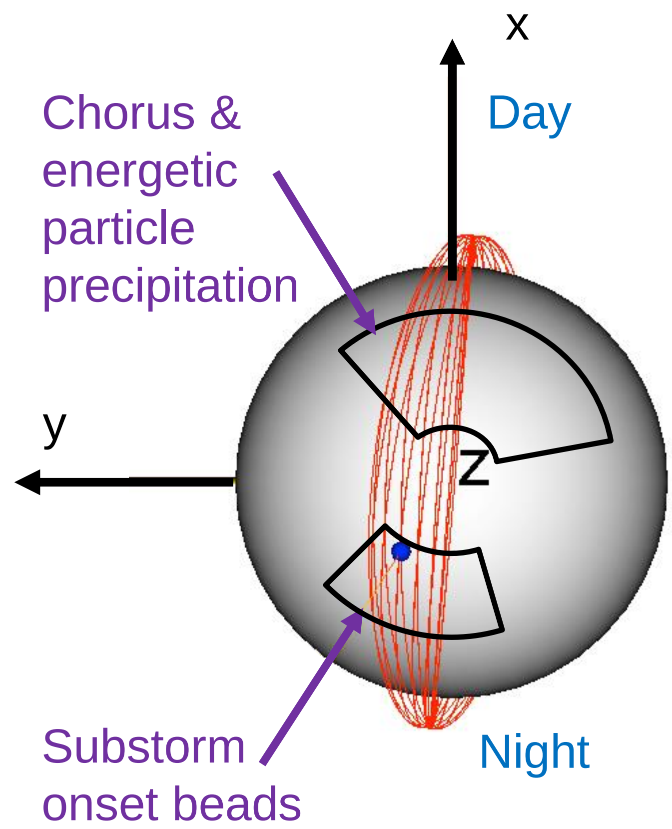
- Daily motion of magnetic dipole helpfully spreads coverage in magnetic longitude
- Can optimise SSO plane choice

