Imaging the Earth's magnetic environment in soft X-rays with SMILE

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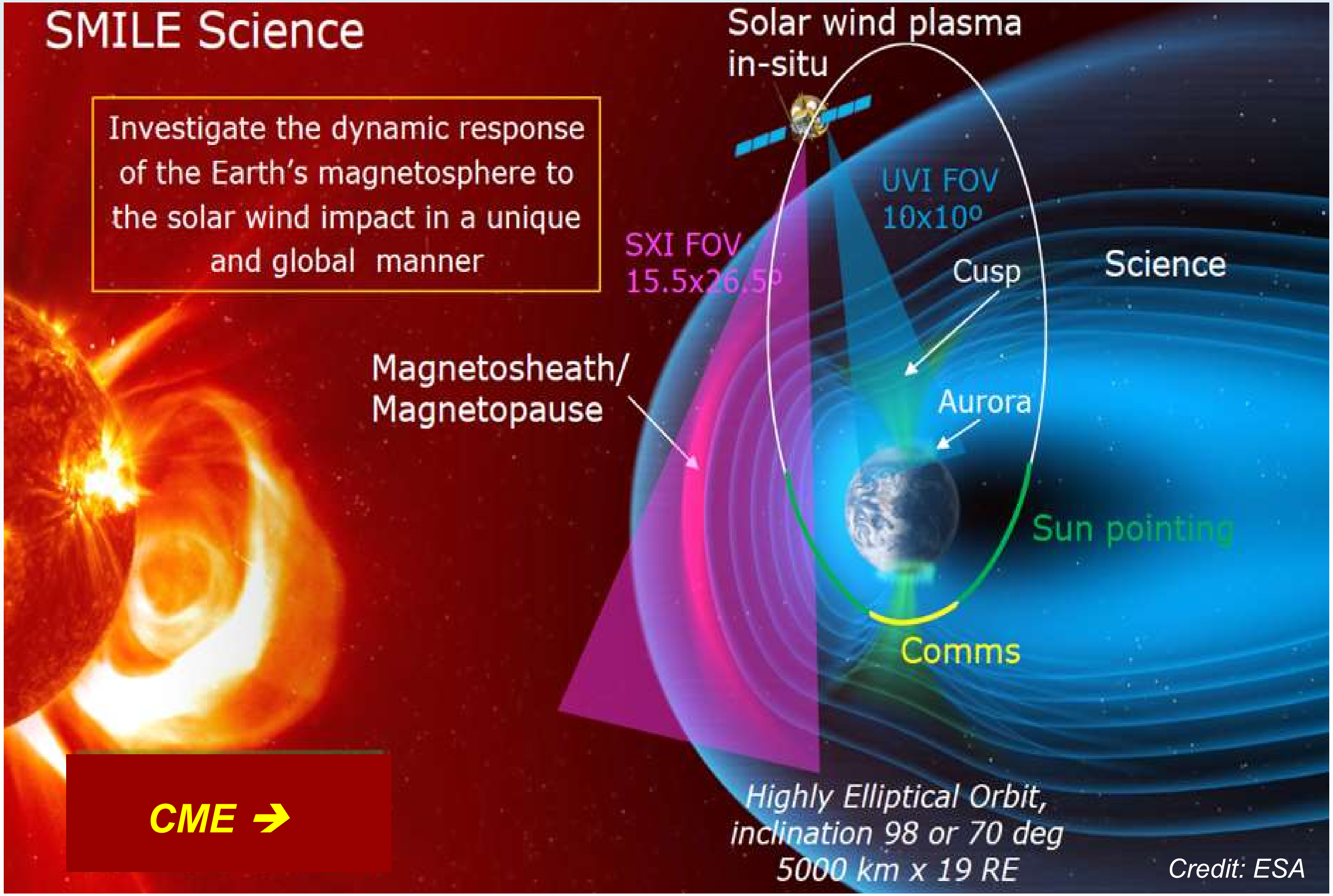
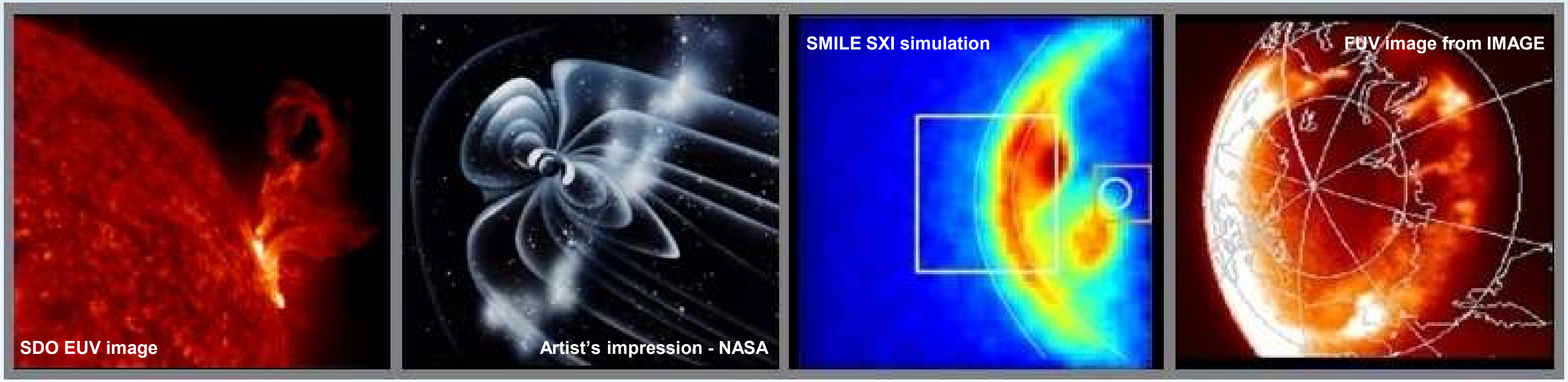
SMILE

