One Man’s Trash…

K.D. Kuntz (JHU/GSFC)
with a great deal of help

Essentials for Diffuse Analysis

Diffuse emission often fills the FOV & sometimes the entire sky!
(Local Hot Bubble, the Galactic halo, WHIM, etc.)

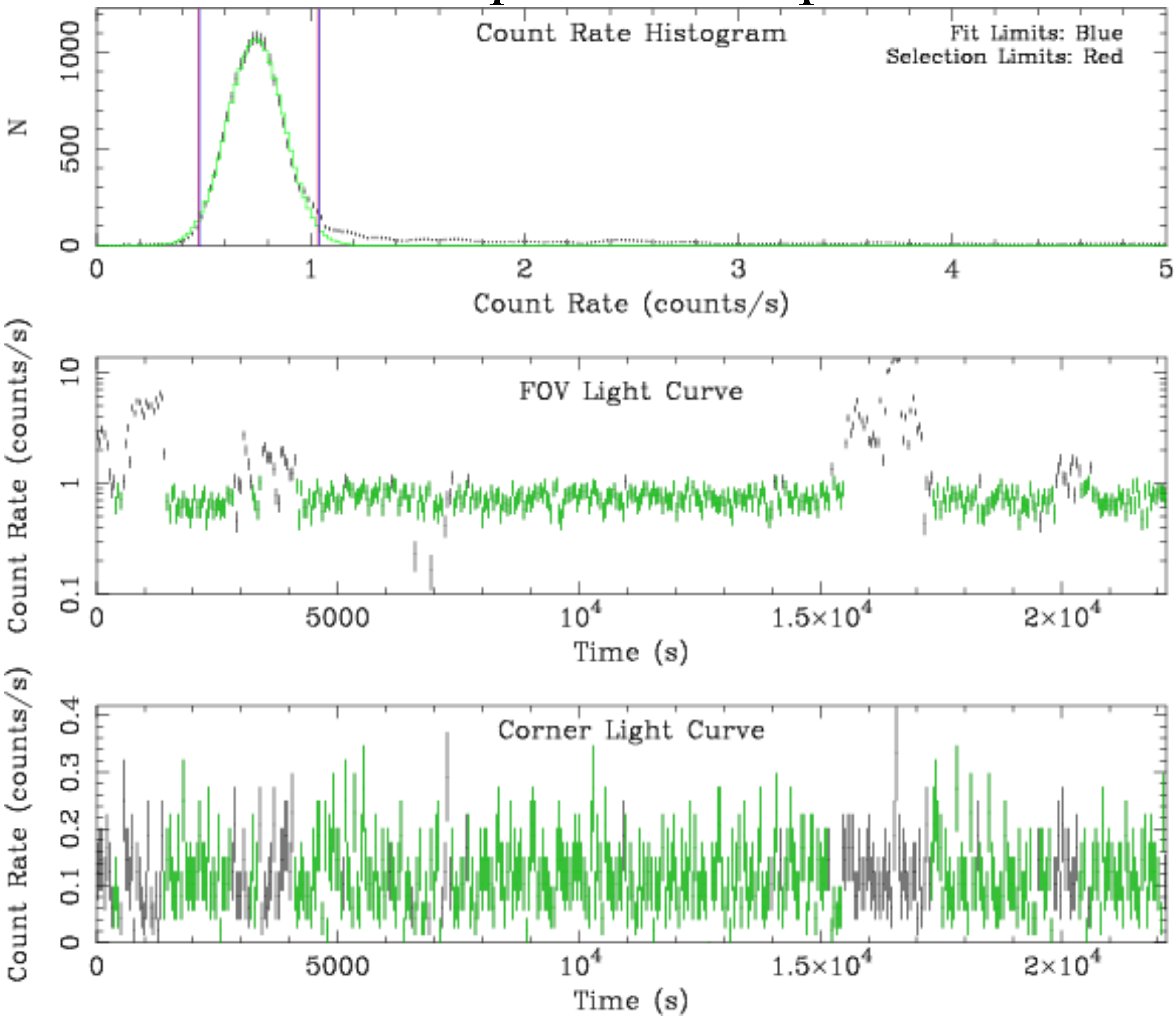
How can we analyze these data?
Need to have all the foregrounds *well* characterized:

- Cosmic Foregrounds (observation dependent)
- Quiescent Particle Background due to high energy particles striking the detector environment, producing bremsstrahlung, fluorescence, and secondary electrons, all detected as X-rays.

Since XMM is in HEO, it samples many different particle populations from the pure solar wind to the radiation belts, so it was expected that the spectrum of the QPB might be time variable.

Thus the US XMM-GOF started studying the problem.

First Unpleasant Surprise



First Unpleasant Surprise: SPF

"Soft Proton Flares": order of magnitude increases in the background.

Attributed to protons because e^- would have been removed by B_{def}.

Low energy because

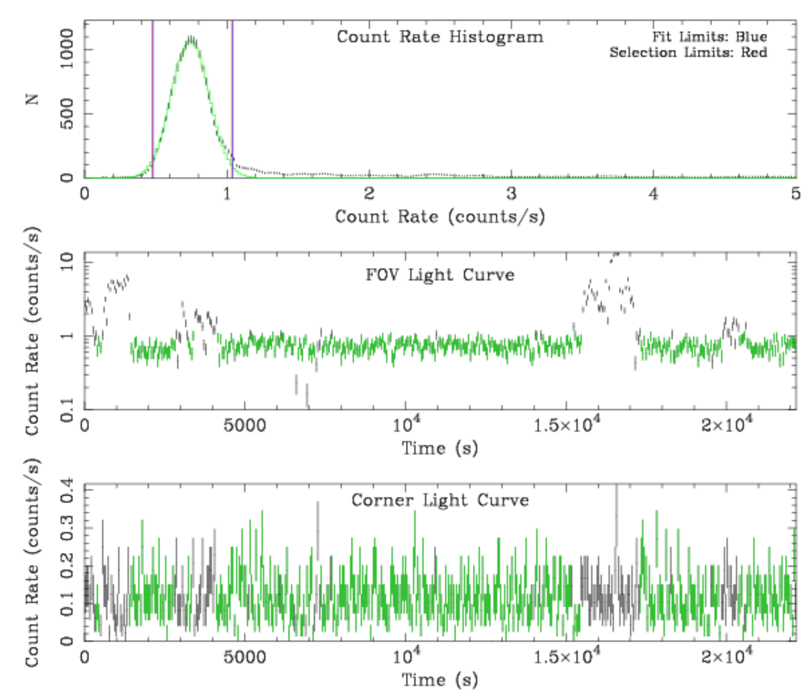
- No correlation with protons with E>1MeV in the radiation monitor
- Not seen in the shielded corner data
- Simultaneous observations with MOS1 & MOS2 with mis-matched filters places upper limit on energy of a few 10's of keV
- Simulations showed that the mirrors were quite efficient at focussing low energy protons.

Solution: filter out effected times.

(Doesn't always work)

Consequence: ⅓ of time removed on average.

However, noted that some seasons had more problems than others.

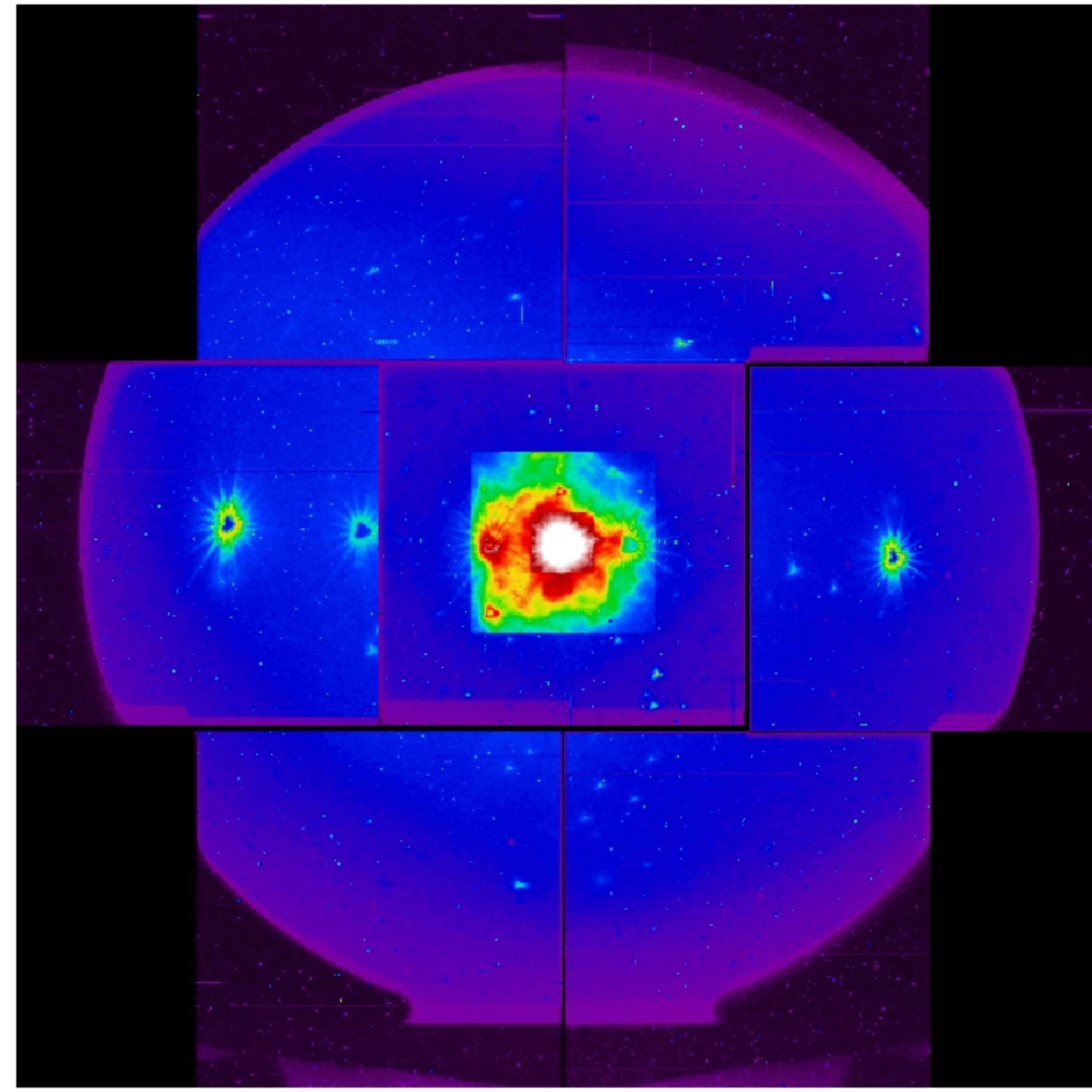


Quiescent Particle Background

The MOS design was clever: a round mask blocked X-rays from the large-PSF region in the corners, which record only the signal due to the QPB.
The count-rates are quite low, but the measurement is simultaneous with the source observation, allowing one to track the temporal changes.

