AurEx: A low-altitude multi-spacecraft mission to discover the driver of the terrestrial substorm

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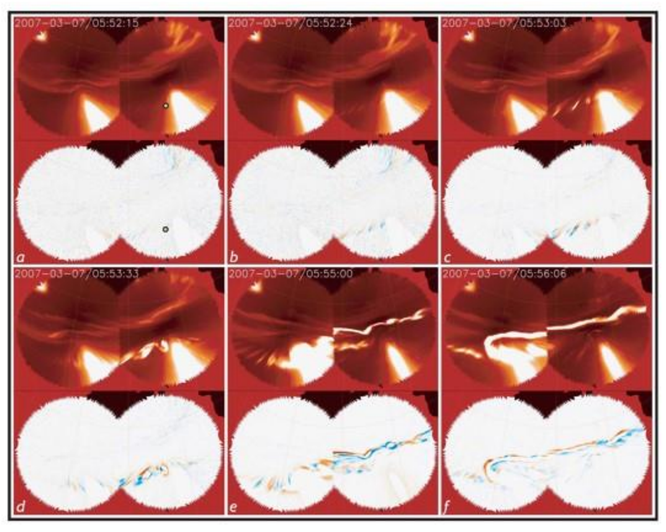
Abstract

The aurora borealis and australis are beautiful, often dynamic phenomena, but despite their relative familiarity, the processes that power them and drive their motion and complexity are still very far from being well understood. As well as being important in their own right, aurora provide a key to resolving the open question of what causes the huge release of magnetic energy that constitutes a magnetospheric substorms. Several single spacecraft missions have advanced our knowledge of auroral science, but have also demonstrated the limits of what can be discovered with measurements from one spacecraft making a short overflight of a developing aurora. Multiple spacecraft arranged at appropriate separations, capable of making key in situ measurements and also carrying auroral imagers to provide context are the logical next step in scientific investigations of how magnetosphere-ionosphere coupling processes control auroral evolution and in particular the onset of substorms.

What is an auroral substorm?

Akasofu [1977]:
"The first indication of a substorm is a sudden brightening of one of the quiet arcs lying in the midnight sector of the oval (or a sudden formation of an arc)."

Physically: Explosive release of stored magnetic energy in Earth's magnetotail, possibly closely analagous to solar coronal mass ejection
Siscoe et al, [2009]



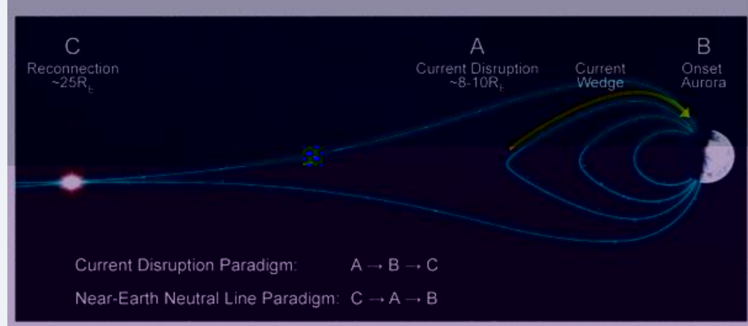
Rae et al. [2009]

Where and why does the substorm start?

Earliest auroral event in a substorm is brightening of the most equatorward arc

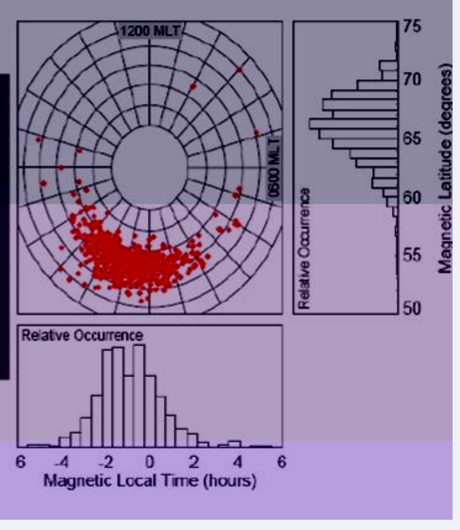
Where does this arc map to in the magnetosphere?

Why does this arc brighten first?



Does this arc map closer to A or C?