Solar wind Magnetosphere Ionosphere Link Explorer



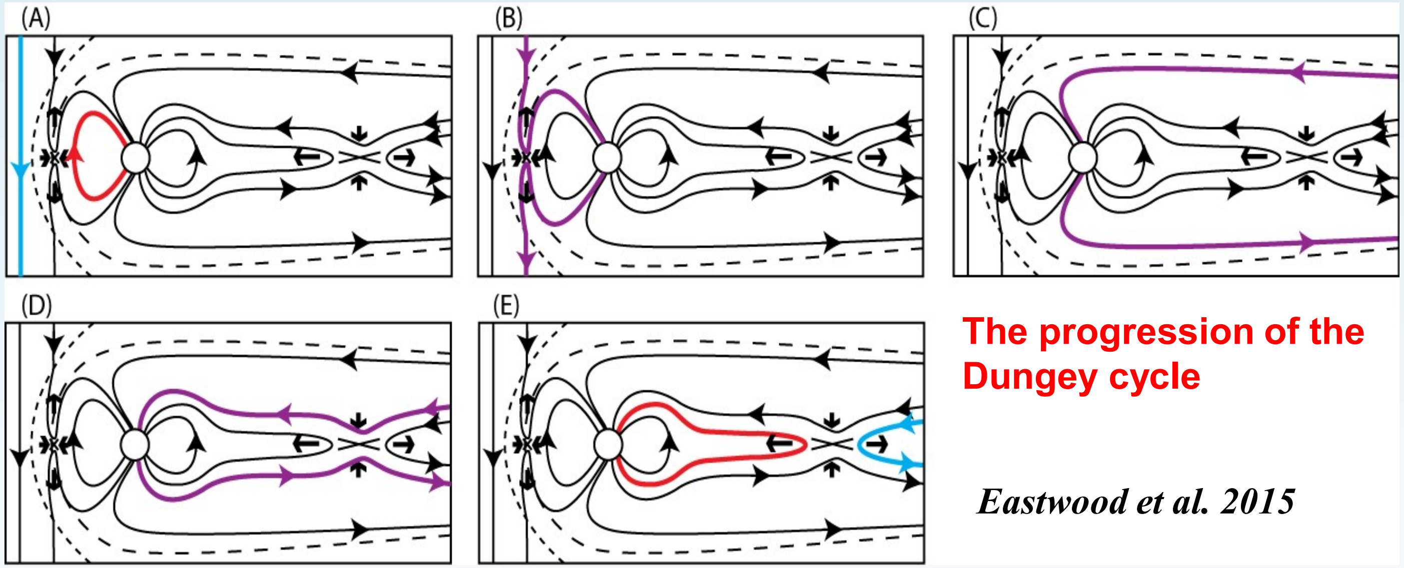
SMILE mission and instruments



- SMILE is a joint scientific mission, from inception to launch and operations, by the **European Space Agency** and the **Chinese Academy of Sciences**, it is under development and due for launch at the end of 2023
- SMILE will investigate the dynamic response of geospace to the solar wind impact, exploring the **full chain of events that drive Space Weather**
- SMILE combines X-ray imaging of the dayside magnetosheath and the cusps (with the Soft X-ray Imager, **SXI**), simultaneous UV imaging of the Northern aurora (UltraViolet Imager, **UVI**) and in situ monitoring of the solar wind and magnetosheath conditions (Light Ion Analyser, **LIA**, and **MAG**netometer) from a very elliptical orbit

SMILE scientific motivations

Study the full chain of events that drive Sun-Earth relations



The progression of the Dungey cycle

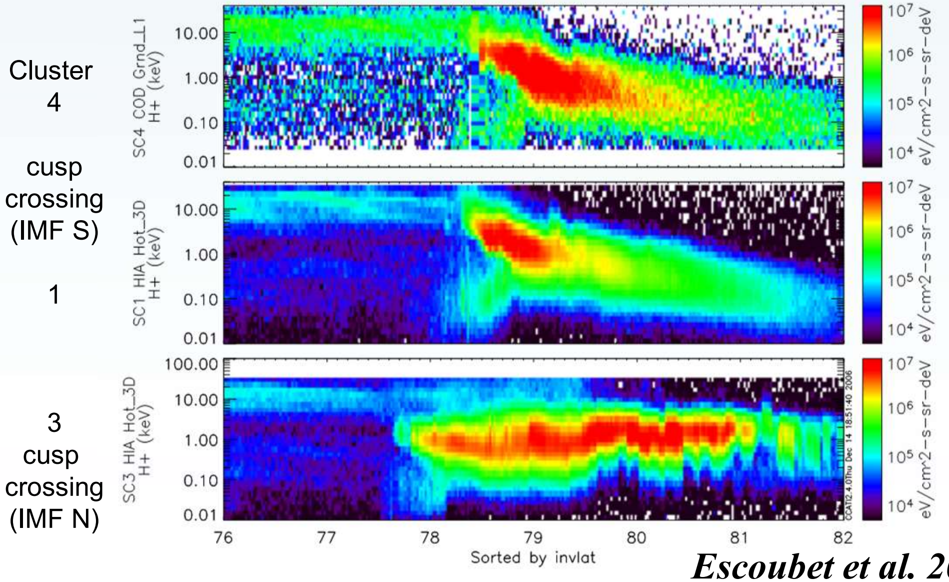
Eastwood et al. 2015

- Structure and dynamics of the magnetosphere mainly controlled by magnetic reconnection: Basic theory of magnetospheric circulation well known, microscale explored by many in situ measurements
- Reality of how complex interaction takes place on a global scale, and how it evolves, still not understood
- SMILE can answer questions which help distinguishing modes of interaction

SMILE scientific motivations

What are the fundamental modes of the dayside solar wind / magnetosphere interaction?

- When/where is **reconnection** steady/transient/bursty, patchy or global?
- Dependent on solar wind parameters or intrinsic instabilities?
- Component or anti-parallel
- Role of the magnetospheric cusps in solar wind/magnetosphere coupling



Escoubet et al. 2008

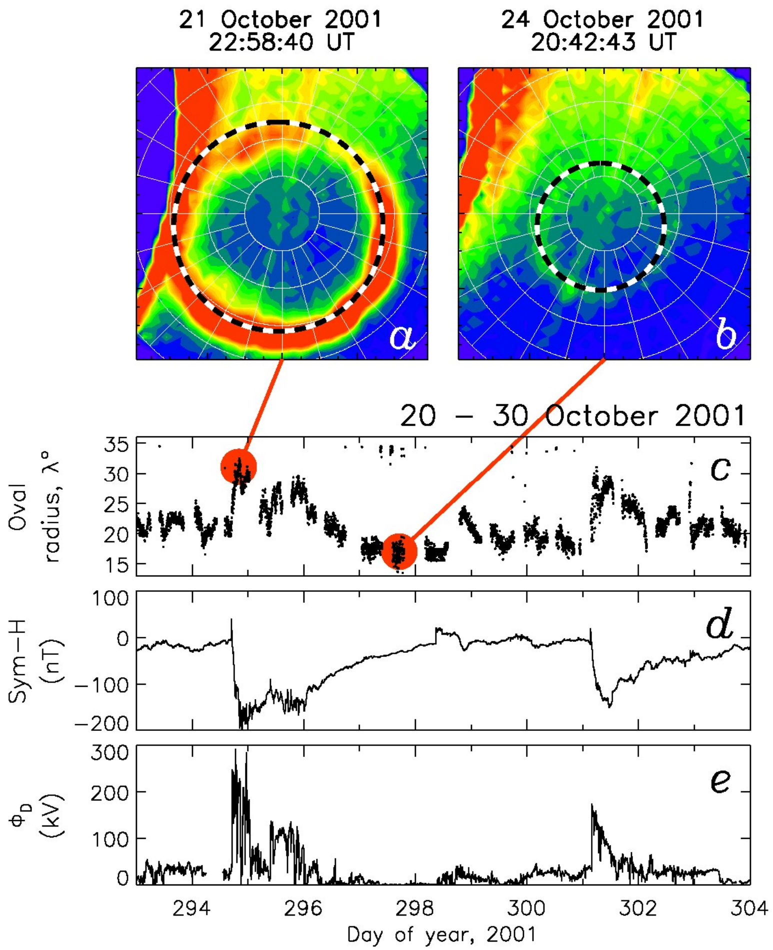
Ion energy decreases towards pole for IMF S, and vice versa

Cusps expands poleward after IMF turns N

SMILE scientific motivations

What defines the substorm cycle?