The GOF task was to figure out how to use these corner data and filter-wheel-closed observations to construct the spectrum of the background for a given region of a given observation.

And we worked on that. (And still are!)

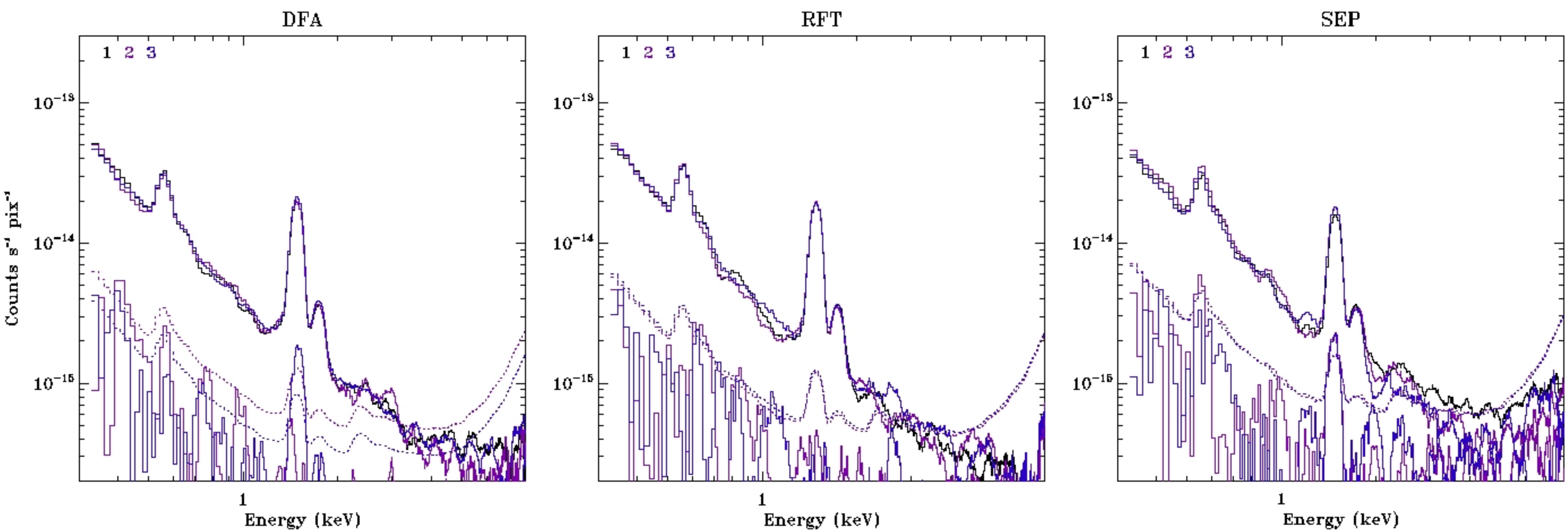


The first six(?) years of MOS2 observations, stacked.

Quiescent Particle Background

To test our algorithm, we applied it to multiple observations of the same field of view to determine if variation between observations was comparable to the noise.

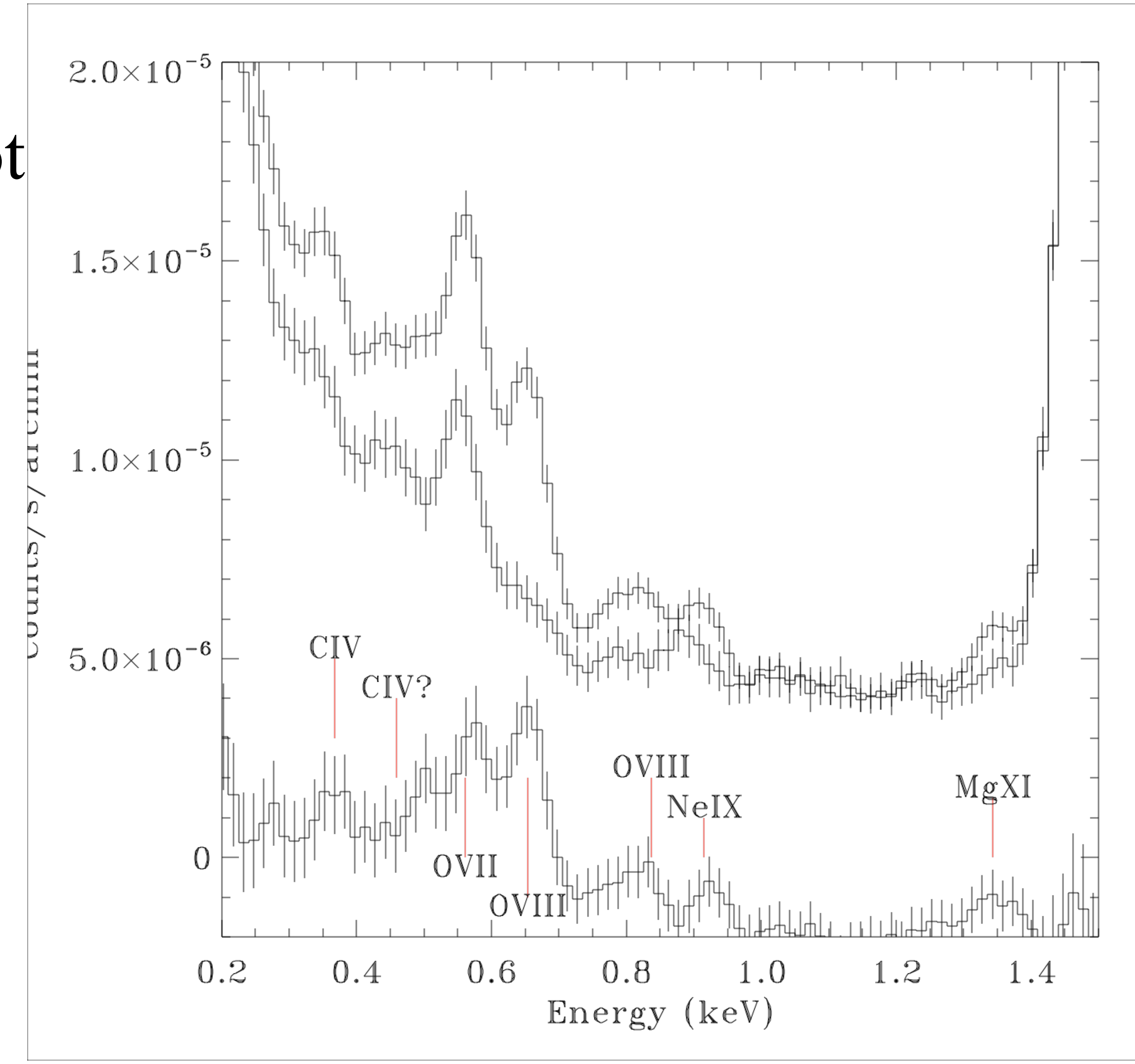
Indeed, the differences were comparable to the expected uncertainties, and we were greatly satisfied:



Second Unpleasant Surprise

Of the multiple observations of the Hubble Deep Field North, two did not agree with the others.
The disagreement was much greater than the uncertainties!

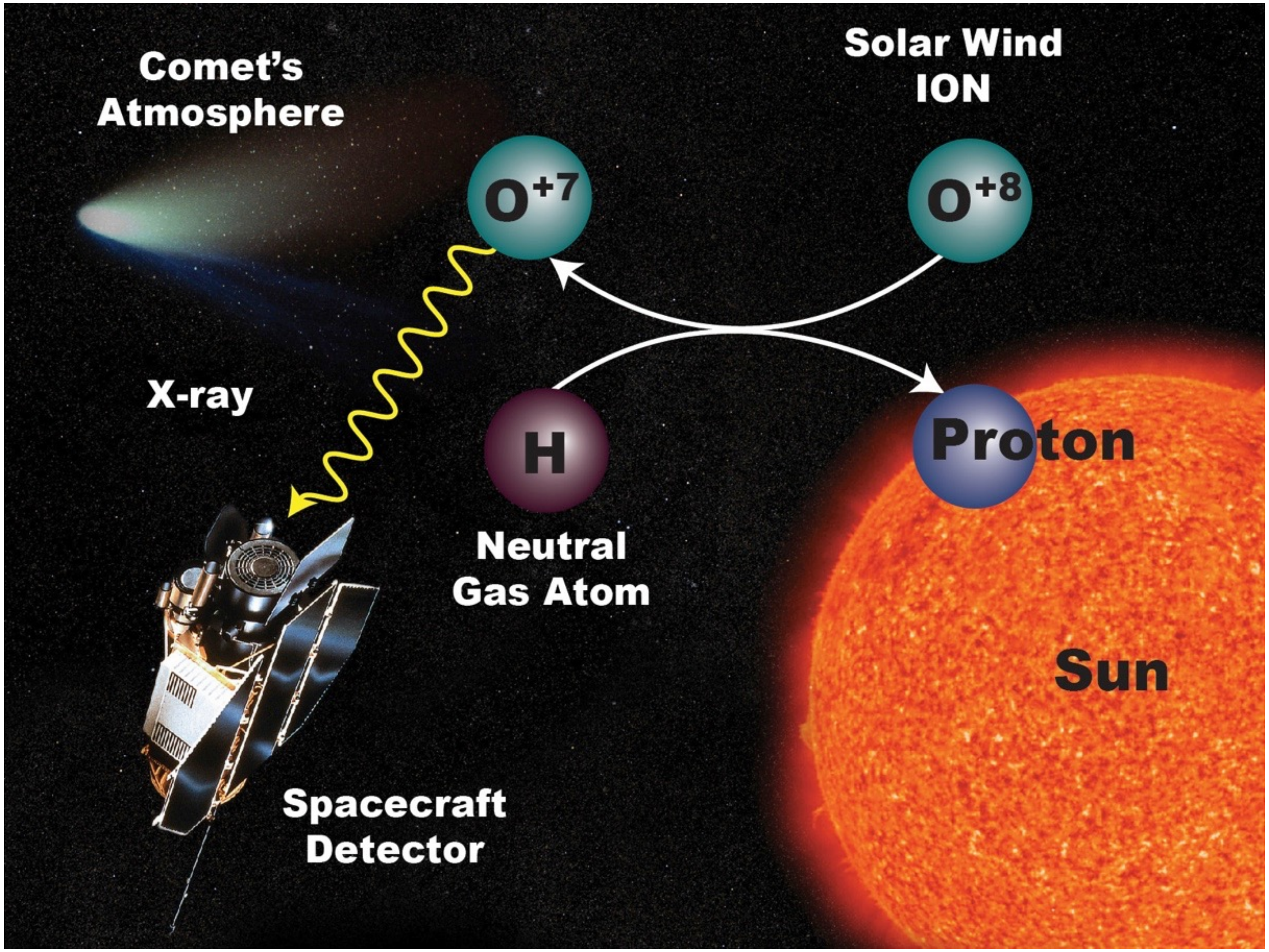
The difference showed a clear line spectrum: just what was expected from solar wind charge exchange.



