Finding our SMILE

From an X-ray astronomer’s headache to imaging the Earth’s magnetosphere

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@JennyaCarter #SMILEesacas
November 2019

With input from, and thanks to:
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S. E. Milan, S. F. Sembay, A. R. Fogg (U. Leicester);
A. Samsonov, G. Branduardi-Raymont (MSSL)

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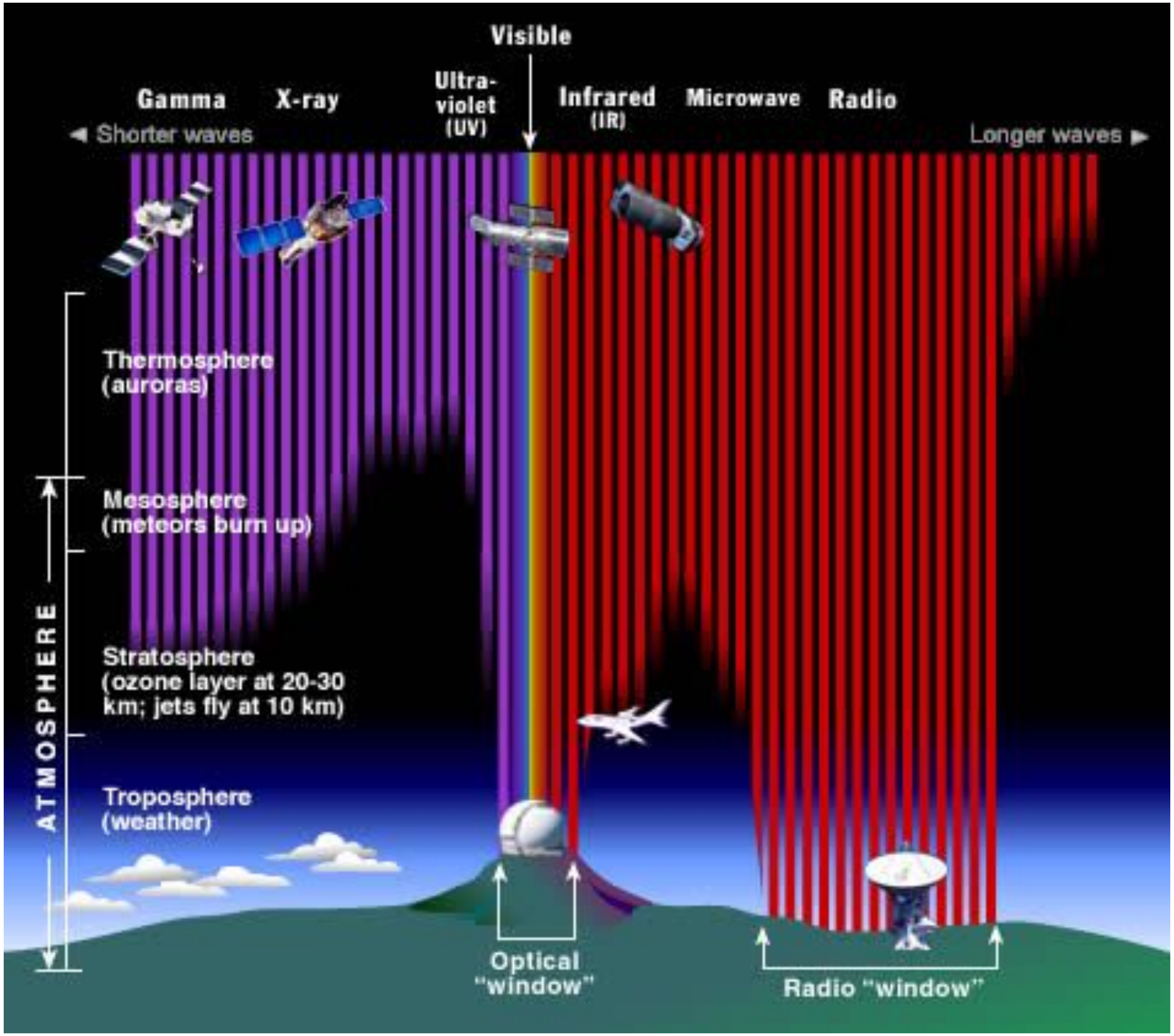
The X-ray sky: early ROSAT days



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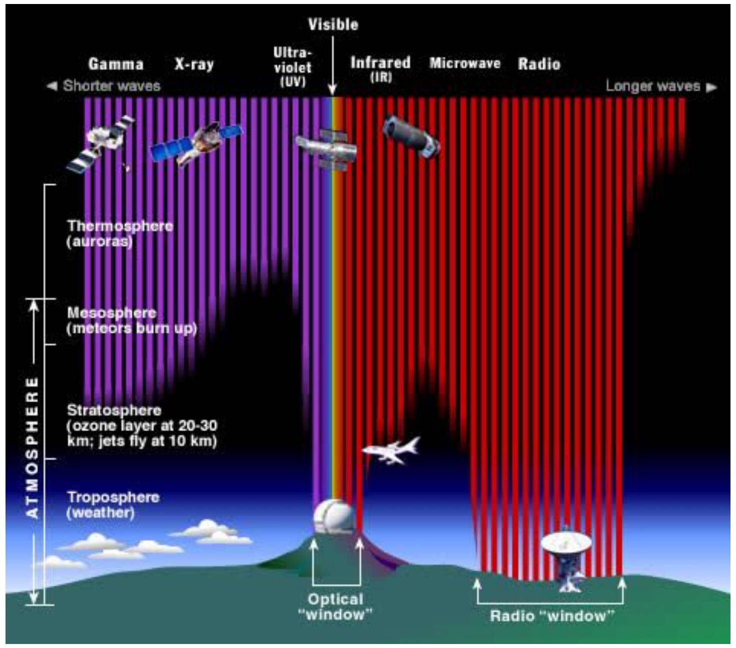

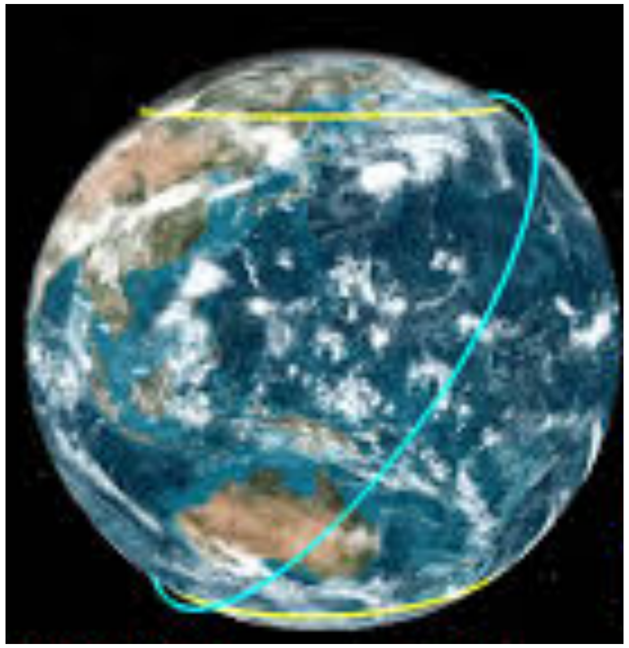

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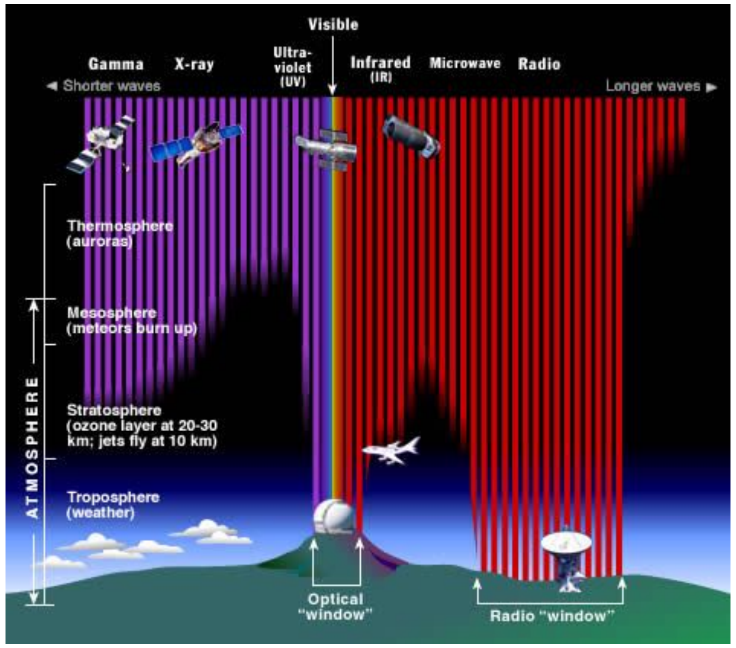
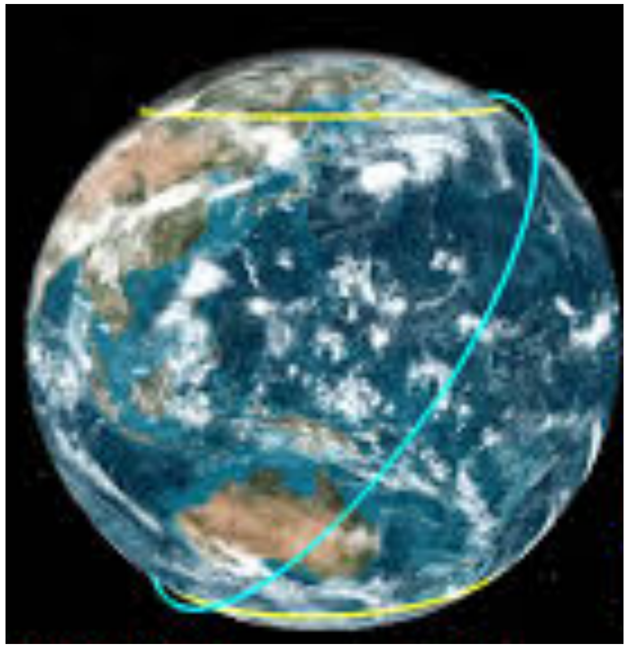
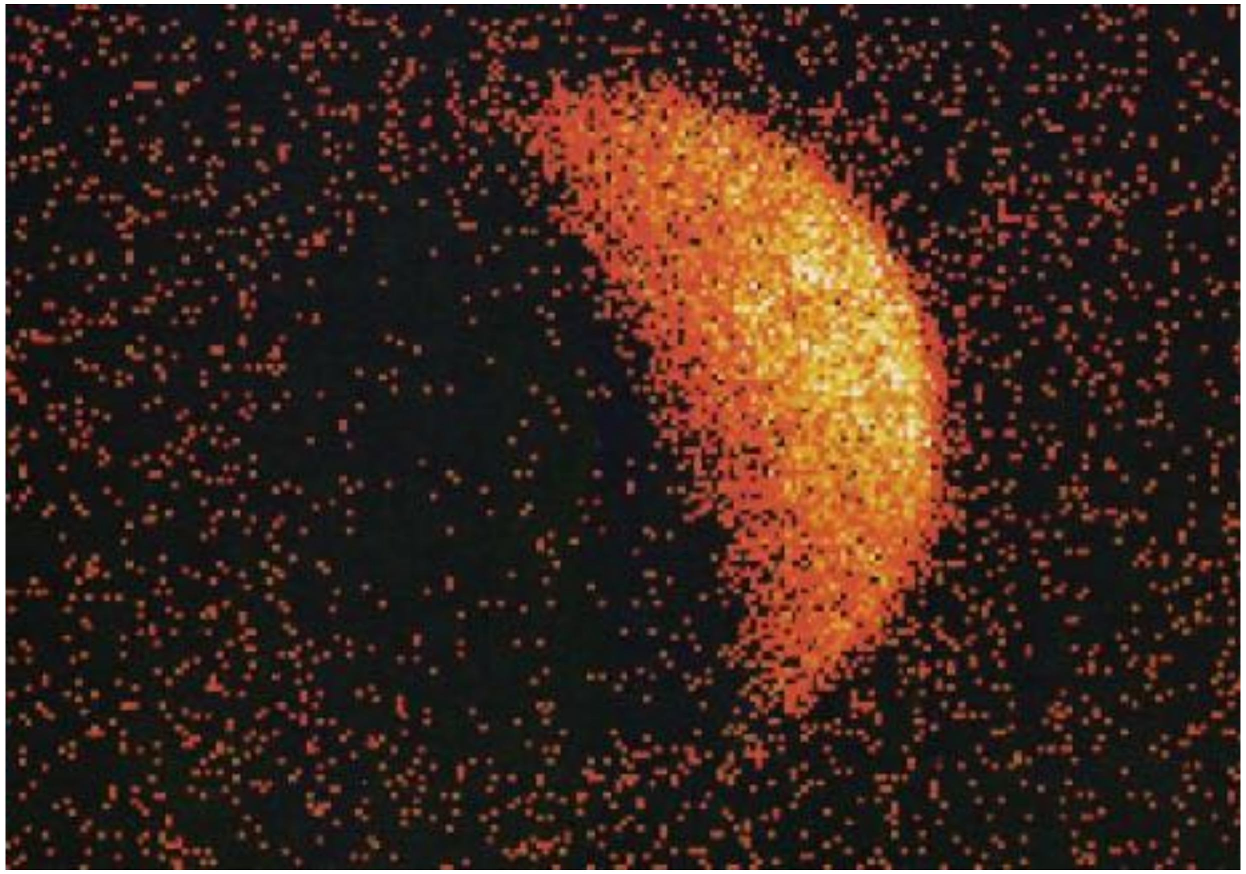
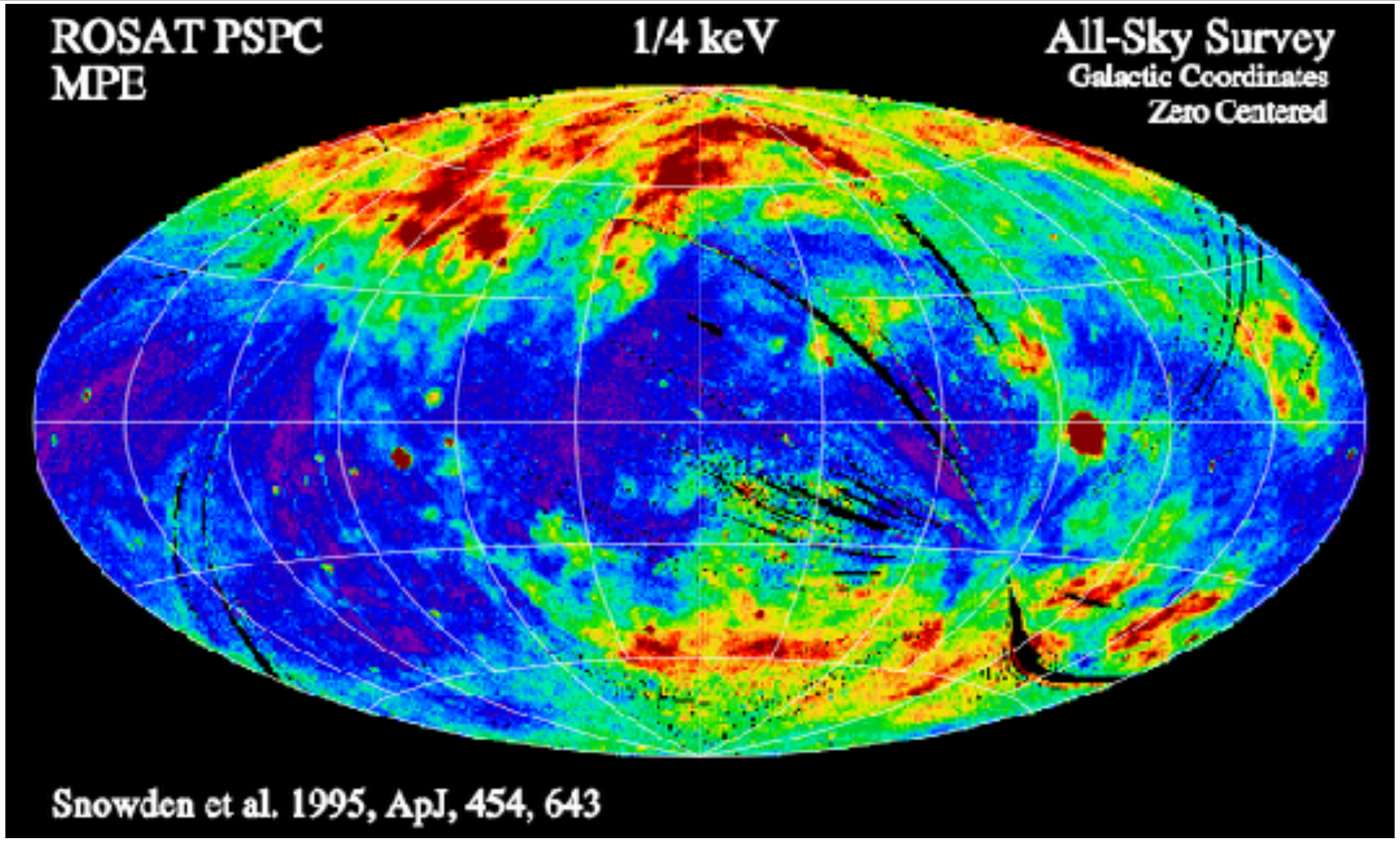






Credit: J. Schmitt (MPE)

The X-ray sky: all sky maps



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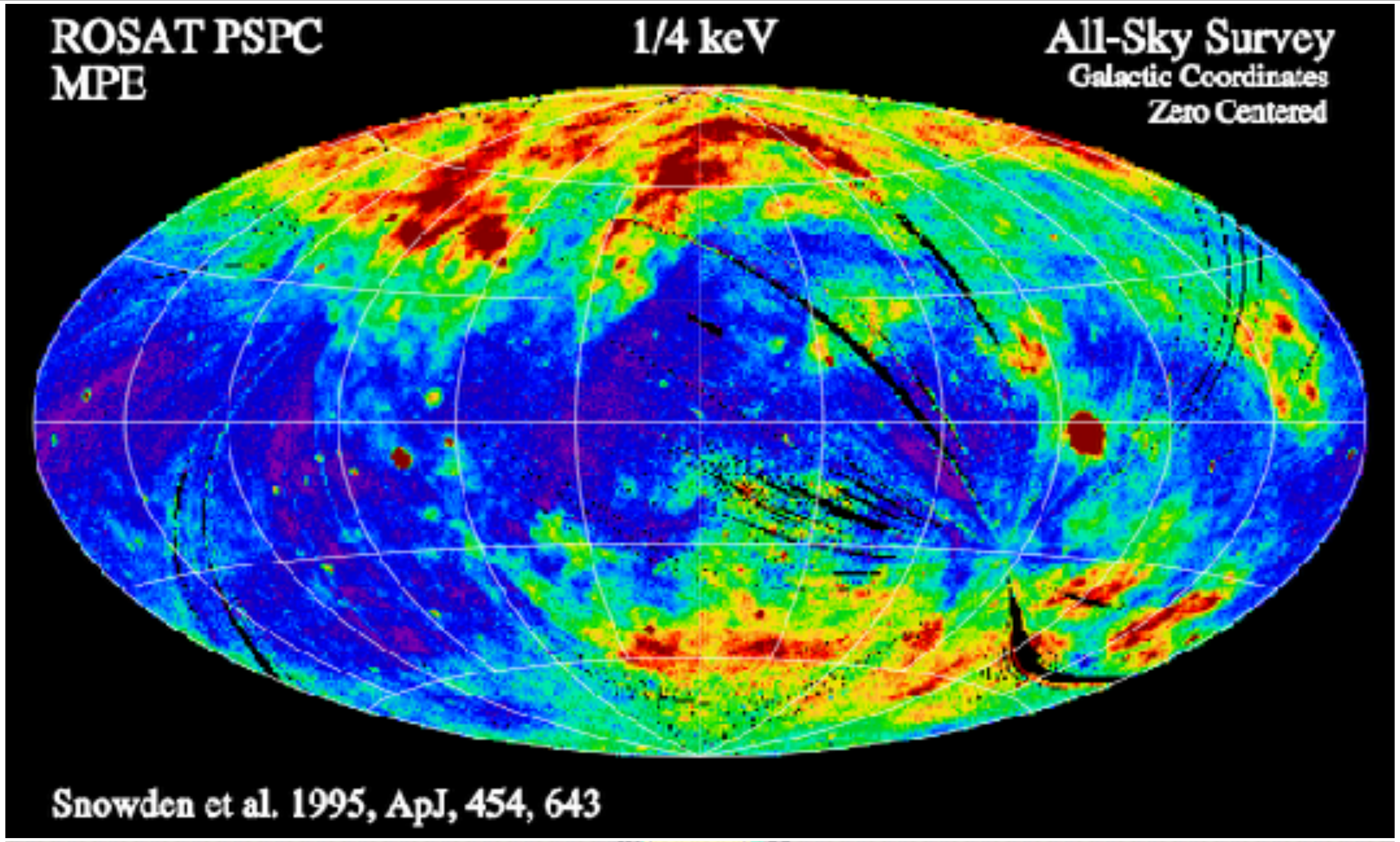
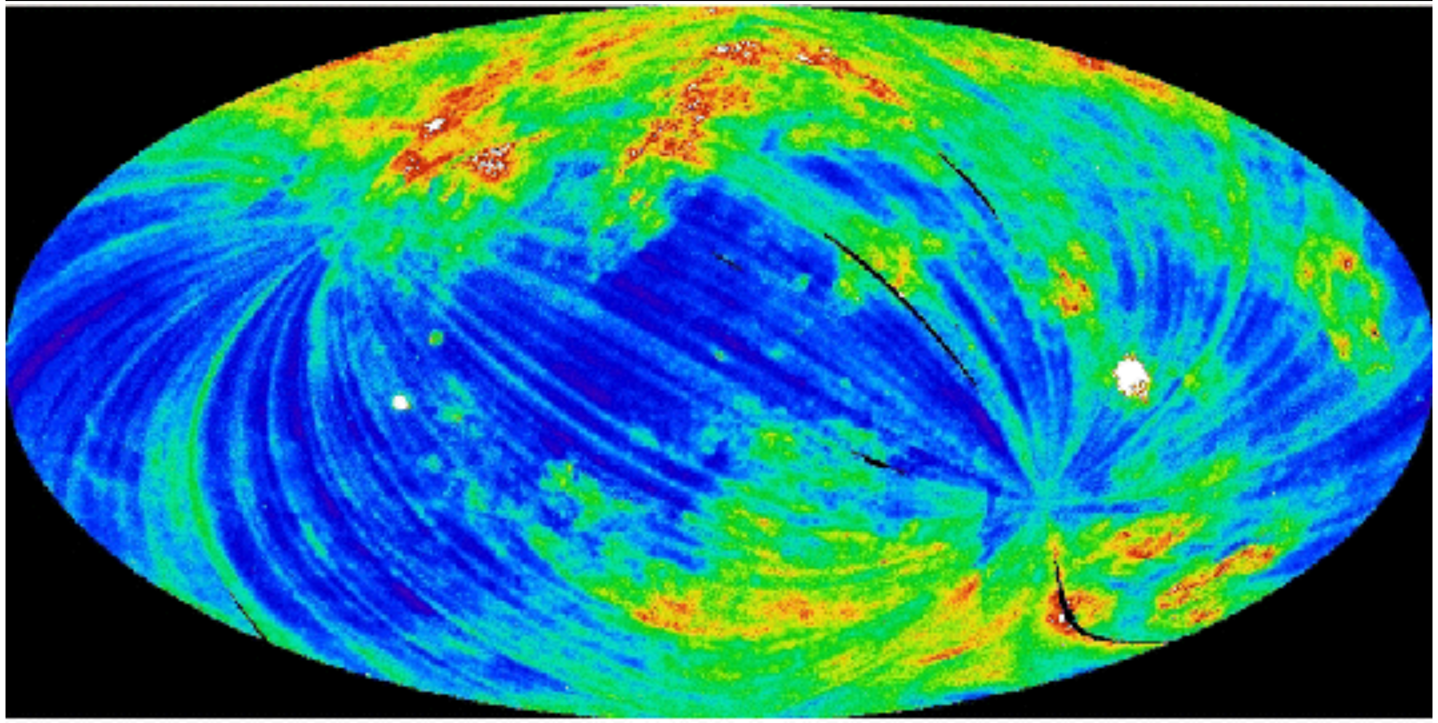
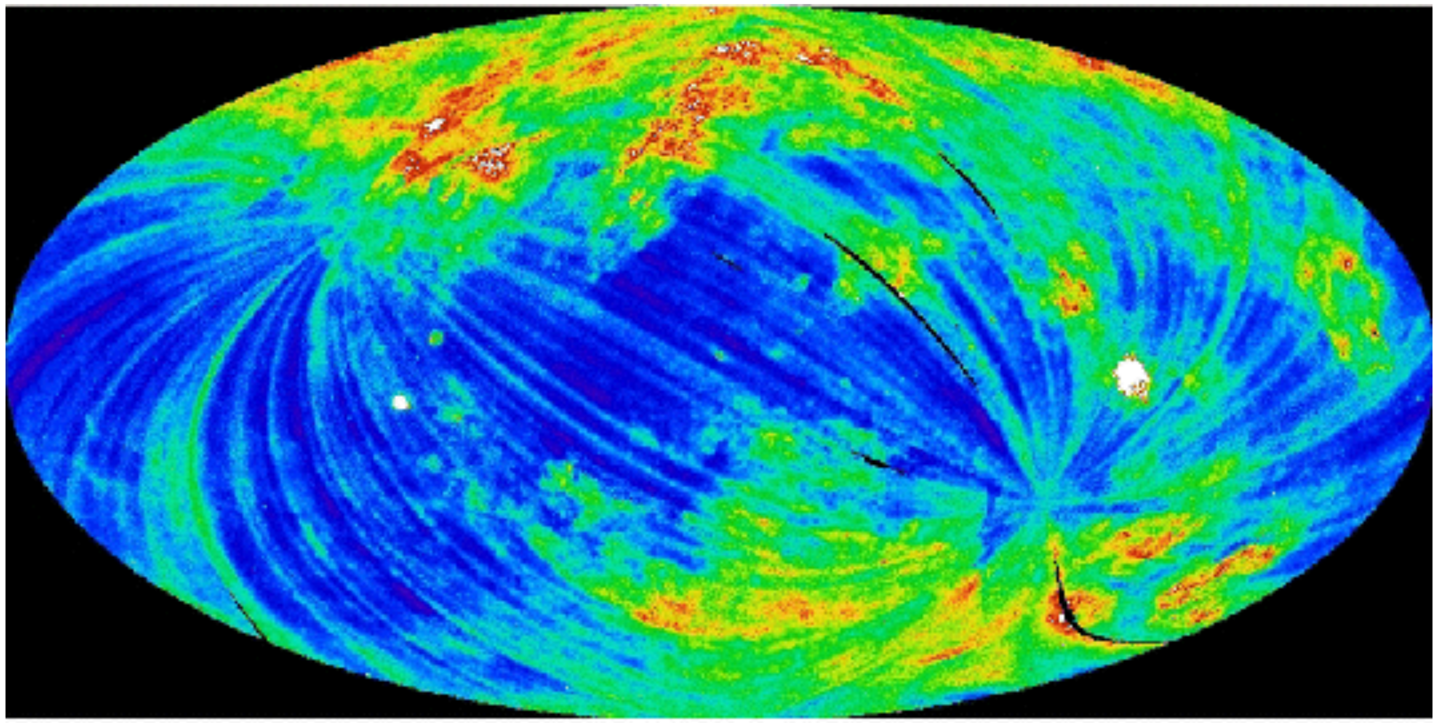
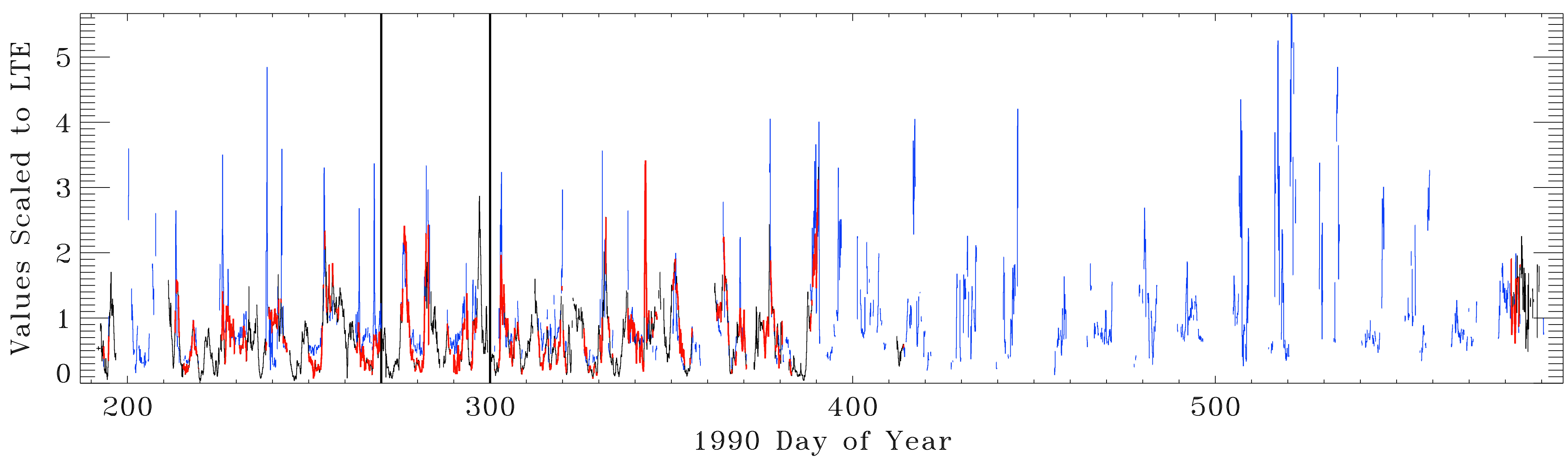