- Auroral oval responds to changes in magnetospheric or solar wind conditions: IMF orientation, dynamic pressure triggers?
- Other modes of magnetospheric behaviour: e.g. saw-tooth events, auroral beads

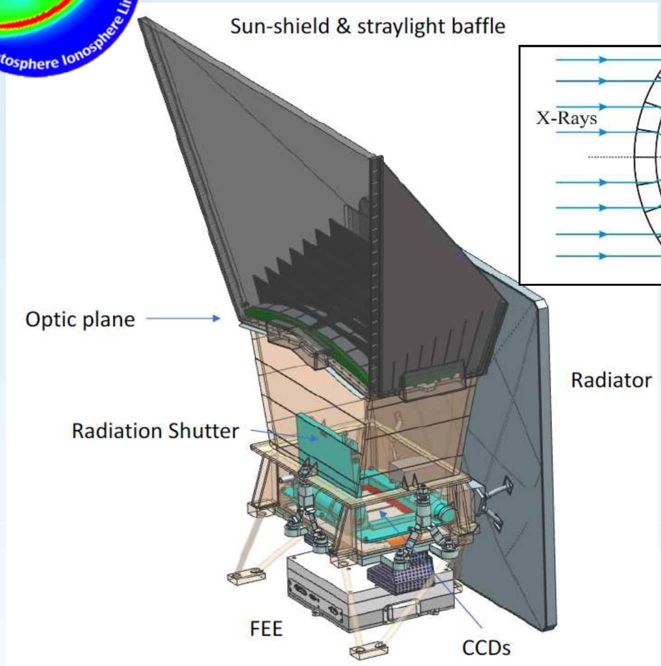


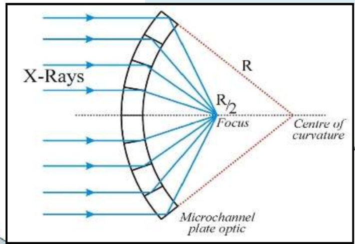
Milan 2009

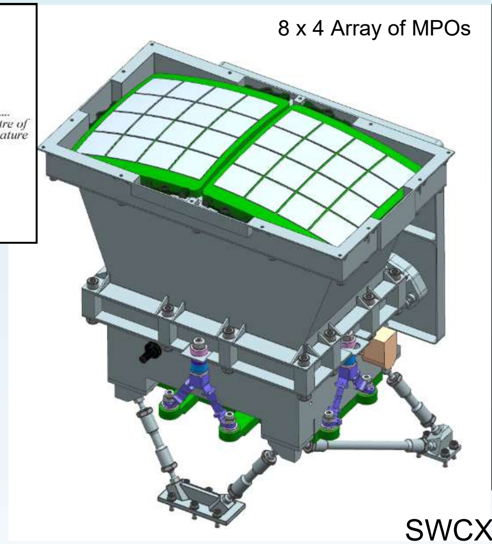
How do CME-driven storms arise?
How do they relate to substorms?

- Fast solar wind and long intervals of S IMF: Is solar wind driving the only storm trigger?
- Relation storm – substorm? How do storms end? Space weather relevance

SMILE Soft X-ray Imager (SXI)







Lobster-eye Micropore Optic

Ultra-wide field of view ~16° x 26°

Focal length 30 cm

Optic Mass < 1kg

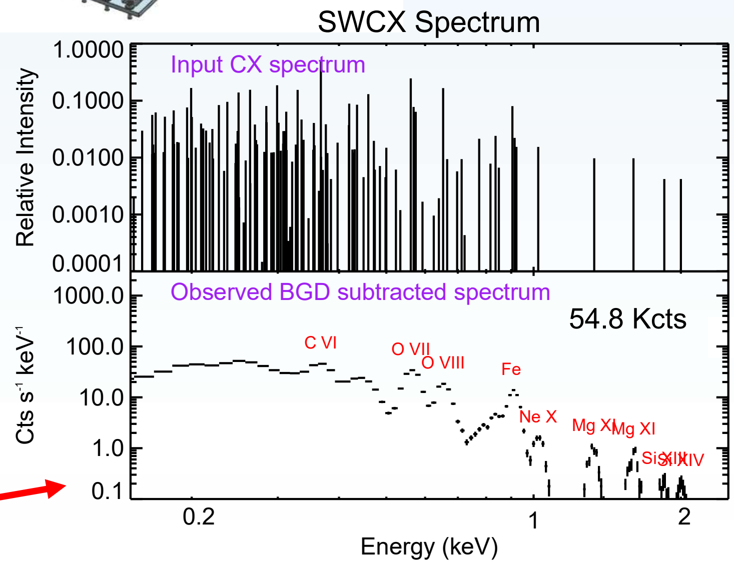
Instrument ~36 kg

CCD Detector Plane

Photon counting: Photon lists with ~4 s time resolution

High QE in soft X-rays ~90% at 500 eV

Medium energy resolution ~50 eV FWHM at 500 eV



PI S. Sembay, Univ. of Leicester, UK

SXI performance versus requirements

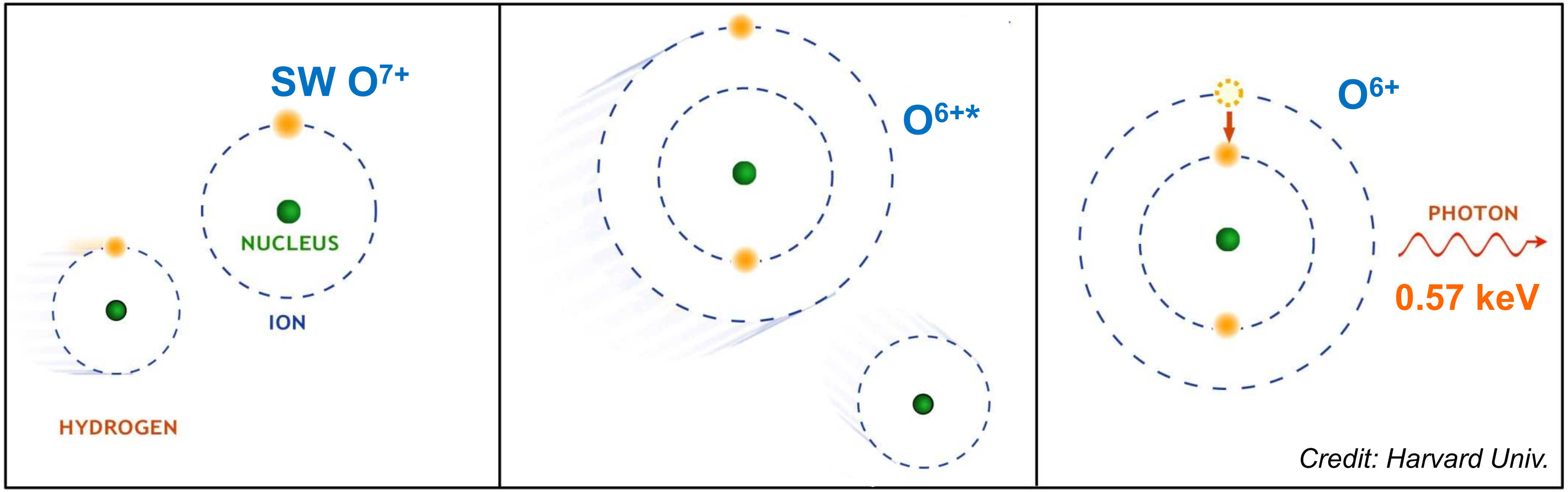
The SMILE Consortium comprises a number of Working Groups whose aim is to help ensuring that the mission science objectives are achieved and optimised

Among these the **Modelling WG** dedicates its efforts to verifying that the SXI performance satisfies the scientific requirements of the mission

Two main requirements on SXI can be expressed as:

- For solar wind flux > 4.9×10^{8} cm^{-2} s^{-1} the location of the subsolar magnetopause shall be determined with a better accuracy than 0.5 R_E and better than 5 min time resolution from locations on orbit greater than 15 R_E geocentric
- The poleward and/or equatorward edges of the mid-altitude cusp in X-ray images shall be identified with 0.25 R_E accuracy at a time resolution of at least 5 min for solar wind flux > 4.9×10^{8} cm^{-2} s^{-1}.