Chorus Waves



Substorm onset



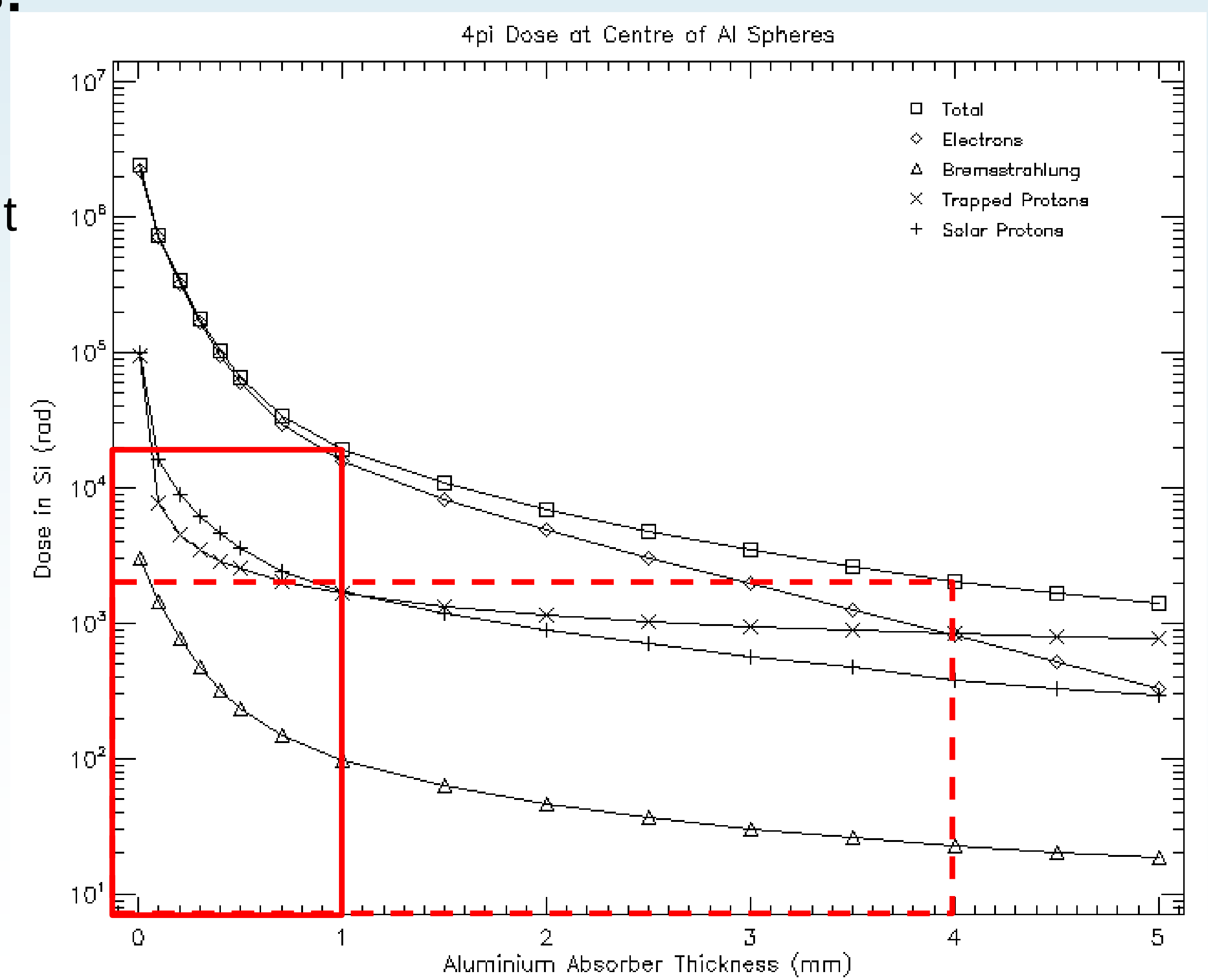


Solar-magnetic coordinates

Proposed BEADS Orbit:

Radiation Analysis:

- For 900 km orbit, the radiation environment is relatively benign
- Annual dose:
  - 20 krad behind 1 mm Al
  - 2 krad behind 4 mm Al



Courtesy: SPENVIS

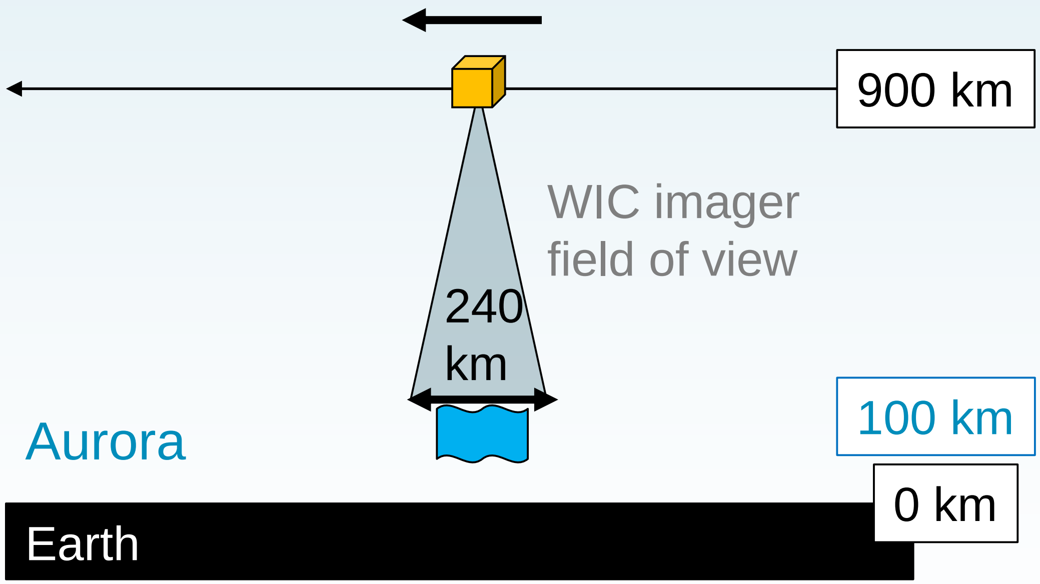
BEADS Mission Design

- Proposed orbit
- Mission scenario
- Payload
- Spacecraft
- Scenario vs Boundary Conditions
- Launcher capabilities

Mission Scenario

Auroral Imaging: 1 spacecraft

- “Off the shelf” WIC imager has 17° x 17° field of view, which is ~240 km square at auroral altitudes
- $V_{spacecraft}$ ~7.4 km/s
- A stationary auroral arc crosses the imager field of view in ~ 30 seconds
- Too quick…