The X-ray sky: long-term enhancements



X-rays: black
Solar wind flux
Solar wind protons



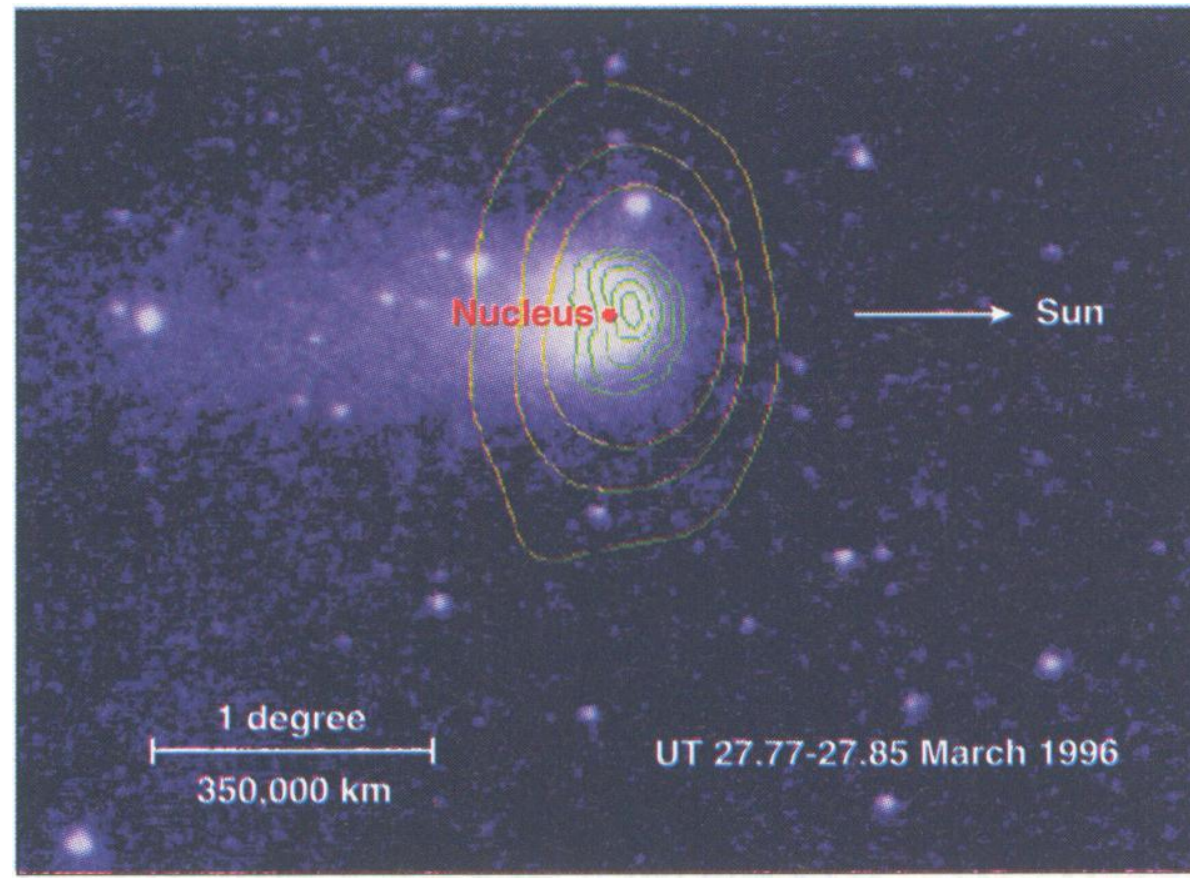
Kuntz 2015, Freyberg 1994

The X-ray sky: comets as X-ray emitters

Comet: Hyakutake 1996 B2

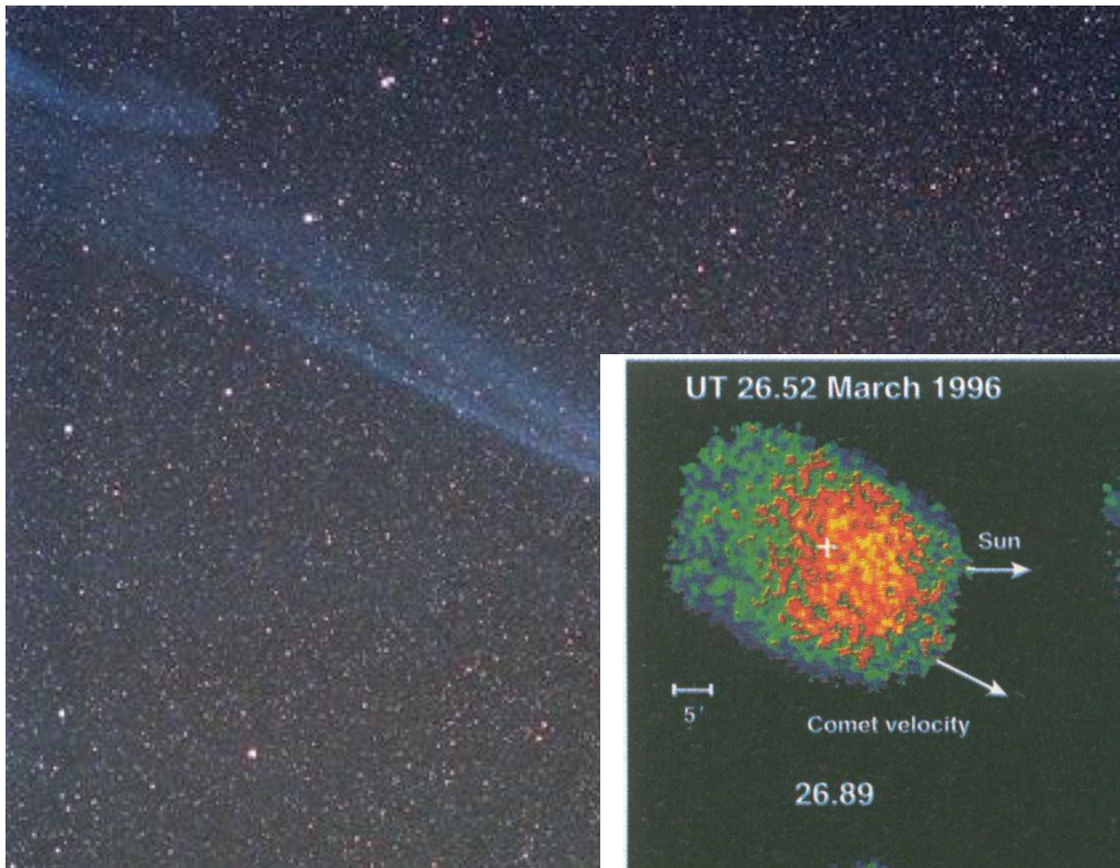
The X-ray sky: comets as X-ray emitters

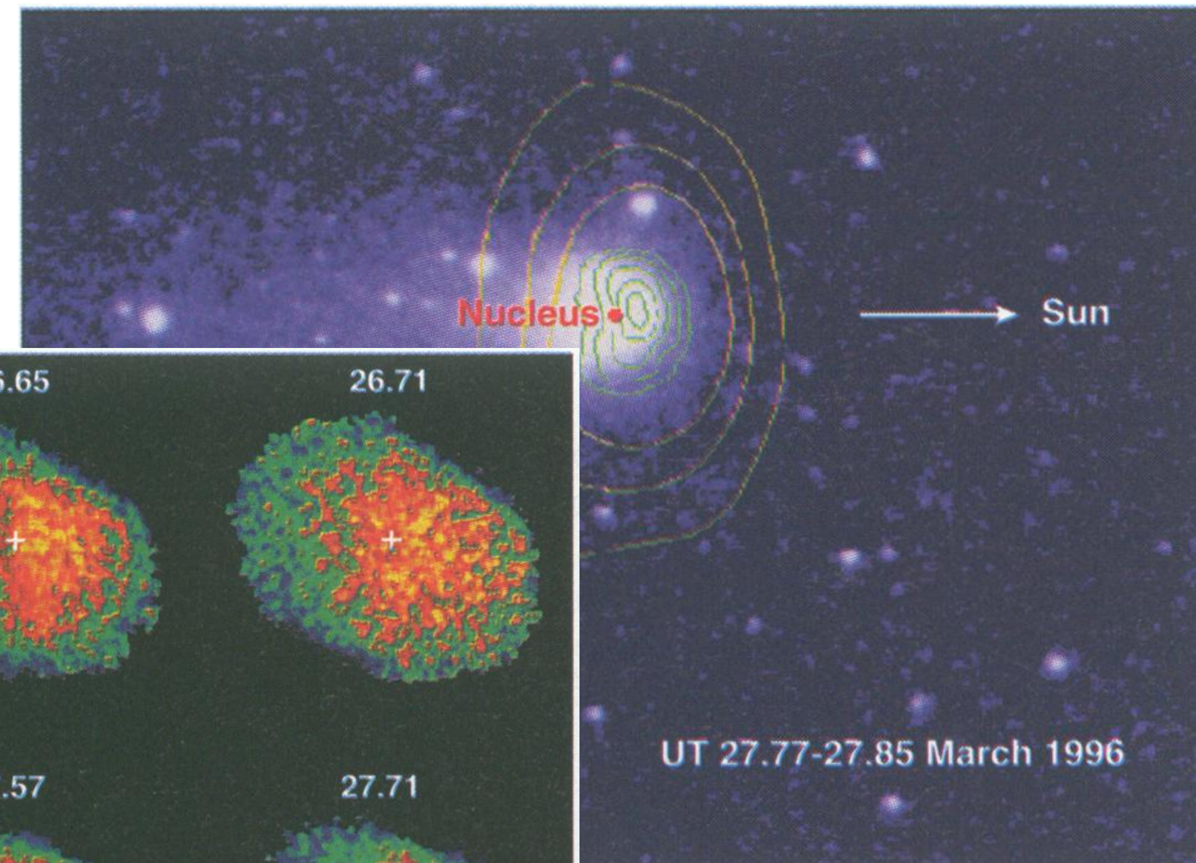
Comet: Hyakutake 1996 B2

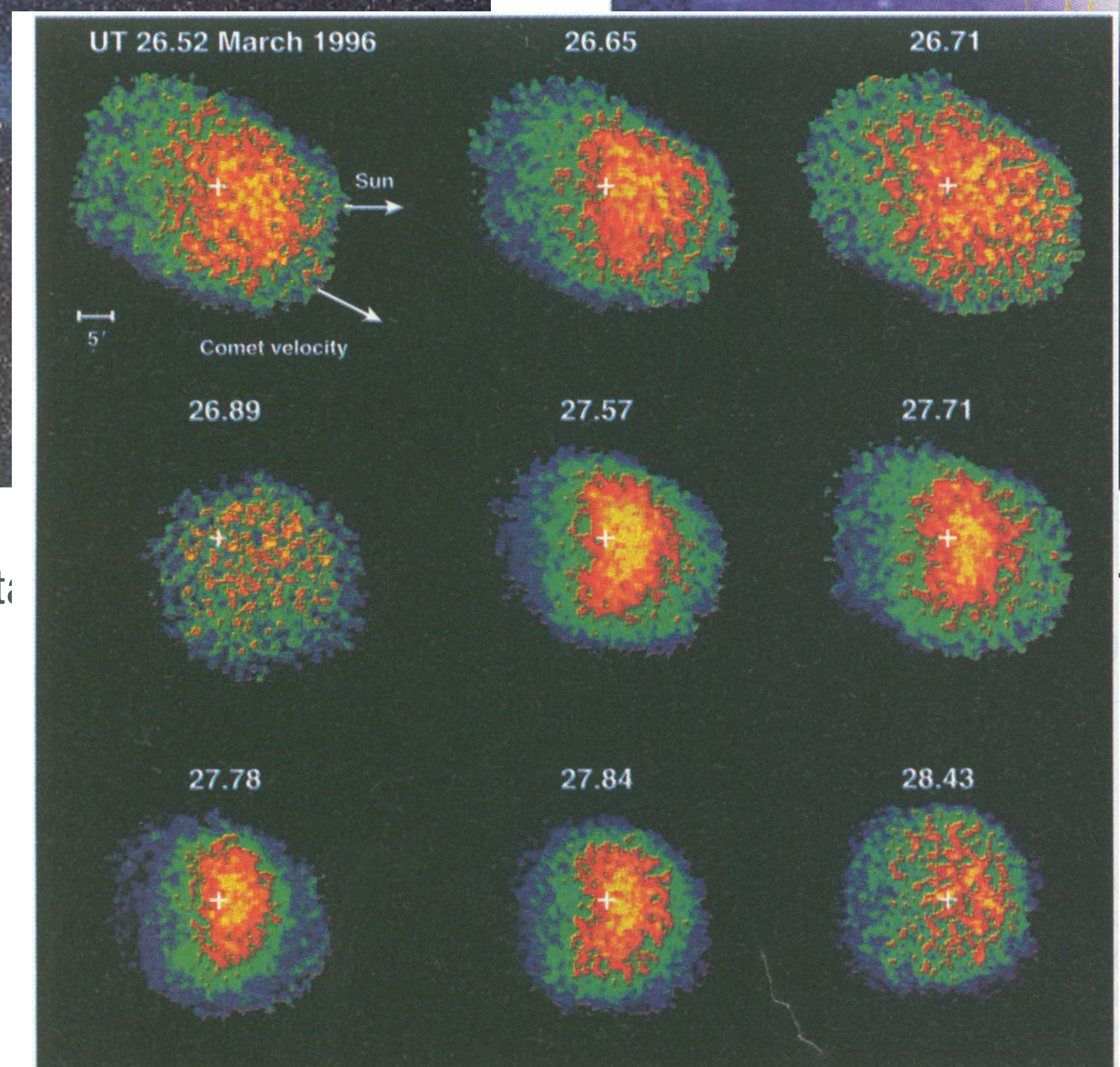


Lisse et al. 1996 - cometary X-rays related to solar wind?

The X-ray sky: comets as X-ray emitters







Comet: Hyakut

netary X-rays related to solar wind?

HRI images with time, band 0.1 - 2.0 keV

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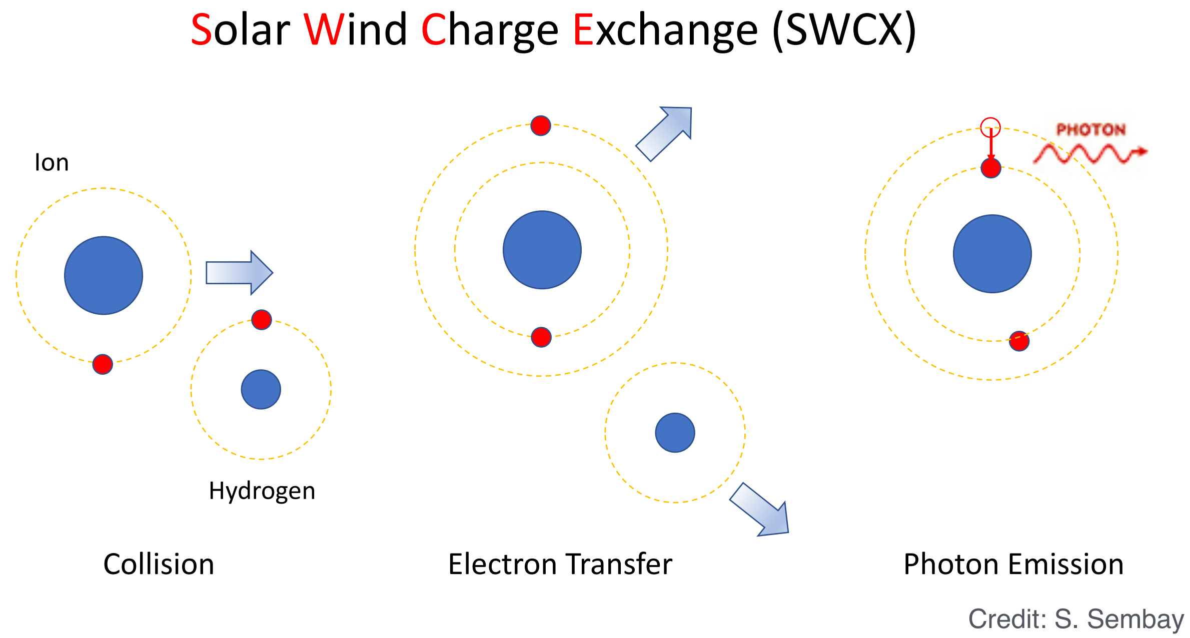
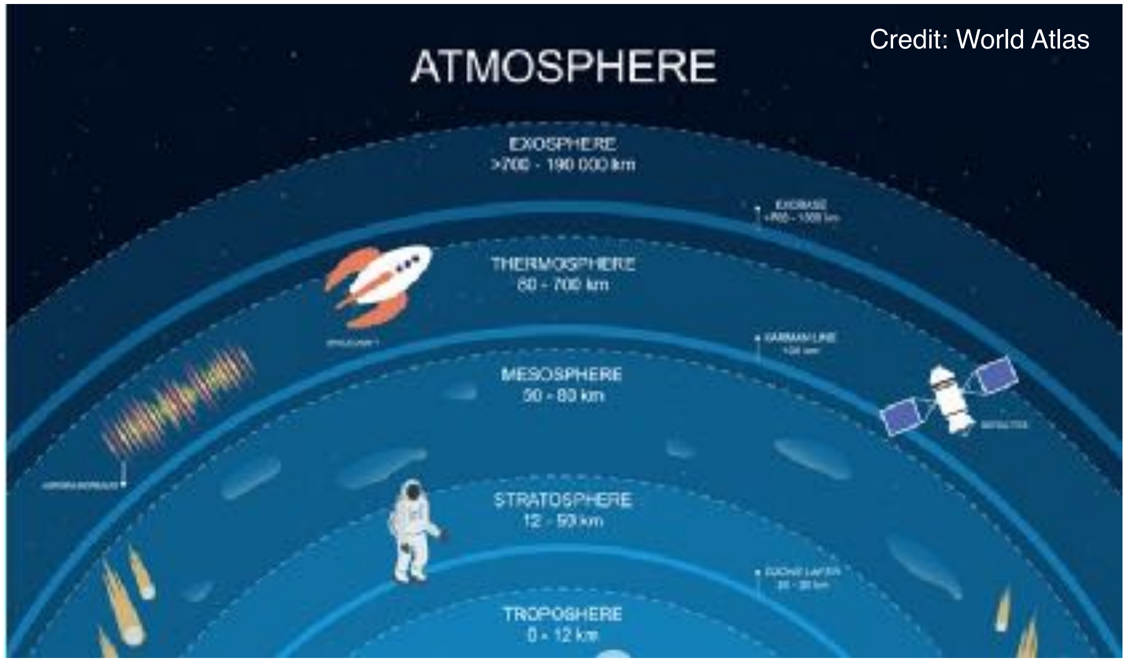
Charge exchange emission

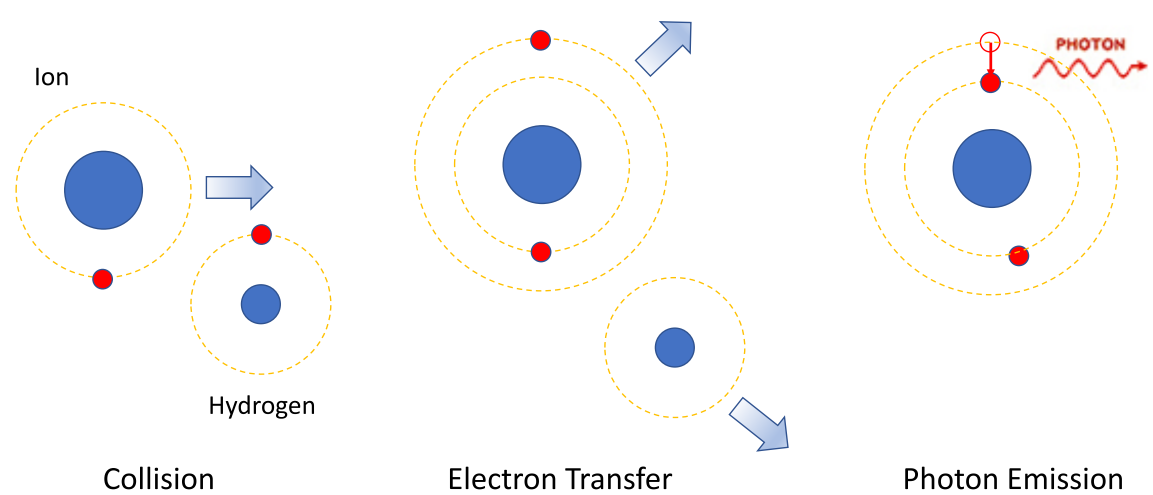




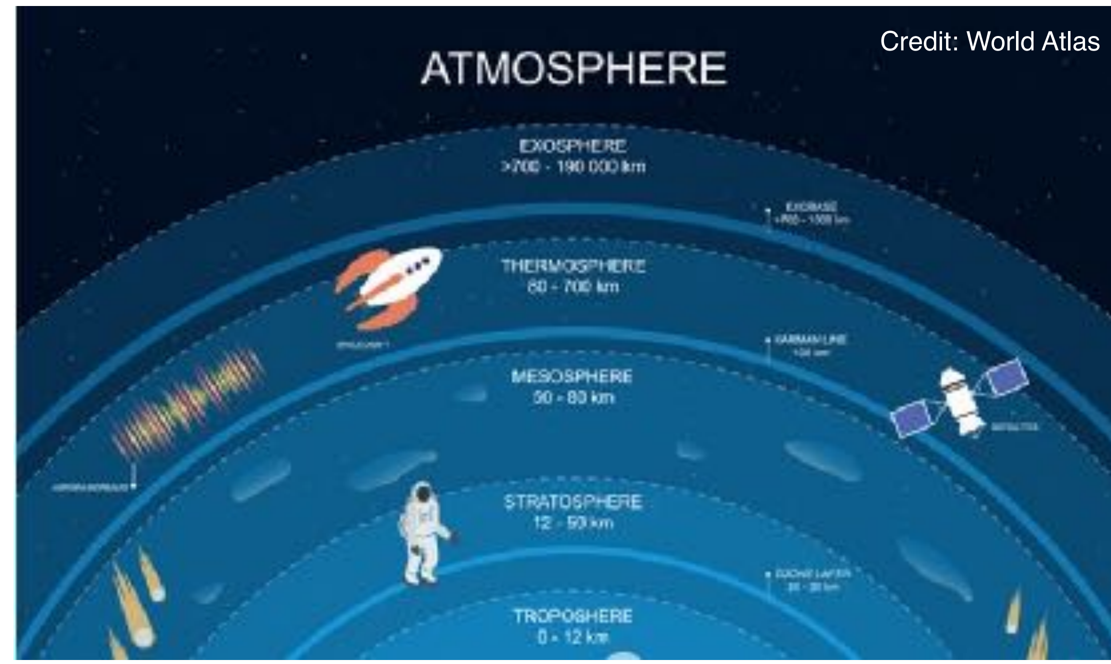
Cravens 1997: Geocoronal X-rays?

Charge exchange emission

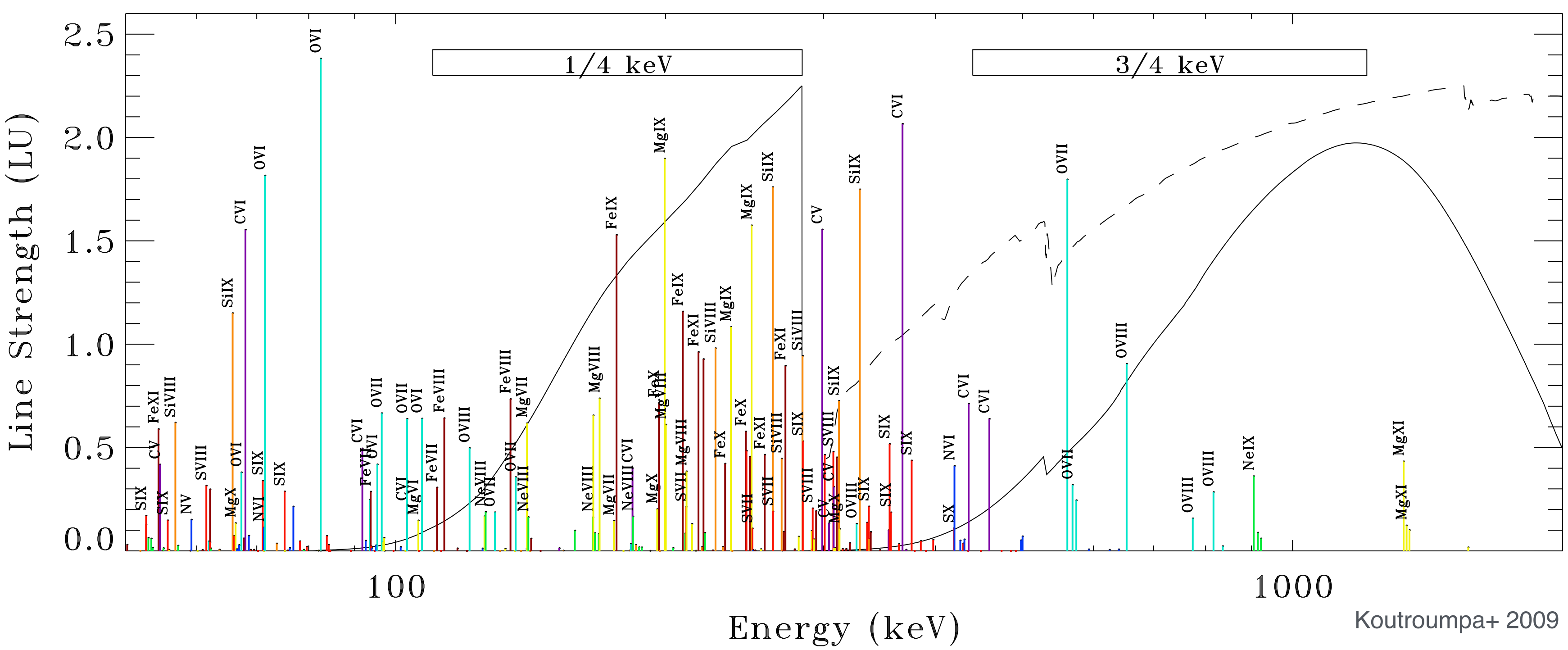
Solar Wind Charge Exchange (SWCX)



Credit: S. Sembay



Cravens 1997: Geocoronal X-rays?