SWCX

Solar Wind Charge Exchange: interaction between high-state ions in the solar wind and any neutral atom; the electron is transferred into an excited state, and relaxes producing FUV and X-ray photons:

$$A + B^{+n} \rightarrow A^{+} + B^{+(n-1)*} \rightarrow A^{+} + B^{+(n-1)} + \nu_X$$



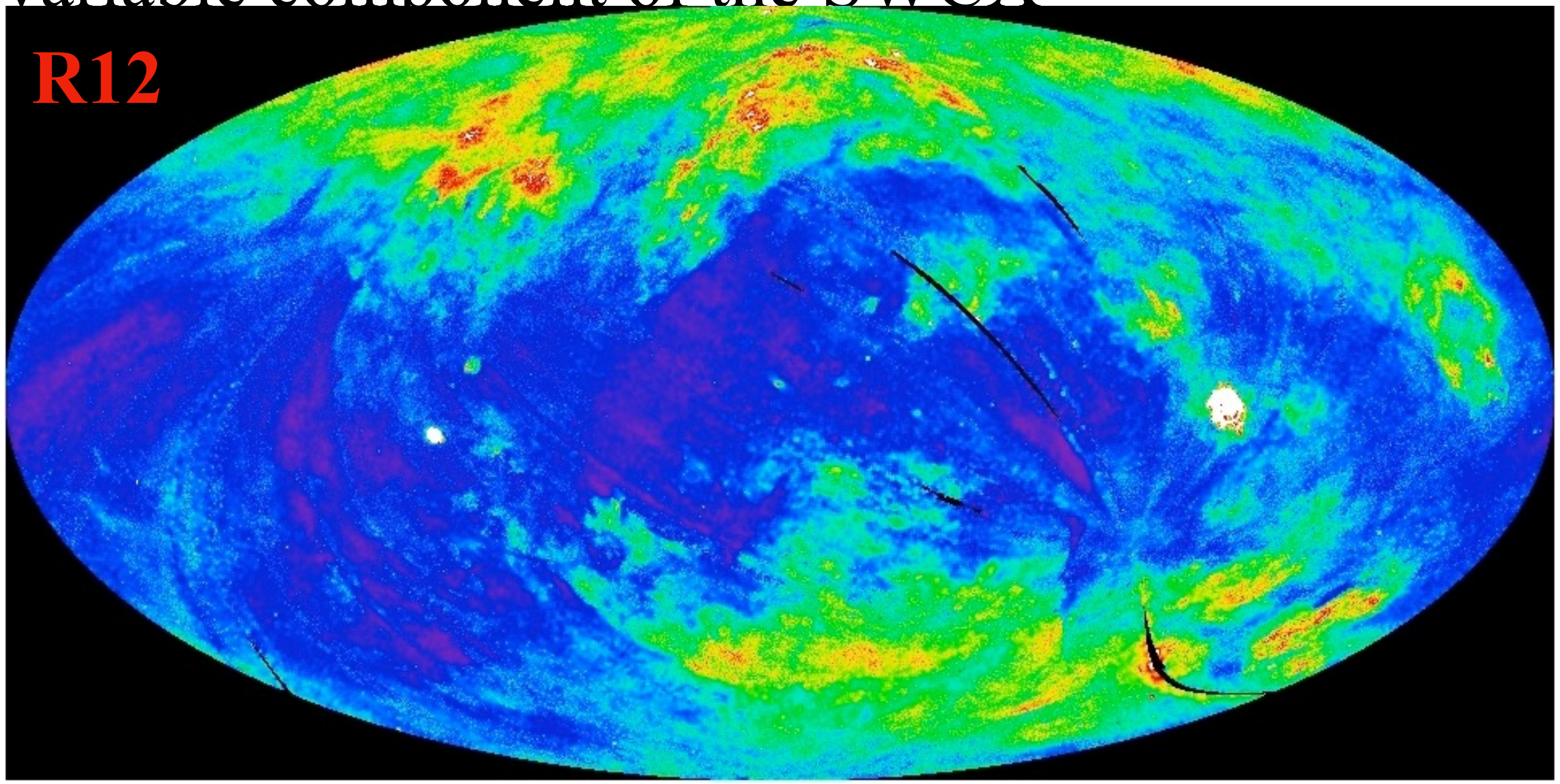
SWCX

First seen by ROSAT in the All Sky-Survey, though it was not recognized. The Long-Term Enhancements (LTEs) in the X-ray background with
time-scales of hours to days.

Since each point viewed multiple times over successive orbits, the LTEs could be "measured" by a constrained minimization routine.

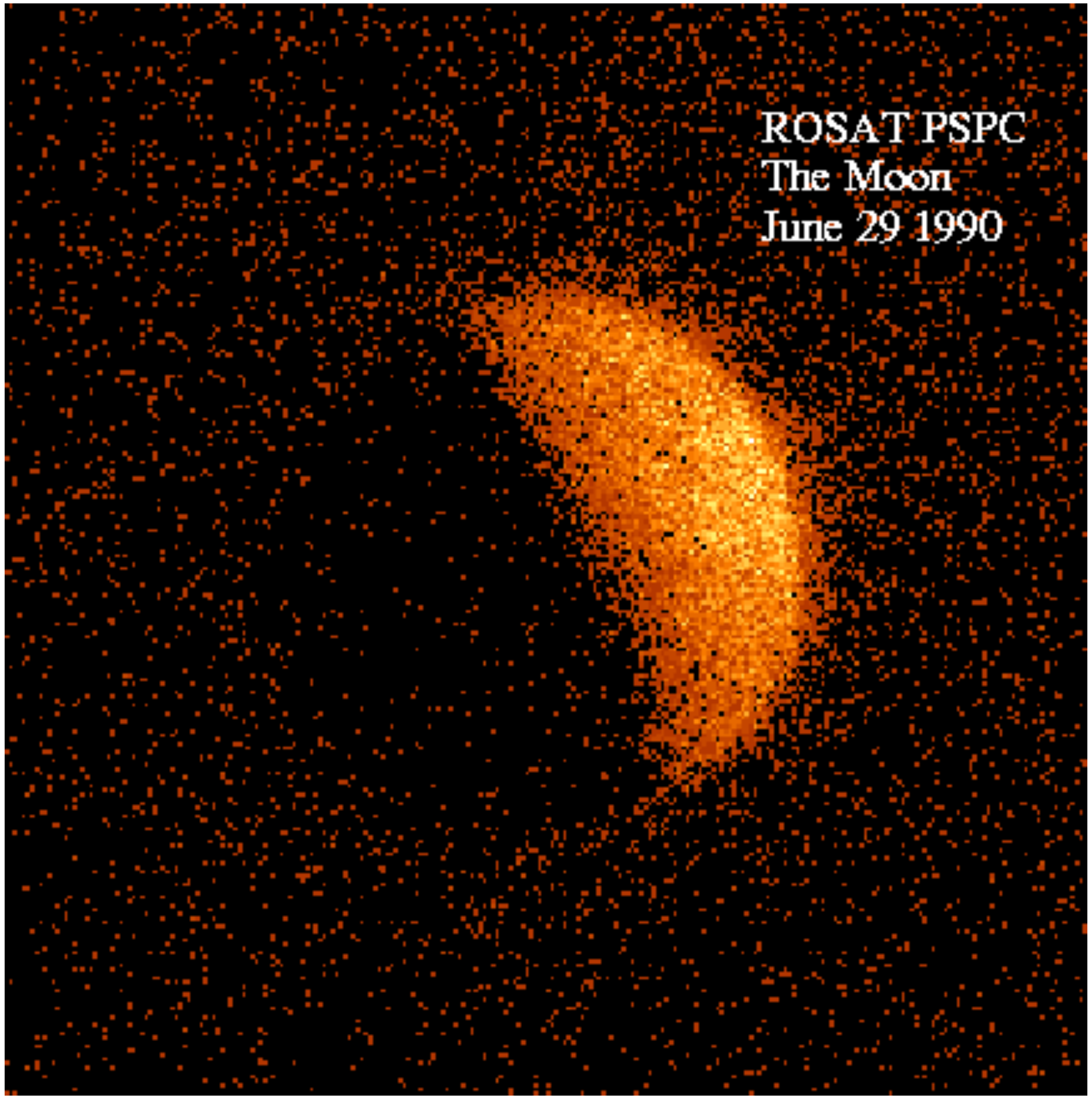
Steve Snowden did a pretty good job, what remains are

- Faint residuals of the LTEs
- Non-time-variable component of the SWCX



SWCX

LTEs removed without actually knowing what they were, but…
Observation of the dark side of the moon had same rate as the contemporary LTE rate → the emission is cis-lunar

