# Cross-Scale
# Multi-scale Coupling in Space Plasmas

Steve Schwartz & Peter Falkner
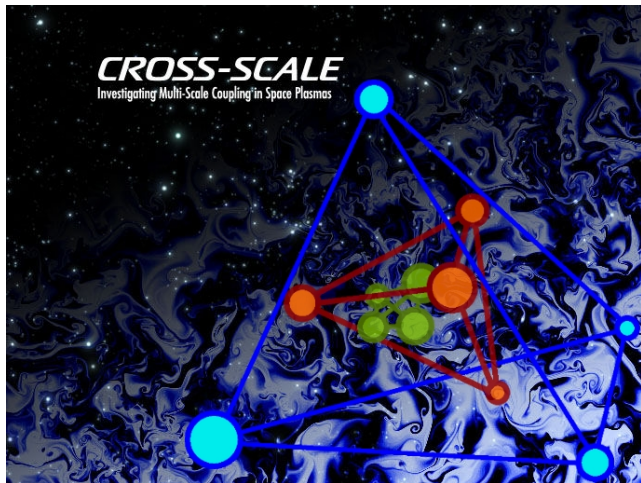
On behalf of the Cross-Scale Science Study Team
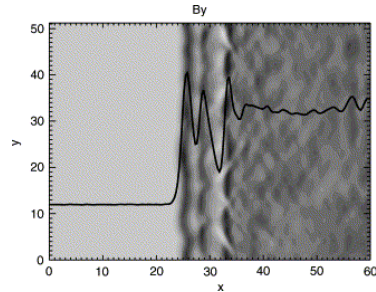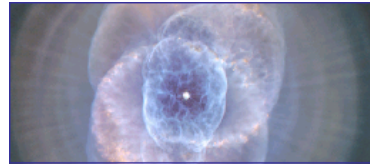
1 December 2009

# Outline



- Science
- Payload
- Operations
- Mission
- Development Approach

# Scientific Objectives

Universal Plasma Processes
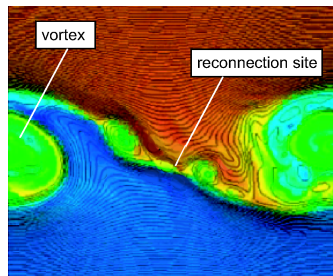
- How do shocks accelerate and heat particles?





By

CV Q: "How does the Solar System [and other plasma systems] work?"

# Scientific Objectives



Universal Plasma Processes

- How do shocks accelerate and heat particles?

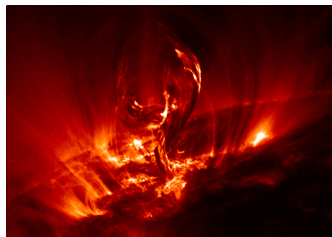- How does reconnection convert magnetic energy?



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Universal Plasma Processes

- How do shocks accelerate and heat particles?
- How does reconnection convert magnetic energy?
- How does turbulence control transport in plasmas?



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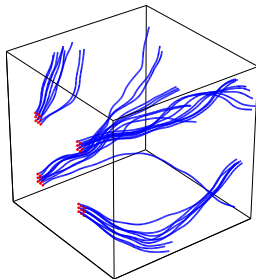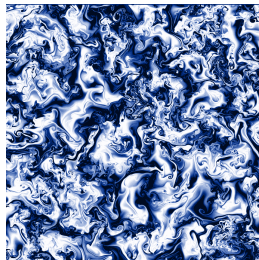- How does reconnection convert magnetic energy?
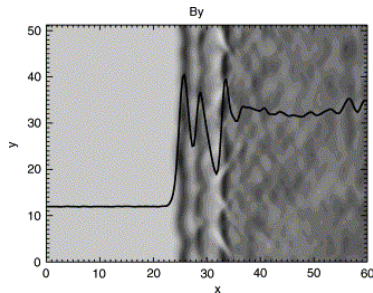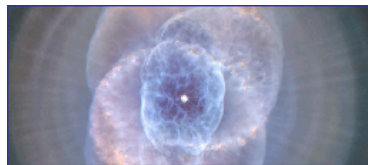- How does turbulence control transport in plasmas?



By



CV Q: "How does the Solar System [and other plasma systems] work?"

# How do shocks accelerate and heat particles?

Questions:

- Acceleration?
- Energy partition?
- Variability?