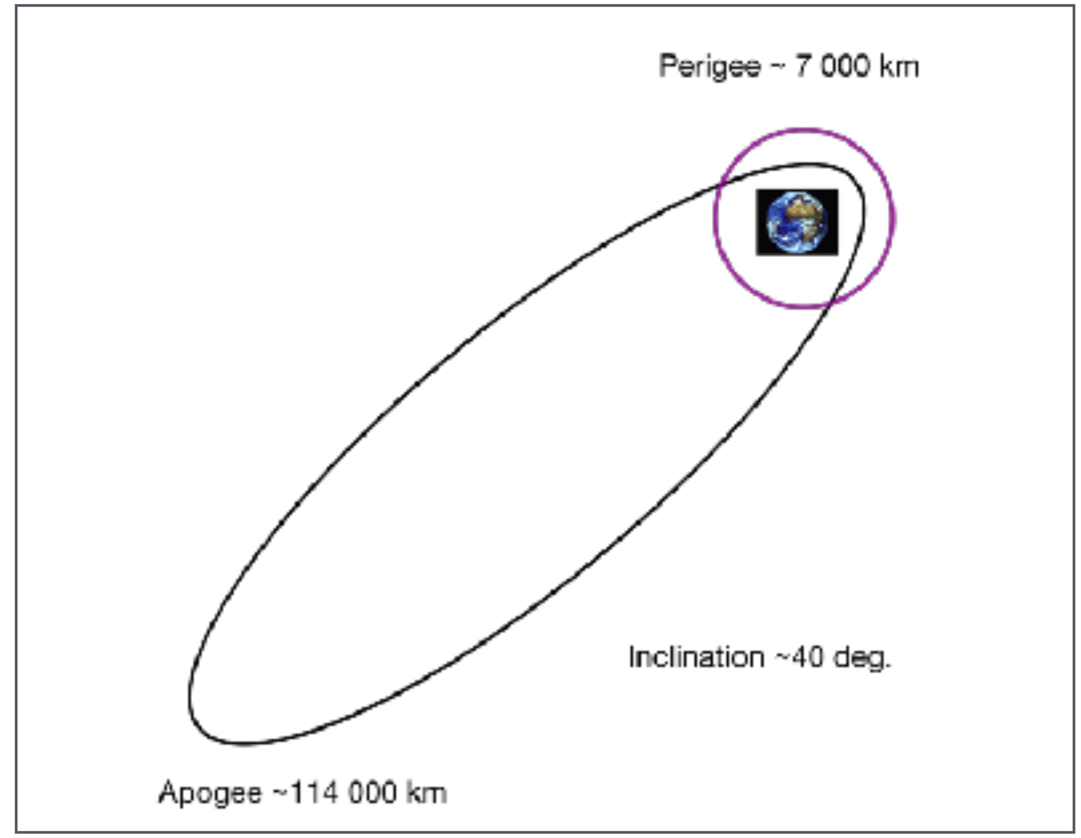
Koutroumpa+ 2009

$$P_{X\text{-ray}} = \int \alpha * N_H * N_{sw} * V_{eff} \, ds$$

$$V_{eff} = \sqrt{(V^2_{SW} + 3kT/m)}$$

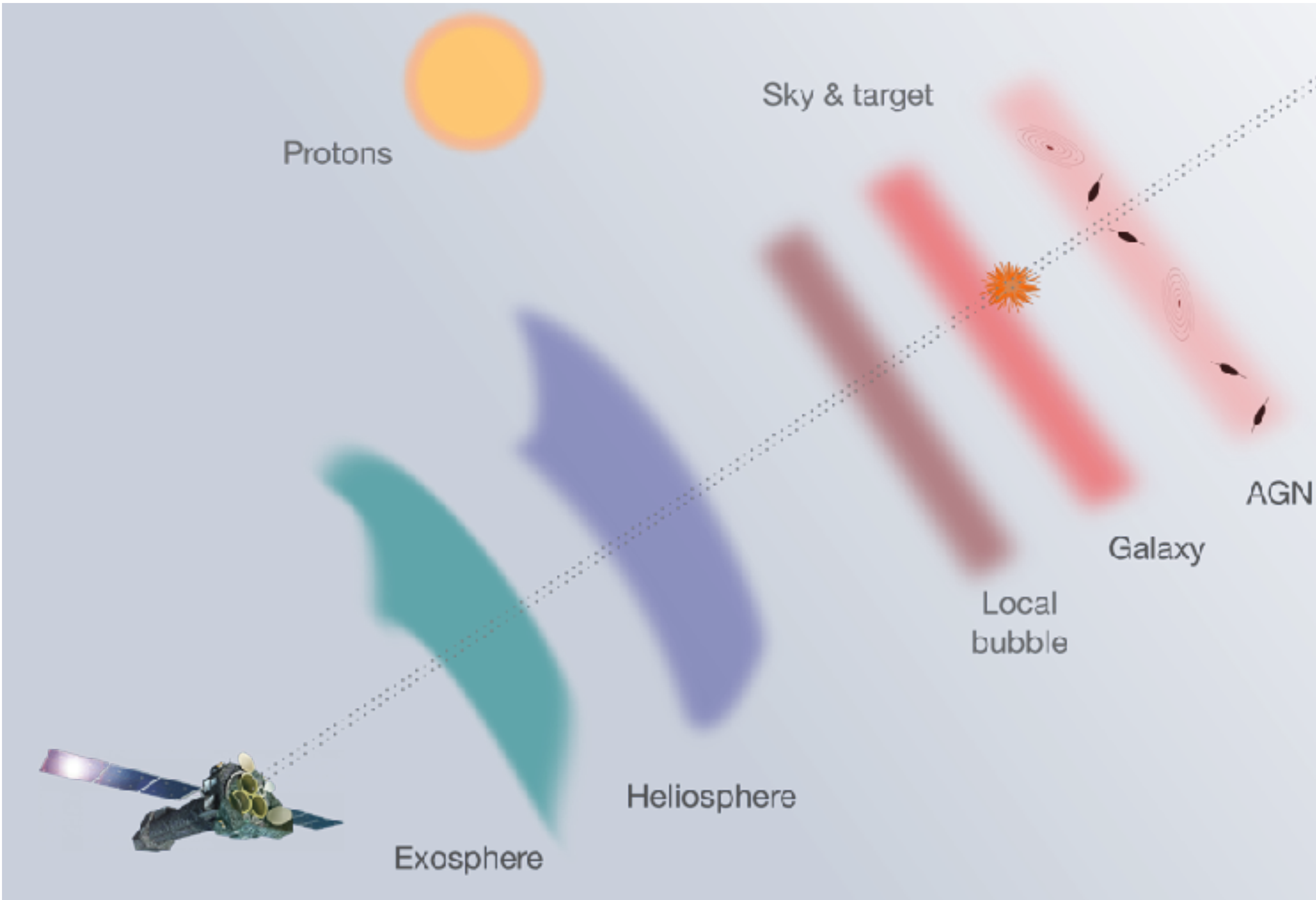
The X-ray sky: XMM-Newton

Launched: December 1999
Targets: high-energy universe

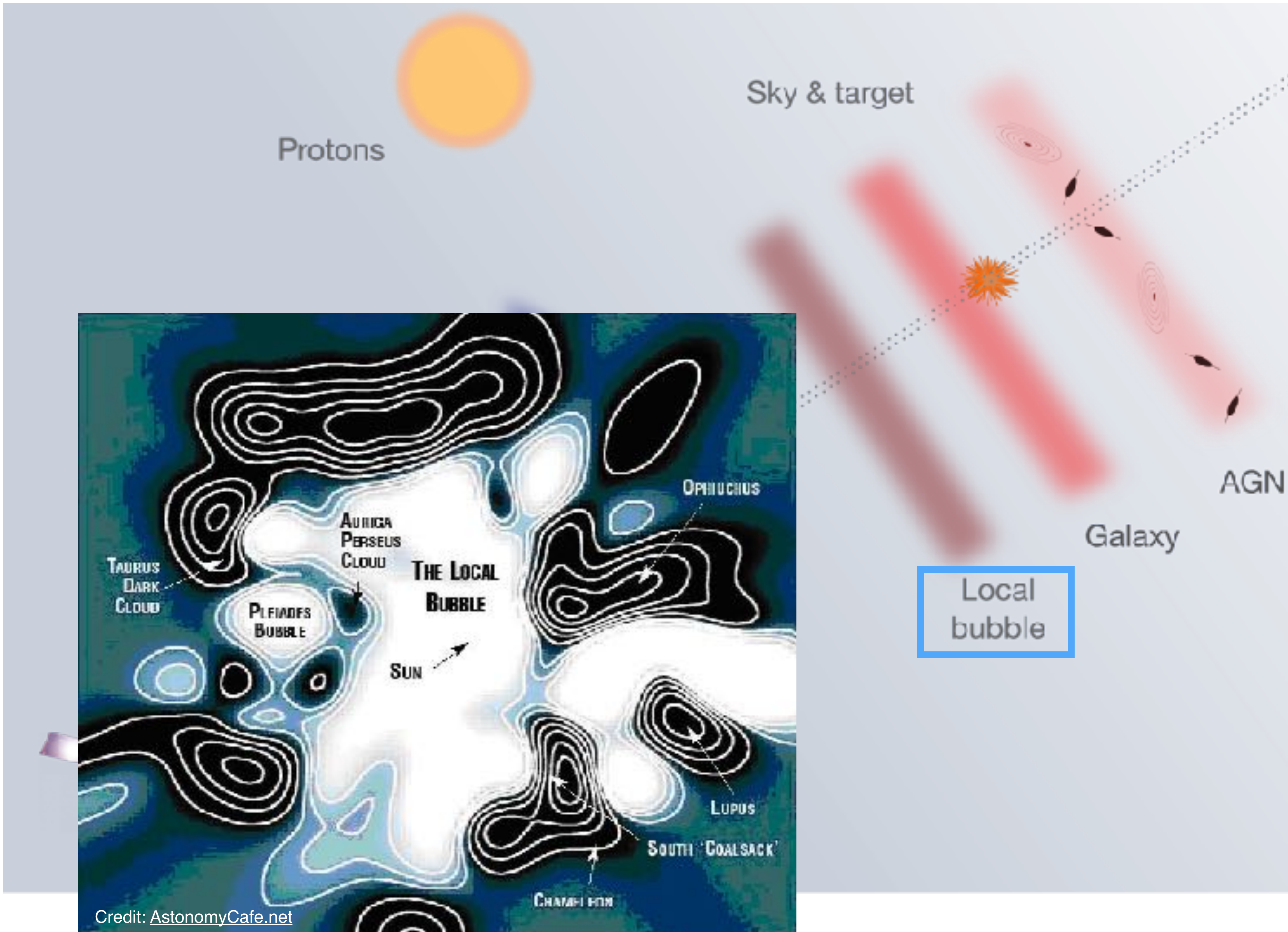


Orbit: with high -ve Z, i.e. below the ecliptic

The X-ray sky: XMM-Newton: line of sight



The X-ray sky: XMM-Newton: line of sight



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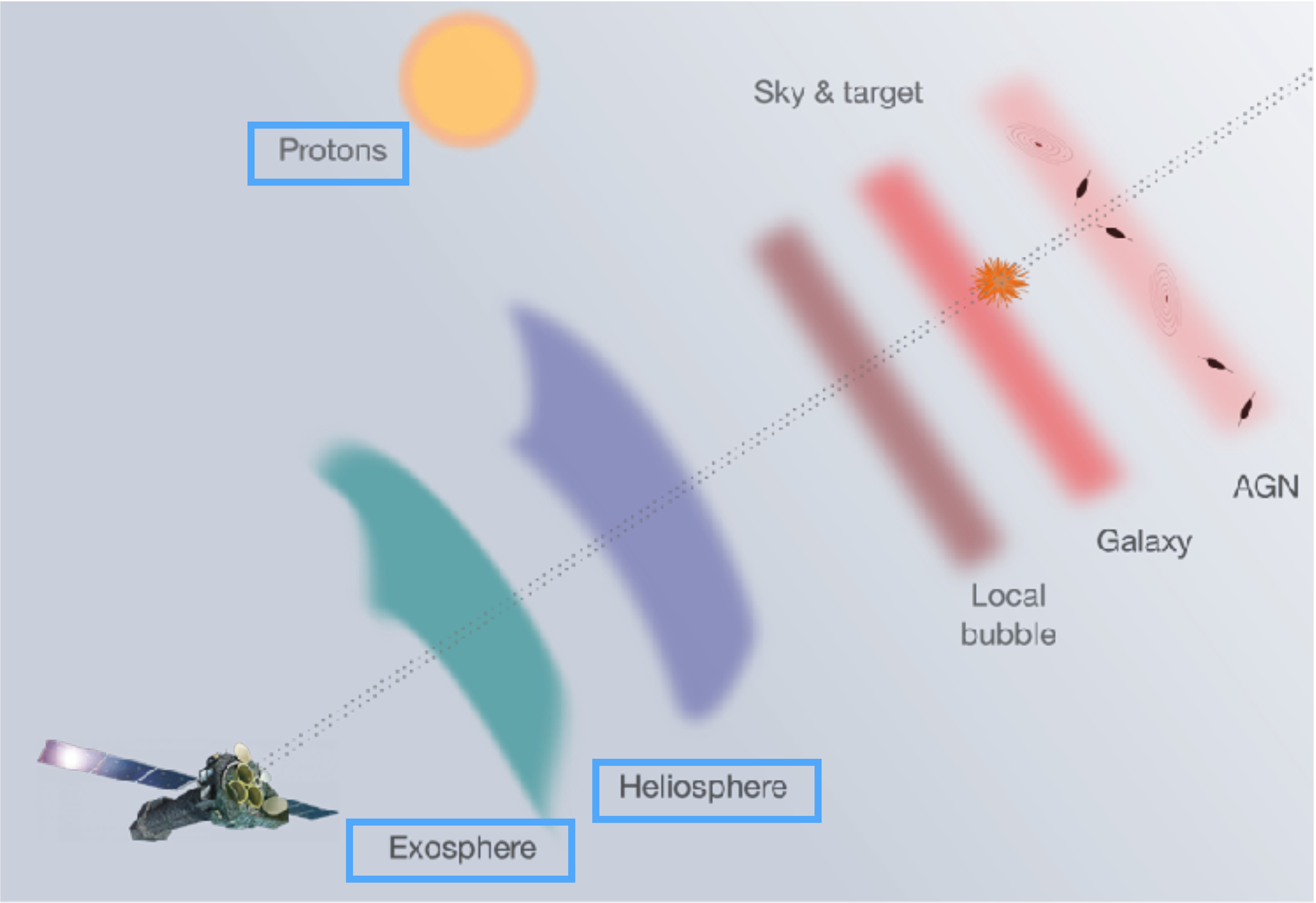
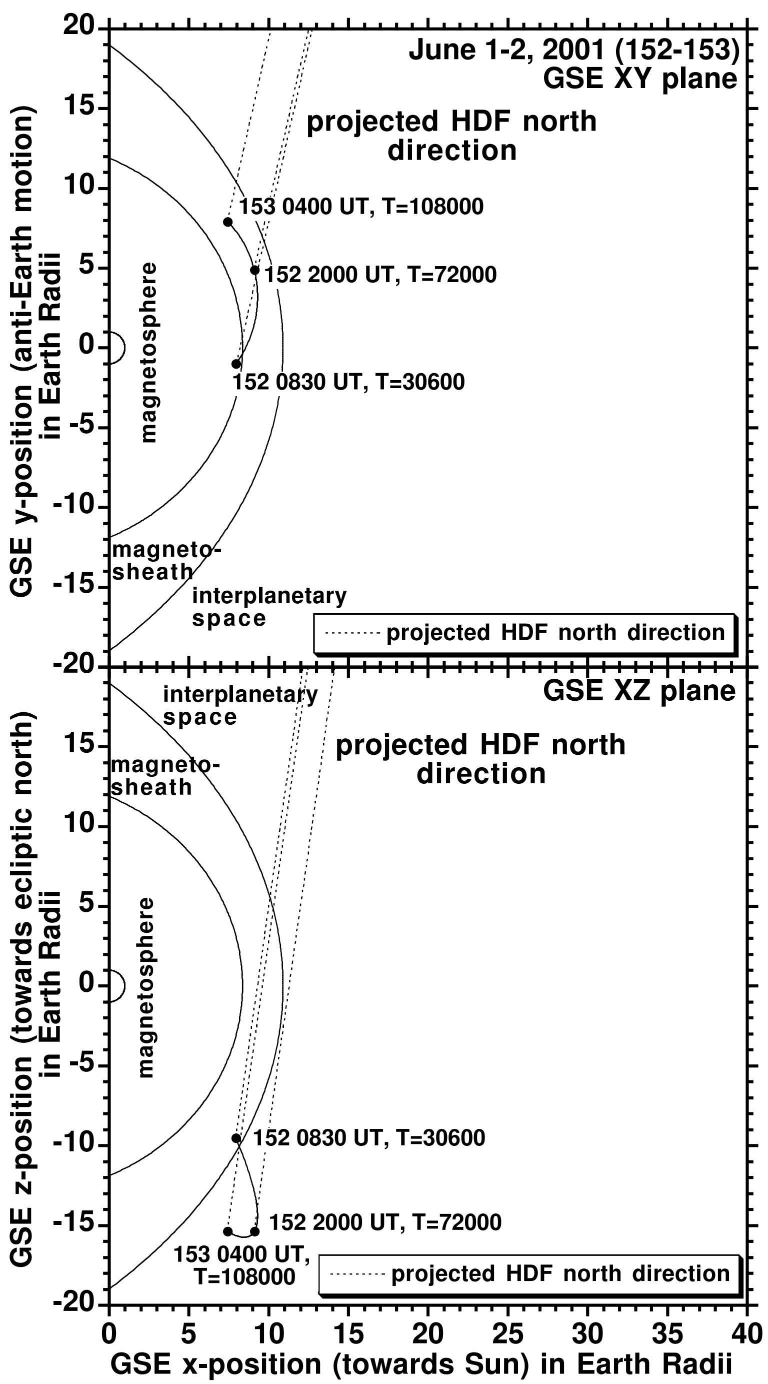
The X-ray sky: XMM-Newton: line of sight



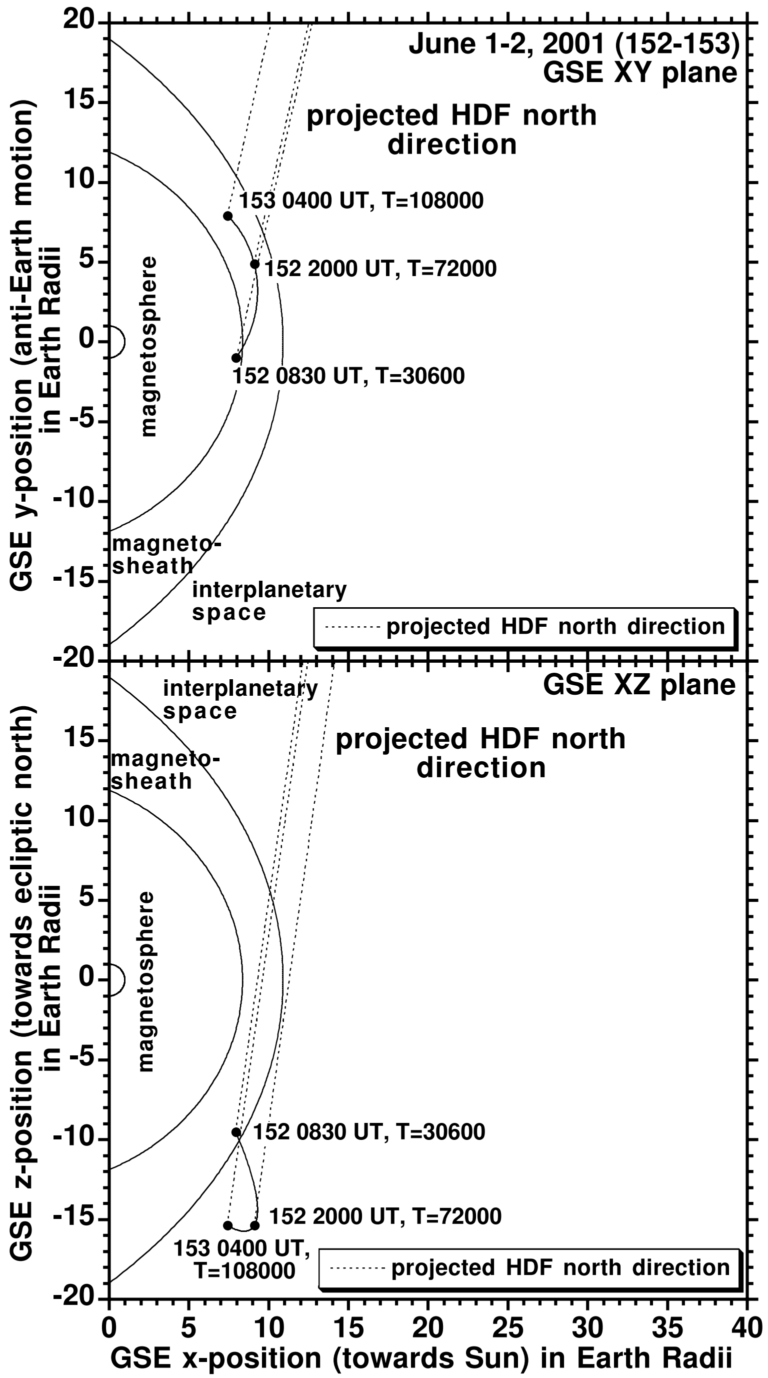
Time variable

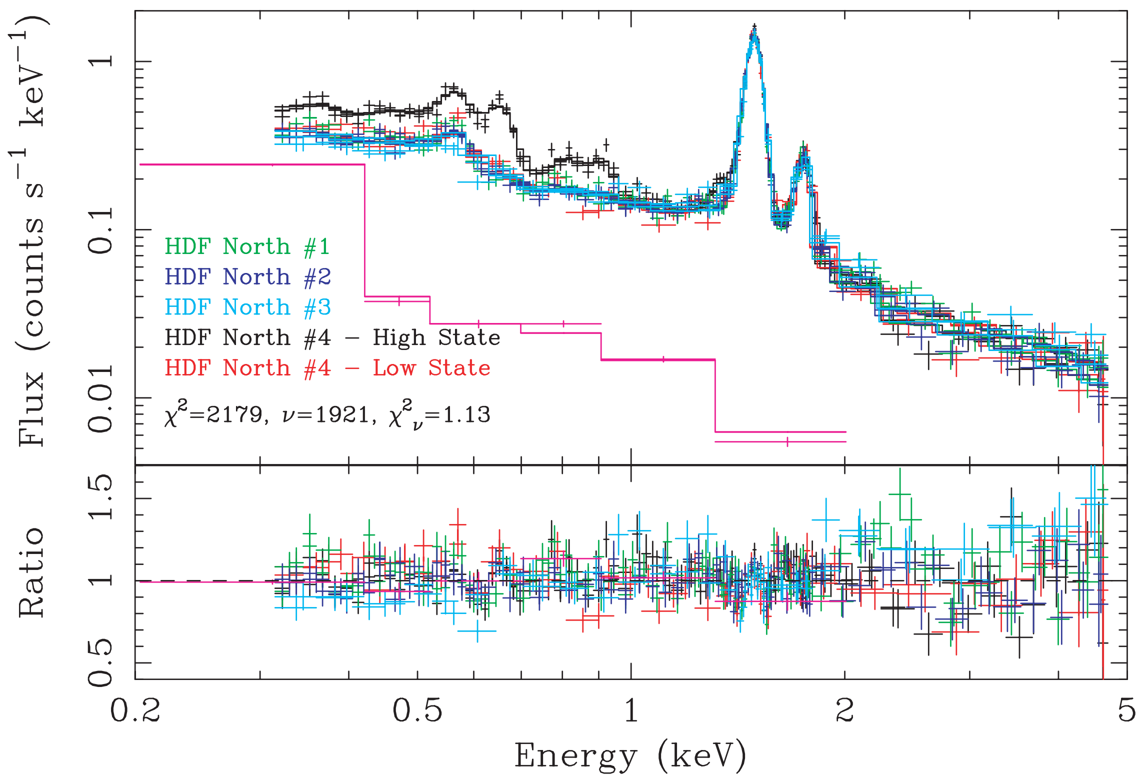
SWCX: detected, XMM: Hubble Deep Field North

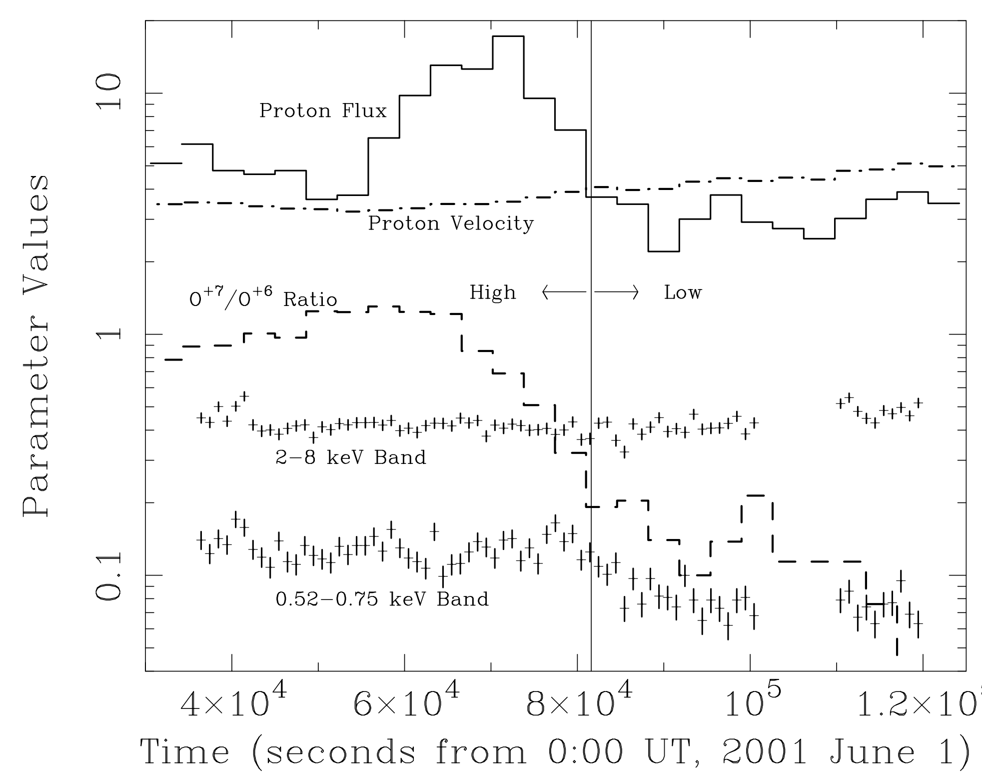


Snowden et al. 2004

SWCX: detected, XMM: Hubble Deep Field North

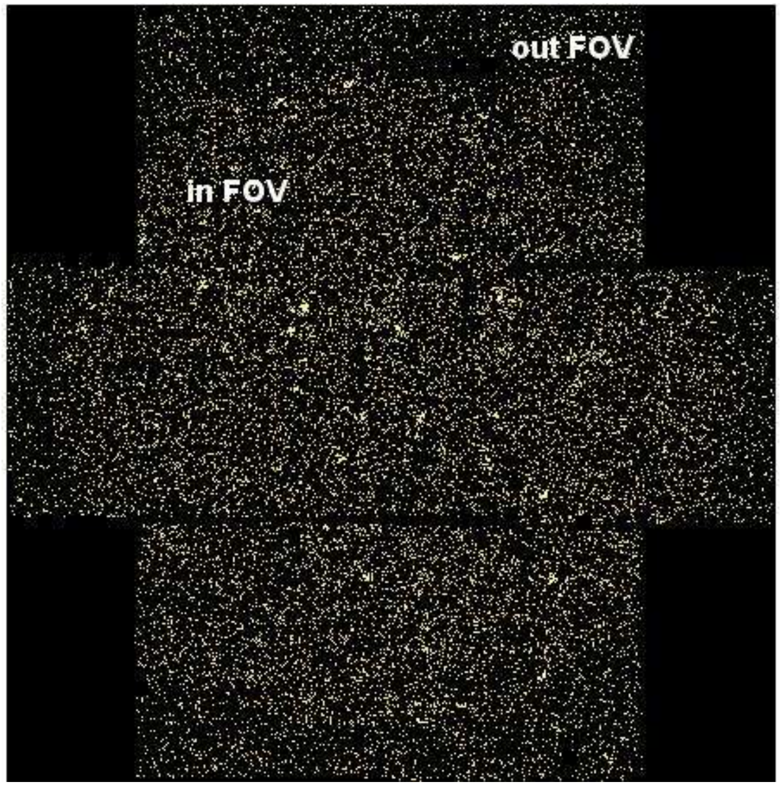


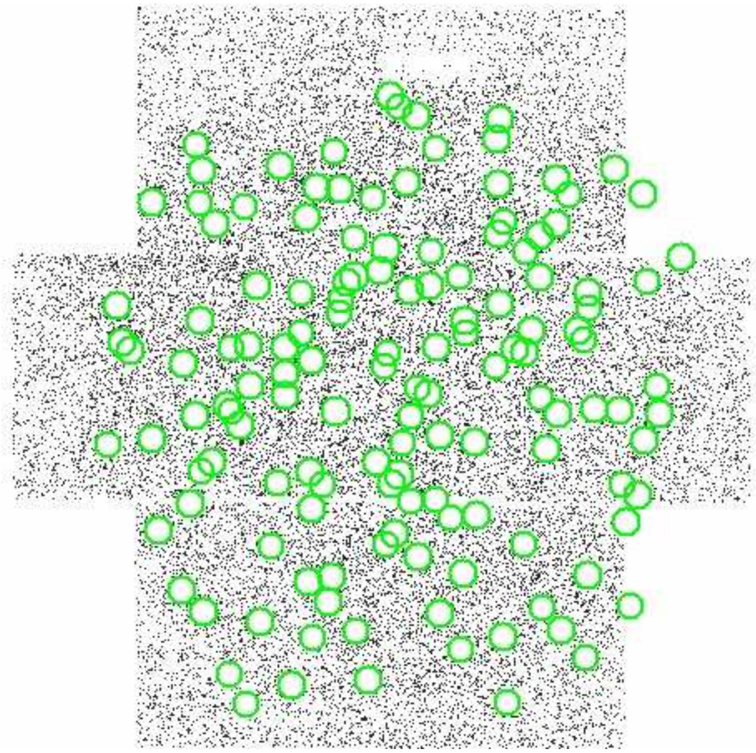




Snowden et al. 2004

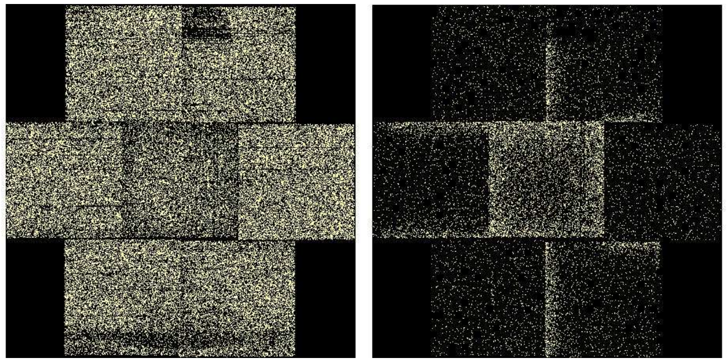
SWCX: detected: XMM-Newton survey & analysis