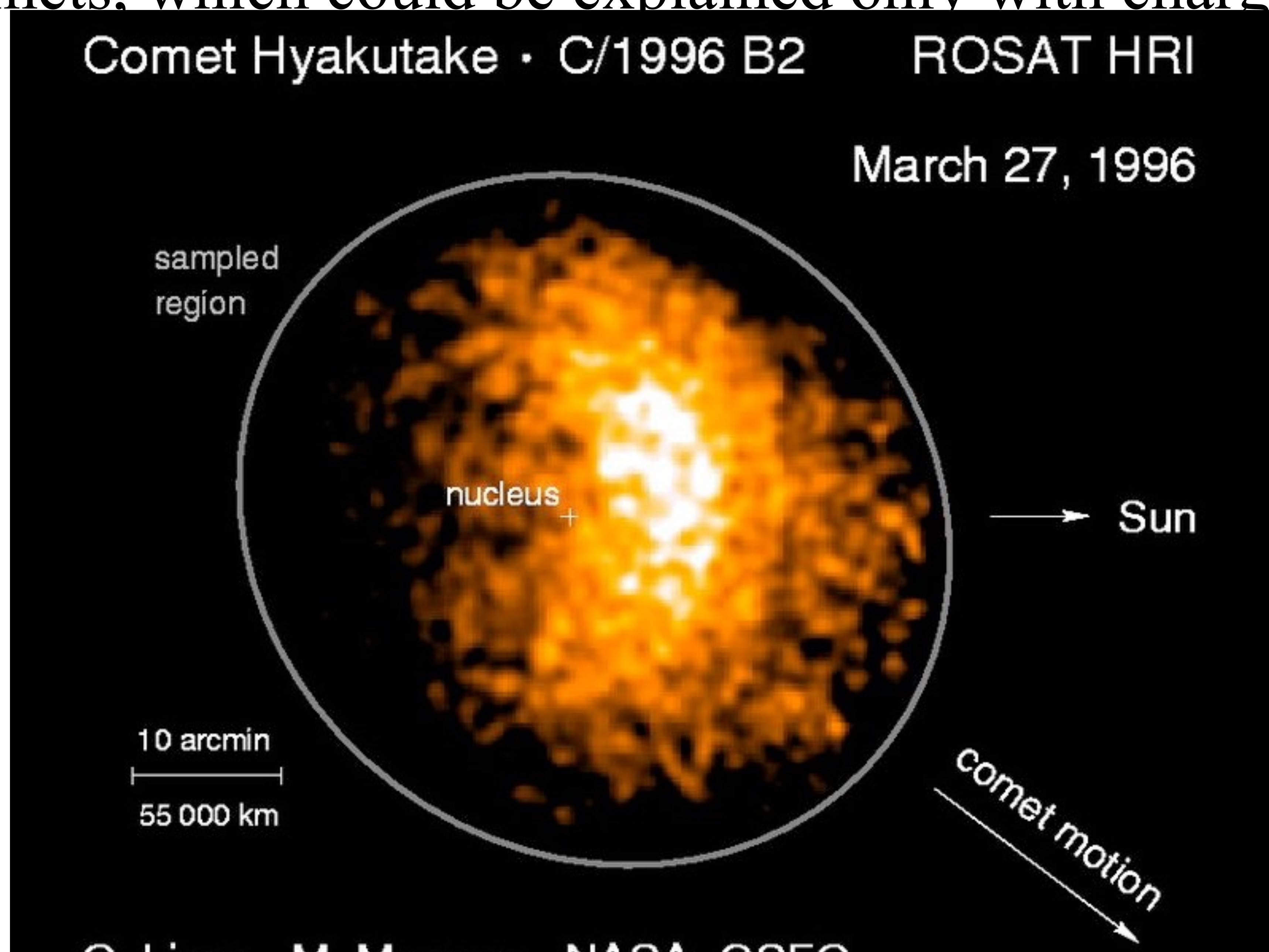


SWCX

LTEs removed without actually knowing what they were, but…

Observation of the dark side of the moon had same rate as the contemporary LTE rate → the emission is cis-lunar

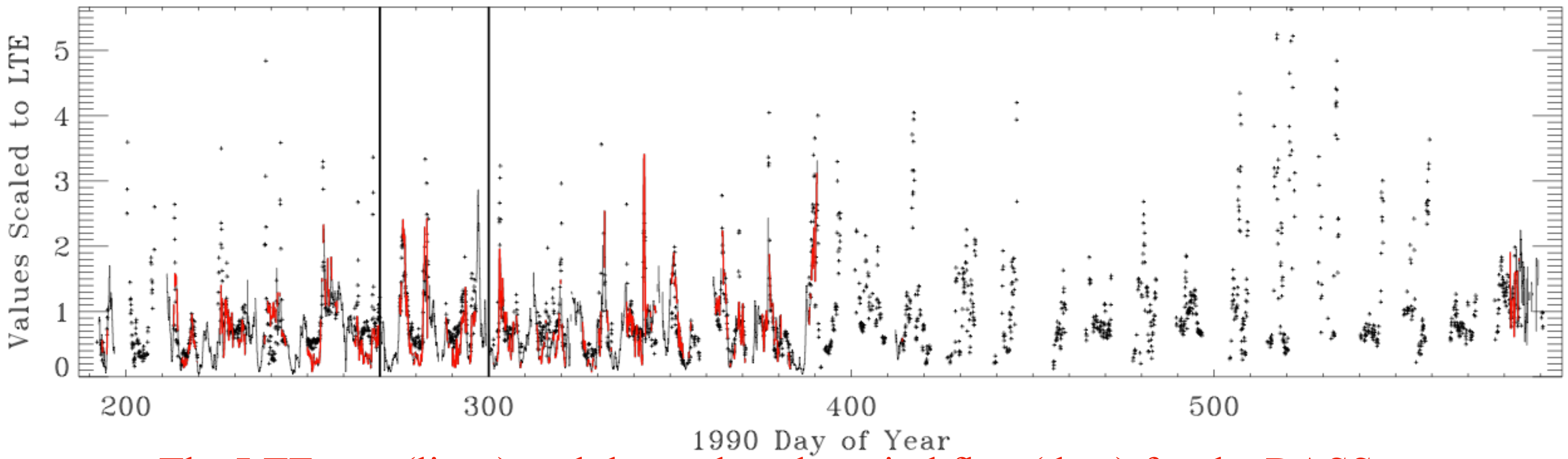
Then there was the unexpected detection of bright X-ray emission from comets, which could be explained only with charge-exchange



SWCX

Correlation between LTEs and solar wind flux noted by Michael Freyberg (LB&B, 1998)

Link shown more strongly by Cravens, Robertson, & Snowden (2001)



The LTE rate (lines) and the scale solar wind flux (dots) for the RASS

This correlation demonstrated that solar wind charge exchange was the cause of the LTEs.

Don Cox (1998) pointed out that the entire heliosphere should be glowing in the X-ray as the solar wind interacted with the neutral ISM flow through the solar system.

The emission attributed to the Local Hot Bubble might be just SWCX!

The Local Hot Bubble

There is an irregular region surrounding the sun that is remarkably devoid of neutral material (observationally, the Local Cavity) mostly co-located with a region filled with T~10^6 K gas (the Local Hot Bubble, LHB).

There were severe theoretical problems with the LHB

SWCX provided a means to propose that it just didn't exist:

Astrophys Space Sci (2009) 323: 1–16
DOI 10.1007/s10509-009-0053-3

INVITED REVIEW

The trouble with the Local Bubble

Barry Y. Welsh · Robin L. Shelton

Rumors of the demise of the LHB have been greatly exaggerated. - Snowden

Received: 18 March 2009 / Accepted: 29 May 2009 / Published online: 17 June 2009

SWCX

SWCX is more of a problem for XMM than for ROSAT

- SWCX emission is strong in the OVII, OVIII, and CVI lines (just the lines you need to characterize plasmas)

→ Detection of WHIM, already difficult, even more so
→ Project to measure T variation in LHB became impossible
→ Characterizing the Galactic center & bulge (at O) problematic
→ Comparing absorption and emission in the halo even more so…

- Galactic cartography (figuring out where the gas is) becomes v.difficult:
  Separation of local/distant emission using the anti-correlation with HI
  Since XMM has a smaller field of view nearly impossible:
    on- and off-cloud observations are not simultaneous.
  Henley & Shelton (200X) showed this for a cloud observed with both XMM and Suzaku at different epochs and obtaining very diff. results!

→ Measurement of the halo using absorbing clouds very difficult
    (observationally too costly)

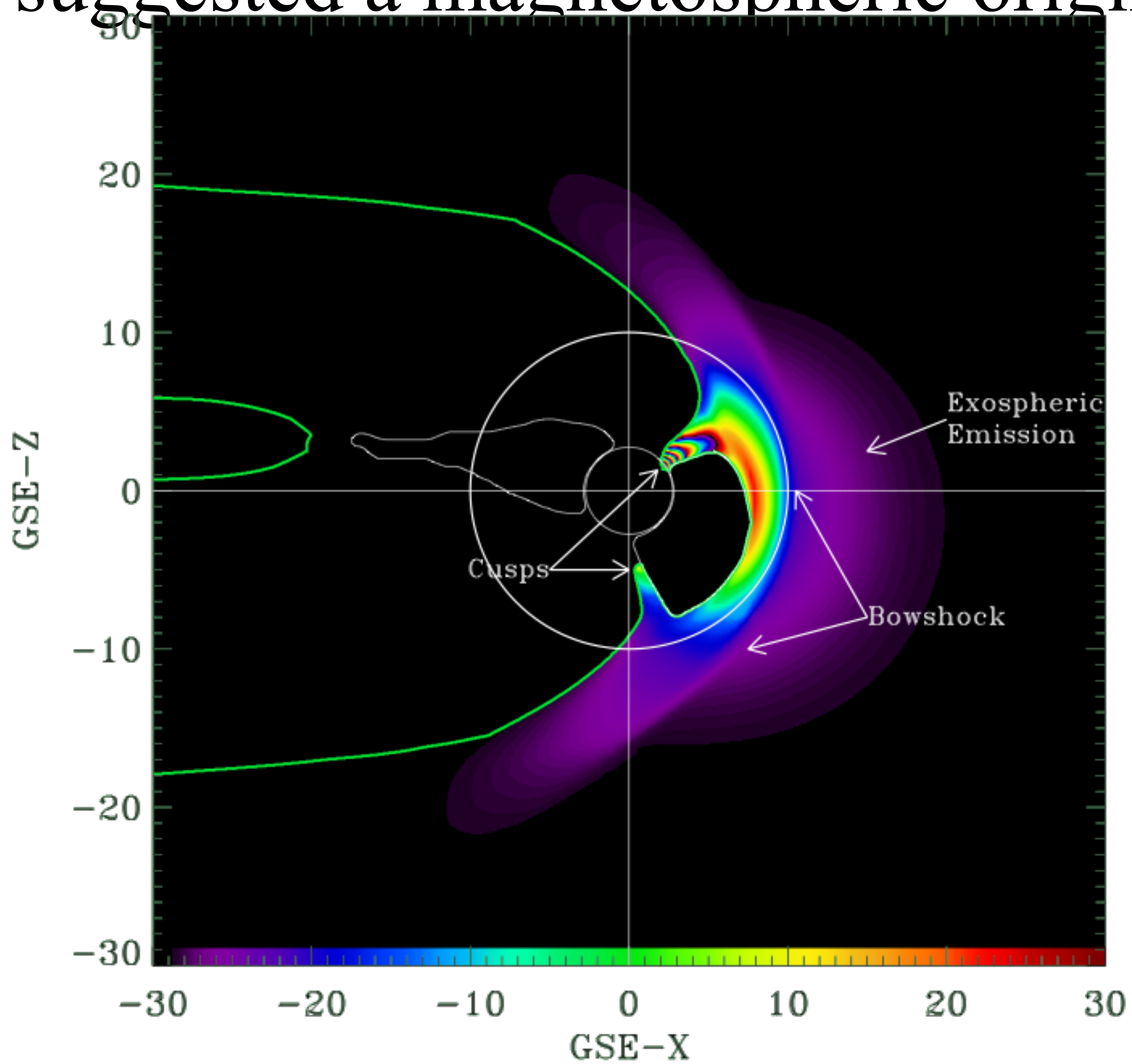
Buoying our Spirits with Work

Can we model the SWCX and get rid of it?