Universality:

- Cosmic ray acceleration
- CR injection at sub-shock with $M \sim 5 - 10$
- Variability/efficiency of electron acceleration? (synchrotron radiation used as proxy for ion acceleration)

# Cross-Scale Coupling at Shocks

Shock

Orientation, motion, curvature, foreshock

# Cross-Scale Coupling at Shocks
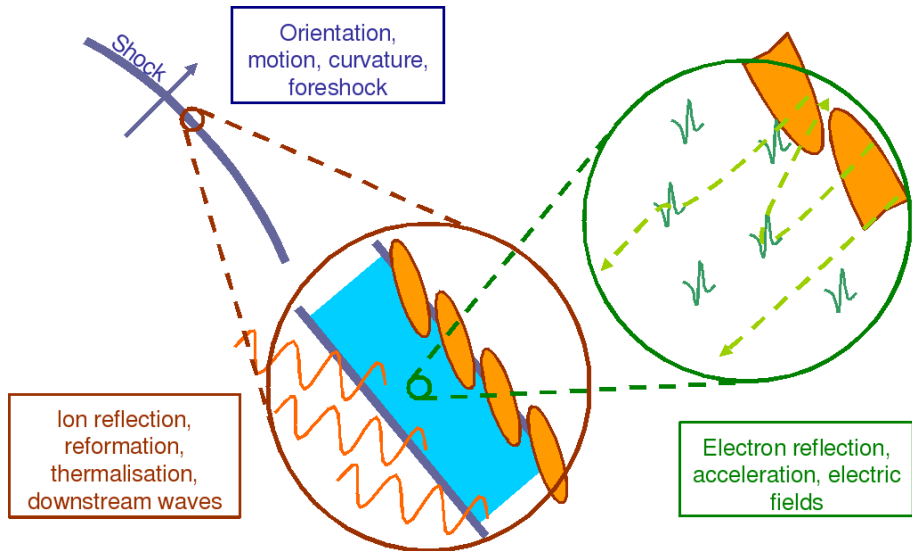


Orientation, motion, curvature, foreshock

Shock

Ion reflection, reformation, thermalisation, downstream waves

# Cross-Scale Coupling at Shocks



Orientation, motion, curvature, foreshock

Shock

Ion reflection, reformation, thermalisation, downstream waves

Electron reflection, acceleration, electric fields
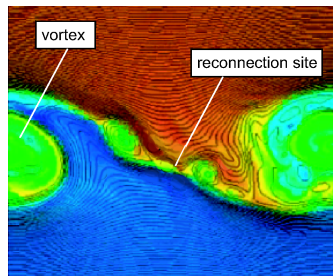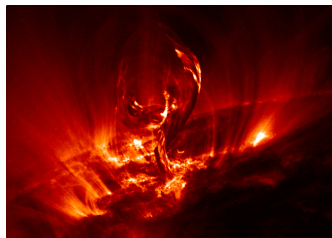
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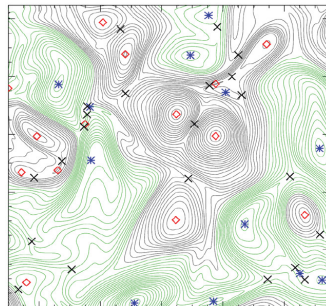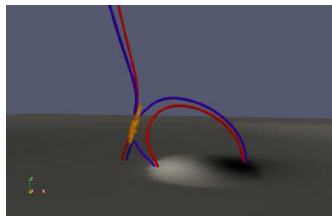# How does reconnection convert magnetic energy?

Questions:

- Initiation?
- Magnetic topology?
- Particle acceleration?

Universality:

- 3D reconnection in solar flares
- Turbulent reconnection
- Relaxation of galactic dynamo to large-scale field
- Disruption events in laboratory plasmas

# Cross-Scale Coupling and Reconnection



Fluid Regime
* Driven Inflow
* Accelerated Jet Outflow
* Changed Topology

# Cross-Scale Coupling and Reconnection



Ion Regime
* Ions and Electrons Decouple
* Hall Currents & Fields
* Ion energisation