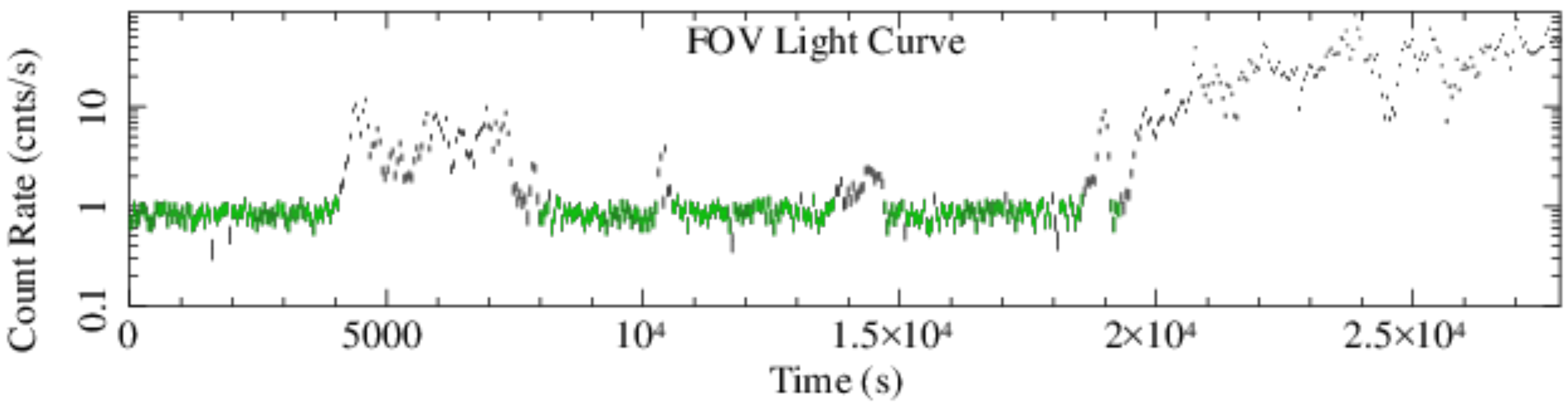


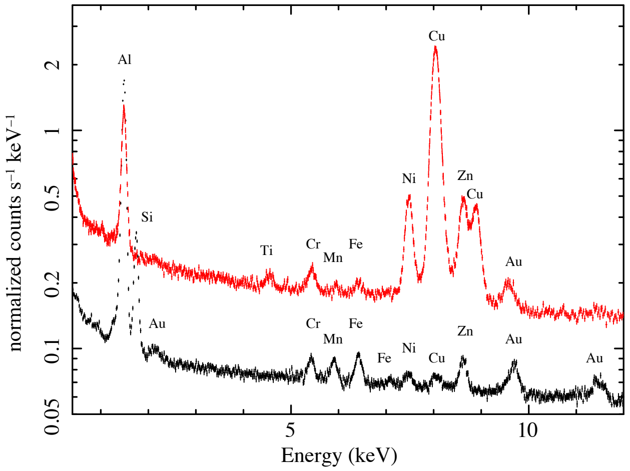


Cleaning X-ray data, for diffuse emission studies

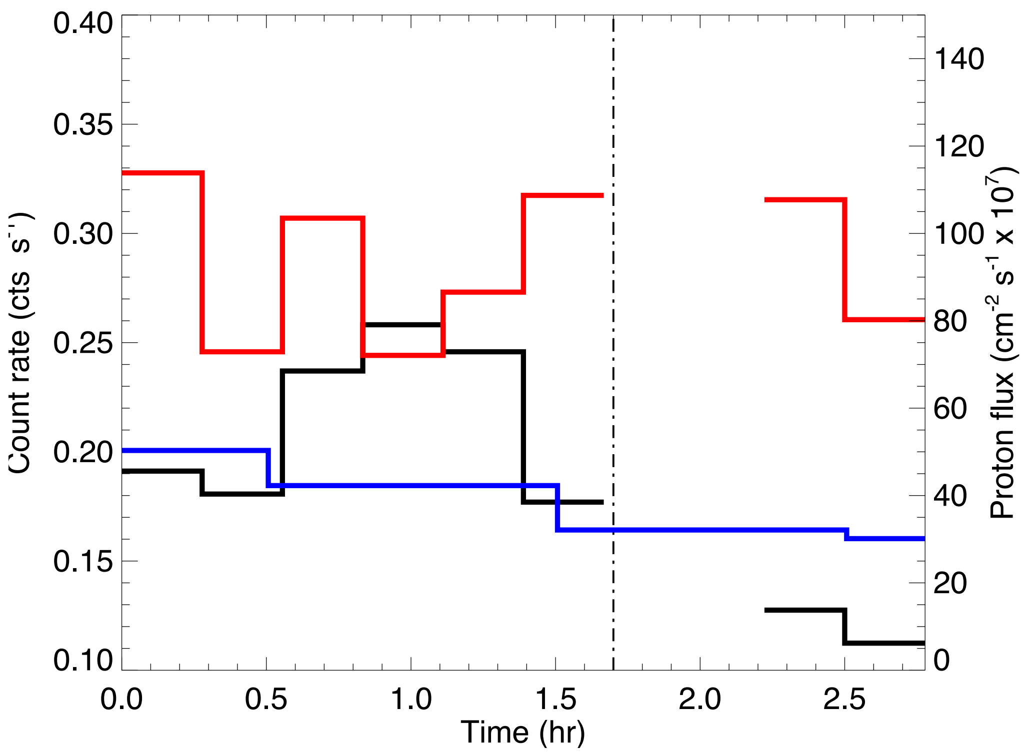
- point source removal
- soft proton removal
- particle-induced background







SWCX: detected: XMM-Newton survey



Carter et al. 2011

Archival study: 2000 - 2011

Checked for time variable SWCX

~3.5 % observations show time-variable SWCX

Solar cycle dependence

More SWCX seen at ~sub solar point

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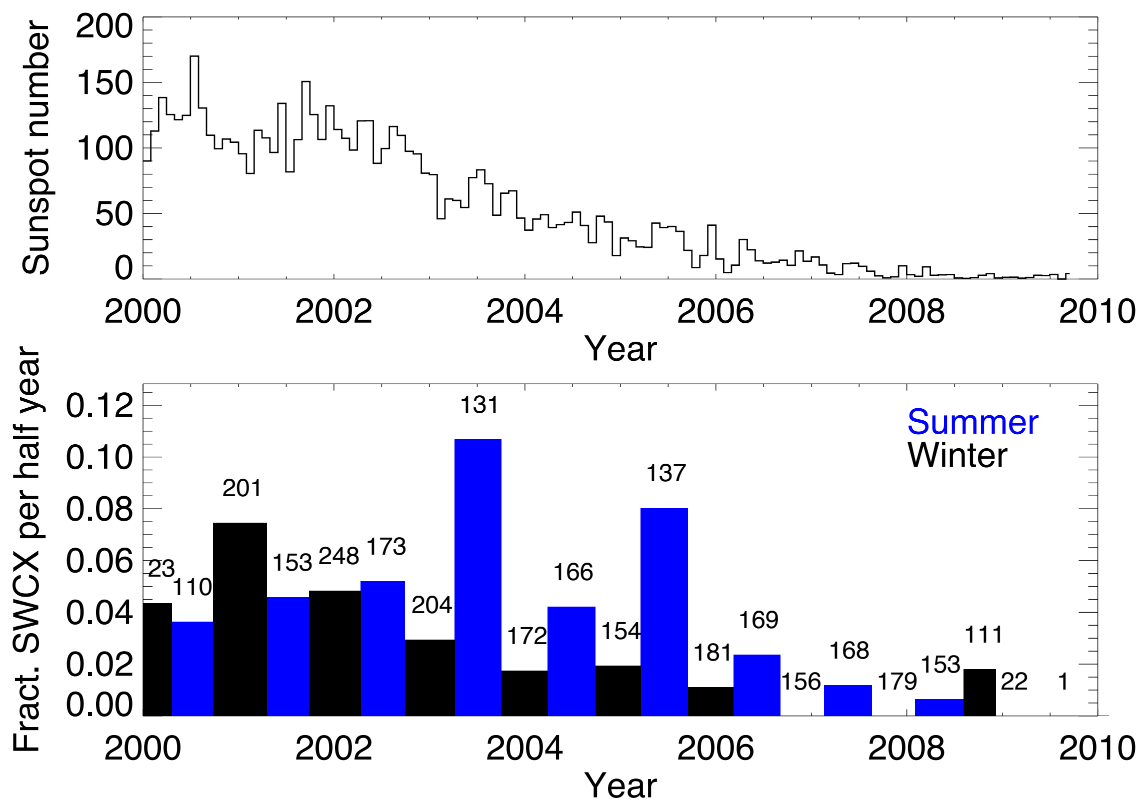
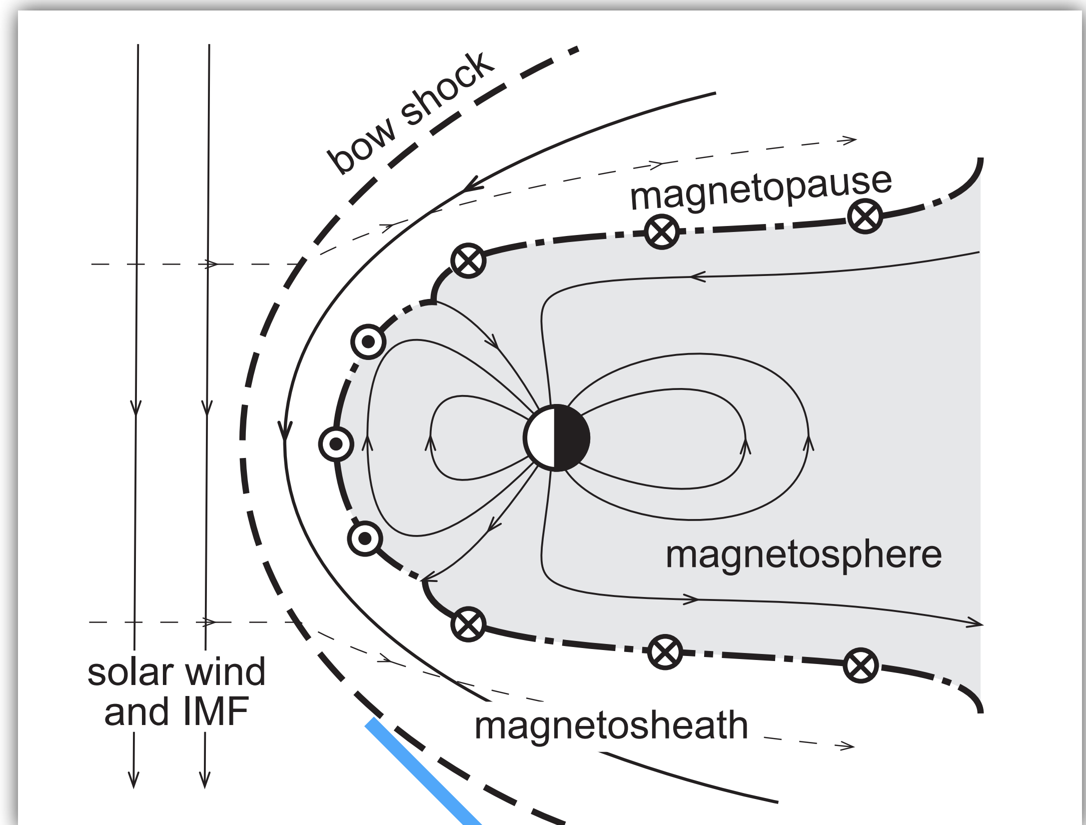
SWCX: detected: XMM-Newton survey results





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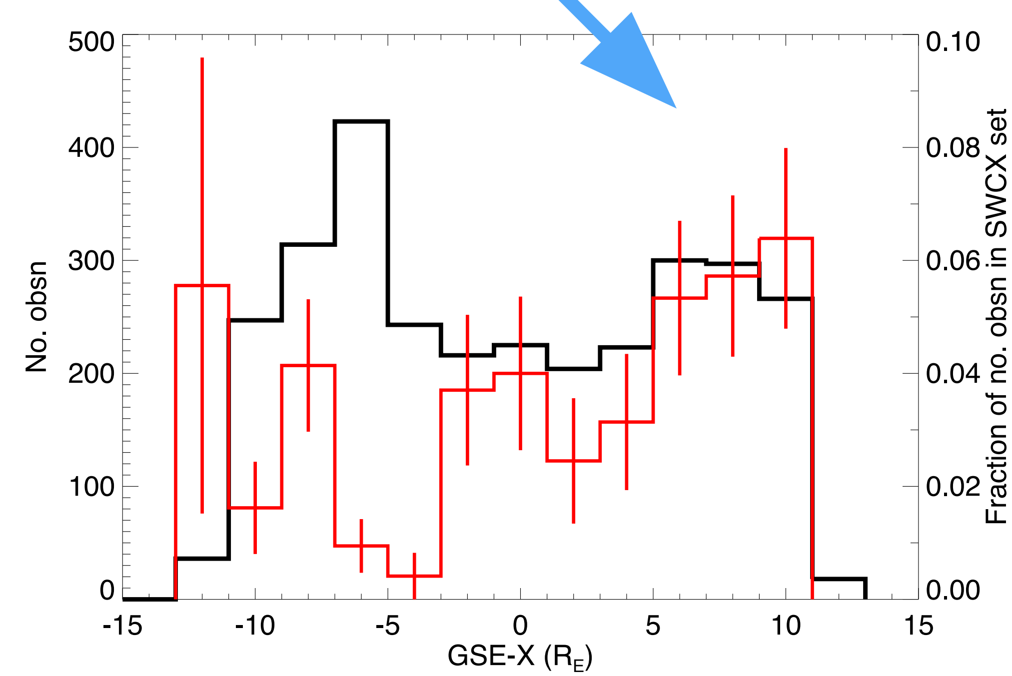
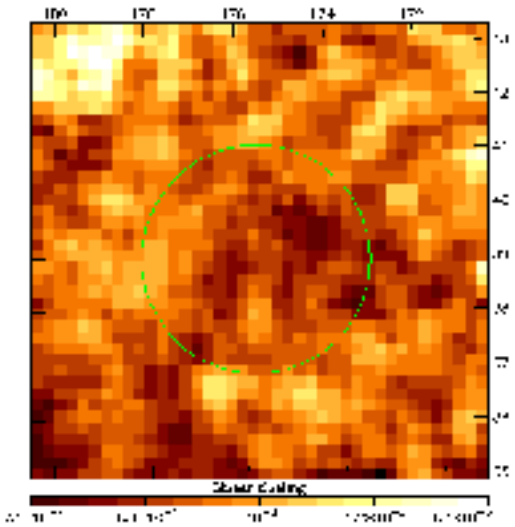
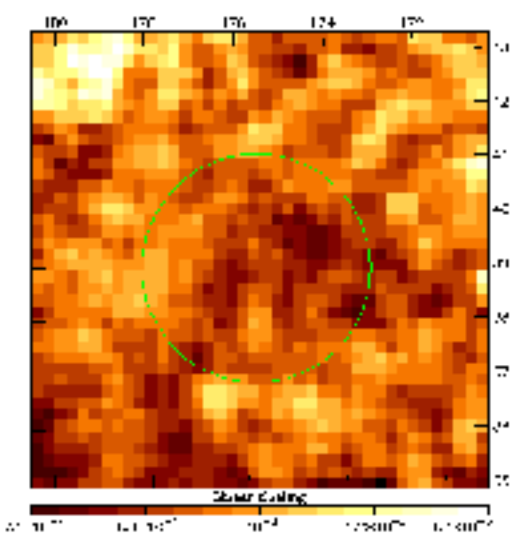


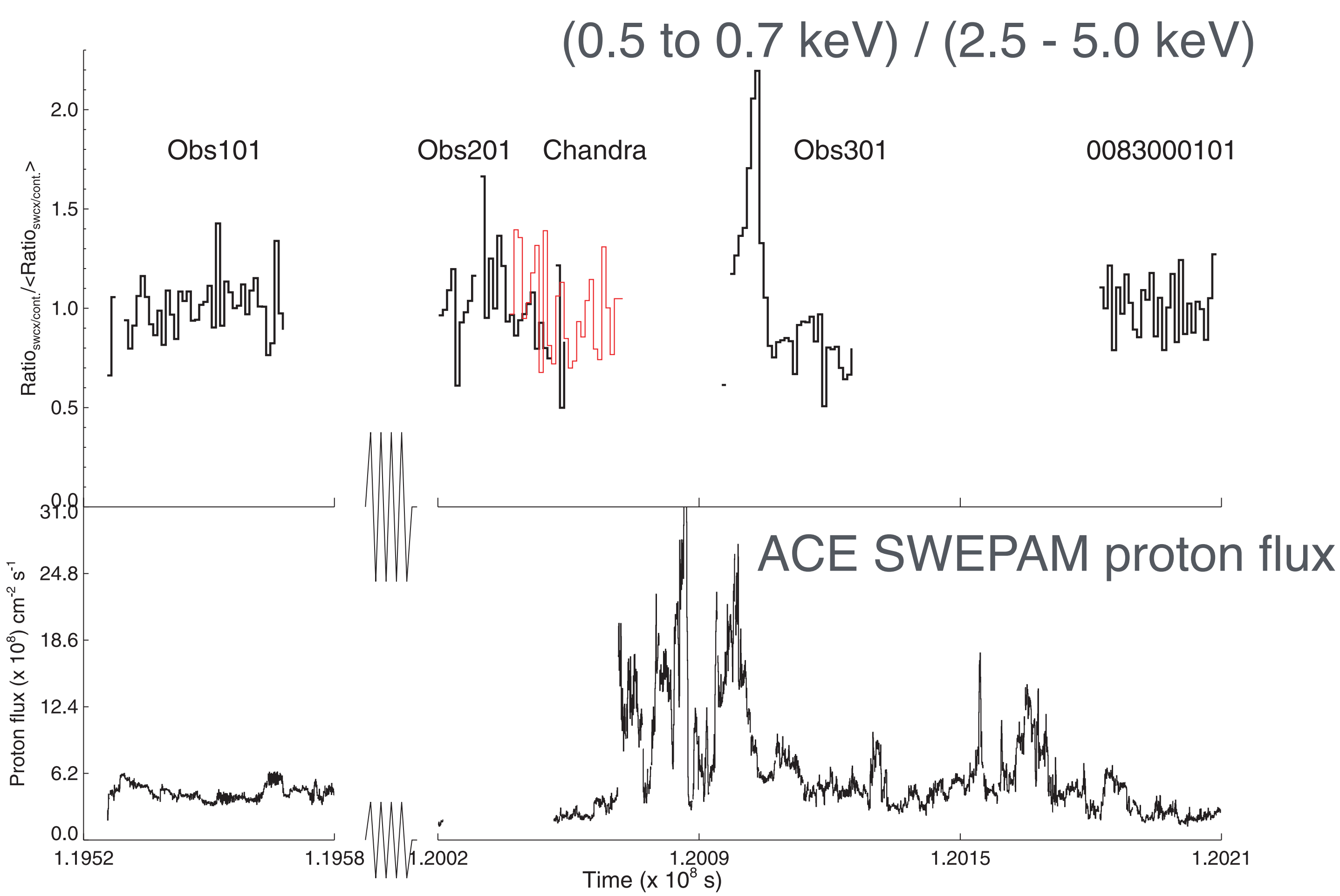
XMM-Newton: detecting a Coronal Mass Ejection



Carter et al. 2010

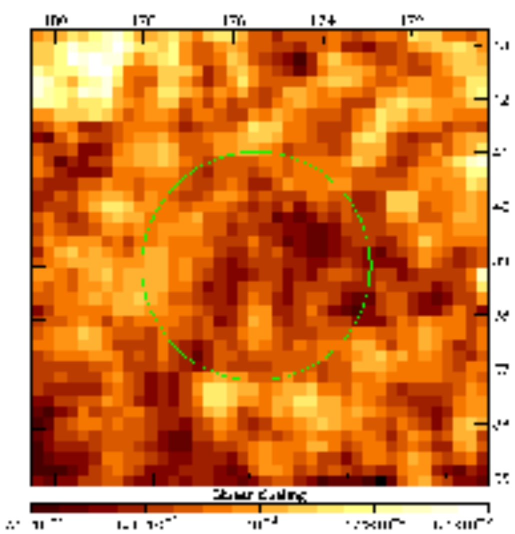
XMM-Newton: detecting a Coronal Mass Ejection