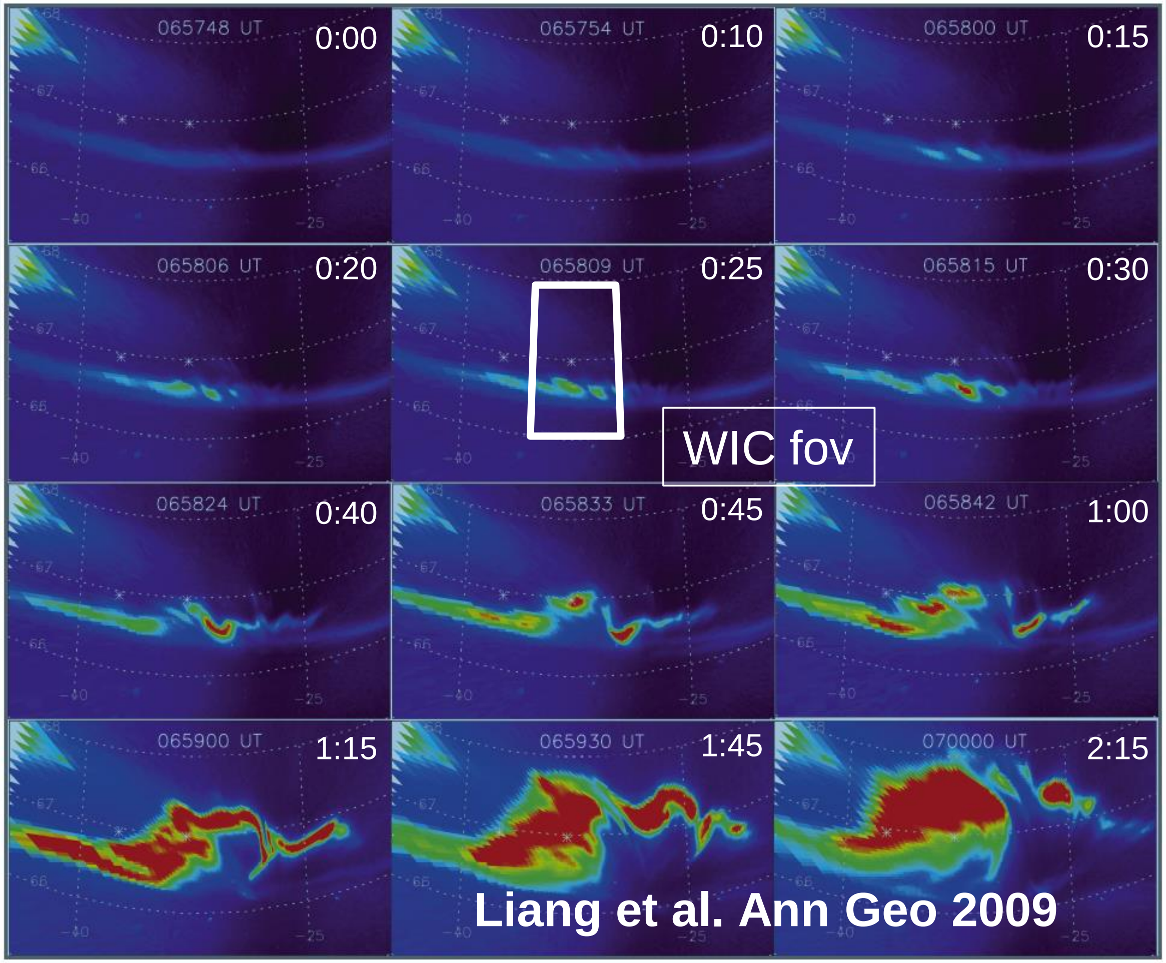


Mission Scenario

Auroral Imaging:

1 minute scale event

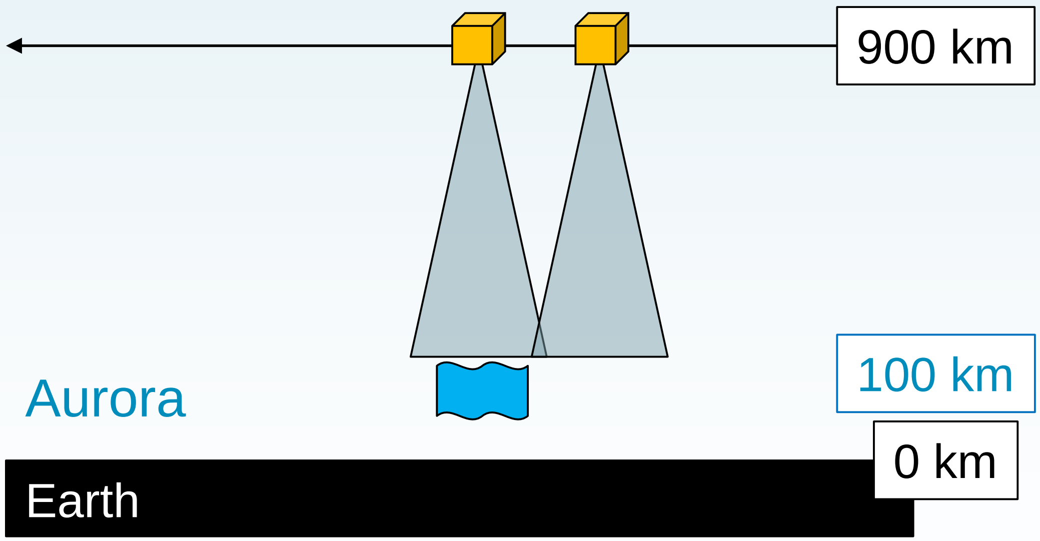
- "Linear" growth 0-15 s
- Early non-linear 15-30 s
- Further evolution 30-60 s
- Major changes 60-135 s