Fluid Regime
* Driven Inflow
* Accelerated Jet Outflow
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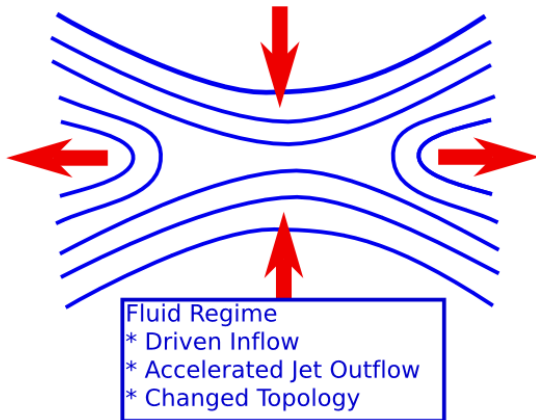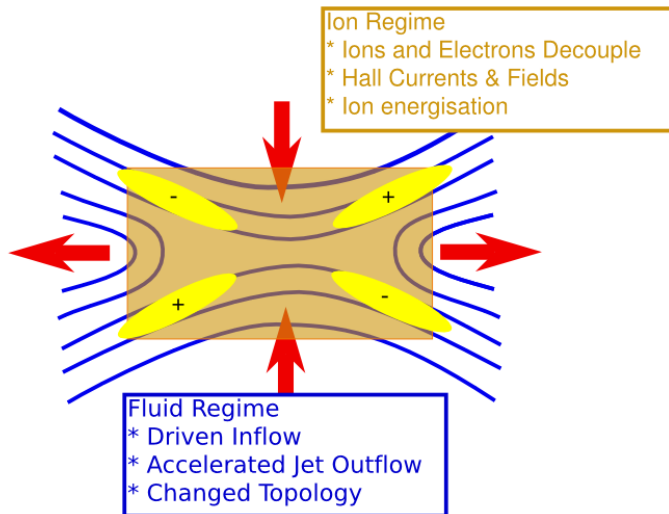
# Cross-Scale Coupling and Reconnection



**Electron Regime**
* Field-line Diffusion
* Electron Acceleration
* Variable "Resistivity"

**Ion Regime**
* Ions and Electrons Decouple
* Hall Currents & Fields
* Ion energisation

**Fluid Regime**
* Driven Inflow
* Accelerated Jet Outflow
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# Scientific Objectives



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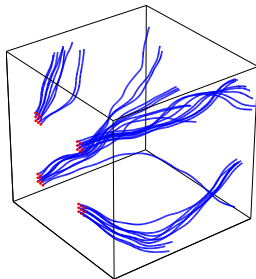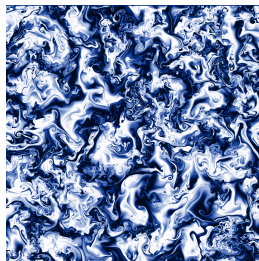


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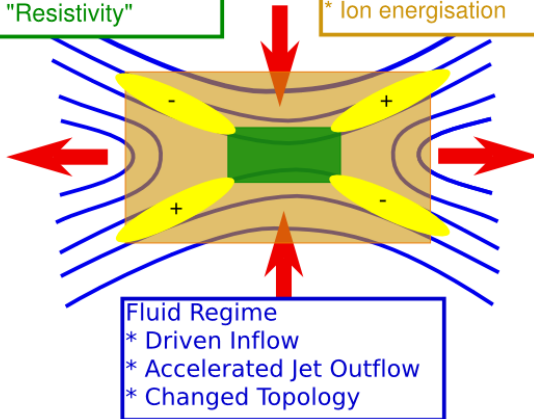
# How does turbulence control transport in plasmas?

Questions:

- Energy cascade?
- Anisotropies?
- Coherent structures?

Universality:

- Non-local & inverse cascade
- Field-line wandering/CR modulation & propagation
- Heating, acceleration, kinetic modes, ...
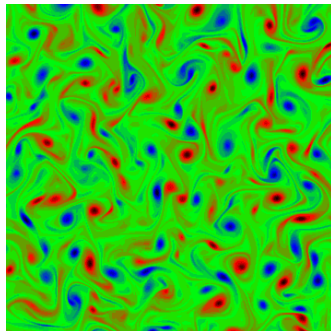
# Cross-Scale Coupling and Turbulence
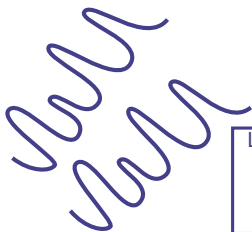
Large-scale motion
Large amplitude
Nonlinear fluid
turbulence

# Cross-Scale Coupling and Turbulence



Ion kinetic waves
Ion acceleration
Non-local k
transport?

Large-scale motion
Large amplitude
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# Cross-Scale Coupling and Turbulence



Ion kinetic waves
Ion acceleration
Non-local k
transport?