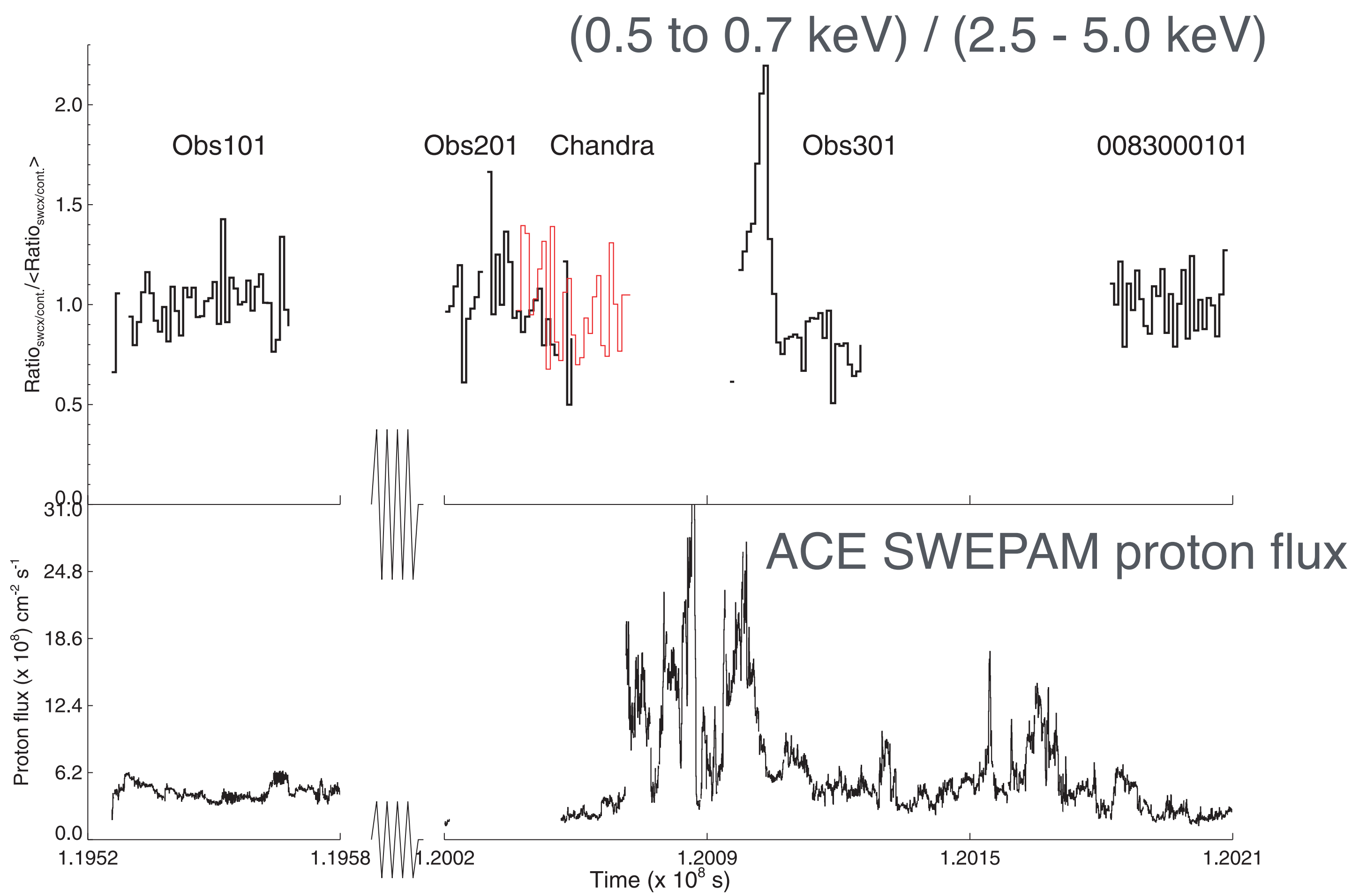


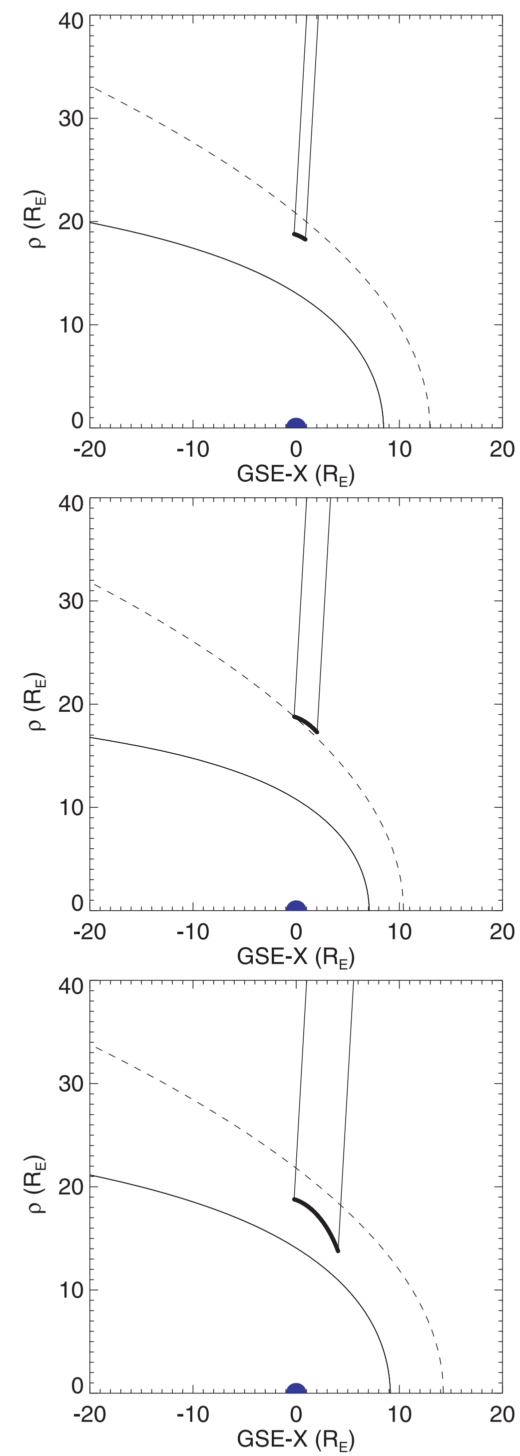


Carter et al. 2010

XMM-Newton: detecting a Coronal Mass Ejection

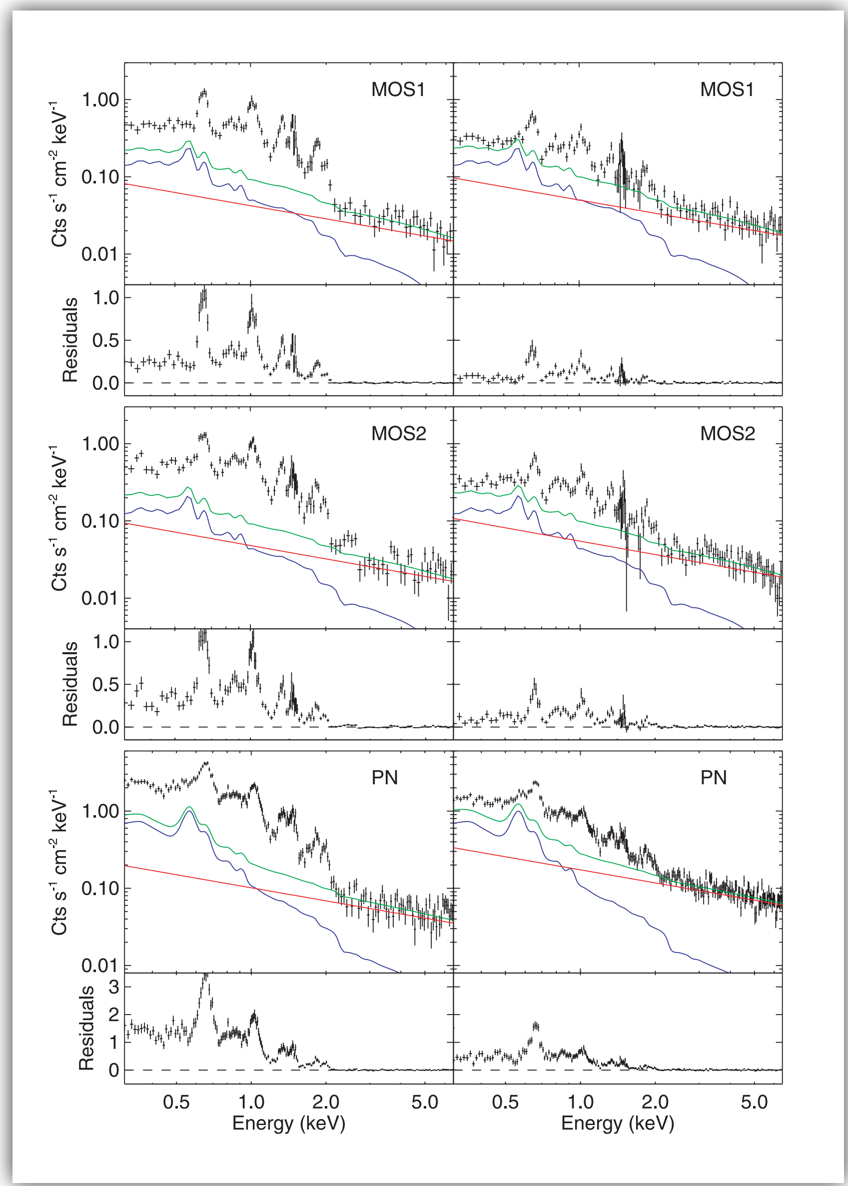


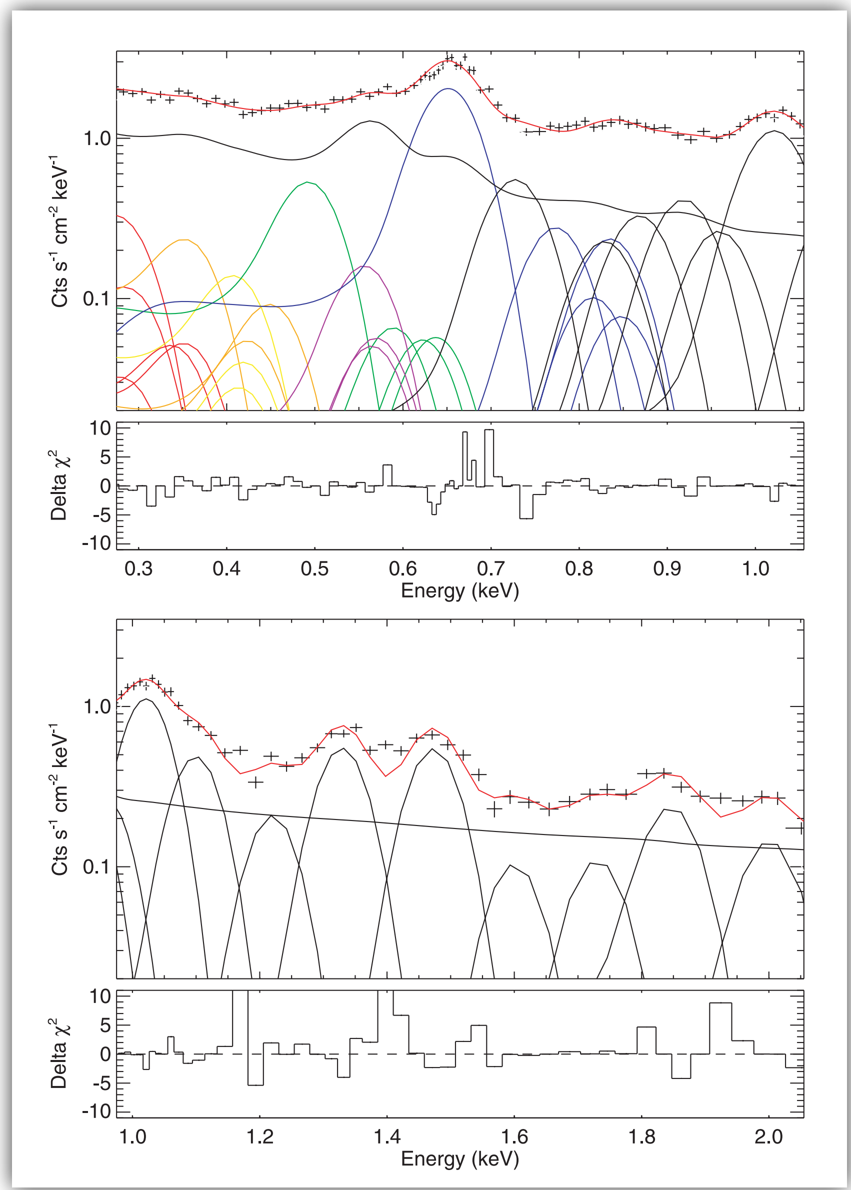


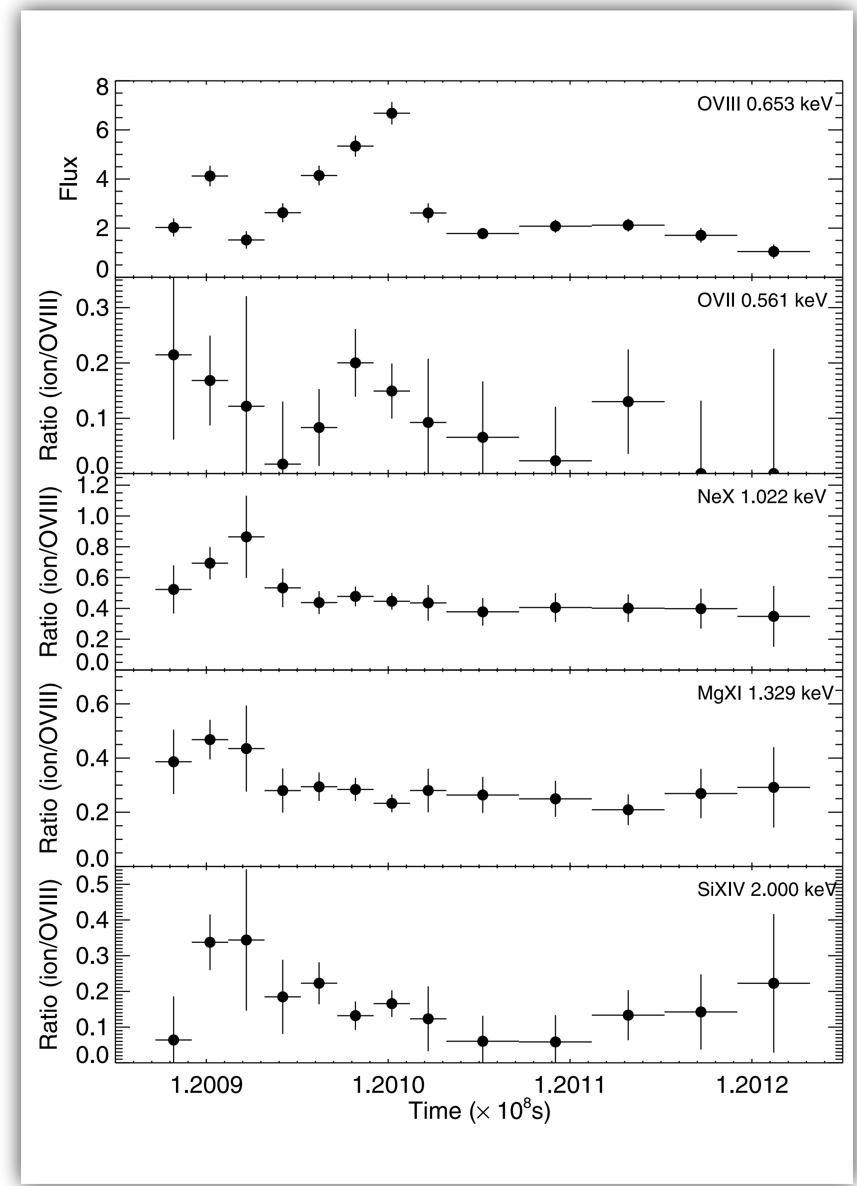


Carter et al. 2010

XMM-Newton: Coronal Mass Ejection spectrum

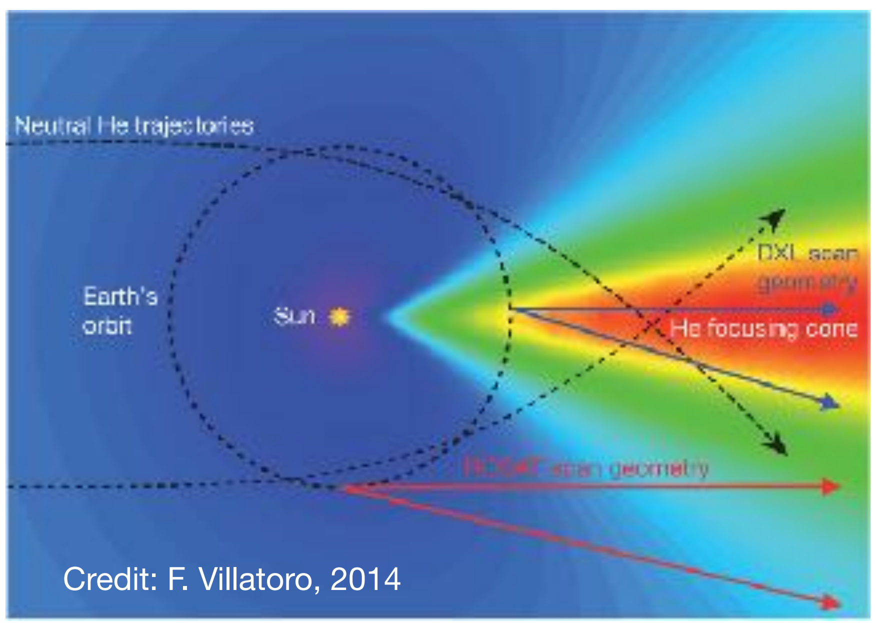






Carter et al. 2010

The Heliosphere: also SWCX: simulations

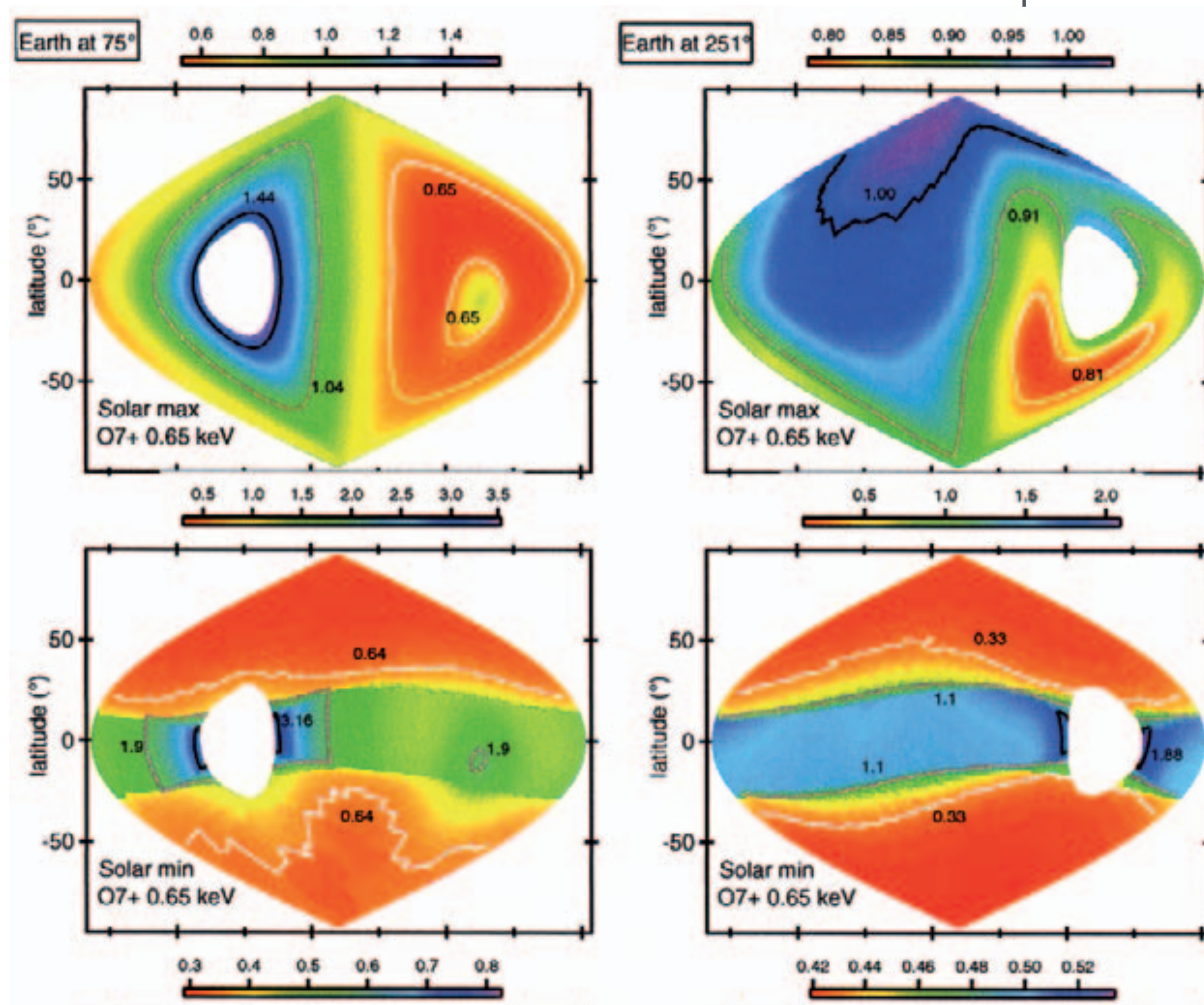


View from downstream

View from upstream

Solar max.

Solar min.



Solar min.: equatorial belt clear

Downwind dominated by CX with He.

Koutroumpa et al. 2006: O7+ line

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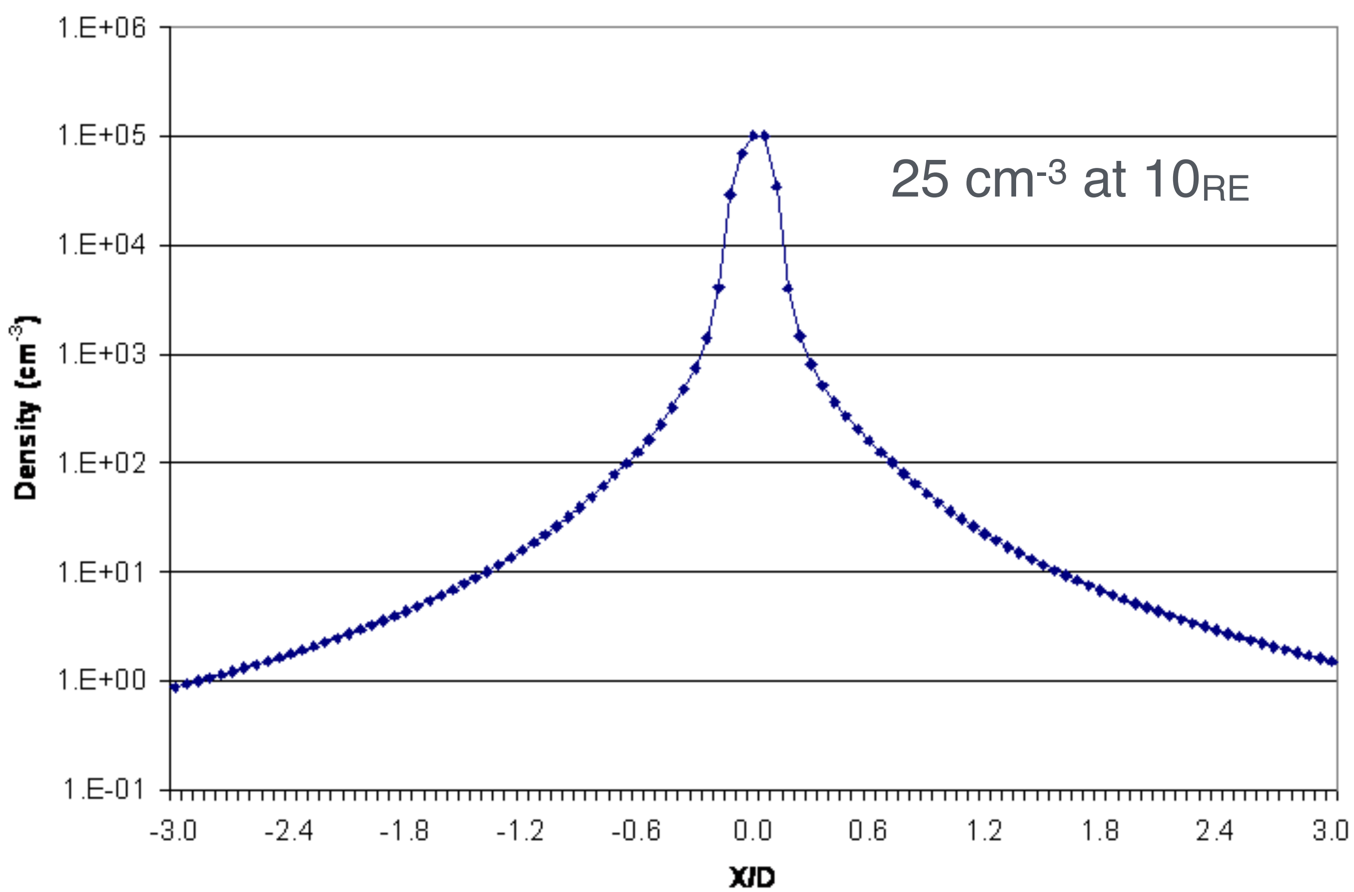
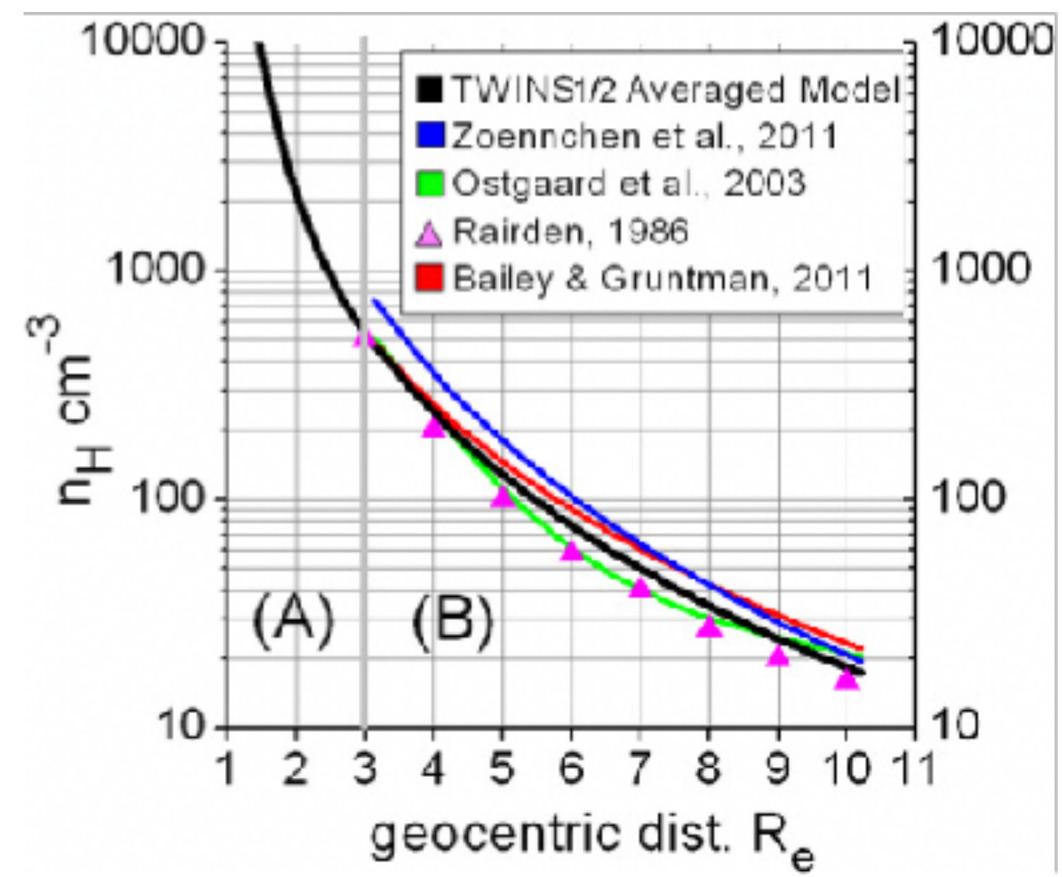
The exosphere: density distribution controversy

$P_{X\text{-ray}} = \int \alpha * N_H * N_{sw} * V_{sw}\, ds$



Hodges 1994



Hodges: some control by season and $F_{10.7}$

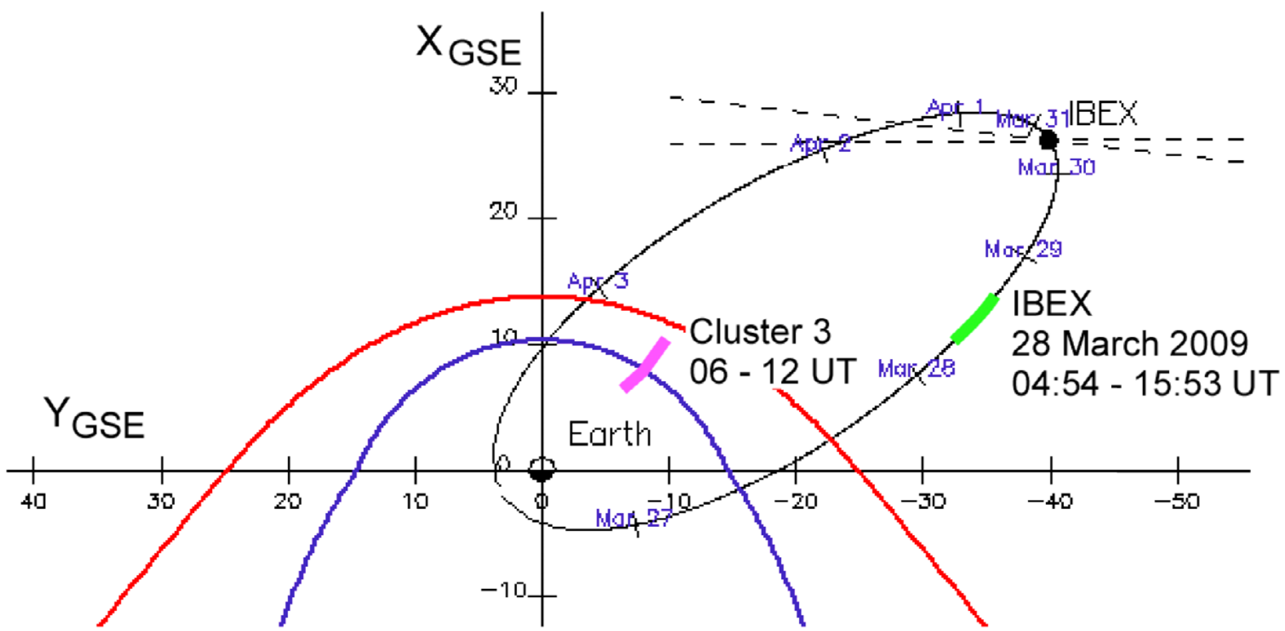
Nightside only, limited distance range

Know N_H, know your X-ray signal

20 cm^{-3} at $10R_E$

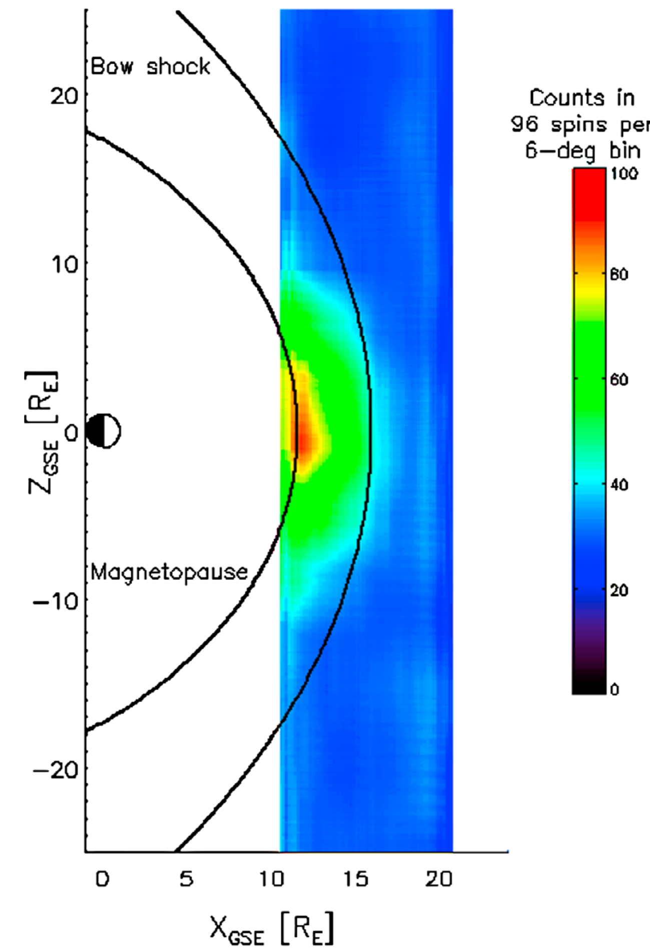
The exosphere: densities, dayside

IBEX Orbit



Fuselier et al. [2010]

IBEX ENA Observation



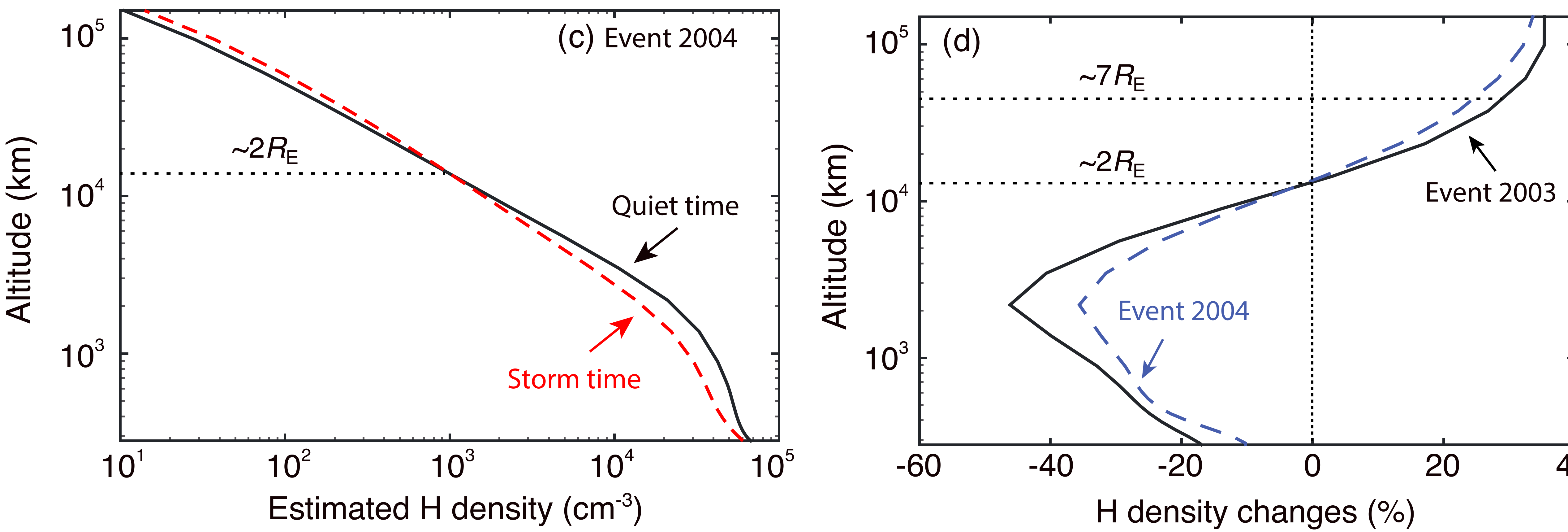
Dayside ~ 4 - 10 cm^{-3} at R_0

Assumes homogeneous magnetosheath

Solar minimum observations

The exosphere: effects of storms

Qin et al. 2017



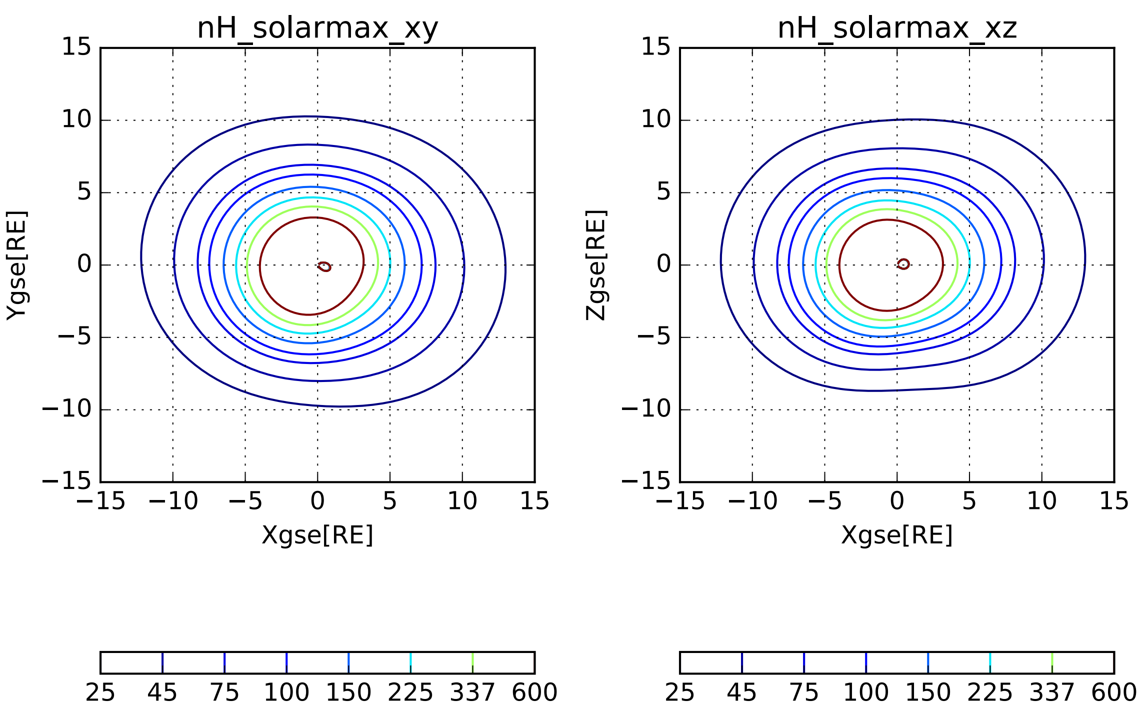
Redistribution of N_H during storms

Competition between CX (H and O+, H and H+) to send H into exosphere)