Solar Wind Charge eXchange (SWCX)



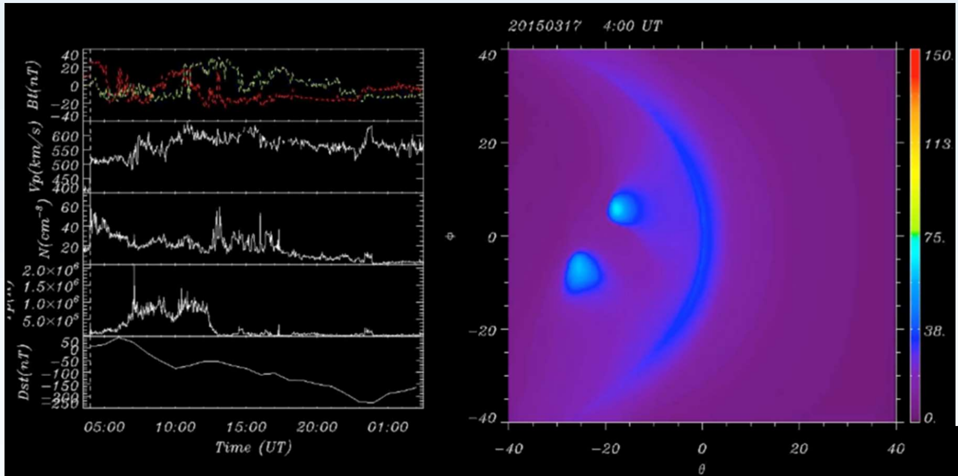
$$P_X = \alpha n_{\rm sw} n_n \langle g \rangle \text{ eV cm}^{-3} \text{ s}^{-1}$$

X-ray emission proportional to density of solar wind ions and neutrals, hence brightest in the dayside magnetosheath and the cusps

17th March 2015 storm event

Before storm: 04 UT, N=15 cm^{-3}, V= 410 km/s

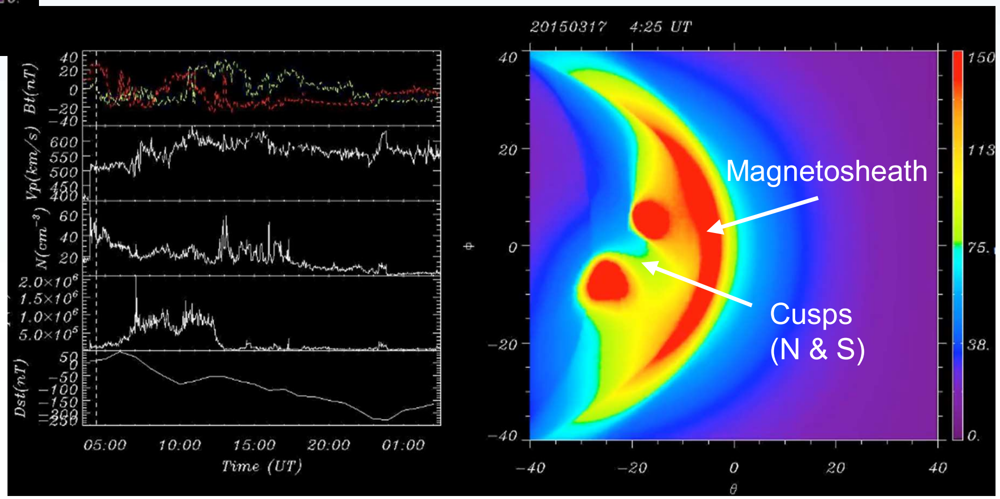
Solar wind input   X-ray emissivity line-of-sight integrated



Predicted SWCX X-ray emissivity from MHD simulation

During storm: 04:25 UT, N=50 cm^{-3}, V= 510 km/s

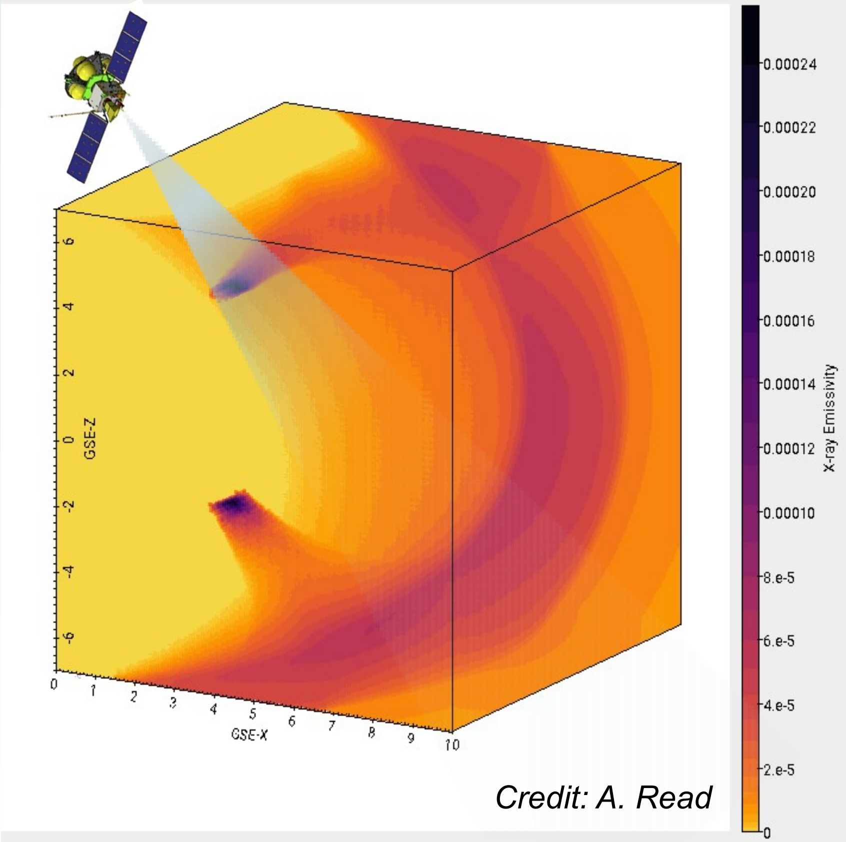
Solar wind input   X-ray emissivity l-o-s integrated