Whistler waves
Electron trapping
Dissipation
Anomalous resistivity
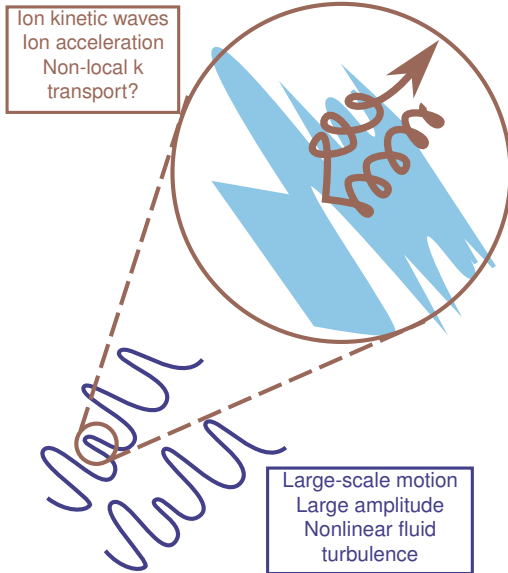
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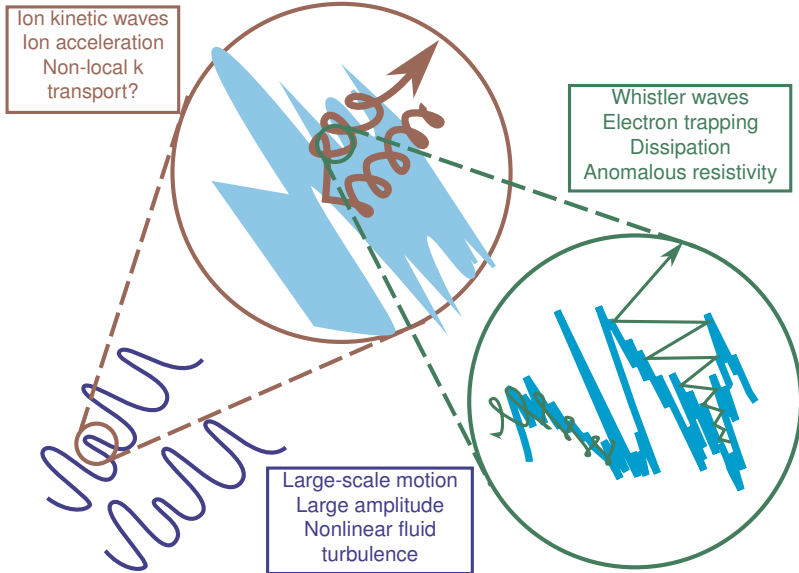
# Science Requirements: Conspiracy of Scales
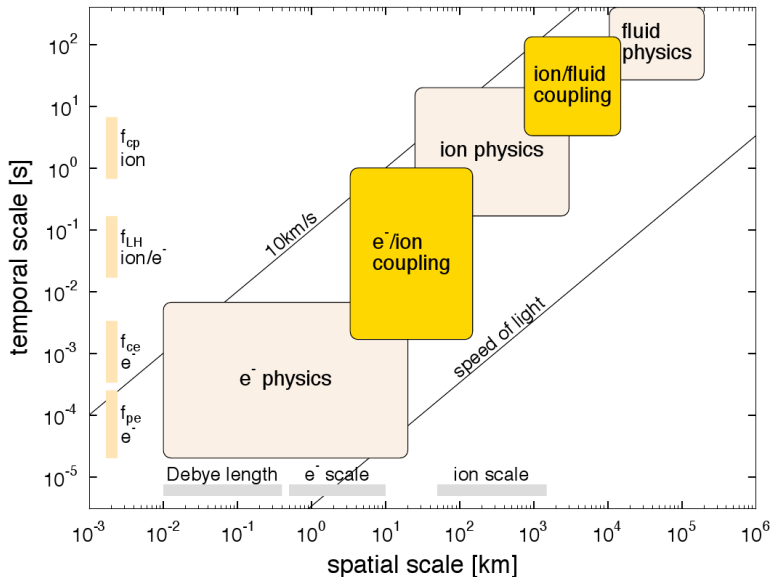
# Observational Challenges

- Time-varying
- Fundamentally 3D
- 3 spatial & temporal scales
  electron, ion & fluid
- Nonlinearly coupled
  $\langle Behaviour \rangle \neq Behaviour$ of $\langle \rangle$
- *Simultaneous* multi-scale
- Focus: *coupling* between scales
- Collisionless $\Rightarrow$ Kinetic
- Plasma $\Leftrightarrow$ EM fields
- Near-Earth: unique *in situ* plasma
  laboratory

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10 km; 10 ms: comprehensive P/L
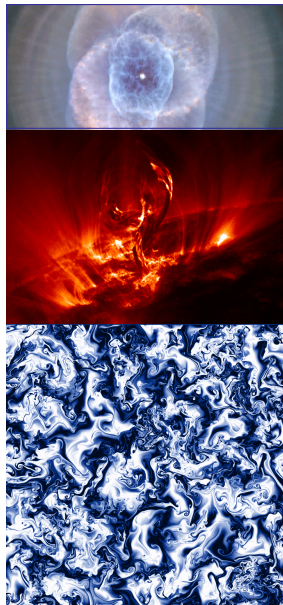
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500 km; 1-5 s: targetted P/L