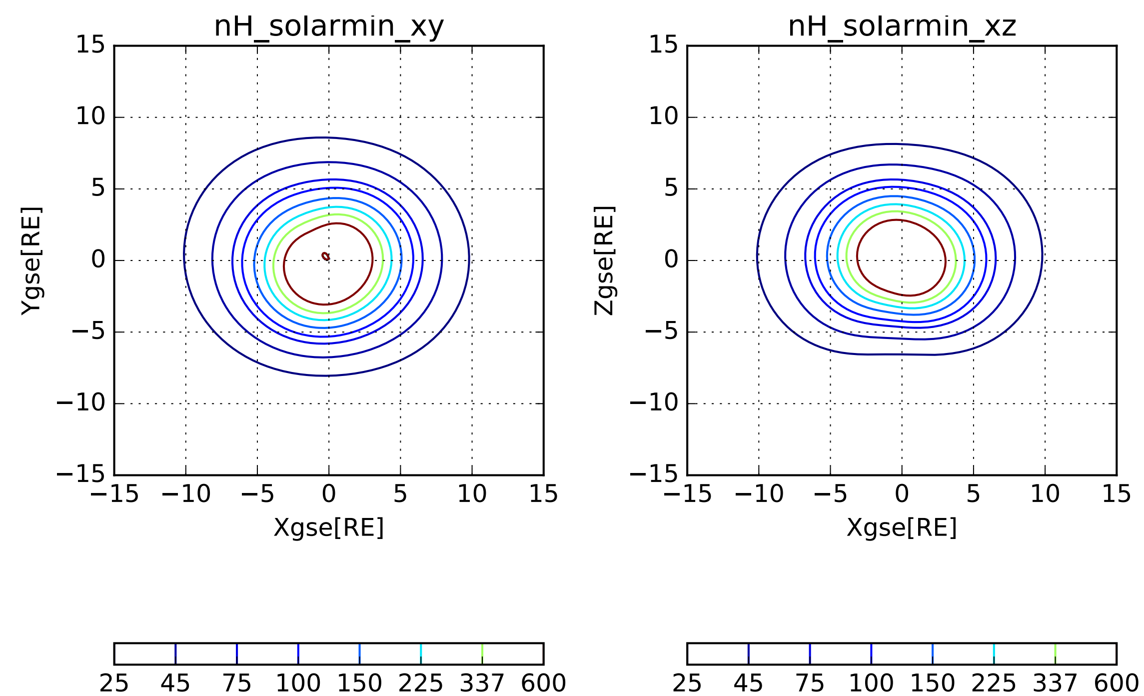
Makes changes to ring current through energetic neutral atom production

The exosphere: solar cycle dependence

Neutral density at solar maximum



Neutral density at solar minimum



At solar maximum, N_0 = ~45 cm^{-3}
At solar minimum, N_0 = ~25 cm^{-3}

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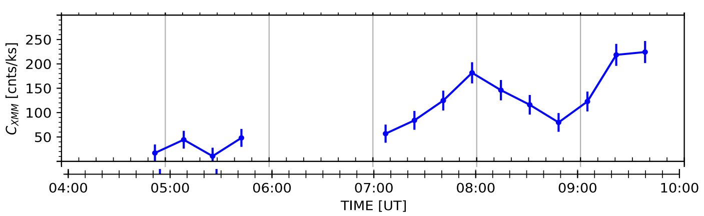
The exosphere: extracted from XMM observations



- (summed background) = SWCX to get 'C_{XMM}'

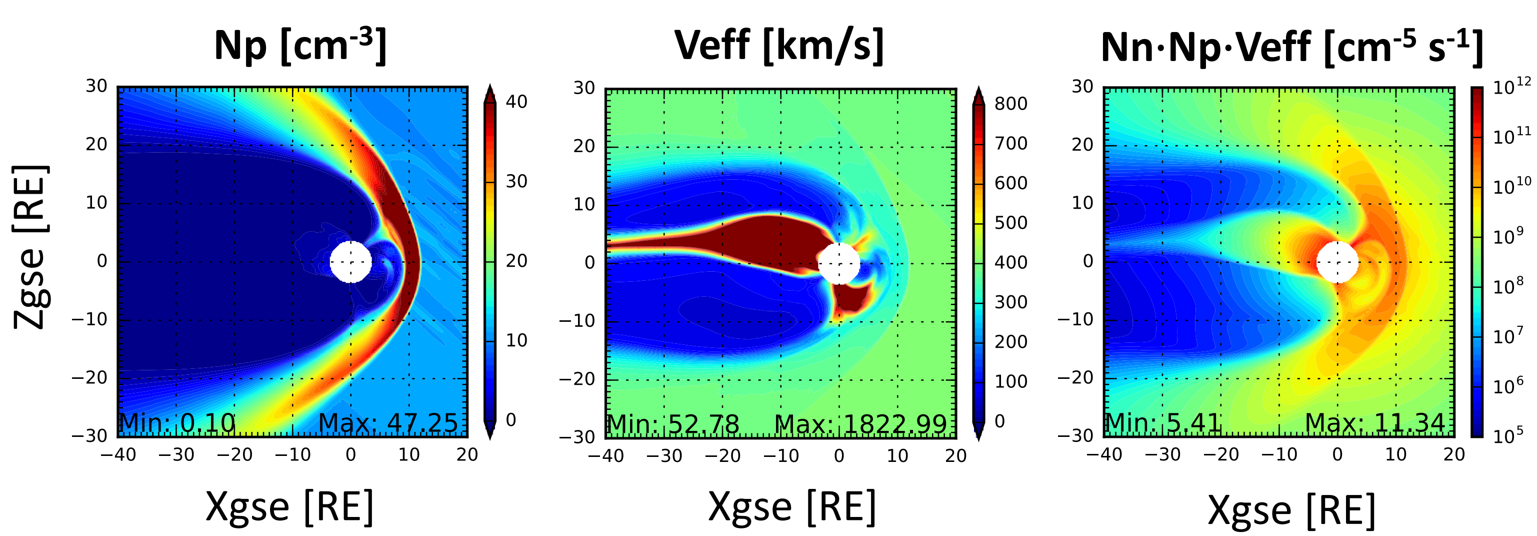
$P_{X\text{-ray}} = \int \alpha * N_H * N_{sw} * V_{eff}\, ds$

$V_{eff} = \sqrt{(V^2_{SW} + 3kT/m)}$

Estimate N_0 by adjusting modeled count rates (C_{Xray}) to XMM count rates (C_{XMM}):

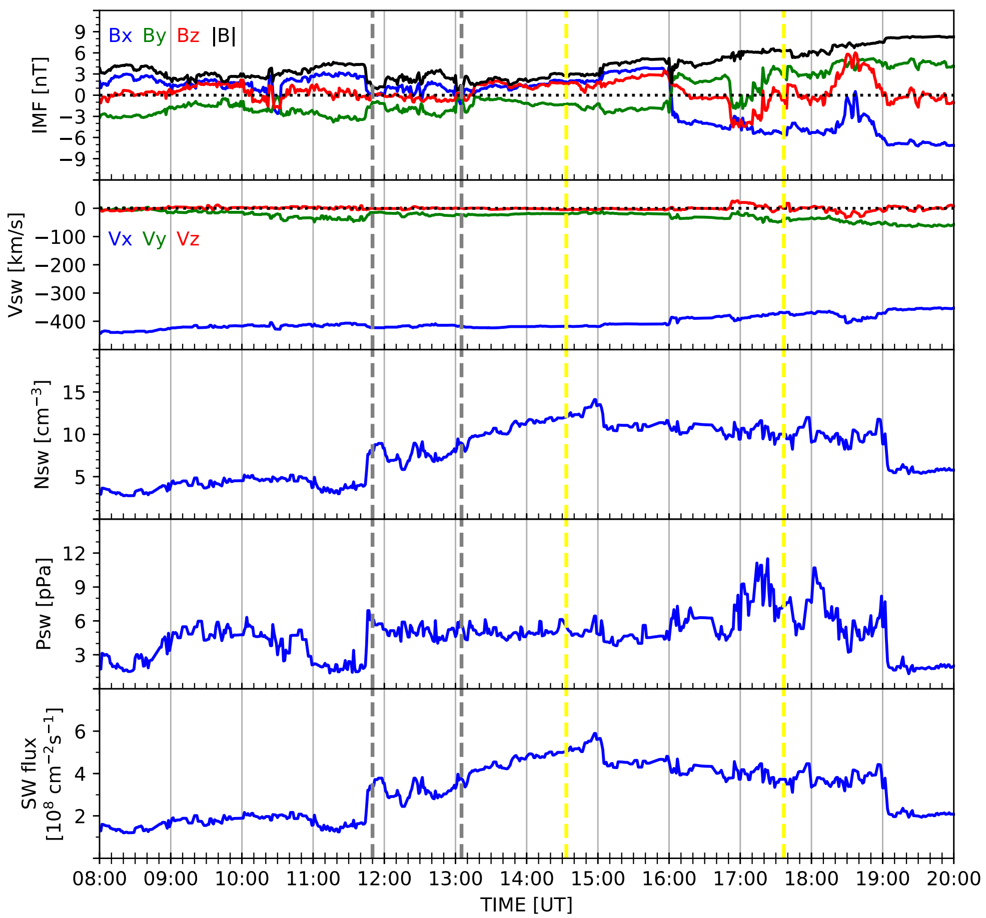
$$C_{Xray} = C_{XMM} \quad \rightarrow \quad N_0 = \frac{4\pi E_{ave}}{\alpha \Omega A Q} C_{XMM}$$

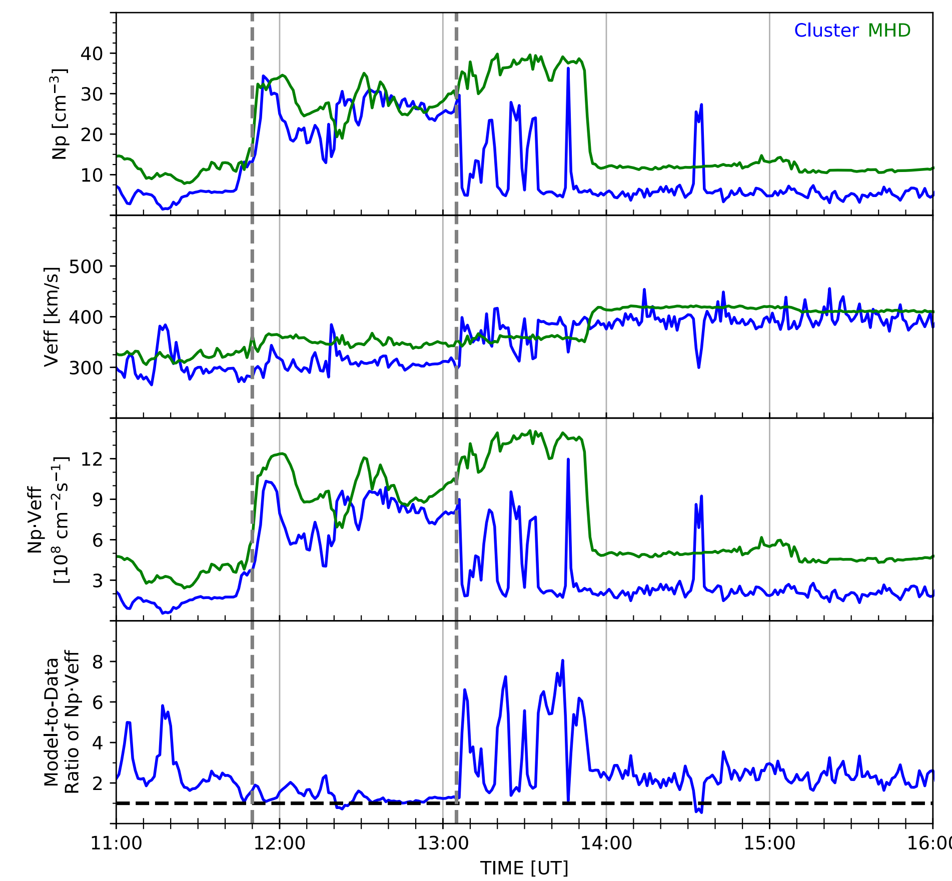
MHD simulations, extract plasma parameters; Q

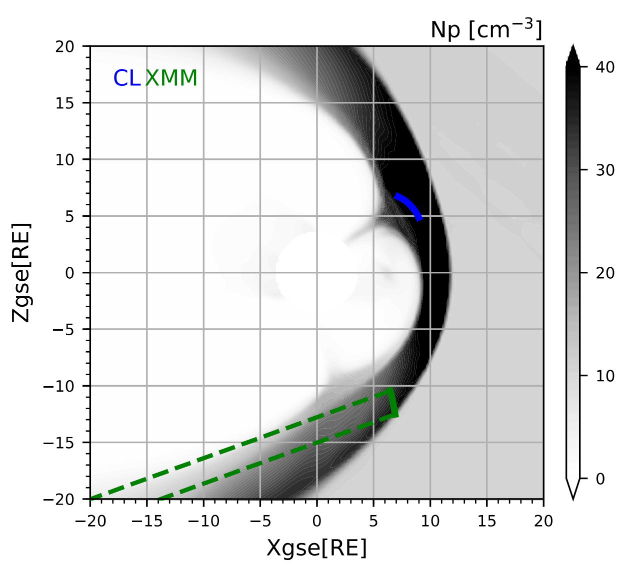


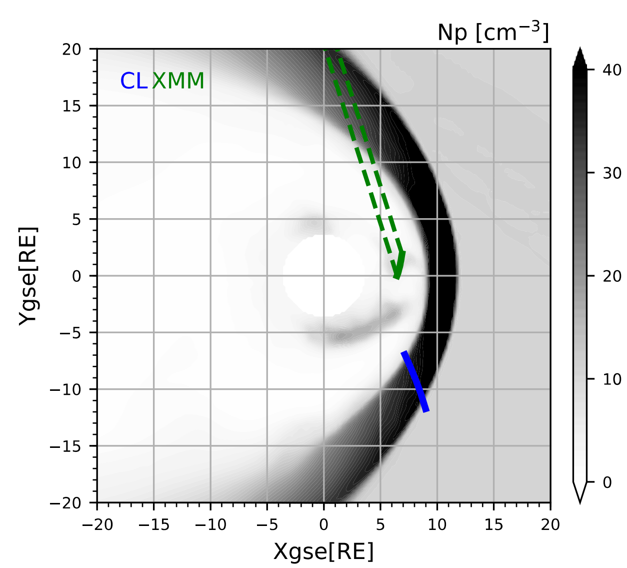
Extract N_H at 10 R_E (N_0)

The exosphere: densities higher than thought







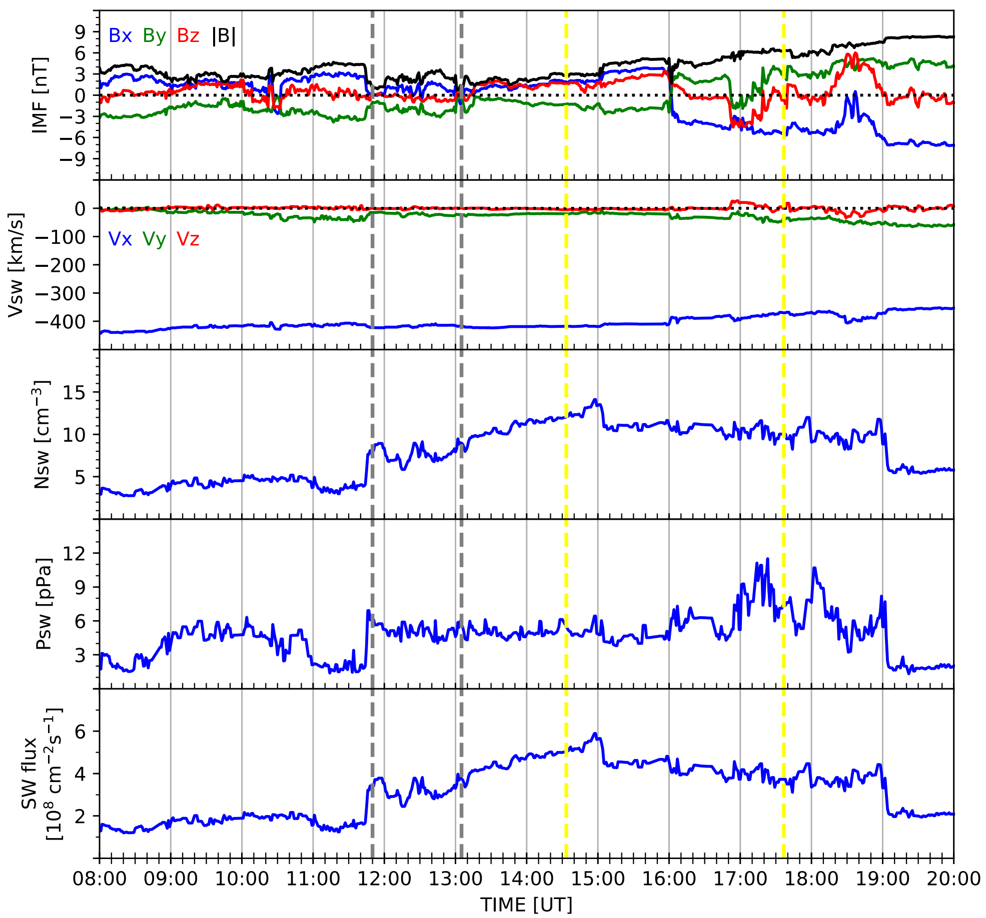


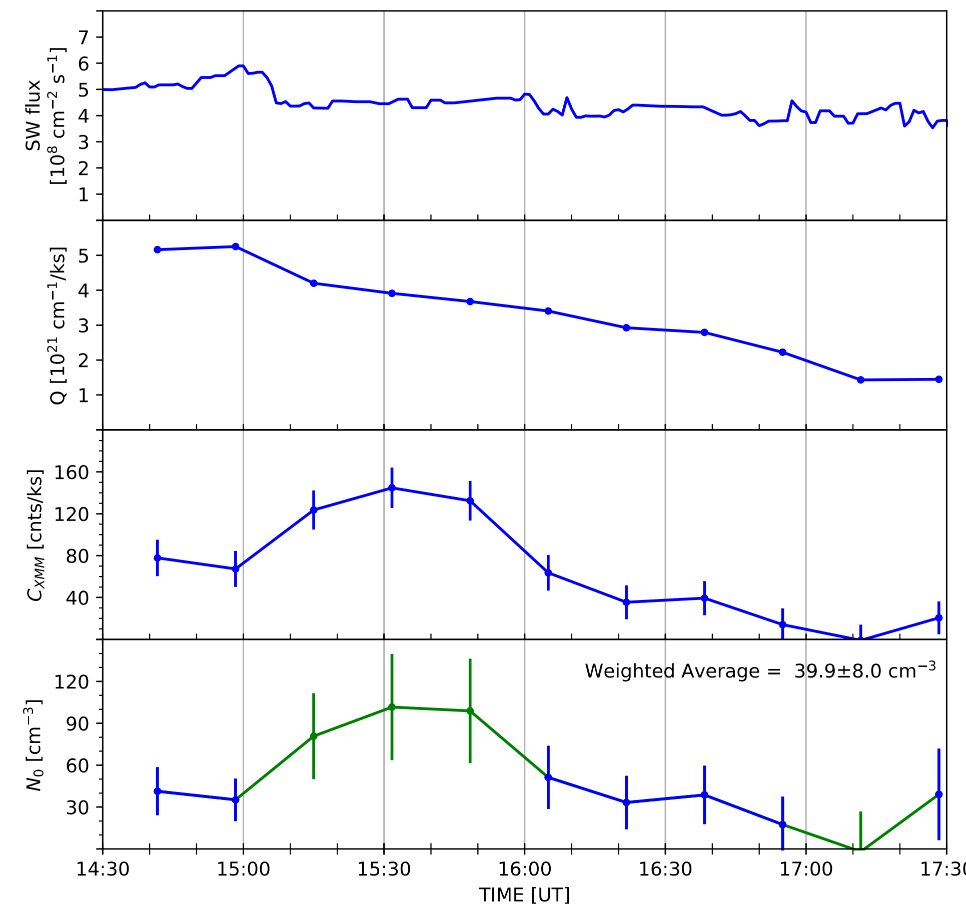
XMM-Newton moves ~17,000 km

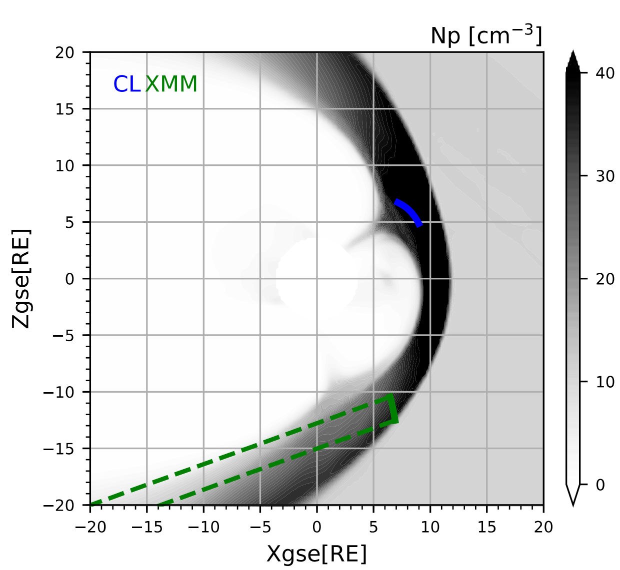
Density, case 1: ~43 cm^{-3}

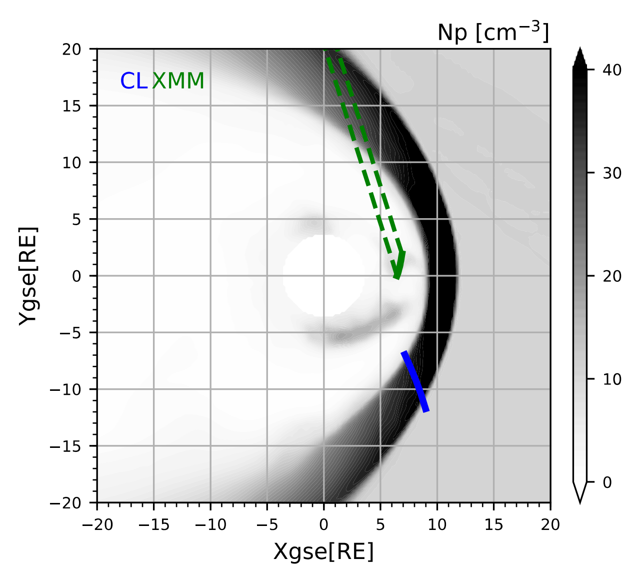
Density, case 2: ~60 cm^{-3}

The exosphere: densities higher than thought









XMM-Newton moves ~17,000 km

Density, case 1: ~43 cm^{-3}

Density, case 2: ~60 cm^{-3}

Making the problem an asset

MagEX

NASA lunar sortie science opportunity

Proposal submitted 2007

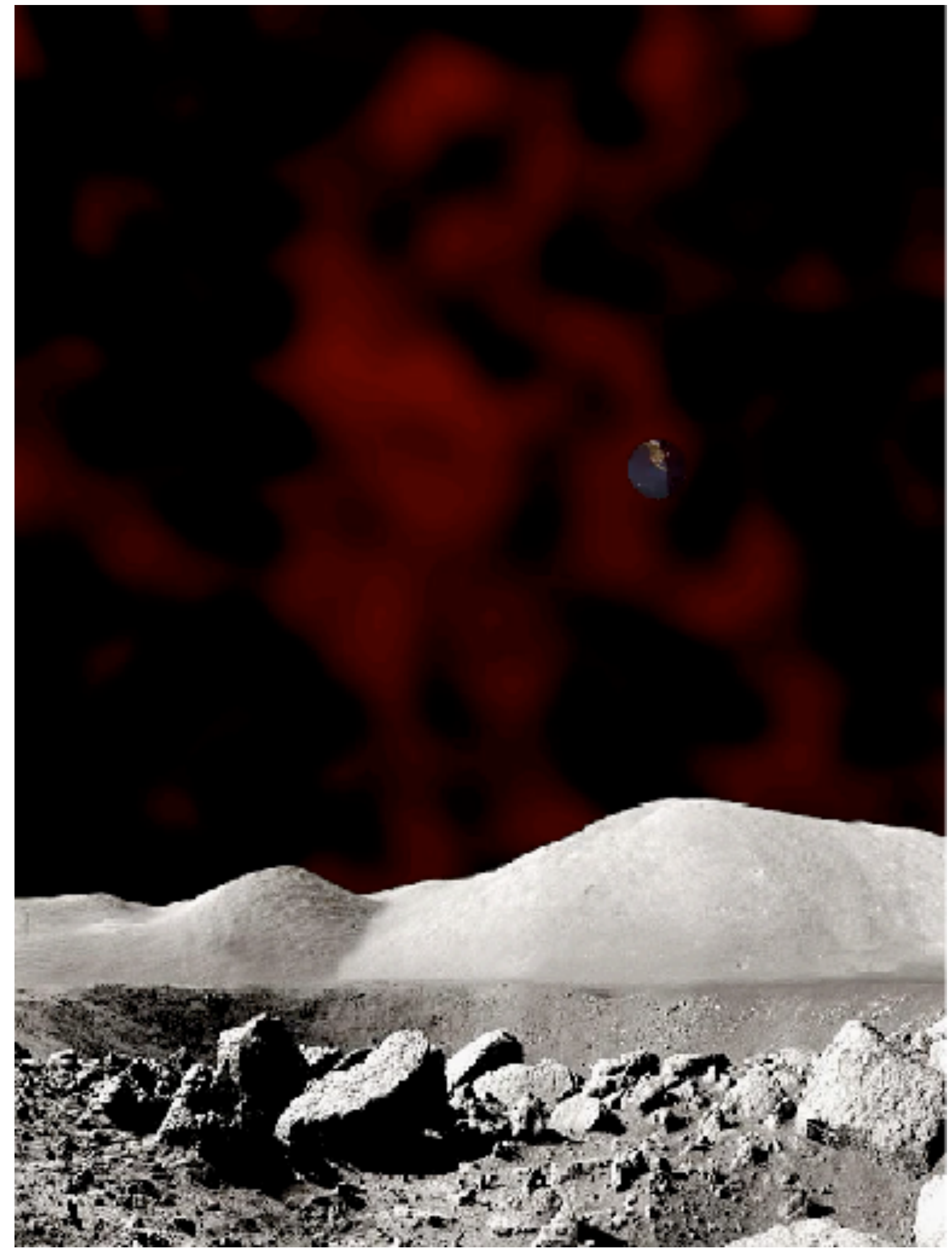
Astronaut deployed X-ray imager on surface

Making the problem an asset

NASA lunar sortie science opportunity

Proposal submitted 2007

Astronaut deployed X-ray imager on surface



If at first you don't succeed….

MagEX

NASA: 2007

If at first you don't succeed….

NASA: 2007

ESA: 2010

If at first you don't succeed….

MagEX

NASA: 2007

AXIOM

ESA: 2010

MAGIC

NASA: 2010

If at first you don't succeed….