Substorm onset is most probable in the MLT and magnetic latitude zones shown below
(Frey et al., 2004)

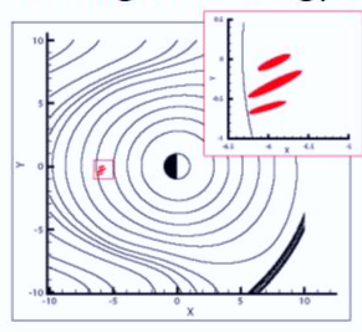


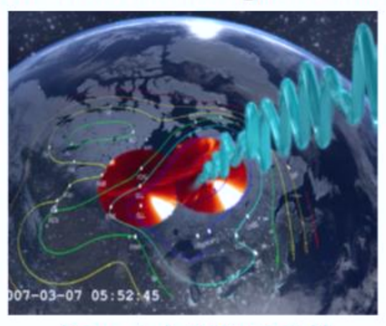
Auroral Beads

Auroral beads appear and grow on the equatorward arc, as the substorm begins (right)

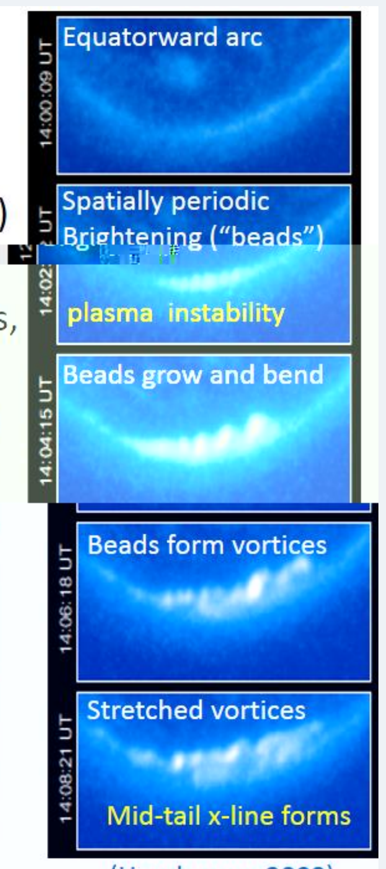
Beads are the manifestation of a plasma instability, i.e. growth of electromagnetic waves, as confirmed by ground observations (below)

The electromagnetic waves may destabilise the tail and provide a conduit for explosive release of magnetic energy stored in the magnetotail.





(Rae et al, 2009; 2010)



(Henderson, 2009)

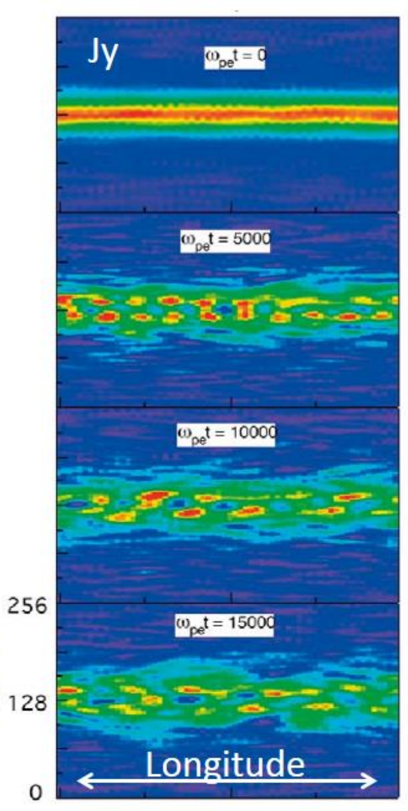
Plasma Instability Models (i)

Free energy sources produce plasma instabilities that predict "bead-like" auroral structures

Two leading competing models are:

(i) Excess current drives cross-field current instability (CCI; Lui, 1991)

(ii) Pressure gradients drive the Shear-Flow Ballooning Instability (SFBI; Voronkov et al., 1997, Raeder et al., 2013)



Idealised evolution of CCI showing appearance and development of longitudinal structure with well defined spatial scales (e.g., Lui, 1991)

Plasma Instability Models (ii)

Distinguishing characteristics => observational 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 aurora
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