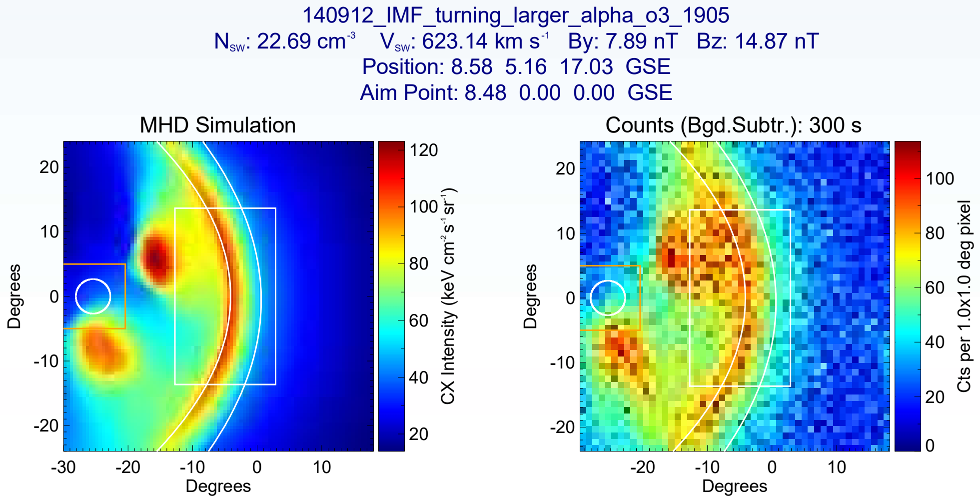
T. Sun, NSSC, CAS, China

From X-ray emissivity to observed counts

Detectable X-ray emission calculated by integrating along the line of sight through the modelled X-ray emissivity cube



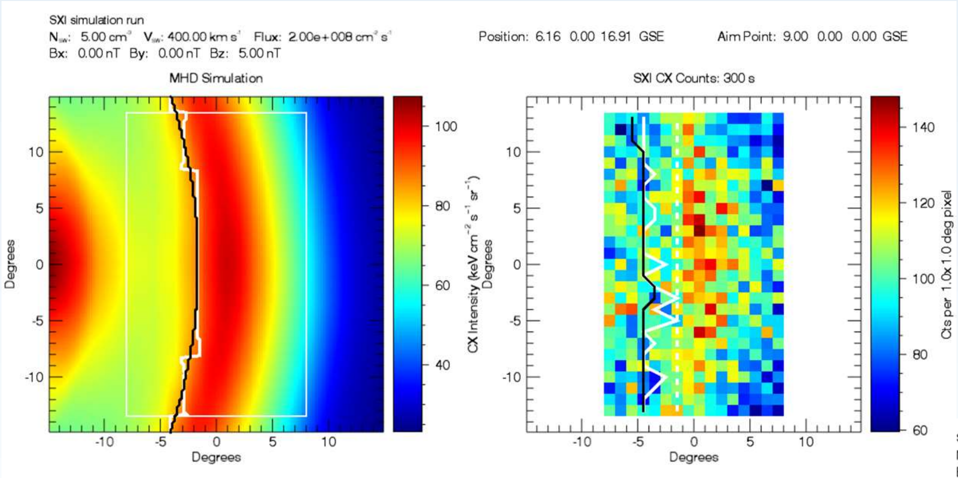
➔ SXI_SIM produces expected count maps



➔ **SXI performance study versus SMILE science requirements**

Extracting magnetopause location from SXI images: techniques under study (1)

Gradient method

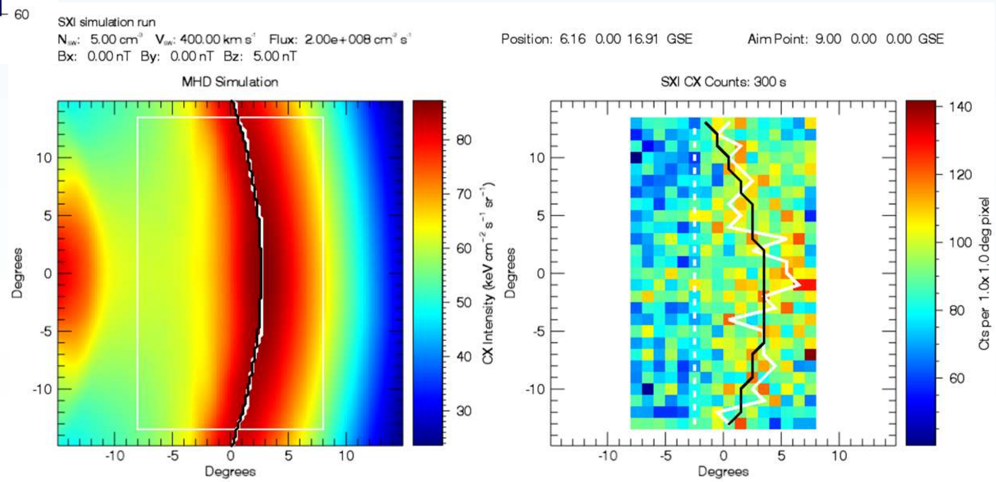


Take locations along image slices on the Earth-Sun line through
MHD simulated X-ray emissivity (left) and SXI count images (right), where

X-ray emission gradient is greatest

X-ray emission is greatest

Maximum method



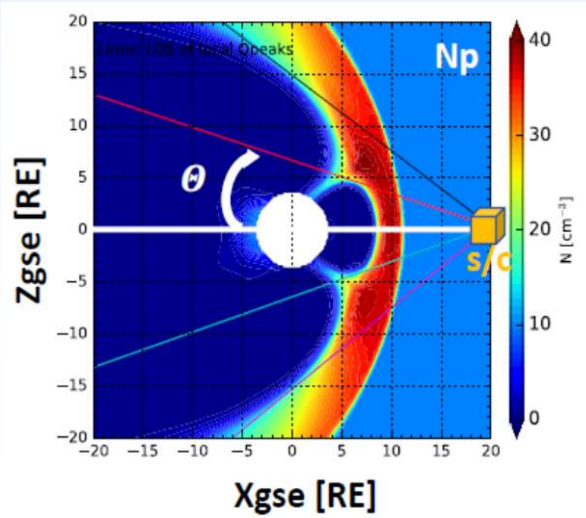
True magnetopause location likely to be in between the two estimates

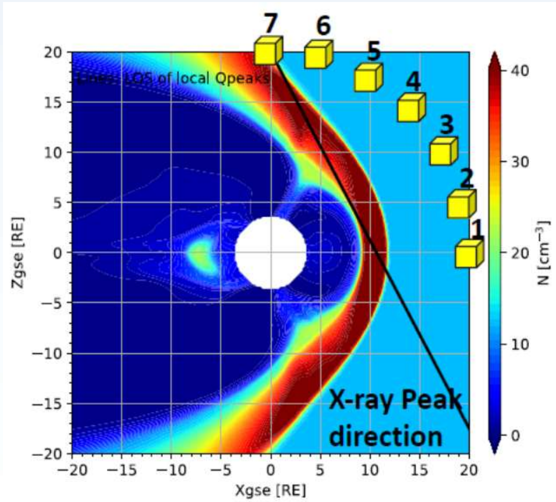
Credit: A. Samsonov

Extracting magnetopause location from SXI images: techniques under study (2)

Tangential direction approach

- The direction with maximum X-ray intensity is the tangential direction
- Use two-point observations to pinpoint the tangent point
- Position of the magnetopause is at the tangent point