MagEX

NASA: 2007

AXIOM

ESA: 2010

MAGIC

NASA: 2010

AXIOM-C

ESA: 2012

If at first you don't succeed….try many times

NASA: 2007

ESA: 2010

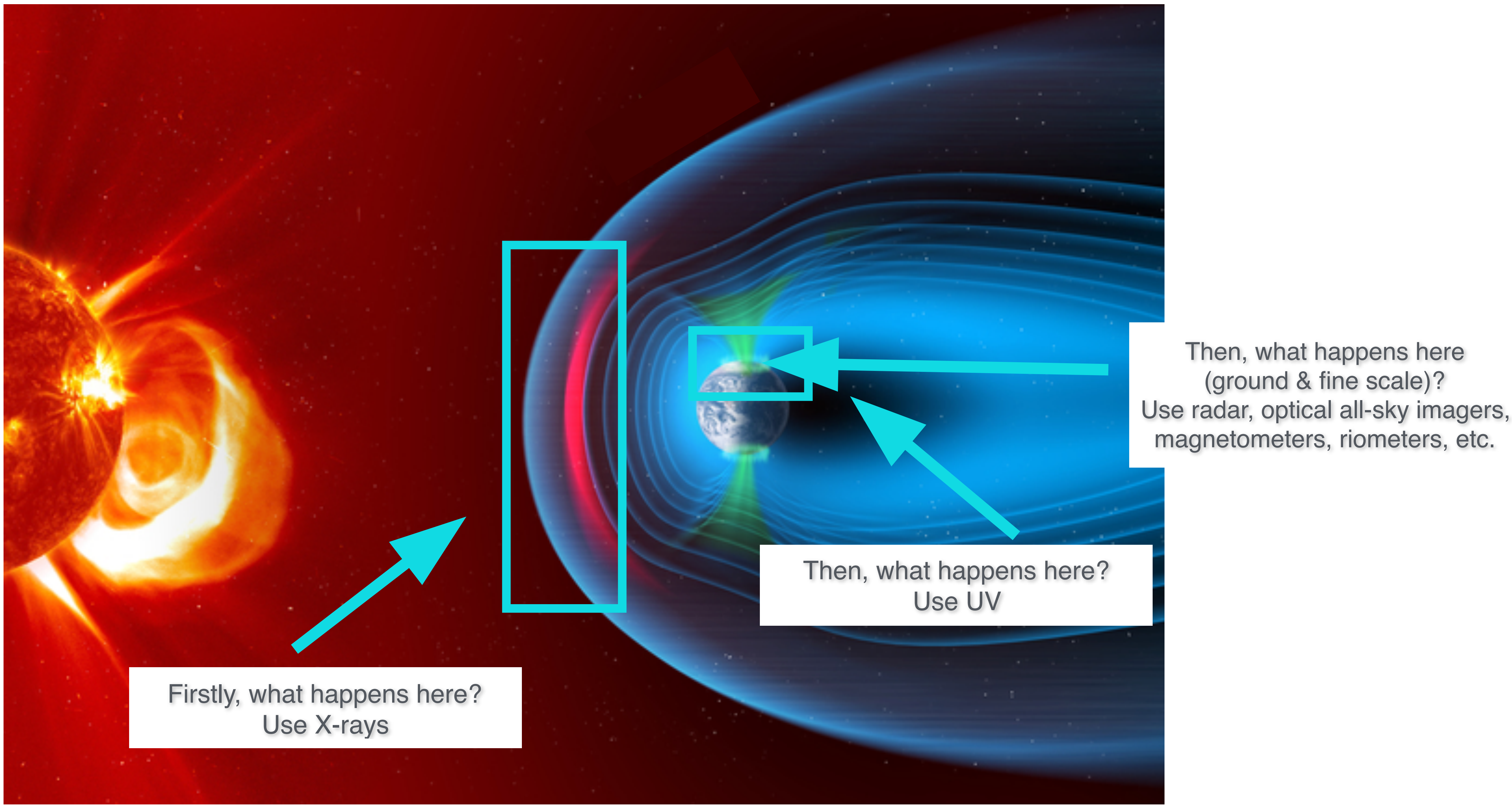
NASA: 2010

ESA: 2012

Selected for study June 2015

ESA and Chinese Academy of Sciences

Viewing geospace simultaneously



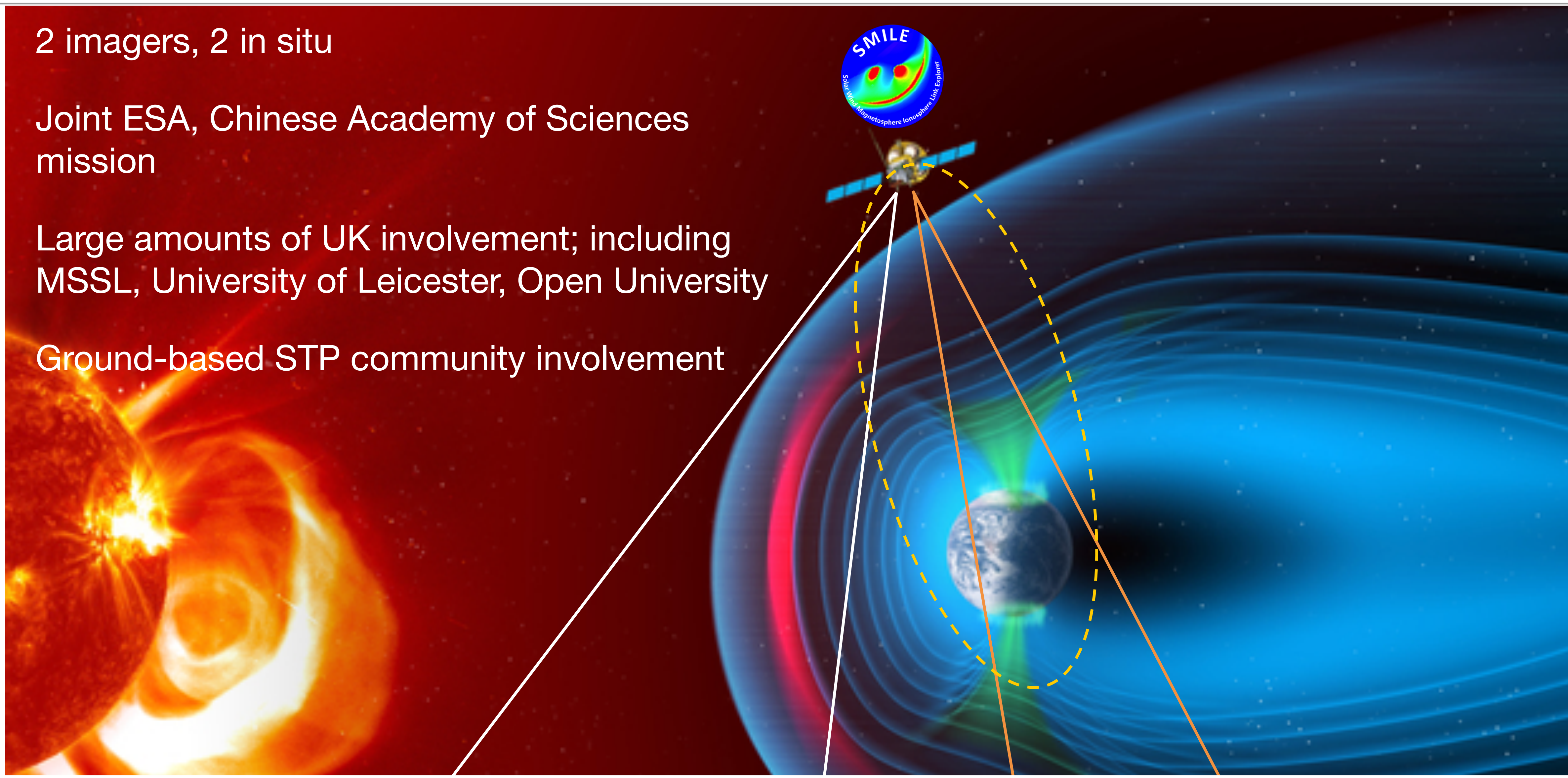
SMILE

2 imagers, 2 in situ

Joint ESA, Chinese Academy of Sciences mission

Large amounts of UK involvement; including MSSL, University of Leicester, Open University

Ground-based STP community involvement

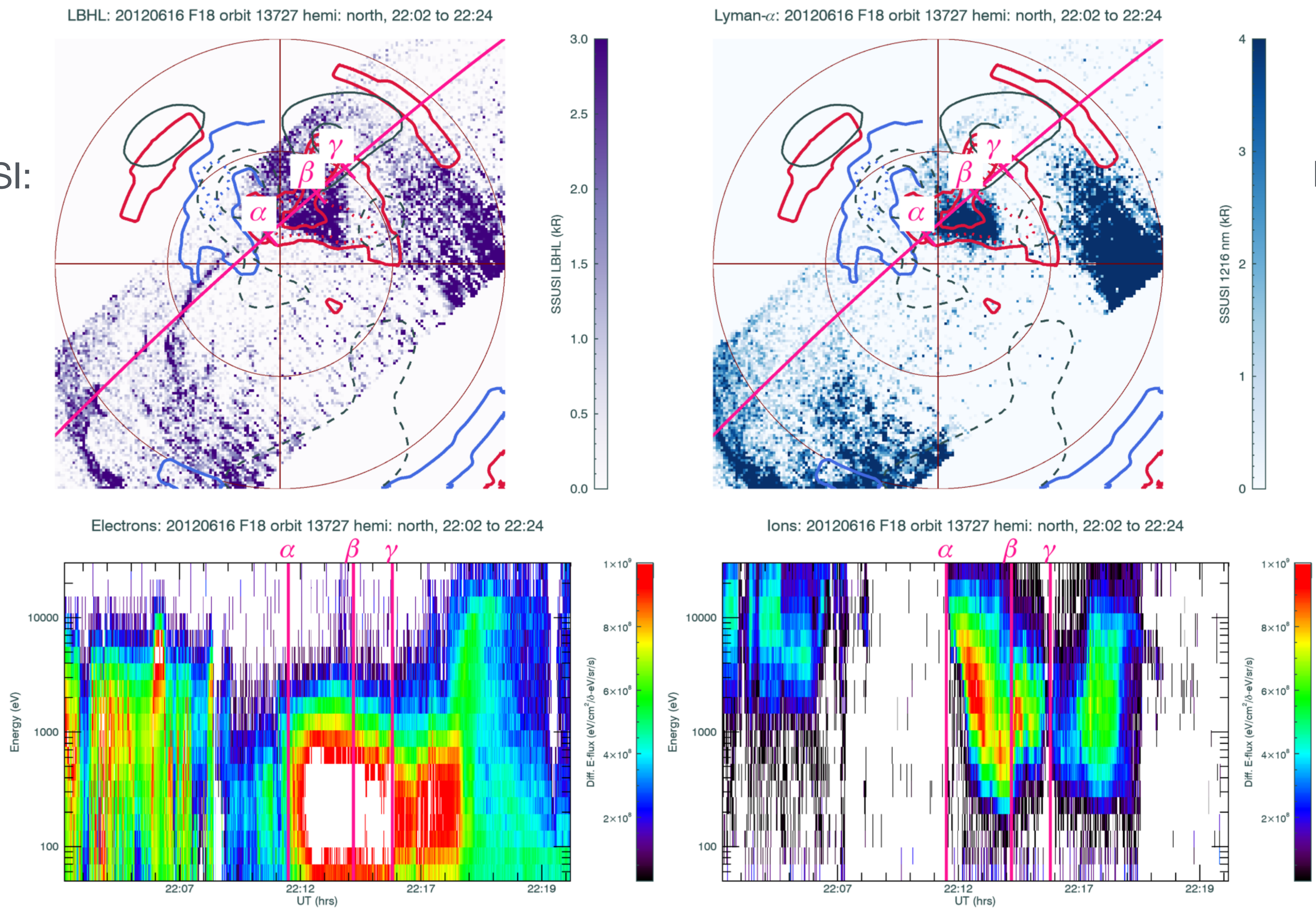


Science questions:

- What are the fundamental modes of the dayside solar wind - magnetosphere interaction?
- What defines the substorm cycle?
- How do CME-driven storms arise, and how do they relate to substorm?

Preparing for SMILE: observations

DMSP/SSUSI:
LBH-long
~electrons

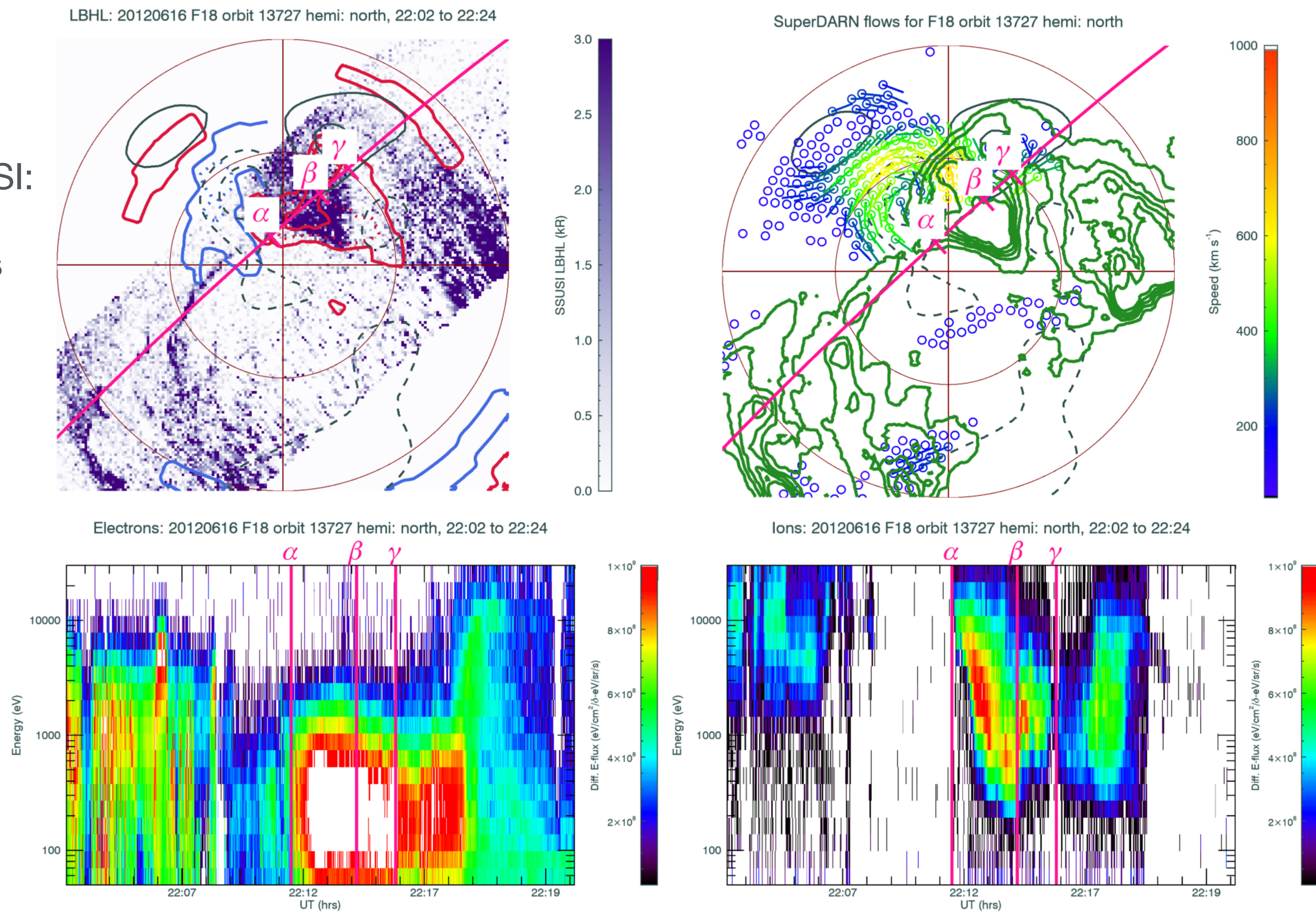


DMSP/SSUSI:
Lyman-α
protons

Carter et al.,
under review

Preparing for SMILE: observations

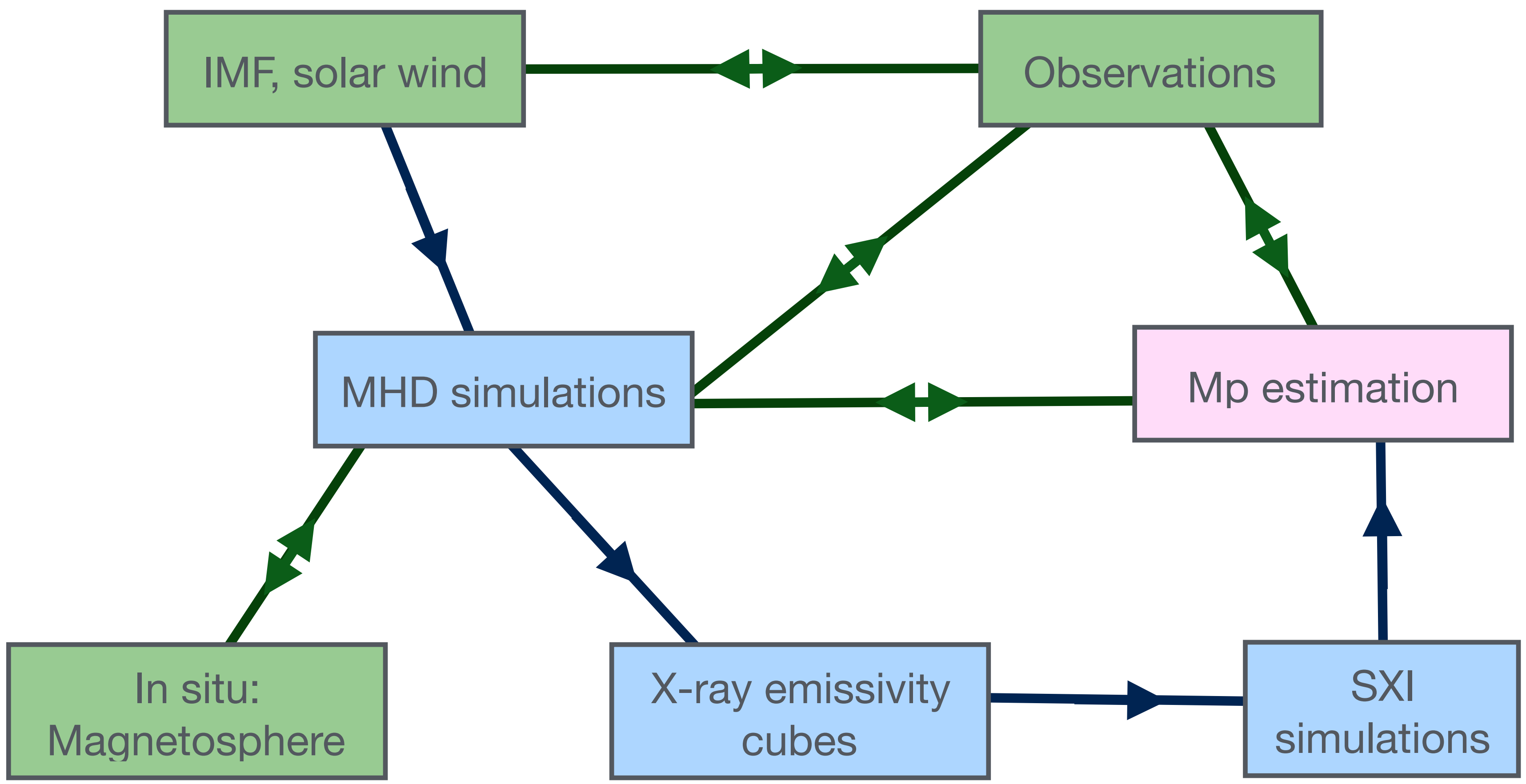
DMSP/SSUSI:
LBH-long
~electrons

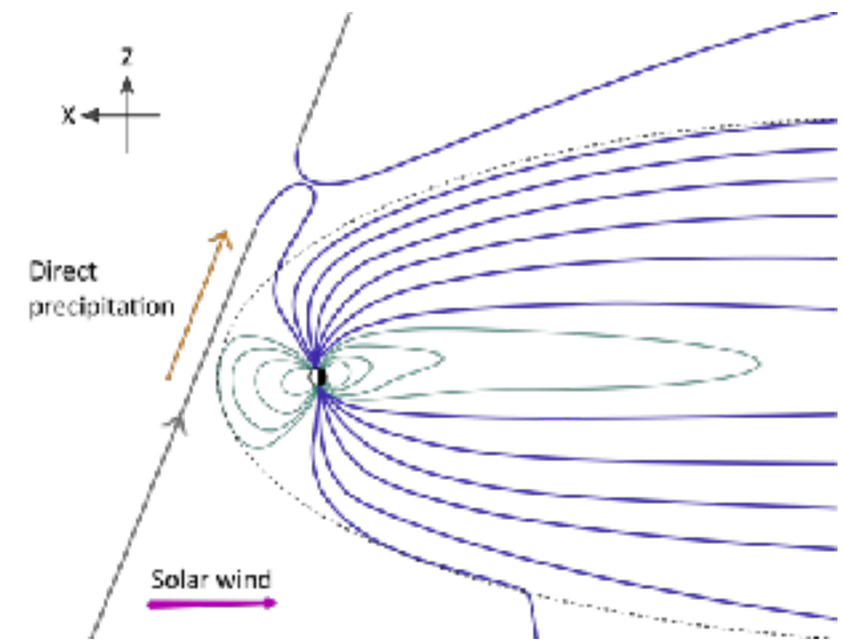


SuperDARN
Flows

Carter et al.,
under review

Linking ground-based observations and SMILE





Sustained, highly northward IMF case: cusp spot emissions, FACs, ionospheric convection, precipitating particles

Carter, Samsonov, Sembay, Branduardi-Raymont, …in progress

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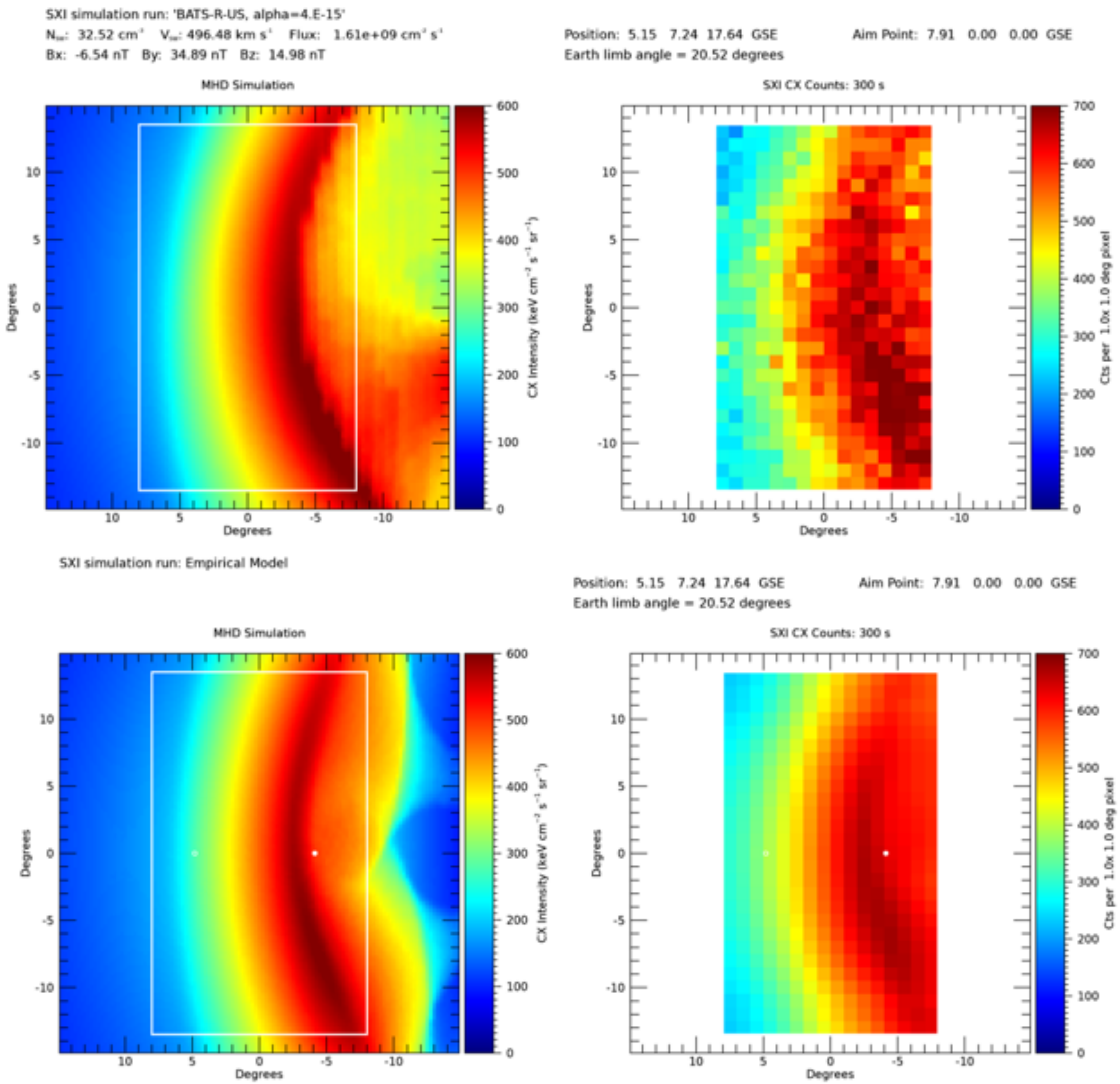
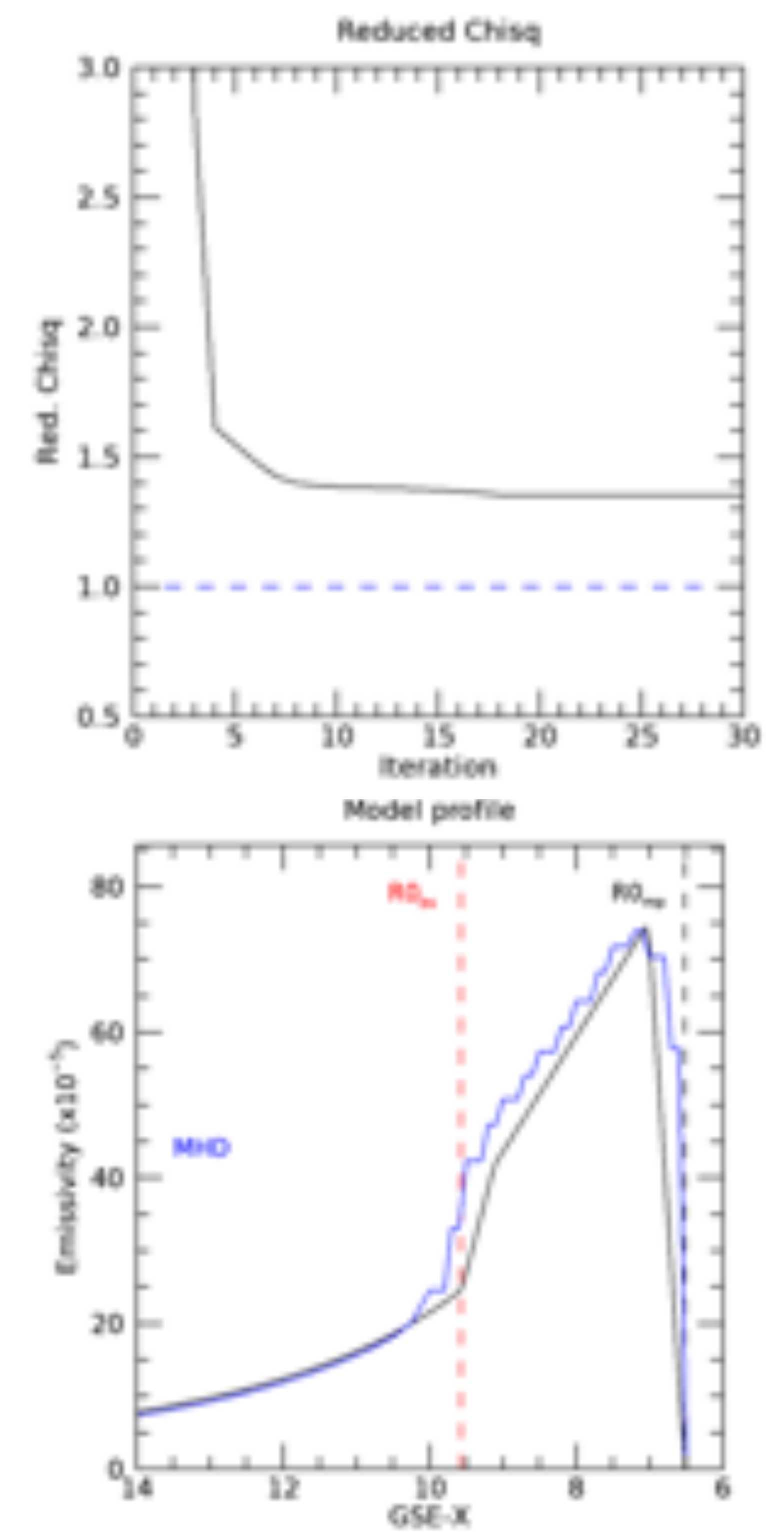
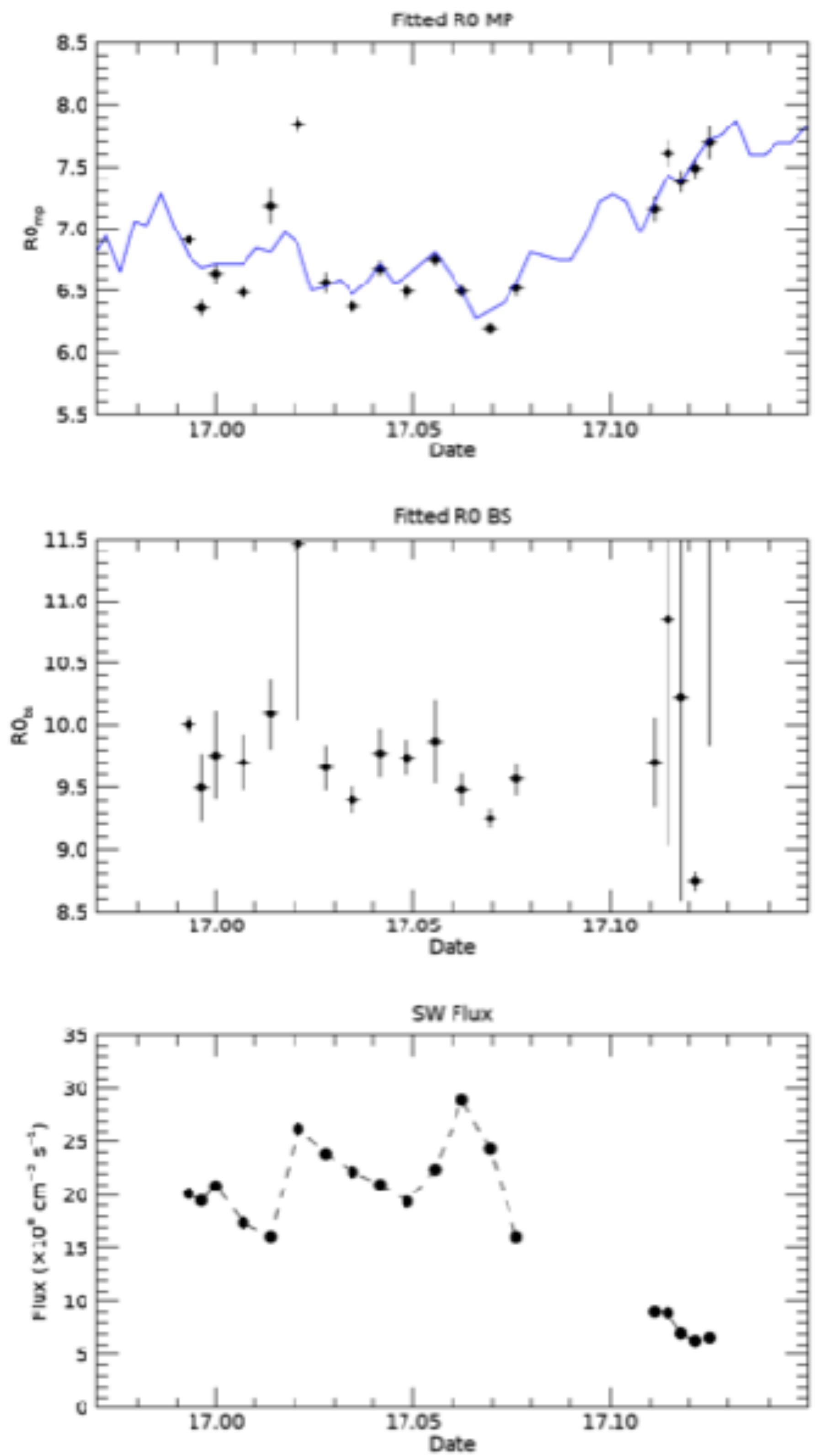
Linking ground-based observations and SMILE