Mission Scenario

Auroral Imaging: 2 spacecraft

- Two spacecraft are required to provide adequate imaging duration
- Separate the spacecraft by 27 s (200 km) along their orbit to give some imager coverage overlap
- A stationary auroral arc crosses the imager fields of view in ~ 60 seconds

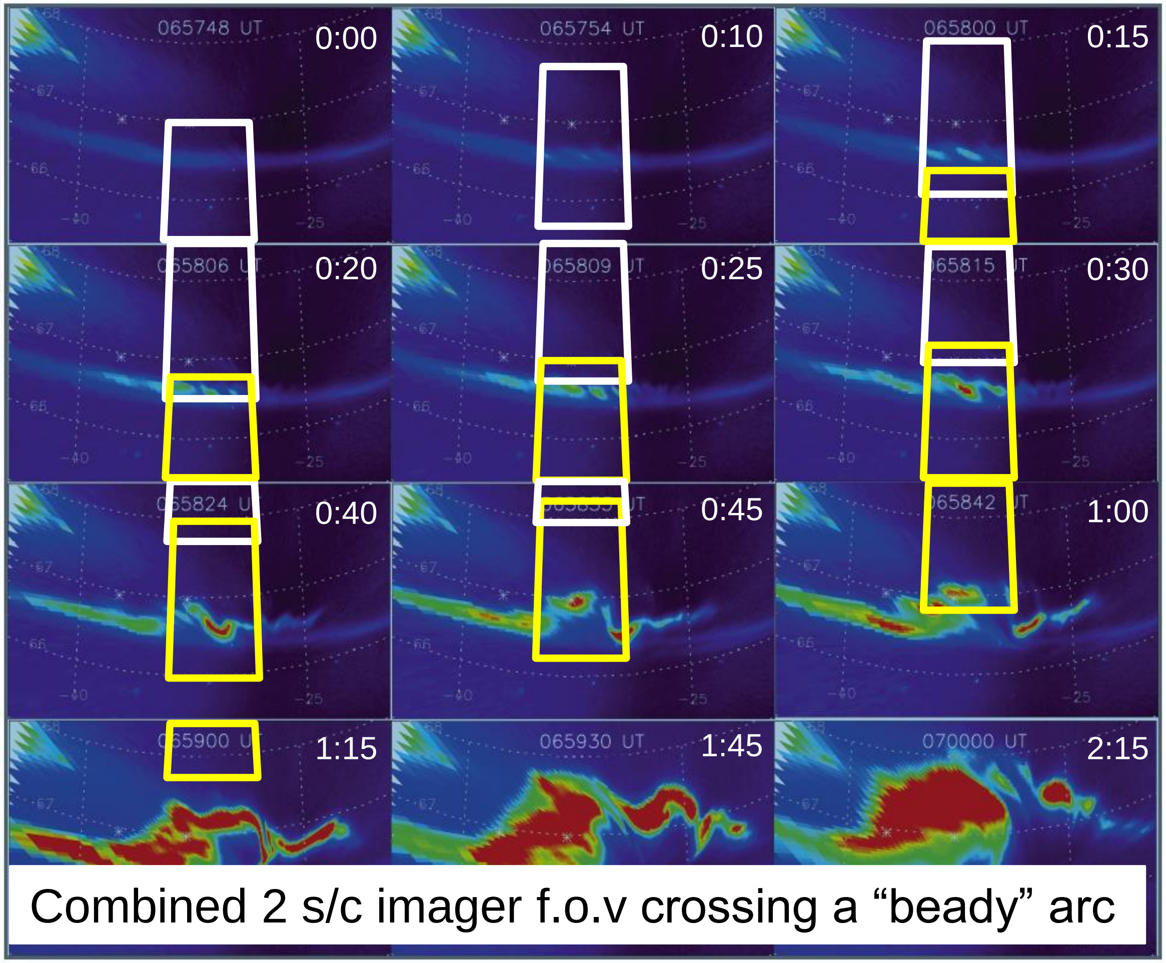


Mission Scenario

Auroral Imaging: 2 spacecraft

1 minute scale event

- "Linear" growth 0-15 s
- Early non-linear 15-30 s
- Further evolution 30-60 s
- Major changes 60-135 s