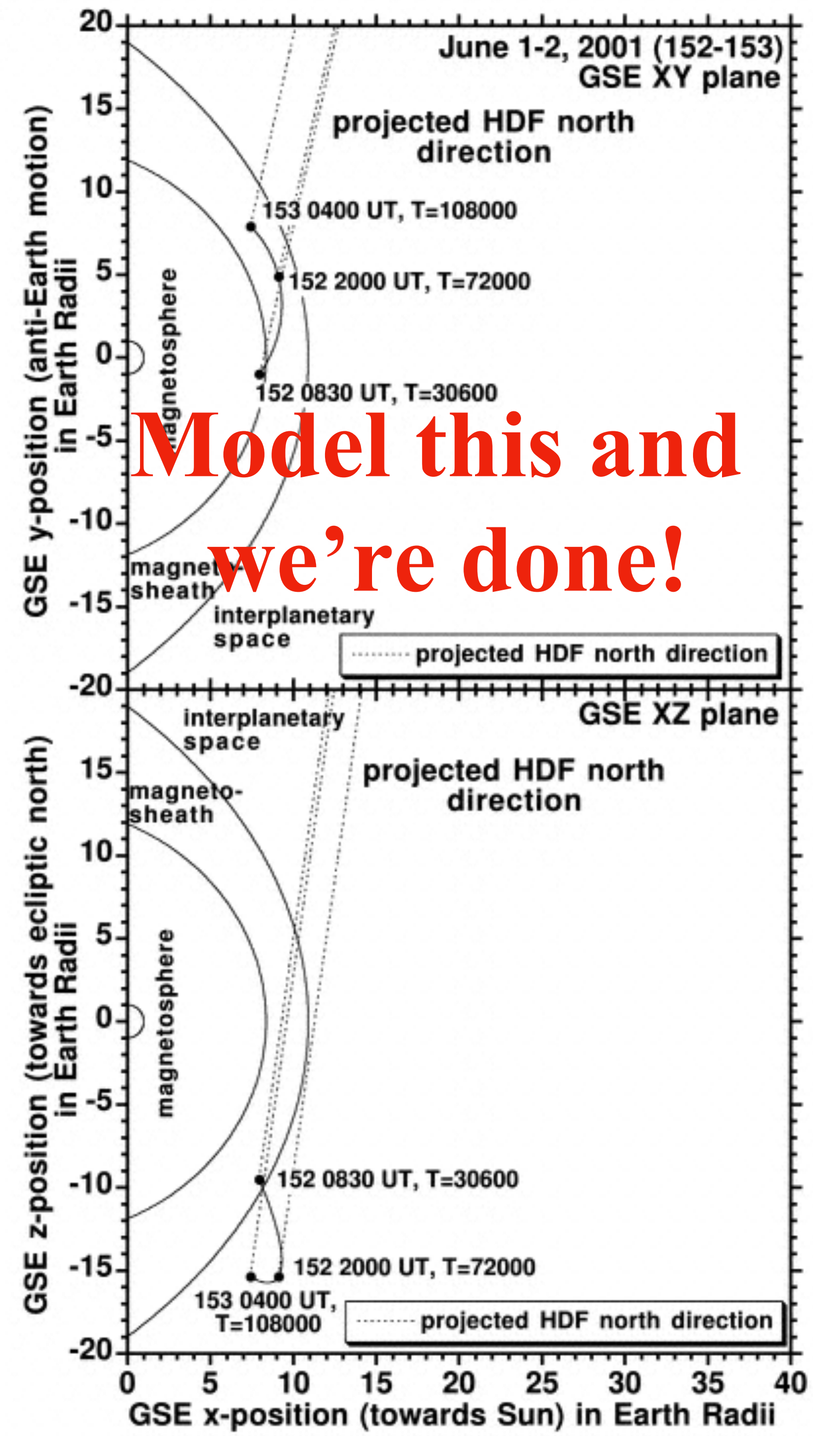
Since it is produced nearby, we should know enough, right?

Start with HDFN event:

Fortuitous observing geometry suggested a magnetospheric origin



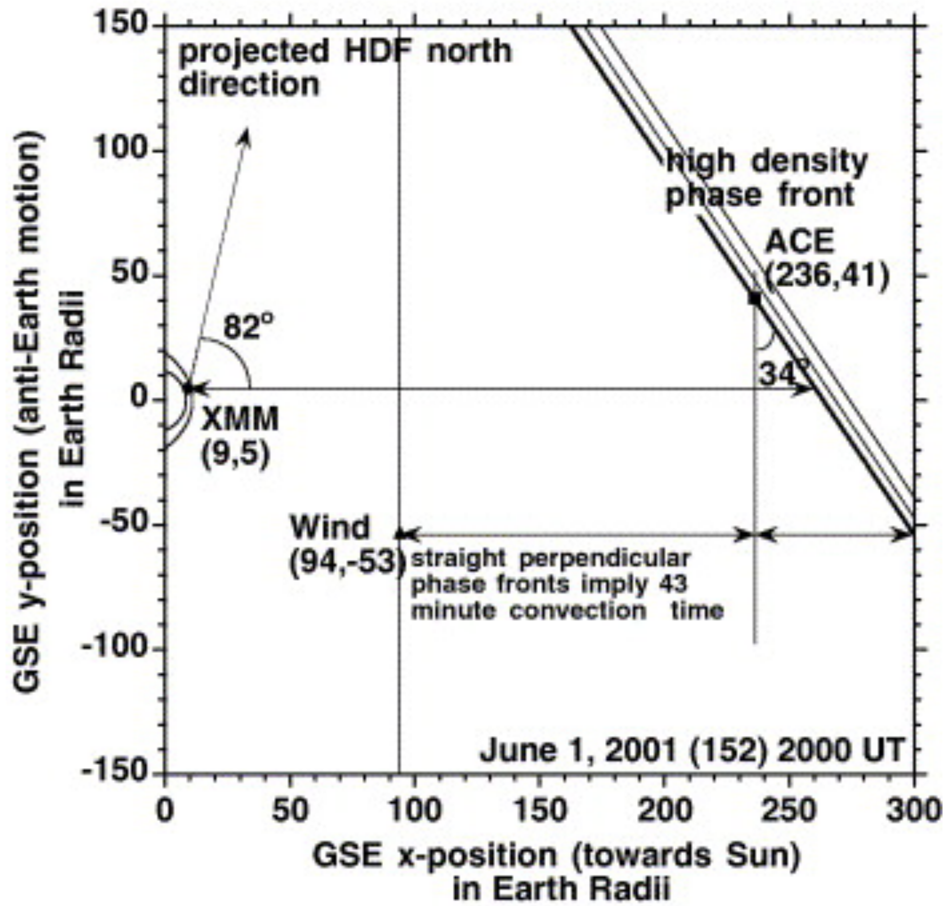
Modern view of X-ray emissivity from magnetosheath.



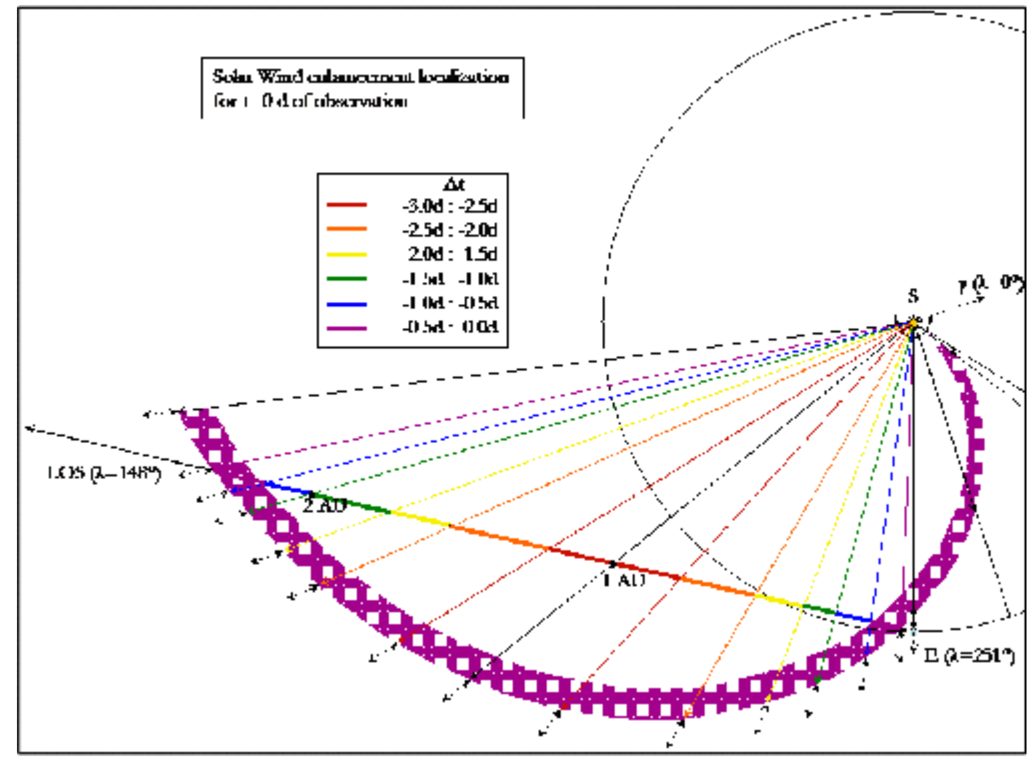
Model this and we're done!

Snowden, Collier, & Kuntz (2004)

But Where is This Stuff, Really?



Collier et al. 2005



Koutroumpa et al. 2006

Shortly there were more models for the emission:

- A local wavefront in the solar wind (Collier et al. 2005)
- The heliospheric Parker spiral (Koutroumpa et al. 2006)

Which dominates, the magnetospheric or heliospheric emission?

But Where is This Stuff, Really?

Two groups, in parallel ransacked the XMM archives to answer this Q:

- GSFC group concentrated on LOS with multiple observations with different observation geometries - a rather limited sample (K&S 2008)
- Leicester group used an efficient way of identifying SWCX events in all observations (Carter et al. 2008, 2009, 2011)

Both reached the same conclusion, both magnetospheric and heliospheric events were being observed but the model of the magnetosphere was too crude to allow a definitive conclusion.

