Bead Evolution and Development of Substorms (BEADS)

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

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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

- 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

Near-Earth Neutral Line Paradigm: C → A → B

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
Primary: THEMIS Discoveries inspire BEADS science

- 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
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

Magnetotail mapping: Donovan et al [2012]
Primary: Distinguishing between instabilities through observational and theoretical tests

<table>
<thead>
<tr>
<th>Plasma Instability</th>
<th>Frequency</th>
<th>Spatial Scales</th>
<th>Growth Rates</th>
<th>Auroral Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-field Current Instability (CCI)</td>
<td>25mHz</td>
<td>10 km</td>
<td>0.1/s</td>
<td>Electron aurora</td>
</tr>
<tr>
<td>Ballooning Instability</td>
<td>25 mHz</td>
<td>10km</td>
<td>0.1/s</td>
<td>Electron and proton precipitation</td>
</tr>
<tr>
<td>Current-driven Alfvenic instability</td>
<td>100s mHz</td>
<td>Variable</td>
<td>1/s</td>
<td>Electron aurora monoenergetic</td>
</tr>
<tr>
<td>Tearing</td>
<td>1-100mHz</td>
<td>Variable</td>
<td>0.01/s</td>
<td>Unknown</td>
</tr>
<tr>
<td>Drift Kink/Sausage</td>
<td>1-100mHz</td>
<td>Variable</td>
<td>0.01/s</td>
<td>Unknown</td>
</tr>
<tr>
<td>Lower-hybrid drift</td>
<td>Hz</td>
<td>Variable</td>
<td>1/s</td>
<td>Unknown</td>
</tr>
</tbody>
</table>
Primary: Distinguishing between drivers - Alfvén wave driven aurora

Shear Alfvén Waves become dispersive as they approach Earth, and may transfer energy to electrons.
Primary: Wave-driven acceleration

Courtesy: Andy Kale and Clare Watt
Primary: Distinguishing between drivers – Quasi-static potential driven aurora

Dense ionosphere < 300 km

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°
Tertiary Science Objective: Understanding Radiation Belt dynamics

Van Allen Probe Orbits
Tertiary: Radiation Belt Dynamics in response to Solar Driving
**BEADS Science Goals**

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

**Secondary**
To understand the physics controlling Van Allen Radiation Belt Precipitation

**Tertiary**
To understand Radiation Belt dynamics
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

Frey et al. [2004]  
Meredith et al. [2012]
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

![Diagram](image.png)

- Chorus Waves
- Substorm onset
- Chorus & energetic particle precipitation
- Substorm onset beads
- 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
Auroral Imaging: 1 spacecraft

- “Off the shelf” WIC imager has 17° x 17° field of view, which is ~240 km square at auroral altitudes
- \( V_{\text{spacecraft}} \approx 7.4 \text{ km/s} \)
- 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

Liang et al. Ann Geo 2009
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

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

**WIC Wideband (UV) Imaging Camera**

- **Technology readiness level**
  - 9 (used on IMAGE mission, 2000-7)
- **Measurement capability**
  - $17^\circ \times 17^\circ$ f.o.v., $0.66^\circ$ resolution, cadence $\sim 5$ s
- **Requirements placed on spacecraft**
  - 3 axis stabilisation nadir pointing

**E-ESA/ I-ESA Electron/ion spectrometers**

- **Technology readiness level**
  - $\geq 7$ (e.g. Cluster, Solar Orbiter)
- **Measurement capability**
  - 10s eV to $\sim 20$ 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

• Manoeuvres
  – The relative spacing of the spacecraft should be variable
  – The spacecraft should de-orbit at end of mission
## BEADS Spacecraft Examples (100-150 kg)

**FN-1 (Fengniao-1)**

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

**Status:**

In orbit since Nov 2012

Credit DFH
**BEADS Spacecraft Examples (100-150 kg)**

**SSTL-150**  
*(Surrey Satellites UK)*

<table>
<thead>
<tr>
<th>Mass /kg</th>
<th>103 (excl payload)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power/ W</td>
<td>120</td>
</tr>
<tr>
<td>Volume/ m³</td>
<td>0.91 x 0.67 x 0.77</td>
</tr>
<tr>
<td>pointing</td>
<td>25 arcsec, 1.5 arcsec/sec</td>
</tr>
<tr>
<td>propulsion</td>
<td>Xe resistojet</td>
</tr>
<tr>
<td>p/l mass/ kg</td>
<td>&lt;= 50</td>
</tr>
<tr>
<td>p/l power/ W</td>
<td>50</td>
</tr>
<tr>
<td>p/l data storage</td>
<td>16 Gbytes</td>
</tr>
<tr>
<td>p/l data rate downlink</td>
<td>80 Mbit/s X band</td>
</tr>
</tbody>
</table>

**Status:**  
Multiple spacecraft in orbit

Credit SSTL
### BEADS Spacecraft Examples (100-150 kg)

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

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass /kg</td>
<td>100 (excl payload)</td>
</tr>
<tr>
<td>Power/ W</td>
<td>180</td>
</tr>
<tr>
<td>Volume/ m³</td>
<td>1.00 x 0.60 x 0.60</td>
</tr>
<tr>
<td>pointing</td>
<td>TBC</td>
</tr>
<tr>
<td>propulsion</td>
<td>Hydrazine thrusters</td>
</tr>
<tr>
<td>p/l mass/ kg</td>
<td>&lt;= 50 kg</td>
</tr>
<tr>
<td>p/l power/ W</td>
<td>&lt;= 50 W</td>
</tr>
<tr>
<td>p/l data storage</td>
<td>8 Gbytes</td>
</tr>
<tr>
<td>p/l data rate downlink</td>
<td>60 Mbit/s X band</td>
</tr>
</tbody>
</table>

Status: Multiple spacecraft in orbit

Credit Airbus
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

<table>
<thead>
<tr>
<th></th>
<th>Mass</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Spacecraft</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Payload</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Spacecraft</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Payload</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Limit</strong></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th><em>Spacecraft</em></th>
<th><em>Payload</em></th>
<th><em>Total</em></th>
<th><em>Spacecraft</em></th>
<th><em>Payload</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>FN-1</td>
<td>95</td>
<td>28.2</td>
<td>123.2</td>
<td>90</td>
<td>29.4</td>
</tr>
<tr>
<td>SSTL-150/Myriade</td>
<td>103</td>
<td>28.2</td>
<td>131.2</td>
<td>120</td>
<td>29.4</td>
</tr>
<tr>
<td>Total</td>
<td>198</td>
<td>56.4</td>
<td>254.4</td>
<td>58.8</td>
<td></td>
</tr>
<tr>
<td>Limit</td>
<td>60</td>
<td>300</td>
<td>65</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

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

**BEADS Primary Science Goal**
To discover the plasma instability responsible for the detonation of the magnetospheric substorm

**BEADS Secondary Science Goal**
To understand the physics controlling Van Allen Radiation Belt Precipitation

**BEADS Tertiary Science Goal**
To understand Radiation Belt dynamics

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