Combined 2 s/c imager f.o.v crossing a "beady" arc

BEADS Mission Design

- Proposed orbit
- Mission scenario
- Payload
- Spacecraft
- Scenario vs Boundary Conditions
- Launcher capabilities

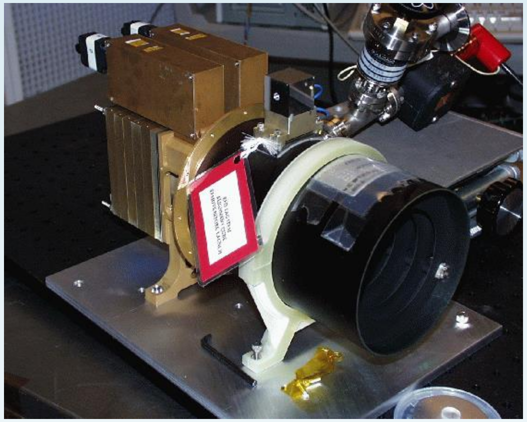
BEADS Payload

- IES from China; 1 of 2 MAG for each spacecraft from China

On Each Spacecraft	Mass / kg	Power / W	TM / kbps	heritage	TRL
Auroral Imager	5	4	105	IMAGE	9
E-ESA	3	3	16.4	Solar Orbiter	7
I-ESA	3	3	16.4	Solar Orbiter	7
MAG	2	2	4.8	Solar Orbiter	7
MAG boom	1			(by spacecraft)	
IES	2.5	2.5	2	(Cluster)	6
Payload DPU	7	10		(various)	6
Margin @ 20%	*4.7*	*4.9*	*28.9*		
Total	**28.2**	**29.4**	**173.5**		

BEADS Example instruments

WIC Wideband (UV) Imaging Camera



- Technology readiness level
  - 9 (used on IMAGE mission, 2000-7)
- Measurement capability
  - 17° x 17° f.o.v., 0.66° resolution, cadence ~5 s
- Requirements placed on spacecraft
  - 3 axis stabilisation nadir pointing

E-ESA/ I-ESA Electron/ion spectrometers

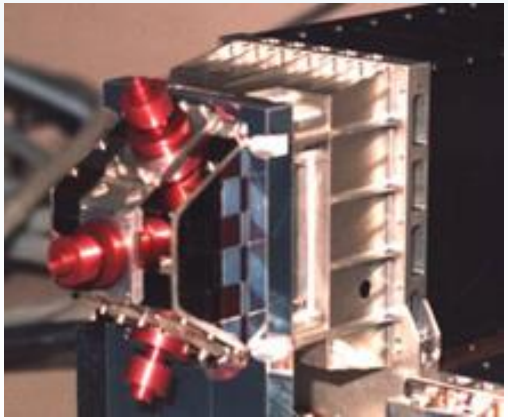
- Technology readiness level
  - >= 7 (e.g. Cluster, Solar Orbiter)
- Measurement capability
  - 10s eV to ~20 keV, all pitch angles, cadence 0.1 s
- Requirements placed on spacecraft
  - Field of view to allow 0-180° pitch angle coverage
  - Electrostatic cleanliness (to be specified)

BEADS Example instruments

MAG Fluxgate magnetometer

- Technology readiness level
  - 9 (Europe); 6 (China; TRL 9 in 2016)
- Planned measurement capability
  - Accurate to <= 1 nT, good temperature stability, cadence ~100 Hz
- Requirements placed on spacecraft
  - Boom; adequate magnetic cleanliness

IES Energetic electron spectrometer



- Technology readiness level
  - 6 (China prototype; TRL 9 in 2015)
- Planned measurement capability
  - 50 keV to 600 keV, all pitch angles
  - Cadence >1 s
- Requirements placed on spacecraft
  - Field of view to zenith, to see precipitating particles

BEADS Mission Design

- Proposed orbit
- Mission scenario
- Payload
- Spacecraft
- Scenario vs Boundary Conditions
- Launcher capabilities

BEADS Spacecraft: some key requirements

- Environmental
  - The preferred orbit has regular eclipses
- Payload Support
  - The payload must operate during eclipses
  - The spacecraft should be adequately magnetically clean and provide a magnetometer boom
  - The spacecraft should have adequate pointing accuracy and stability for auroral imaging
- Manoeuvers
  - The relative spacing of the spacecraft should be variable
  - The spacecraft should de-orbit at end of mission

BEADS Spacecraft Examples (100-150 kg)