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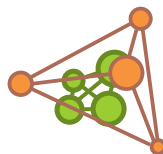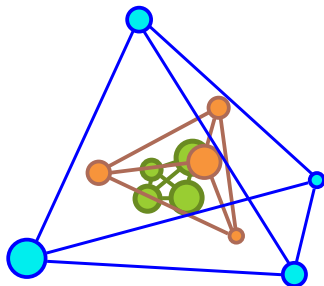- Near-Earth: unique *in situ* plasma
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10 km; 10 ms: comprehensive P/L
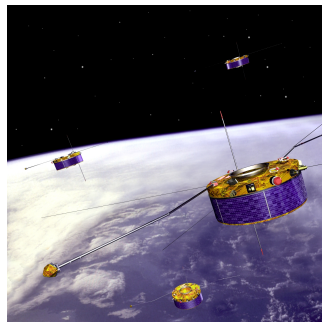500 km; 1-5 s: targetted P/L
5000 km; 30 s: context P/L

# State of the Art

Cluster

- First 3D plasma measurements
- One scale at a time
- Results highlighted need for simultaneous multi-scale
- Success of mission extension also confirming need for all 3 scales in 3D
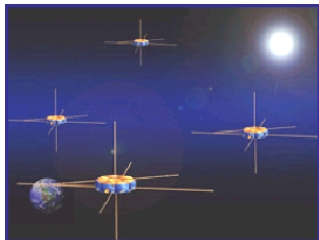
# State of the Art

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MMS

- Access to electron scales in 3D
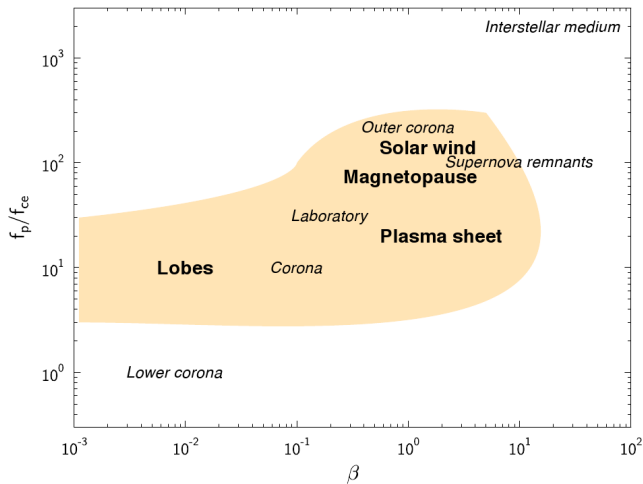- Only one scale at a time

# Science Orbit

- Near-Earth space contains
  - Shocks
  - Reconnection
  - Turbulence
- 7 ESA: dual-scale coupling
- Modular instrument accommodation
- Scale-specific minimal payload
- Standardised bus
- Shared objectives and orbit with JAXA/SCOPE
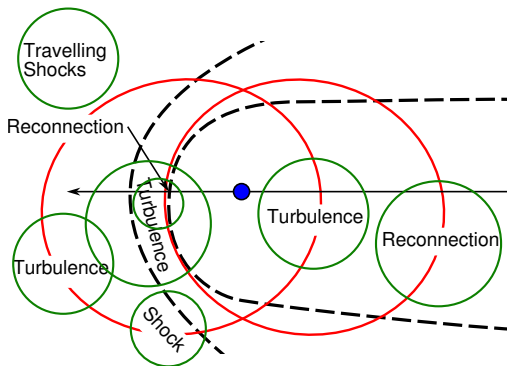
# Science Requirements: Parameter Space



Note wide range of conditions in near-Earth space
Overlap with other plasmas
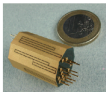
# Measurement Requirements

| Abbrev | Instrument | Measurement * |
|--------|-----------|---------------|
| **EM Fields** | | |
| ACB | AC Magnetic Field | Hi-*f* waveform & spectra |
| MAG | DC Magnetometer | Magnetic field to 128 Hz |
| E2D | Spin-plane electric field wire booms | DC & AC electric field |
| ACDPU | Fields Electronics Box | Density sounder, wave analyser, fields control, processing, power |
| **3D $f(\vec{v})$ Particles** | | |
| EESA | Electron analyser | 3D electron $f(\vec{v})$ to 30 keV |
| IESA | Ion analyser | 3D ion $f(\vec{v})$ to 30 keV |
| HEP | High energy particle detector | 3D particles to 1 MeV |
| ICA | Ion composition analyser | 3D ions to 40 keV/q by mass |
| CPP | Common particle processor | control, data processing |
| ASP | Active S/C Potential control | ion current |

* See Yellow Book & Science Req. Doc for performance, resolution, etc.