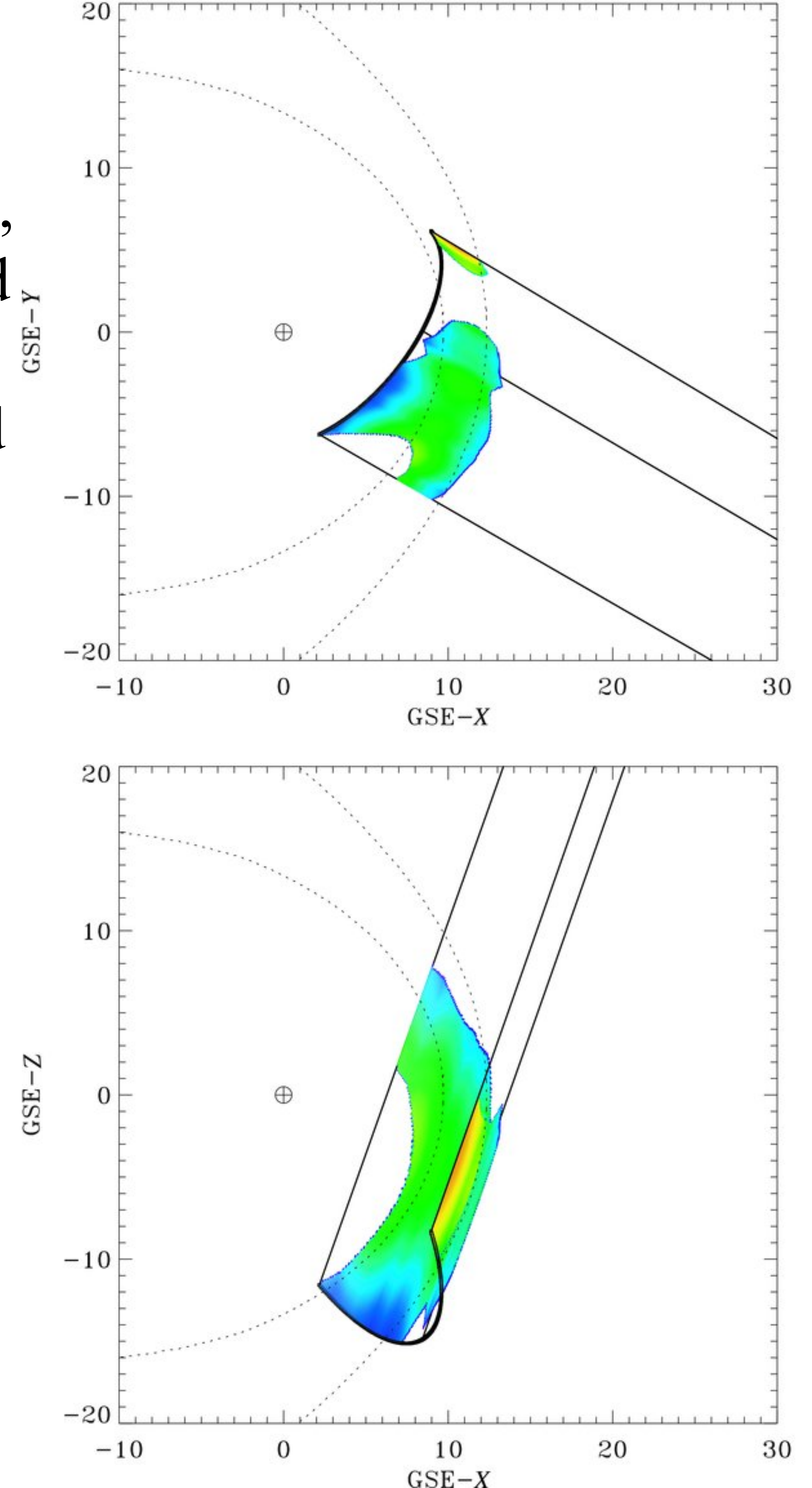
Both groups teamed up with heliospheric/space physics groups with MHD models of the magnetosphere.

- Leicester group using a single MHD model found some events that were clearly magnetospheric, and some that just didn't fit.
- GSFC group quickly(?) realized that different MHD models gave different locations for the location of the magnetosheath…

…could XMM observations provide data to correct MHD?

Pivotal Observation

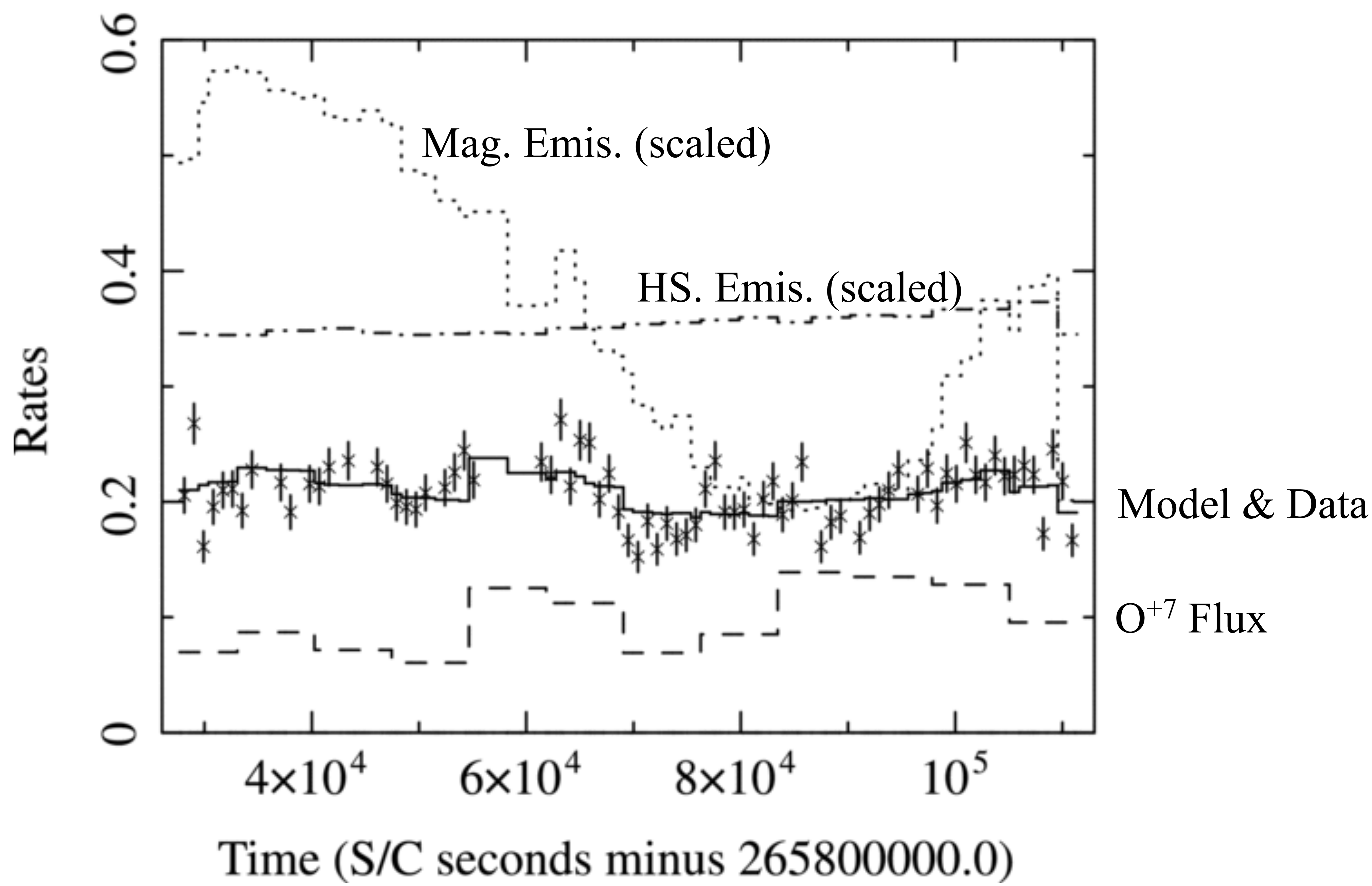
Since XMM can observe for well over a day, let's stare in a particularly dark direction and let the line of sight cut through the magnetosheath, measure the light-curve, and determine the emissivity in OVII and OVIII.



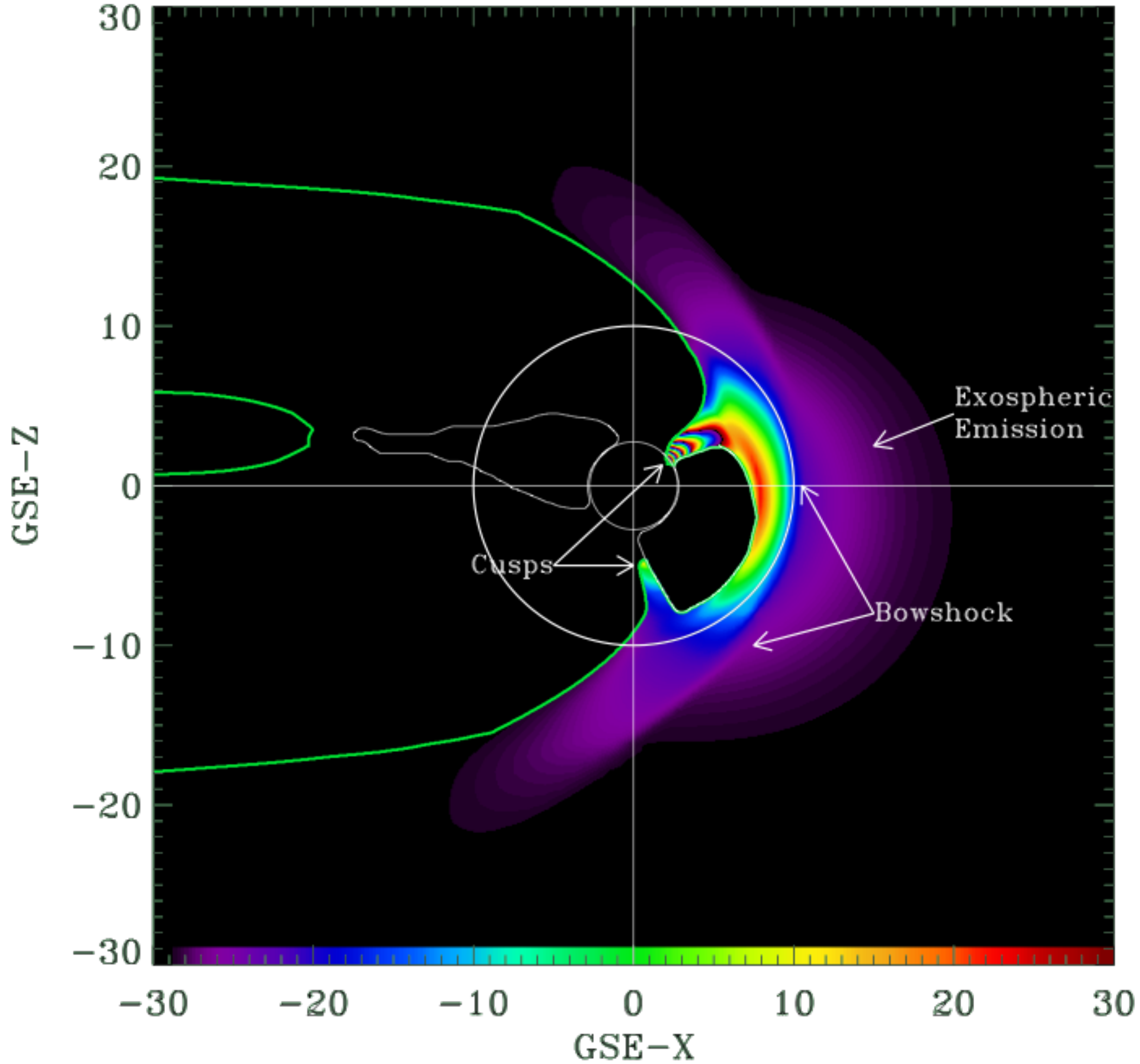
Pivotal Observation (?)