Status:
In orbit since Nov 2012

FN-1 (Fengniao-1) (CAST, China)

Mass /kg	95 (excl payload)
Power/ W	90
Volume/ m^3	1.00 x 0.78 x 0.78
pointing	1000 arcsec, 180 arcsec/sec
propulsion	Hydrazine thrusters
p/l mass/ kg	35
p/l power/ W	30
p/l data storage	0.25 Gbytes
p/l data rate downlink	2 Mbit/s S band

BEADS Spacecraft Examples (100-150 kg)

SSTL-150 (Surrey Satellites UK)

Status:
Multiple spacecraft in orbit

Mass /kg	103 (excl payload)
Power/ W	120
Volume/ m^3	0.91 x 0.67 x 0.77
pointing	25 arcsec, 1.5 arcsec/sec
propulsion	Xe resistojet
p/l mass/ kg	=< 50
p/l power/ W	50
p/l data storage	16 Gbytes
p/l data rate downlink	80 Mbit/s X band

BEADS Spacecraft Examples (100-150 kg)

Myriade/Astrosat-100 (Airbus D&S/CNES)

Mass /kg	100 (excl payload)
Power/ W	180
Volume/ m^3	1.00 x 0.60 x 0.60
pointing	TBC
propulsion	Hydrazine thrusters
p/l mass/ kg	=< 50 kg
p/l power/ W	=< 50 W
p/l data storage	8 Gbytes
p/l data rate downlink	60 Mbit/s X band

Status:
Multiple spacecraft in orbit

BEADS Mission Design

- Proposed orbit
- Mission scenario
- Spacecraft
- Payload
- Scenario vs Boundary Conditions
- Launcher capabilities

BEADS scenario vs. boundary conditions

- European Spacecraft: SSTL-150 (or Myriade)
- Chinese Spacecraft: FN-1

	Mass			Power	
	Spacecraft	*Payload*	*Total*	*Spacecraft*	*Payload*
FN-1	95	28.2	123.2	90	29.4
SSTL-150 /Myriade	103	28.2	131.2	120	29.4
Total	**198**	**56.4**	**254.4**		**58.8**
Limit		60	300		65

Outline resource requirements are consistent with CAS-ESA guidelines

BEADS Mission Design

- Proposed orbit
- Mission scenario
- Spacecraft
- Payload
- Scenario vs Boundary Conditions
- Launcher capabilities

ESA Launcher

VEGA

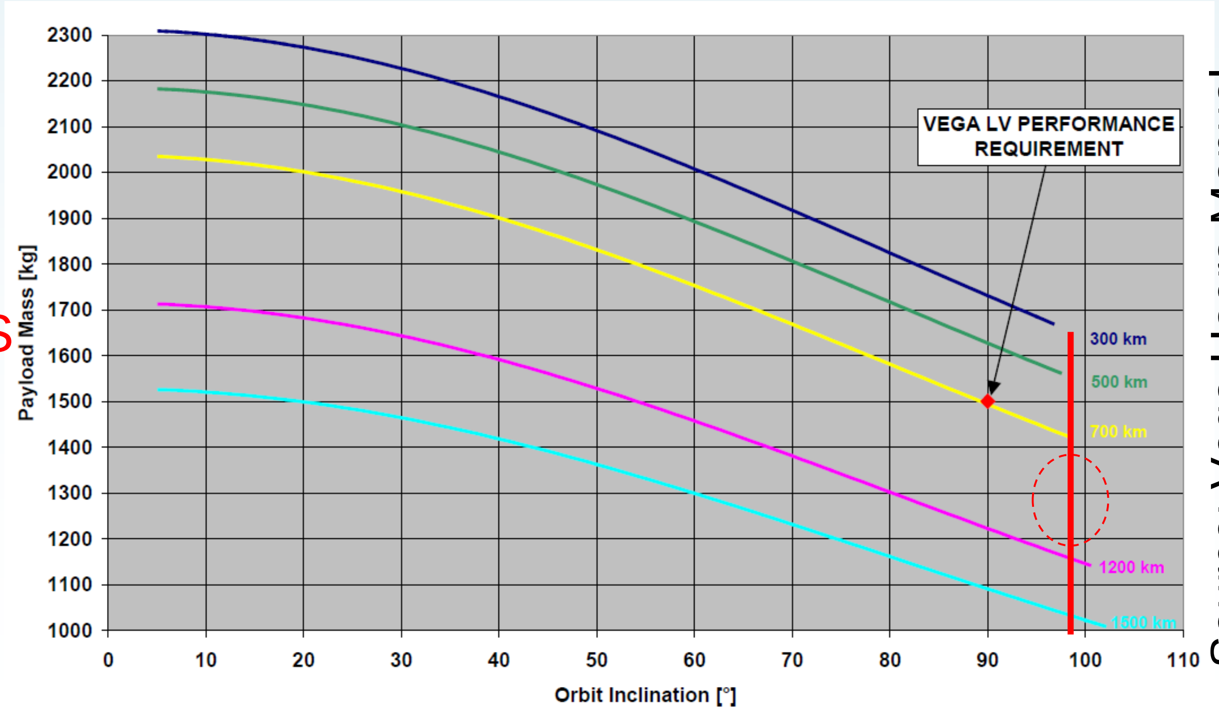
- Estimated mass delivered to 900 km orbit ~ 1200 kg
- Spacecraft stack must be