# Instrumentation - Strong Heritage



ACB



MAG



E2D



ACDPU



EESA



IESA



HEP



ICA
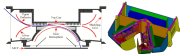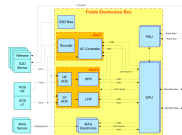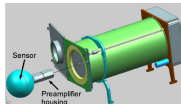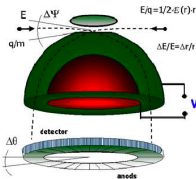
# Payload Deployment

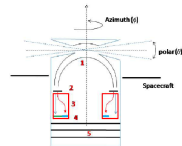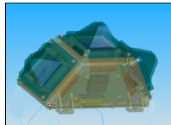| E1 | E2 | E3 | E4/I1 | I2 | I3 | I4 |
|---|---|---|---|---|---|---|
| ACB | ACB | ACB | ACB | ACB | ACB | ACB |
| MAGx2 | MAGx2 | MAGx2 | MAGx2 | MAGx2 | MAGx2 | MAGx2 |
| E2Dinclx4 | E2Dx4 | E2Dinclx4 | E2Dx4 | E2Dx4 | E2Dx4 | E2Dx4 |
| ACDPU | ACDPU | ACDPU | ACDPU | ACDPU | ACDPU | ACDPU |
| EESAx4 | EESAx4 | | EESAx2 | EESAx2 | EESAx2 | EESAx2 |
| ASP | ASP | | IESAx2 | IESAx4 | IESAx2 | IESAx2 |
| | | | HEP | | HEP | ICA |
| CPP | CPP | | CPP | CPP | CPP | CPP |

- Fields suite common
- Particle instruments targeted & balanced
- Initial ion-electron coupling configuration
- Reconfigure or join international partners
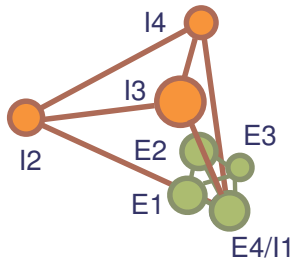
# Science Ops - Early planning, Good data access
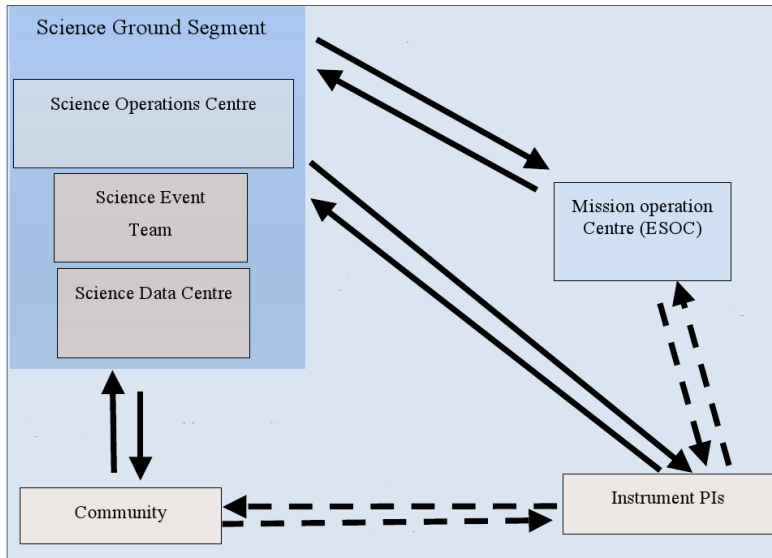
# Science Data Selection

- Summary Data
  - 100% recovered
  - ~ 10% telemetry
  - Comprehensive; science quality
- Full-resolution Data
  - Taken continuously
  - Stored onboard

| S/C 1 | $t_1 1$ | $t_1 2$ | $t_1 3$ | $t_1 4$ | $t_1 5$ | $t_1 6$ | $t_1 7$ | $t_1 8$ | ... | $t_1(i-1)$ | $t_1 i$ |
|-------|---------|---------|---------|---------|---------|---------|---------|---------|-----|------------|---------|

| S/C 2 | $t_2 1$ | $t_2 2$ | $t_2 3$ | $t_2 4$ | $t_2 5$ | $t_2 6$ | $t_2 7$ | $t_2 8$ | ... | $t_2(i-1)$ | $t_2 i$ |
|-------|---------|---------|---------|---------|---------|---------|---------|---------|-----|------------|---------|

| S/C 3 | $t_3 1$ | $t_3 2$ | $t_3 3$ | $t_3 4$ | $t_3 5$ | $t_3 6$ | $t_3 7$ | $t_3 8$ | ... | $t_3(i-1)$ | $t_3 i$ |
|-------|---------|---------|---------|---------|---------|---------|---------|---------|-----|------------|---------|