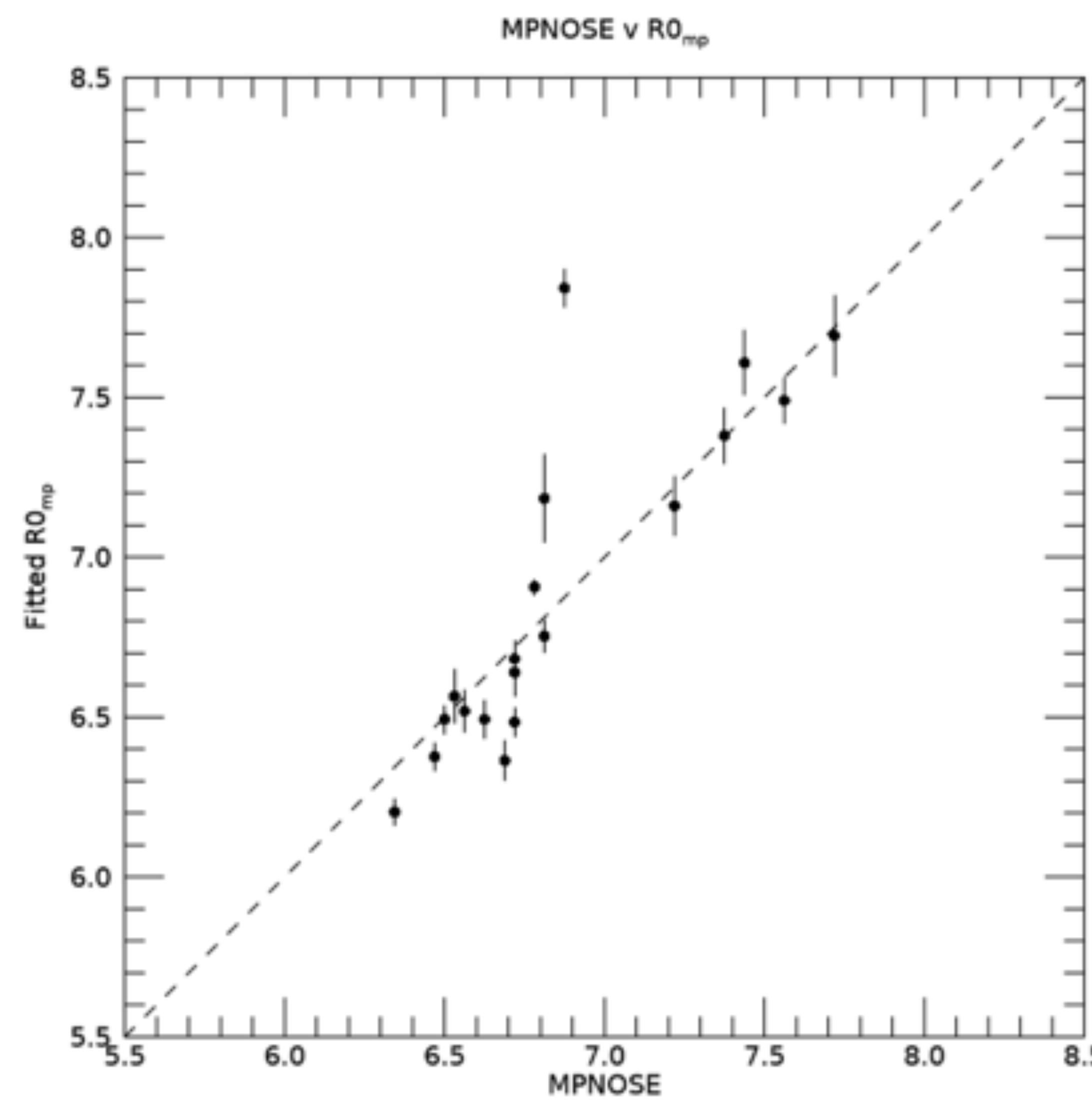


SMILE-SXI simulations: M_p versus time, cf. MHD

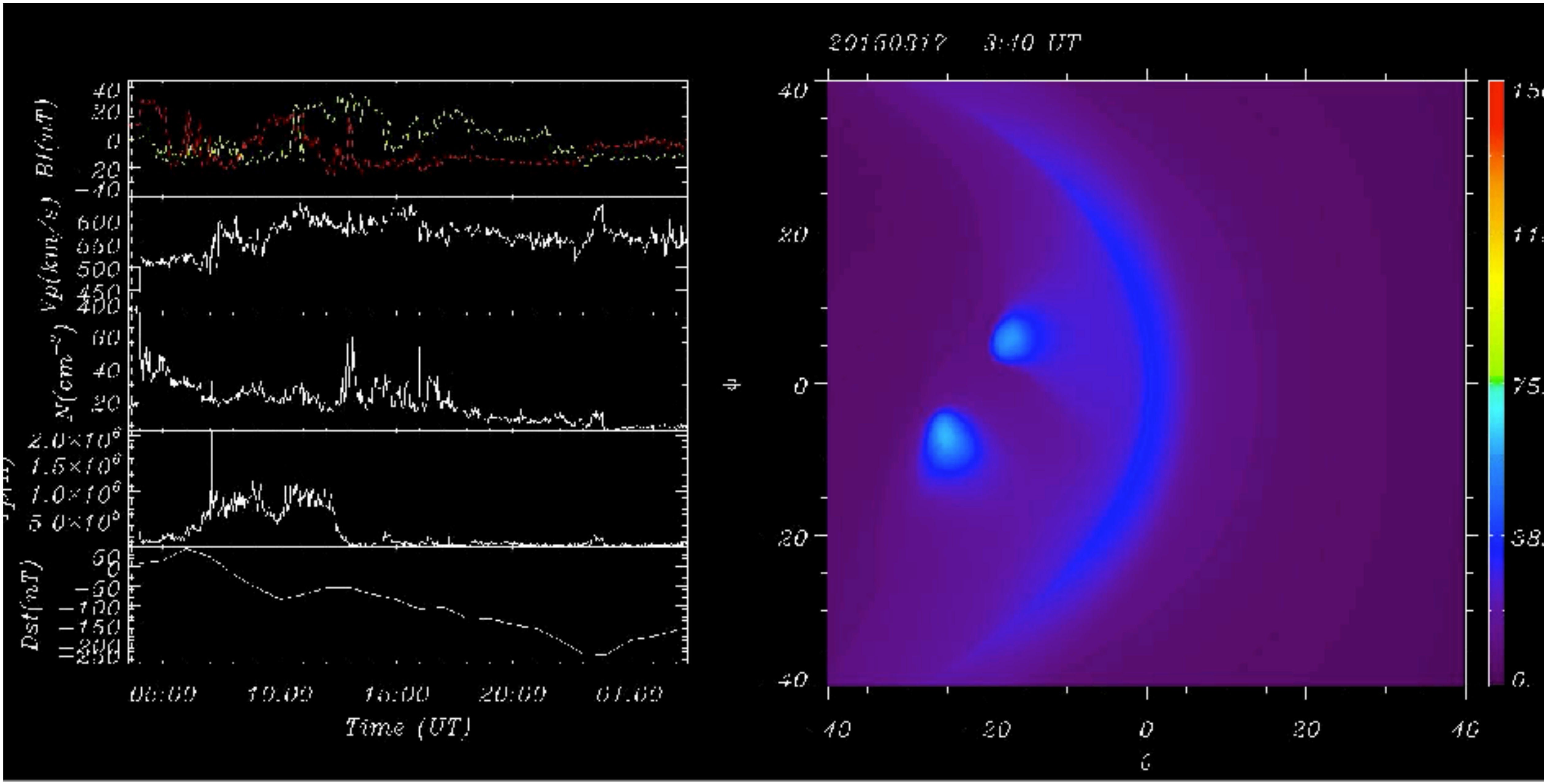


MHD

Find Mp many times in SXI simulations
Find from MHD
Compare



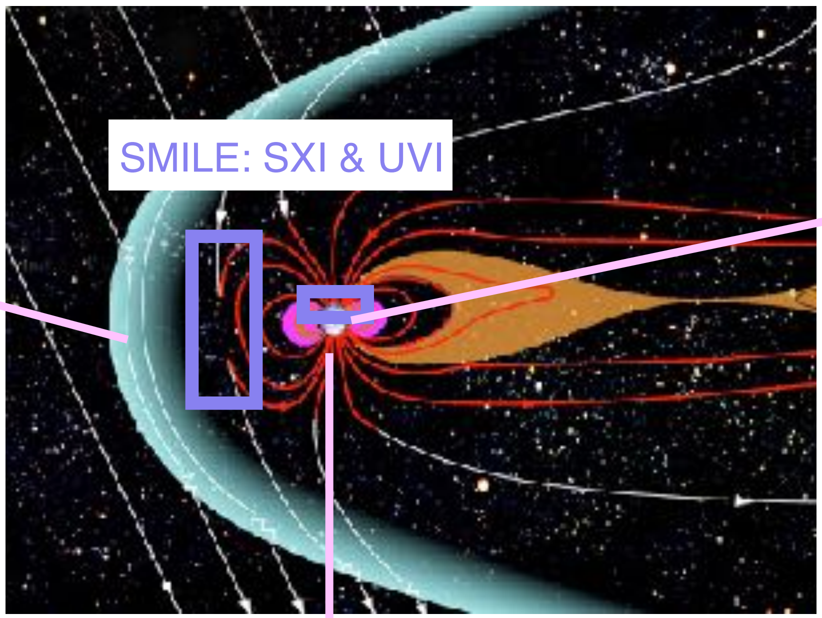
SMILE: SWCX video



T. Sun, NSSC, China

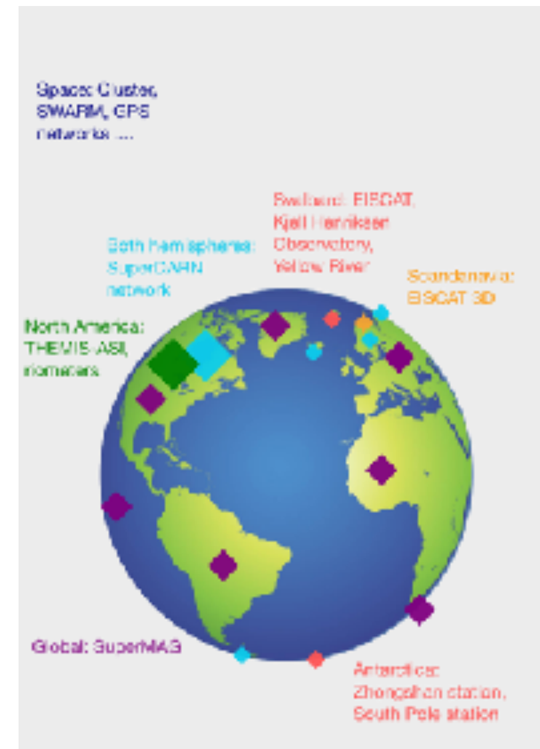
SMILE: multi-scale approach

Magnetosphere response: in situ, e.g. currents, particles



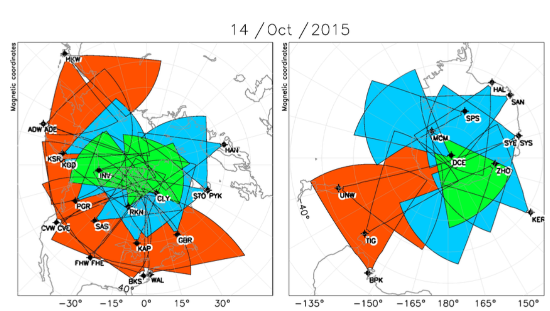
Inter-hemispheric response of ionosphere

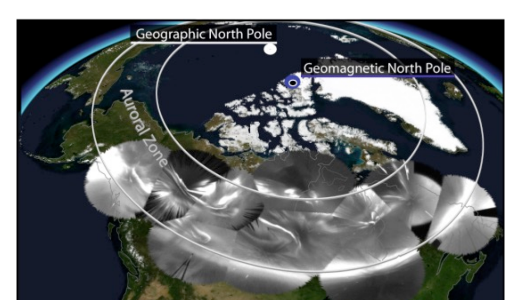
Ionosphere response: large, medium, & fine scale



UK-led working group: 27 members, 6 countries, diverse projects

- To fully exploit SMILE data we need support from the ground-based solar-terrestrial community
- Global, continental, & local ground-based experiments: radar, all-sky imagers, magnetometers, etc.
- Ground-based provides essential multi-scale & multi-cadenced data contemporaneously with SMILE





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Conclusions

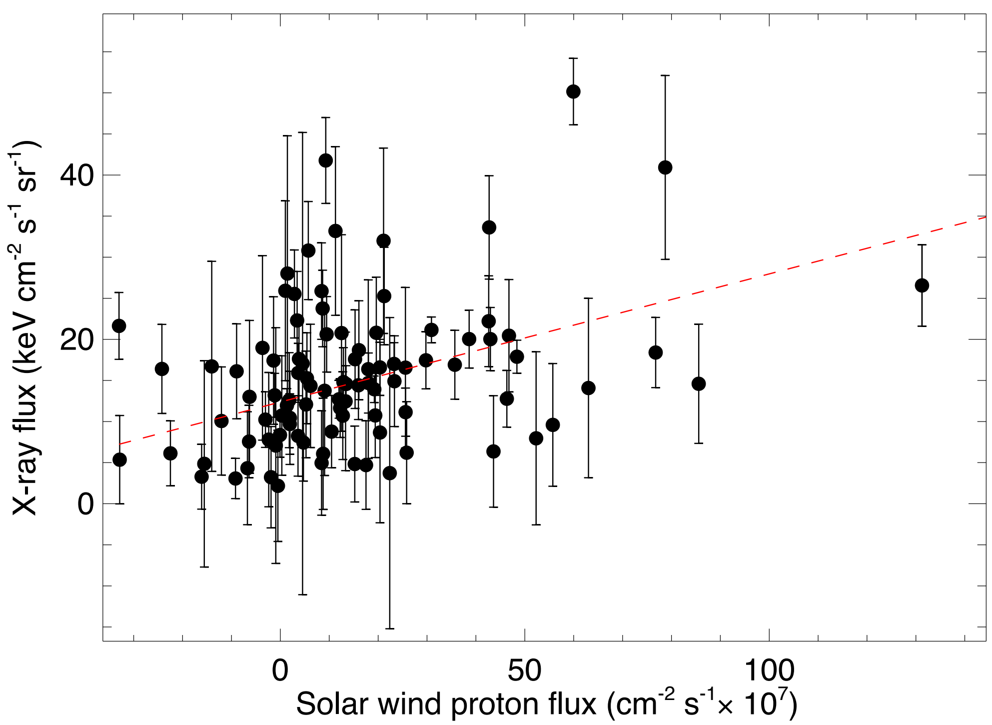
The discover of solar wind charge exchange X-ray emission has led to:

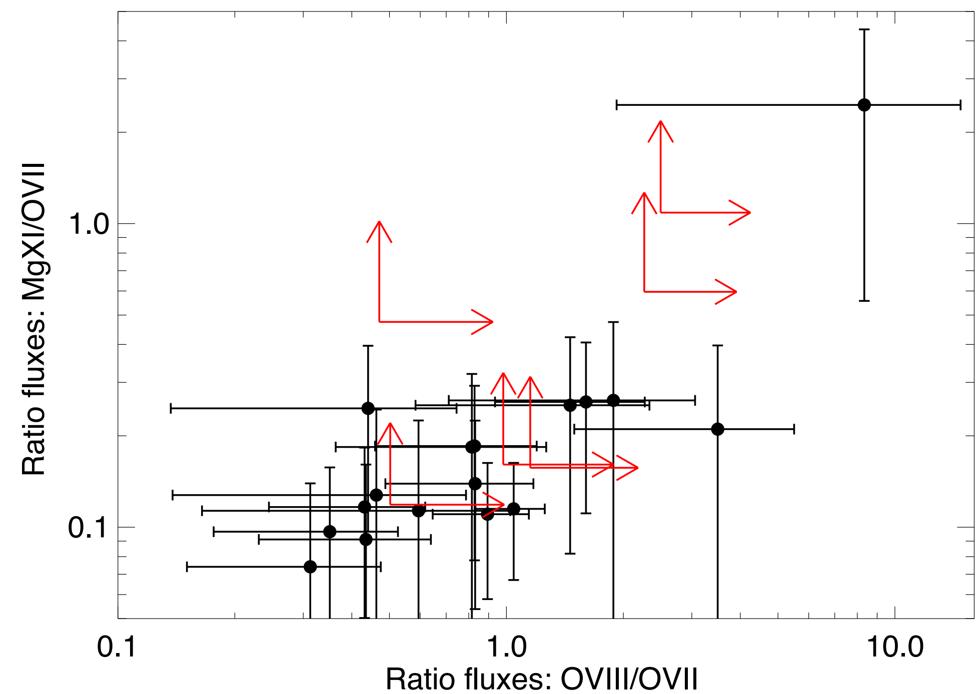
- X-ray investigations of Solar System bodies
- A better understanding of the sources of the X-ray background for X-ray astronomers
- An opportunity to use this X-ray emission to study geospace

SMILE (#SMILEesacas) will:

- Image the magnetospause whilst simultaneously imaging the ionosphere, plus in situ
- Be launched in November 2023
- Benefits from a better understanding of the neutral exosphere
- Is a fantastic chance for the solar-terrestrial and X-ray communities to work together

XMM-Newton: archival study, extra summaries

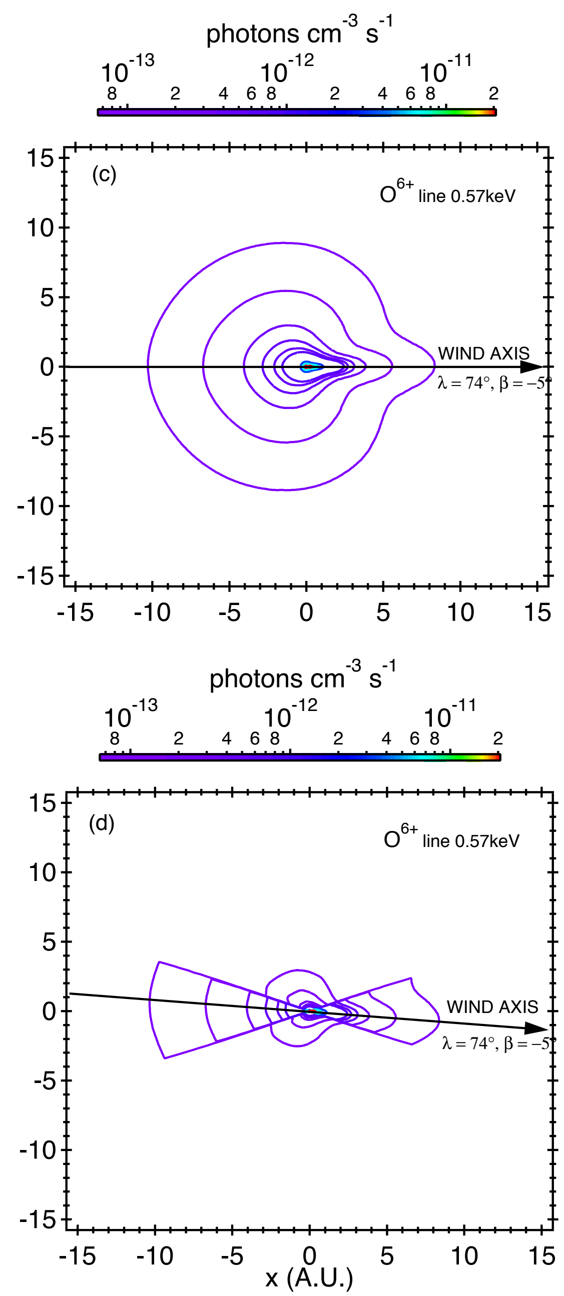




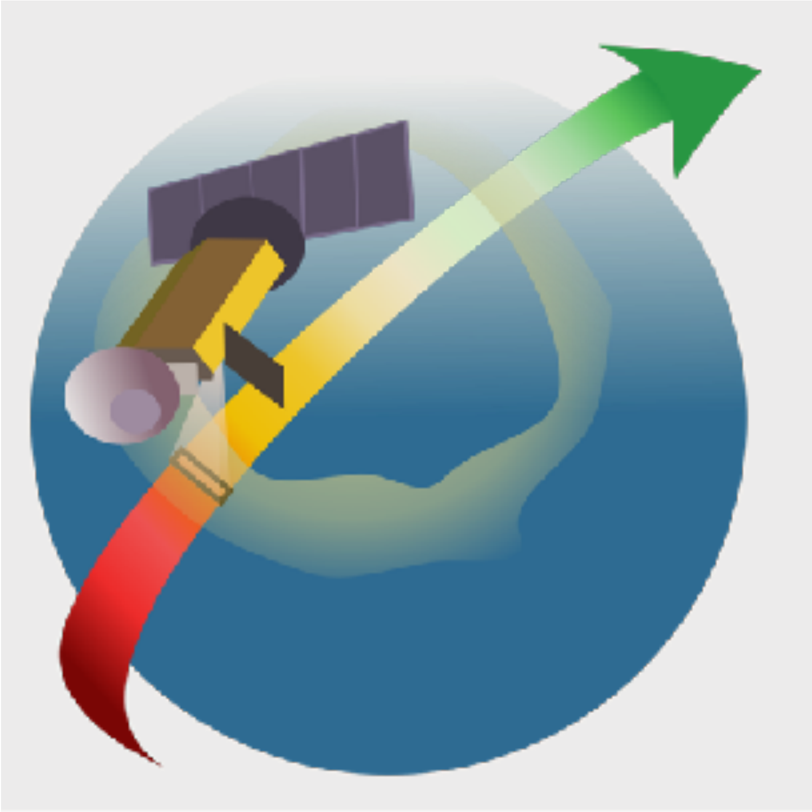
Helium focusing cone: extra, O7+ distributions

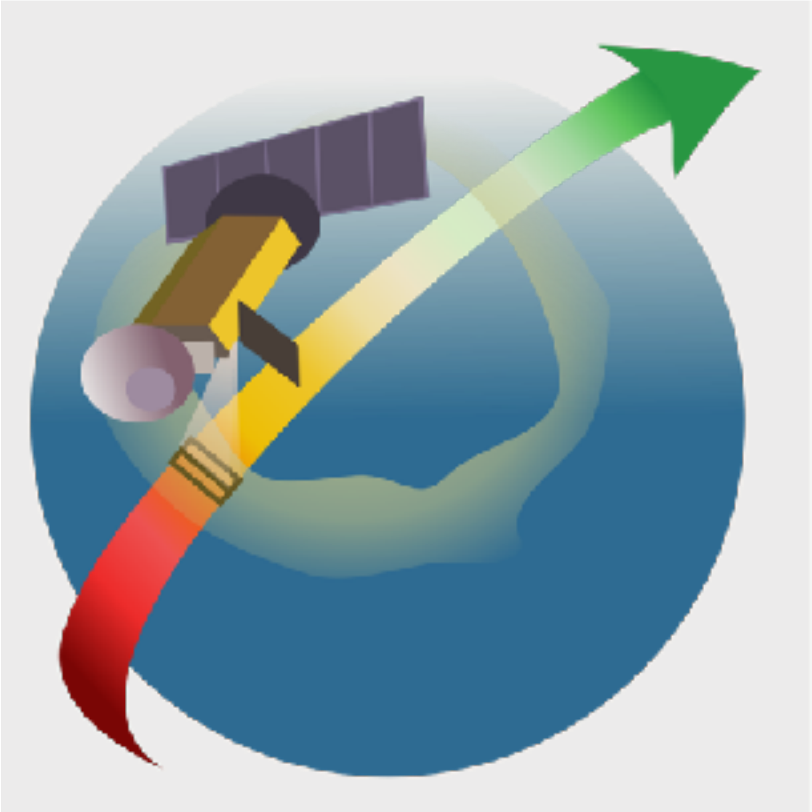
Koutroumpa 2006:

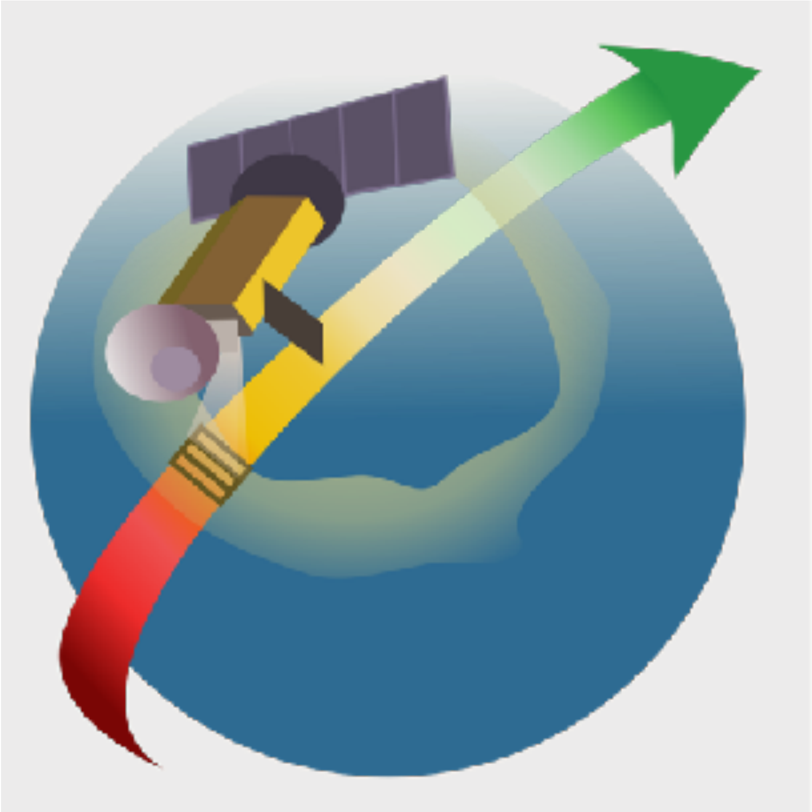
Iso-emissivity contours for summed O7+ emissions at three lines



SSUSI: building up auroral pictures







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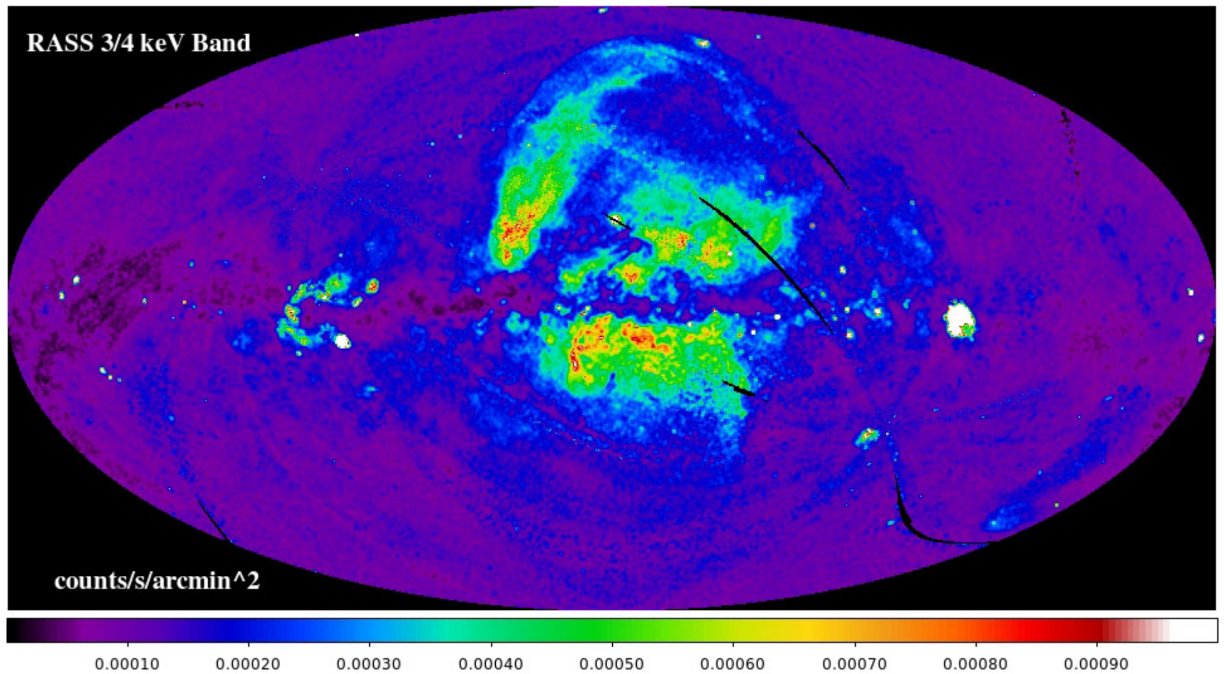
Sky background subtraction: 16-Oct-2001



Sky background for 16-Oct-2001 is bright, along Galactic plane

Model background before 06:00 UT, using Xspec

Absorbed polar law + (nh * APEC) + APEC

Sky background plus instrument particle background is 135 counts per ks