  < 2m diameter

  <3.5 m high

  to fit in the fairing

Vega can launch BEADS



Source: Vega Users Manual

Chinese Launcher

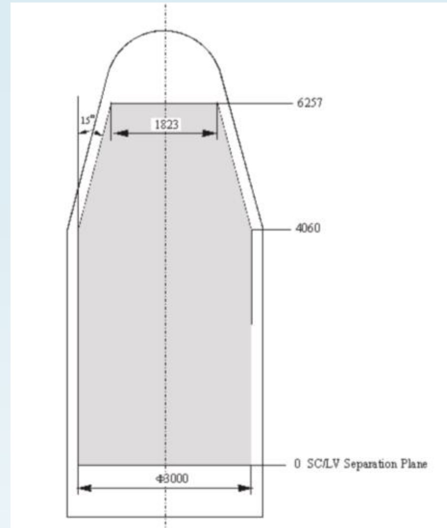
LM-2C/CTS (SSO option)

- Estimated mass delivered to 900 km ~ 1400 kg
- Spacecraft stack must be

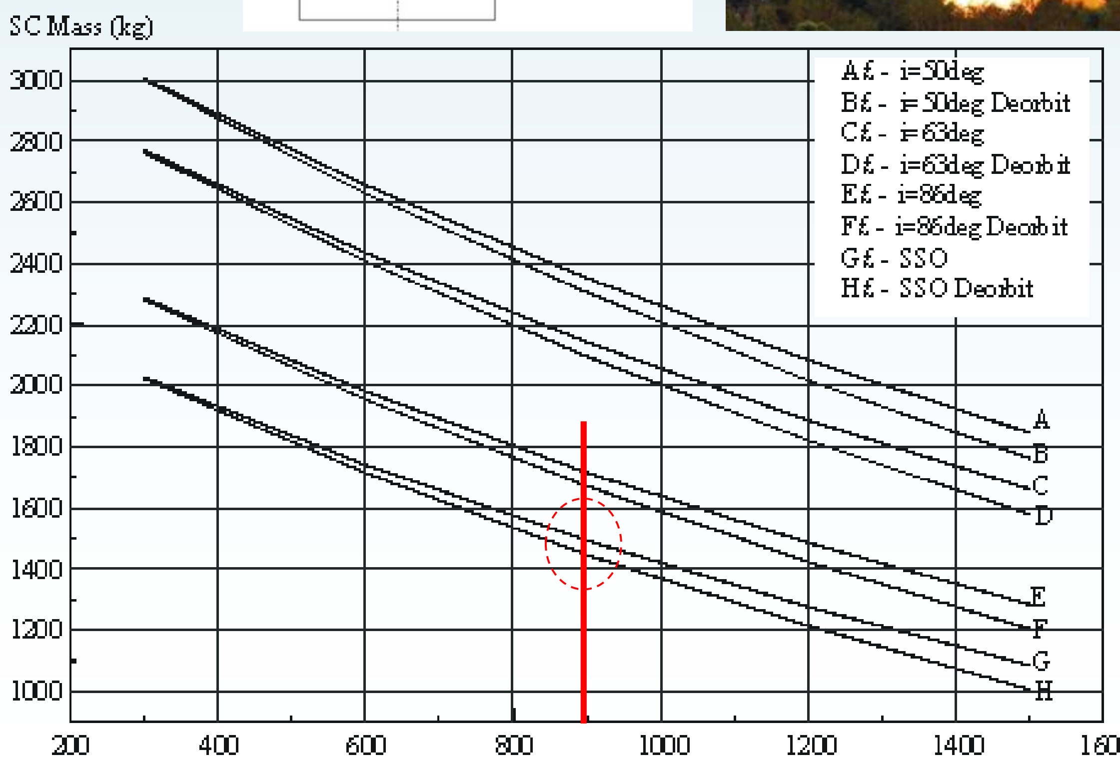
  < 3 m diameter

  < 4 m high

  to fit in the fairing



LM-2C can launch BEADS



Source: LM-2C Users Manual

BEADS Mission Design Summary

Use well-established instruments in a new way to deliver high impact science

Mission design is low risk

Aspect	Comment
Scenario	Pair of spacecraft, each with joint CAS-ESA payload
Orbit	Sun-synchronous low Earth orbit
Launcher	Chinese or European launch, straightforward
Platforms	Proven LEO spacecraft options are available from China and Europe
Payload	Payload with strong heritage; Chinese and European providers