| S/C 4 | $t_4 1$ | $t_4 2$ | $t_4 3$ | $t_4 4$ | $t_4 5$ | $t_4 6$ | $t_4 7$ | $t_4 8$ | ... | $t_4(i-1)$ | $t_4 i$ |
|-------|---------|---------|---------|---------|---------|---------|---------|---------|-----|------------|---------|

| S/C 5 | $t_5 1$ | $t_5 2$ | $t_5 3$ | $t_5 4$ | $t_5 5$ | $t_5 6$ | $t_5 7$ | $t_5 8$ | ... | $t_5(i-1)$ | $t_5 i$ |
|-------|---------|---------|---------|---------|---------|---------|---------|---------|-----|------------|---------|

| S/C 6 | $t_6 1$ | $t_6 2$ | $t_6 3$ | $t_6 4$ | $t_6 5$ | $t_6 6$ | $t_6 7$ | $t_6 8$ | ... | $t_6(i-1)$ | $t_6 i$ |
|-------|---------|---------|---------|---------|---------|---------|---------|---------|-----|------------|---------|

| S/C 7 | $t_7 1$ | $t_7 2$ | $t_7 3$ | $t_7 4$ | $t_7 5$ | $t_7 6$ | $t_7 7$ | $t_7 8$ | ... | $t_7(i-1)$ | $t_7 i$ |
|-------|---------|---------|---------|---------|---------|---------|---------|---------|-----|------------|---------|

# Science Data Selection

- Summary Data
  - 100% recovered
  - ~ 10% telemetry
  - Comprehensive; science quality
- Full-resolution Data
  - Taken continuously
  - Stored onboard
  - Science Event List selects subsets
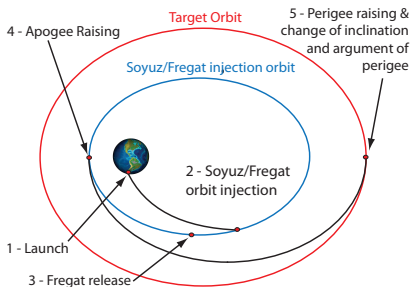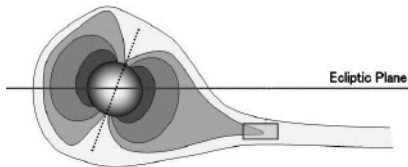- Science Event List part of operations



FR Data to be telemetred

# Mission Overview: Launch & Insertion

- 3 year mission, 7 Spacecraft & 1 transfer stage
- Single Soyuz-Fregat launch from Kourou, October 2017
- Launch mass: 3570 — 3703 kg
- Insertion into: 200 km x 5.3 (5.8) $R_E$ orbit
- Transfer by chemical propulsion module (*optional lunar resonance*)
- Transfer $\Delta V$: 1630 (1420) m/s
- Target Orbit: 10 x 25 $R_E$, $i = 14°$, $\omega = 205°$, $T = 4.3$ days



Ecliptic Plane

4 - Apogee Raising

Target Orbit

5 - Perigee raising & change of inclination and argument of perigee

Soyuz/Fregat injection orbit

2 - Soyuz/Fregat orbit injection

1 - Launch

3 - Fregat release

# Mission Overview: Configuration & Environment

- Configuration $\Delta V$:  14 - 200 m/s
- Scales: electron:  2–100 km, ion: 50–2000 km, fluid: 3000-15000 km
- Electrical power per spacecraft:  220 – 240 W
- Mass per spacecraft:  160 kg to 210 kg (dry)
- Radiation Environment:  33 krad (1.5mm), 9 krad (4 mm)
  *( 54 krad (1.5 mm), 11 krad (4 mm))*
- Operation done by ESOC and ESAC
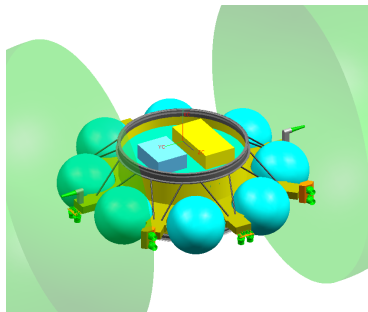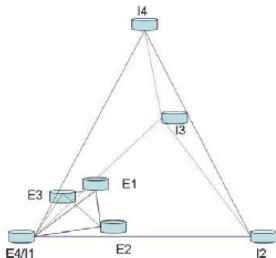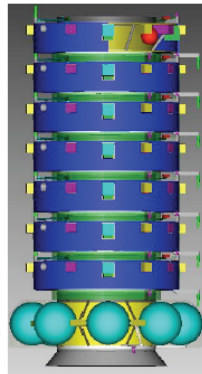
# Mission Concept