The solar wind did not cooperate; it stayed exceptionally low and invariable, so the light-curve had a minimum of variation.

To within uncertainties, model was consistent, but hardly convincing!
(Snowden et al 2009)

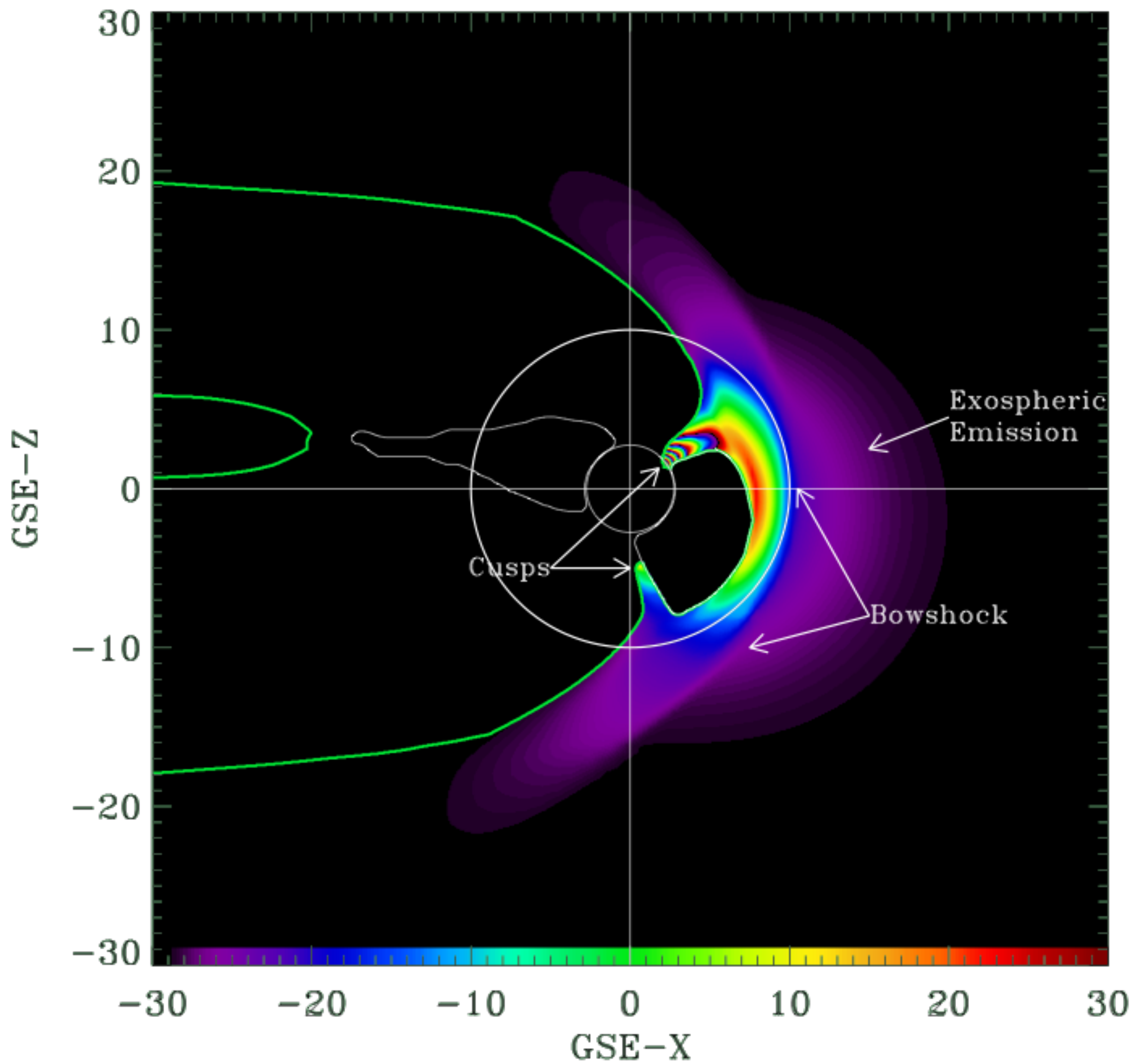


But Where is This Stuff, Really?

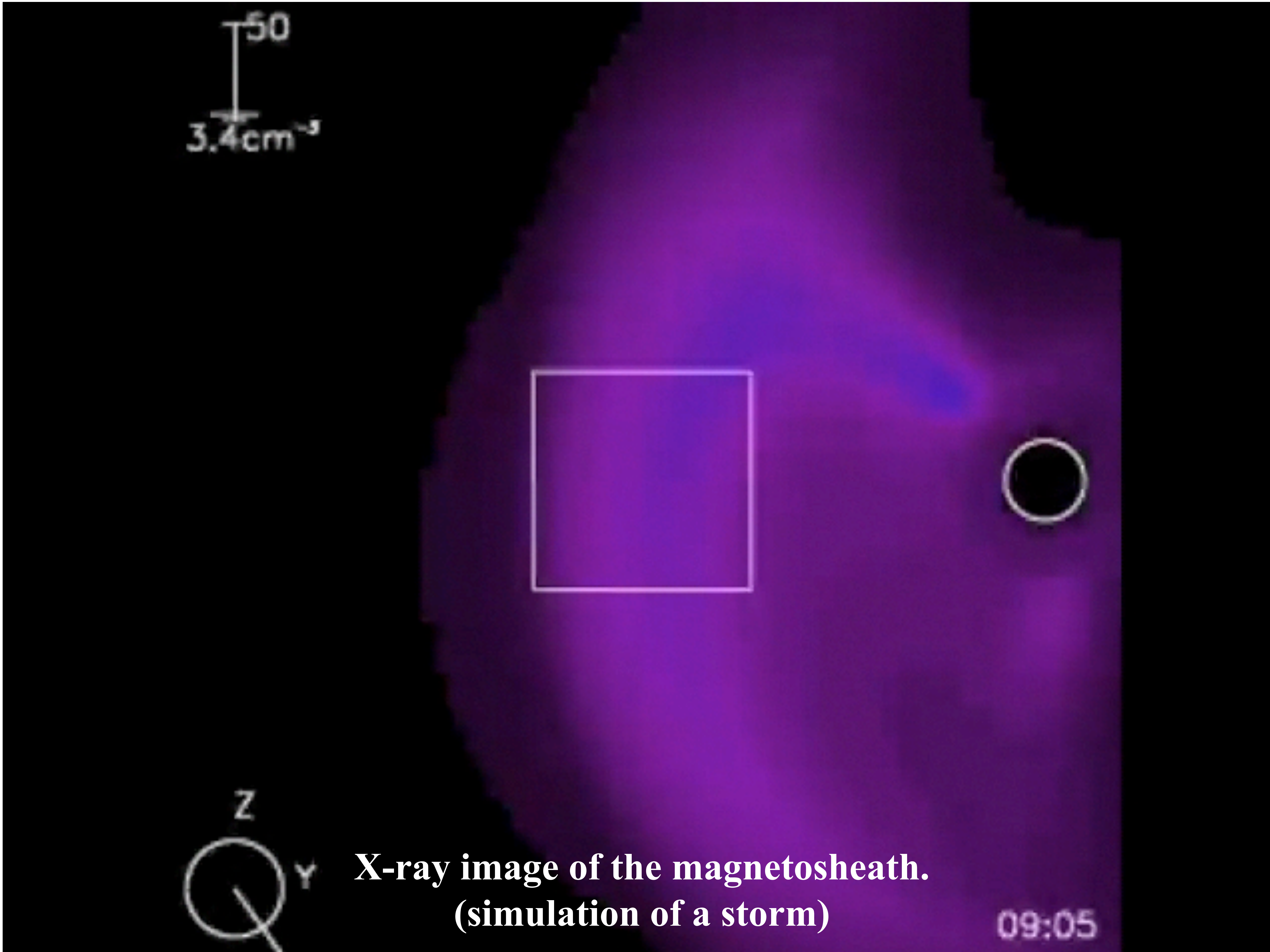


As the solar wind flux (i.e. pressure) varies the magnetopause moves in and out, probably as $(\rho v^2)^{-1/6}$. However, this relation is modified by the strength and direction of the interplanetary magnetic field (IMF) and magnetic reconnection events at the interface of the terrestrial and solar magnetic fields.

We can Use this to Locate the Magnetopause!