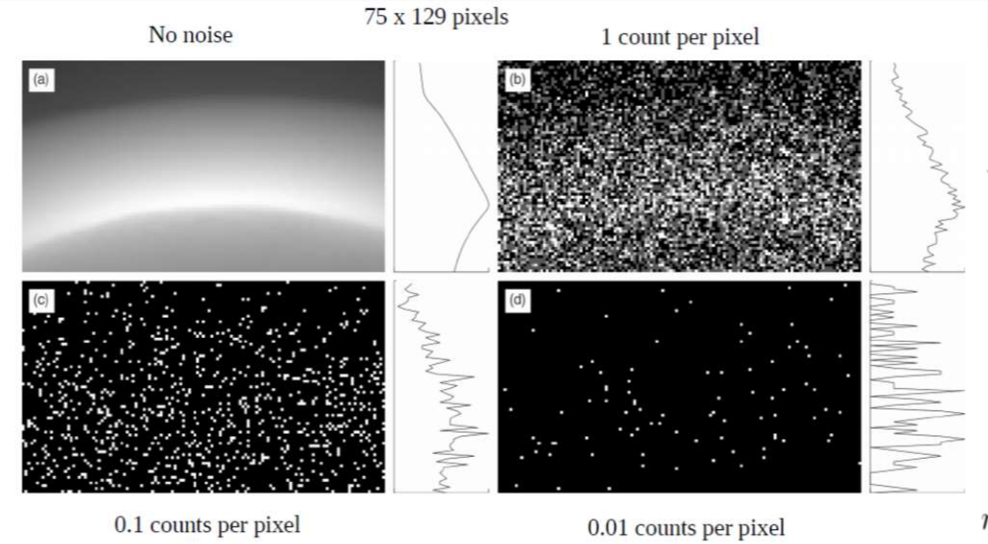


Credit: : H. Connor & M. Collier

Extracting magnetopause location from SXI images: techniques under study (3a)

Boundary fitting in 3D

Reconstruction of 3D boundaries from 2D images:
Assume an X-ray emission model, and a boundary model extension in 3D
→ Model an ensemble of X-ray images
→ Fit to the observed image, best match gives position of magnetopause in 3D



Credit: A. Jorgensen & T. Sun

Emissions model (empirical)

$$F(\vec{r}) = \begin{cases} 0 & \text{inside MP} \\ \left(A_1 + B\sin^8\theta\right)\left(\frac{r}{r_{\text{ref}}}\right)^{-\left(\alpha+\beta\sin^2\theta\right)} & \text{between MP and BS} \\ A_2\left(\frac{r}{r_{\text{ref}}}\right)^{-3} & \text{outside BS} \end{cases}$$

Boundary model (a natural extension of Shue et al. [1997])

$$r(\theta,\phi) = \frac{r_y(\theta)\, r_z(\theta)}{\sqrt{\left[r_z(\theta)\cos\phi\right]^2 + \left[r_y(\theta)\sin\phi\right]^2}}$$

$$r_y(\theta) = r_0\left(\frac{2}{1+\cos\theta}\right)^{\alpha_y} \qquad r_z(\theta) = r_0\left(\frac{2}{1+\cos\theta}\right)^{\alpha_z}$$

Extracting magnetopause location from SXI images: techniques under study (3b)

Forward modelling

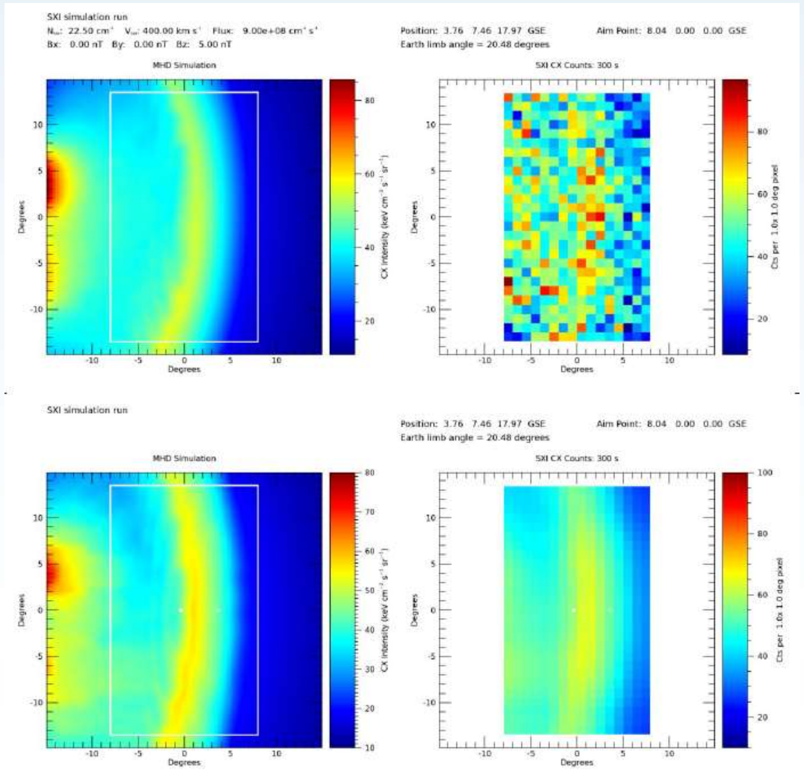
Application of Jorgensen & T. Sun technique to MHD simulations of SXI images

Model compared to dataset via chi-square test

Parameters of empirical model adjusted to minimise chi-square

Requirement of 0.5 R_E accuracy on magnetopause location for 5 min exposure **comfortably satisfied**

Credit: S Sembay



with noise

without noise

Extracting magnetopause location from SXI images: techniques under study (4)

Tangent fitting approach

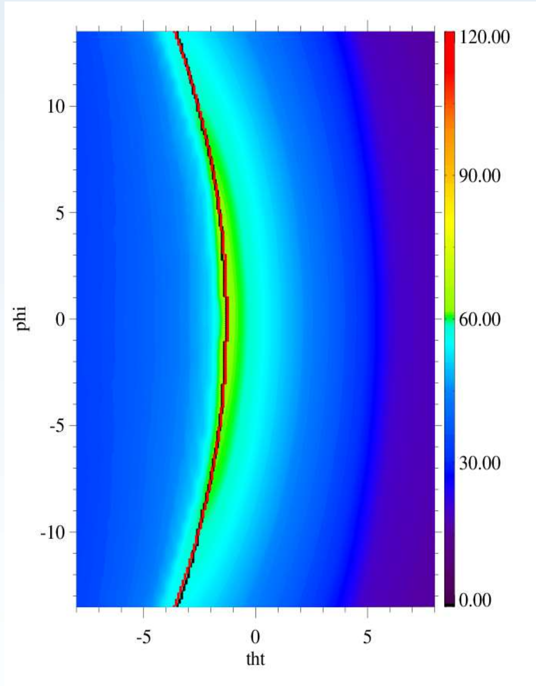
Combines techniques (2) and (3):

- Assume a model for the magnetopause
- For each left free parameter calculate the tangent direction along all longitudes

→ Find the best match

- Technique saves time, and avoids introducing models for X-ray emissivity and bow shock position