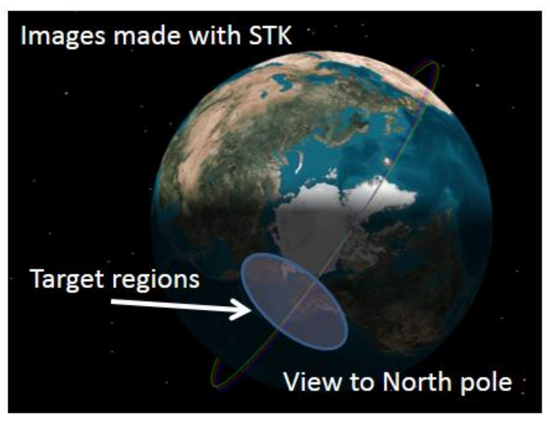
Measurement Requirements

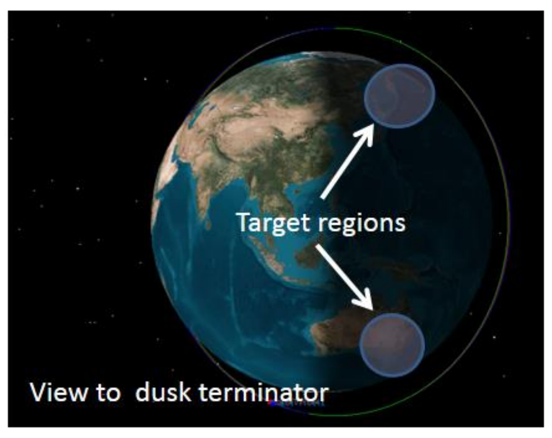
Spacecraft moves at 7.4 km/s; together with arc width, drives cadence

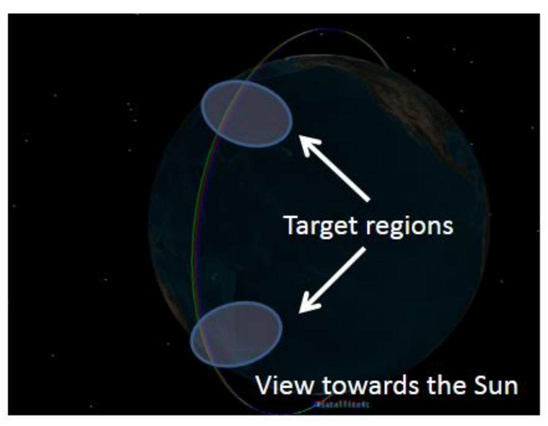
Sensor	Requirement	Rationale
ESA	10s eV-10s keV electrons and ions	Diagnose the auroral acceleration mechanism
	Pitch angle bins <15°	Determine the loss cone
	Electron f(v) at ~s cadence	Resolve auroral arc features
Auroral imager	Electron and proton aurora at ~s cadence	Distinguish between plasma instabilities using growth rate
	Field-of-view ~ few 100 km	Beads <50km up to ~100s km
	Spatial resolution ~1km	Small-scale auroral features
FGM	Vector data DC-AC <~kHz	Diagnose field-aligned currents and wave activity

Example Orbit

- 900 km altitude circular orbit
- 99° inclination sun-synchronous
- Below radiation belts
- Above atmospheric drag region
- Regular overflight of key science regions in both hemispheres



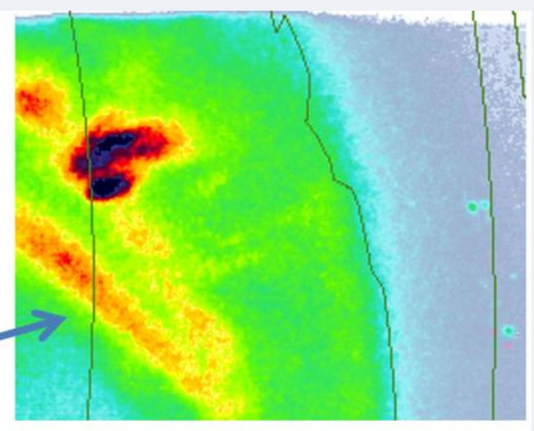




Auroral Imaging

Camera options; WIC has flight heritage, WFAI has wider field of view (also consider MAC flown on Reimei)