- Propulsion module (PM) performs insertion of the stack
  - PM brings stack into 10 by 25 Re orbit, then discarded
  - PM controlled by spacecraft on top of it
  - Analysis of collision between PM and spacecraft: no risk
- 7 identical spacecraft
- Inter-spacecraft ranging on electron scale spacecraft
- Each spacecraft has a direct link with Earth
- 15 rpm spinning spacecraft (after separation)
- Simplified propulsion system for science spacecraft



S/C in control of PM
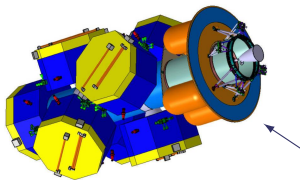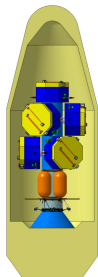
Propulsion module

Dimension of spacecraft driven by power demand

Dimension of spacecraft driven by structural stiffness

# Model Payload

- 5 different payload configurations
- P/L Mass range: 15 – 33 kg
- P/L Power range: 15 – 60 W
- Average data rate: 800 kbps
- Total 93 sub-units
- Up to 1 Tbit mass memory per spacecraft
- Spacecraft configuration allows variation on P/L

# Development Approach

- A: 2 x Proto-Flight Model + 5 recurring flight models
- B: EQM + 7 recurring flight models
- Parallel AIV for the flight model via island approach
- Requires seamless arrival of instruments in time
- Schedule for 2017 launch is challenging
- Minimal technology upgrade activities required
  - 15 rpm star mapper
  - Low gain antenna improvement
  - Inter-spacecraft link adaptation
  - Mass memory optimisation
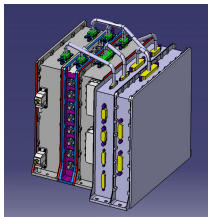
# Most Critical Items

Feasible mission concept with following critical items:

- Cost at Completion
- Schedule (7+1 spacecraft need to be made) for launch 2017
- Number of Instrument sub-units (93 FM) & availability in time
- Number of Spacecraft and resulting AIT/AIV
- EMC requirements driving AIV/AIT
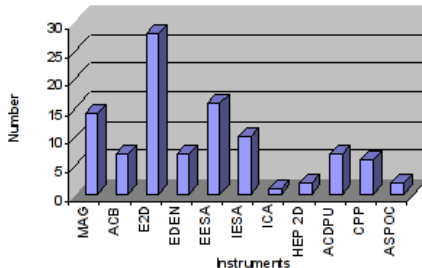
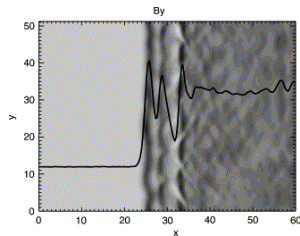# Technology Summary

Feasible mission concept

- Good industrial solutions
- Strong heritage for instruments & space sector
- Clearly-identified but manageable risks
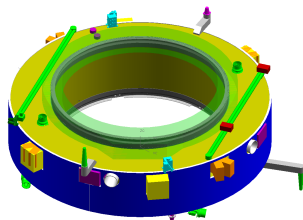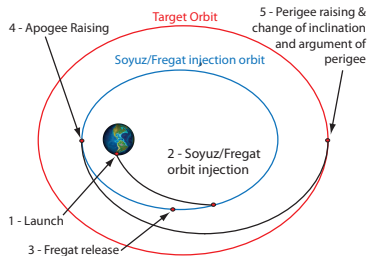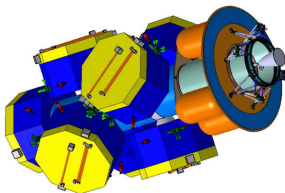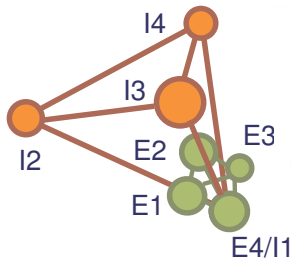
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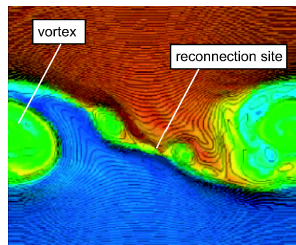
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- How does reconnection convert magnetic energy?



vortex

reconnection site

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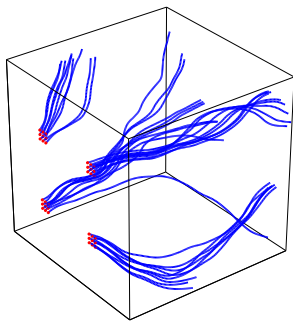
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- How do shocks accelerate particles?
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The mission

- Mature concept within ESA and member states
- Strong synergies with JAXA/SCOPE including CSA