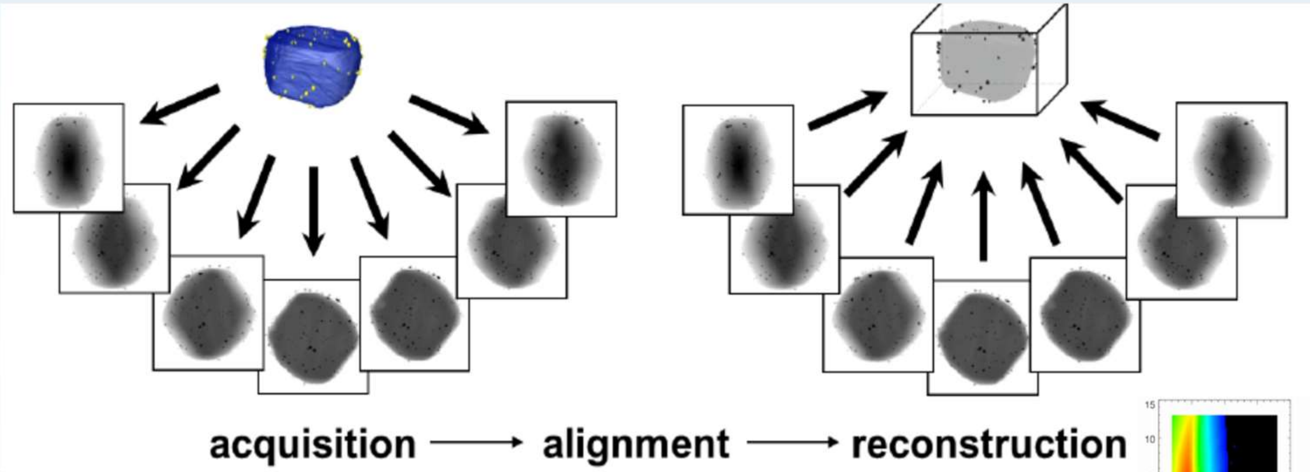
Credit: T. Sun et al.



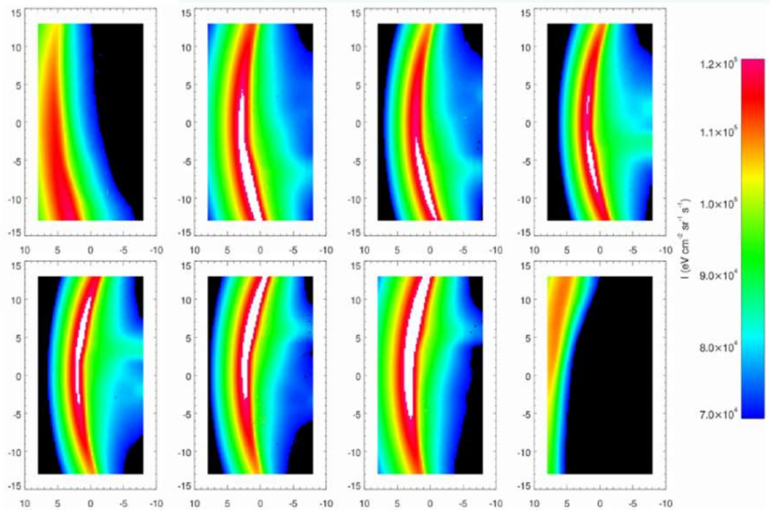
X-ray intensity inside FOV (16^o x 27^o)
Black curve: Position of the maximum X-ray intensity
Red curve: Best fit tangential direction

Extracting magnetopause location from SXI images: techniques under study (5)

Tomographic reconstruction



Images from typical orbit



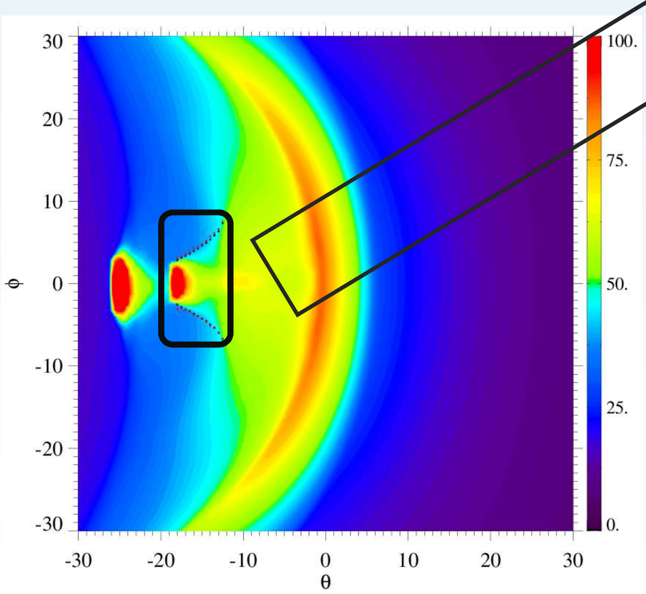
Reconstruct a 3D object from multiple 2D projections

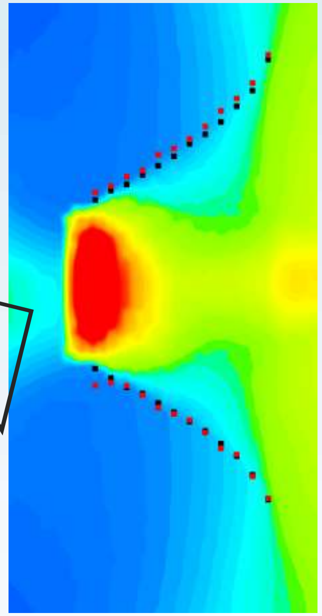
Most significant limitation on reconstruction is probably the small range of viewing angles

Credit: A. Jorgensen & T. Sun

Locating the magnetospheric cusps (1)

The point with apparent increase of **X-ray gradient** in the image corresponds well to the **tangential direction of the cusp boundary**