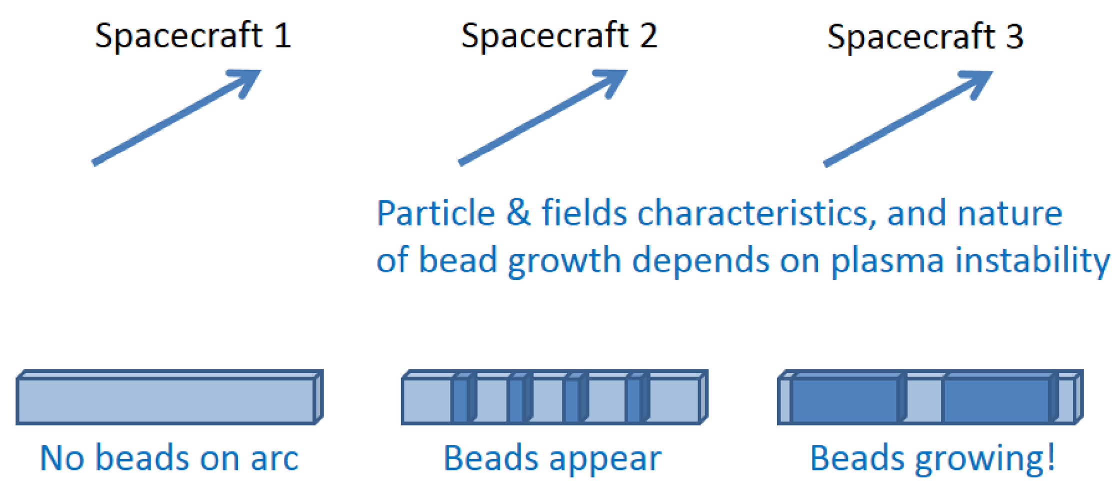
IMAGE FUV/WIC image from 1,900 km altitude: 2.2 km spatial resolution



	Narrow Angle	Wide Angle
Instrument (UV)	WIC	WFAI
Resolution	0.66° x 0.66°	0.23° x 0.23°
(from 900 km alt.)	1 km x 1 km	3.7 km x 3.7 km
Field of view (f.o.v)	17° x 17°	44° x 44°
(from 900 km alt.)	270 km x 270 km	690 km x 690 km
F.o.v crosses arc	~36 sec	~ 93 sec

Multi-spacecraft Measurements

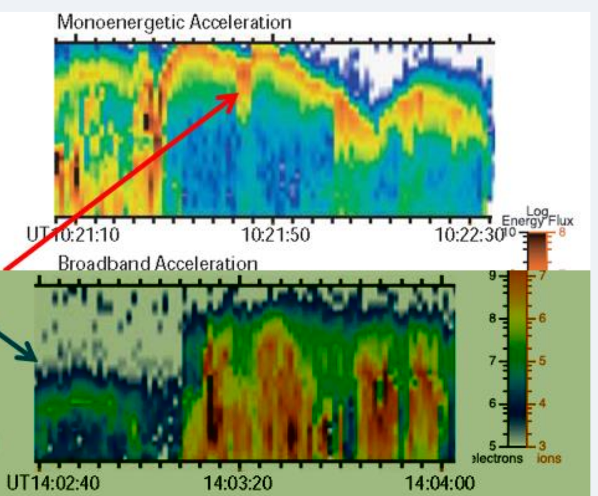
To measure growth rate in a 5 minute (300 second) process, with individual observations of duration ~ 1 minute, we need 2 or better 3 spacecraft, following on the same orbit track



$T = t_0$ | $T = t_0 + 1$ minute | $T = t_0 + 2$ minutes

Role of ESA data

The downgoing electron energy spectrum can distinguish electron acceleration by Alfvenic waves from quasi-static electric potentials (Newell et al JGR 2009).
Particle data can also help identify magnetic geometry of source region



Collecting sufficient events

- Key interval duration: 5 minutes
- Orbit period: 103 minutes
- Two chances per orbit to see events
- Probability to catch key first minute of an event: ~ 2 x 1/103 ~ 1/50
- Number of substorms/ year ~1,100
- **Approx. events/2 year mission ~ 50**

Spacecraft and Payload

Spacecraft

- Requires battery power for ~50% of orbit, including payload operations for part of the time while in eclipse
- Requires de-orbit capability (most likely)
- Radiation environment relatively benign, moderate shielding only : preliminary SPENVIS analysis ~10 krad behind 1.5 mm Al

Payload Lower resource options now exist for some instruments

	Flown option	Mass/kg	Power/W	Flight Heritage
Imager	WIC	5	4	IMAGE
Analyser	PEACE e (HIA i)	4 (+3)	4 (+2.8)	Cluster/Double Star
D.C. Magnetometer	FGM	3.1 (excl. boom)	3.6	
A.C. Magnetometer	STAFF	4.9 (excl. boom)	4	

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

- Solve long-standing problem of initiation of auroral substorm by testing prevailing theories
- Requires combined imaging and in situ observations of the key region during a ~5 minute interval, which requires the use of 2 or 3 identical spacecraft
- Proposed orbit is 900 km sun-synchronous, arranged to regularly cross the key region, so as to deliver ~20 events/year

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