Conclusions

总结

BEADS Primary Science Goal

To discover the plasma instability responsible for the detonation of the magnetospheric substorm

计划的首要科学目标

研究磁层亚暴触发相关的等离子体不稳定性

BEADS Secondary Science Goal

To understand the physics controlling

Van Allen Radiation Belt Precipitation

计划的第二科学目标

研究辐射带粒子沉降过程

BEADS Tertiary Science Goal

To understand Radiation Belt dynamics

计划的第三科学目标

研究辐射带的动力学过程

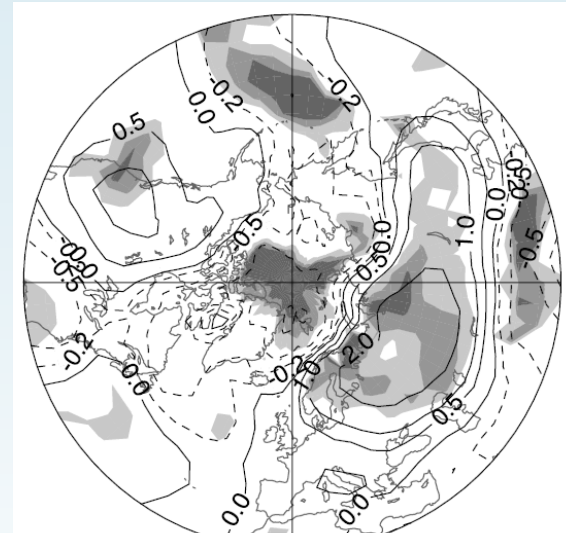
All technical criteria met for three international high-impact science goals

现有工程技术能满足我们三个具有国际影响的科学目标的实现

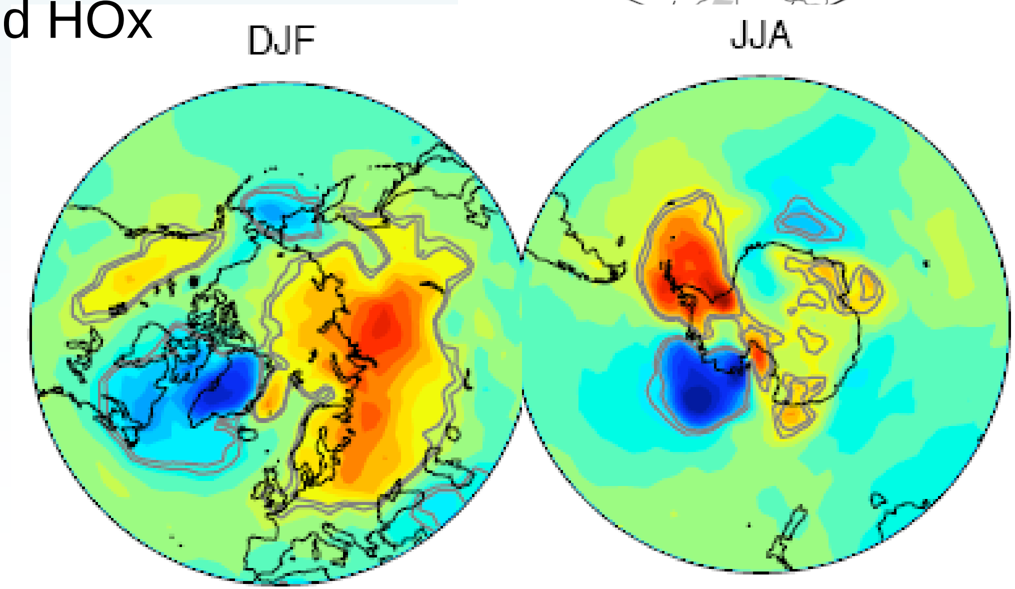
Secondary: Energetic Particle Precipitation and Polar Surface temperatures

- Chemistry Climate models show that when EPP are included, surface temperature variations of -0.5 to +2 K, relative to the no precipitation case.

- Experimentally verified during the winter months when NOx and HOx are long-lived



Rozanov et al. [2005]



Seppälä et al. [2009]