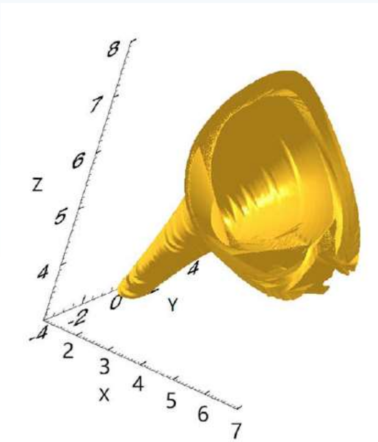


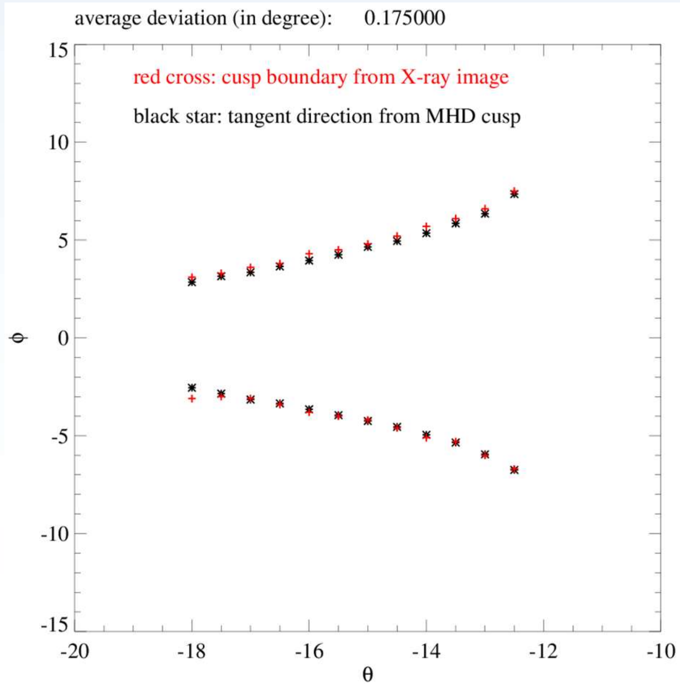


Red dots: From X-ray image, with sudden increase of the X-ray gradient

Black dots: Tangent direction, from MHD cusp boundary

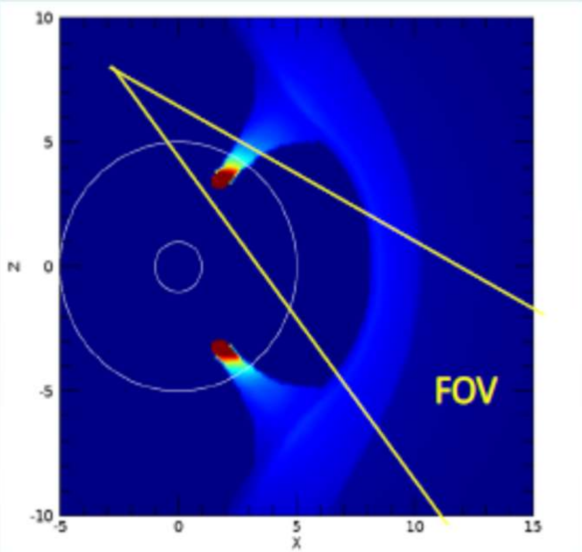
Good agreement with each other. Average deviation is ~0.18 deg.





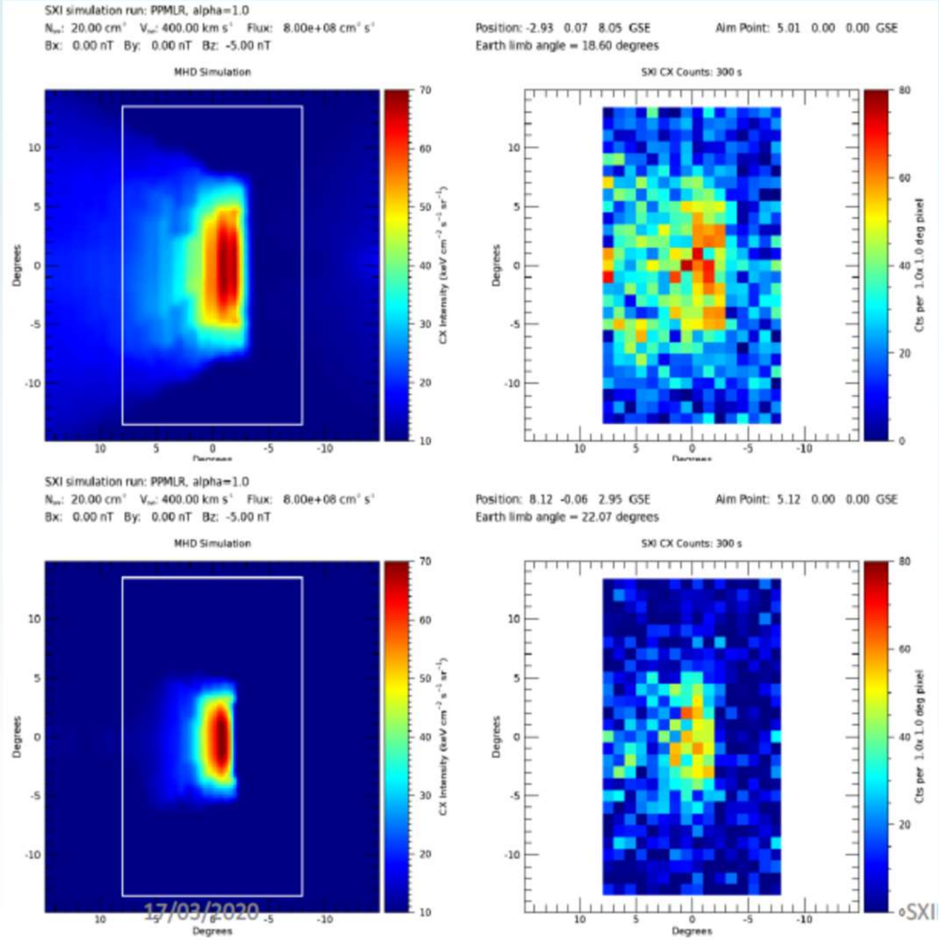
Credit: T. Sun

Locating the magnetospheric cusps (2)



Taking a slice through the MHD simulation

Credit: S. Sembay



Images on the right:

- View of the North (top) and South (bottom) cusps
- MHD simulation (left), SXI simulation (right)
- **Cusp edges can be determined with 0.25 R_E accuracy over 5 min as required**

Conclusions

SMILE aims to investigate the dynamic impact of the solar wind on the Earth's magnetosphere in a global and novel way

SMILE will provide direct scientific input to the studies of space weather by making the remote sensing measurements needed to validate global models of solar wind-magnetosphere interactions

In preparation of SMILE launch and operations:

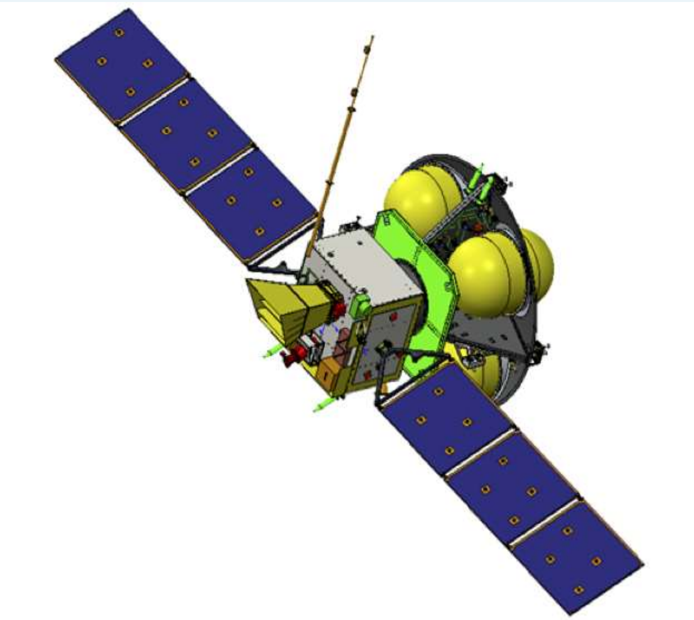
- MHD simulations employed to produce expected SXI images of magnetosheath and cusps for different solar wind conditions
- Simulated SXI images used to establish the instrument performance by:

Applying a variety of techniques aiming to determine the location of the magnetopause

Extracting magnetospheric cusps location and extent

Results found to be consistent with SMILE scientific requirements

Thank you!



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