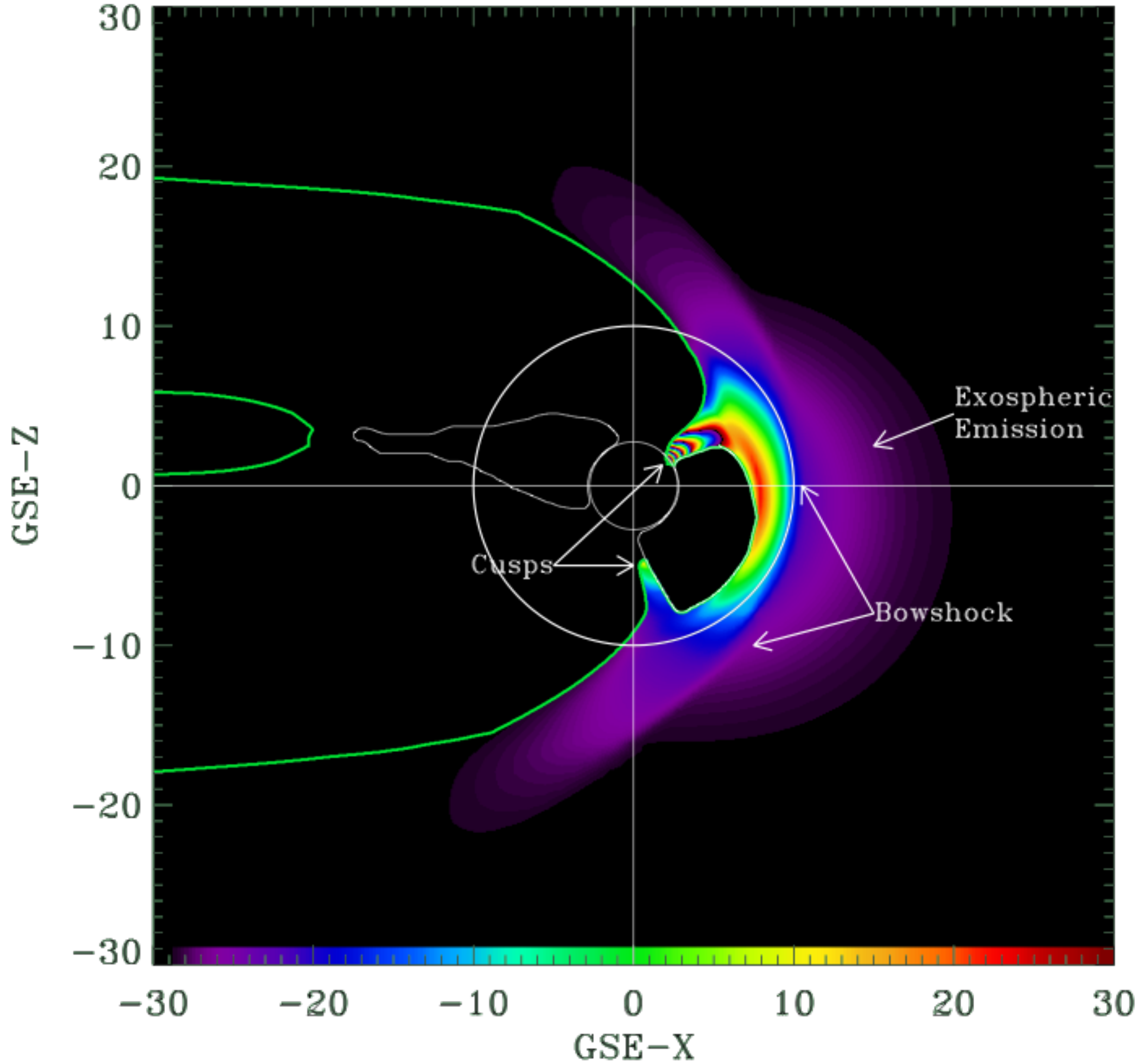


Locating the magnetopause is the primary aim of a whole fleet of satellites bearing magnetometers and other instruments.
Problem: they can only tell where they crossed the magnetopause, not anything about the shape of the magnetopause.



X-ray image of the magnetosheath.
(simulation of a storm)

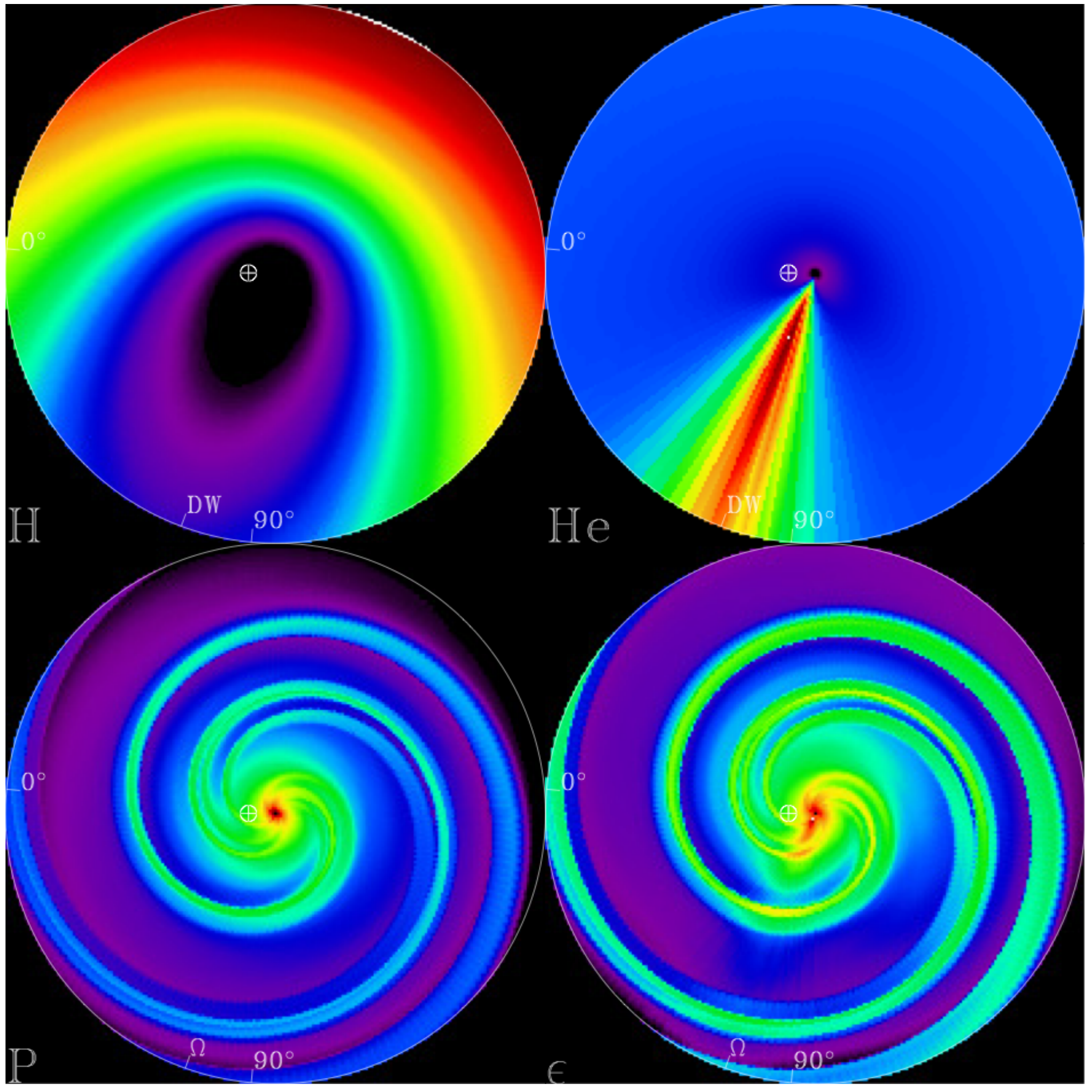
We can Use this to Locate the Magnetopause!



Now, heliophysics graduate students are combing the XMM archive to find useful observations for locating the magnetopause using SWCX events!

Meanwhile in the Heliosphere

The ISM flow of neutral He is gravitationally focussed by the Sun.
The Earth passes through the He Focussing Cone (HFC) in December.
Charge exchange emission from the HFC readily seen in X-rays.
This emission has been studied twice by XMM
(Koutroumpa et al. 2009, 20220)
And we hope to study it with XMM again in the future.



SWCX Studies

Sounding Rocket
2012, 2015,2018

CubeSat
2018

CubeSat
2020

Lunar
2021

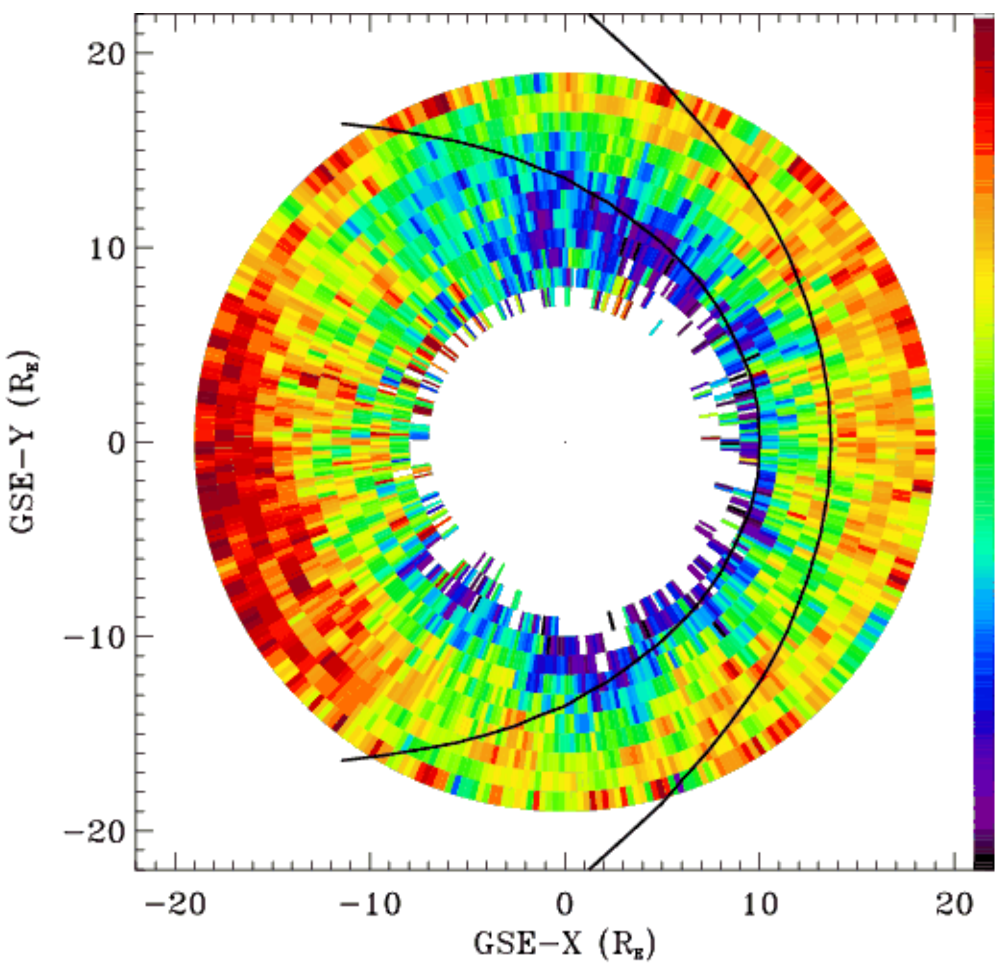
ESA Small Mission
2023

Back to the Beginnings: SPF

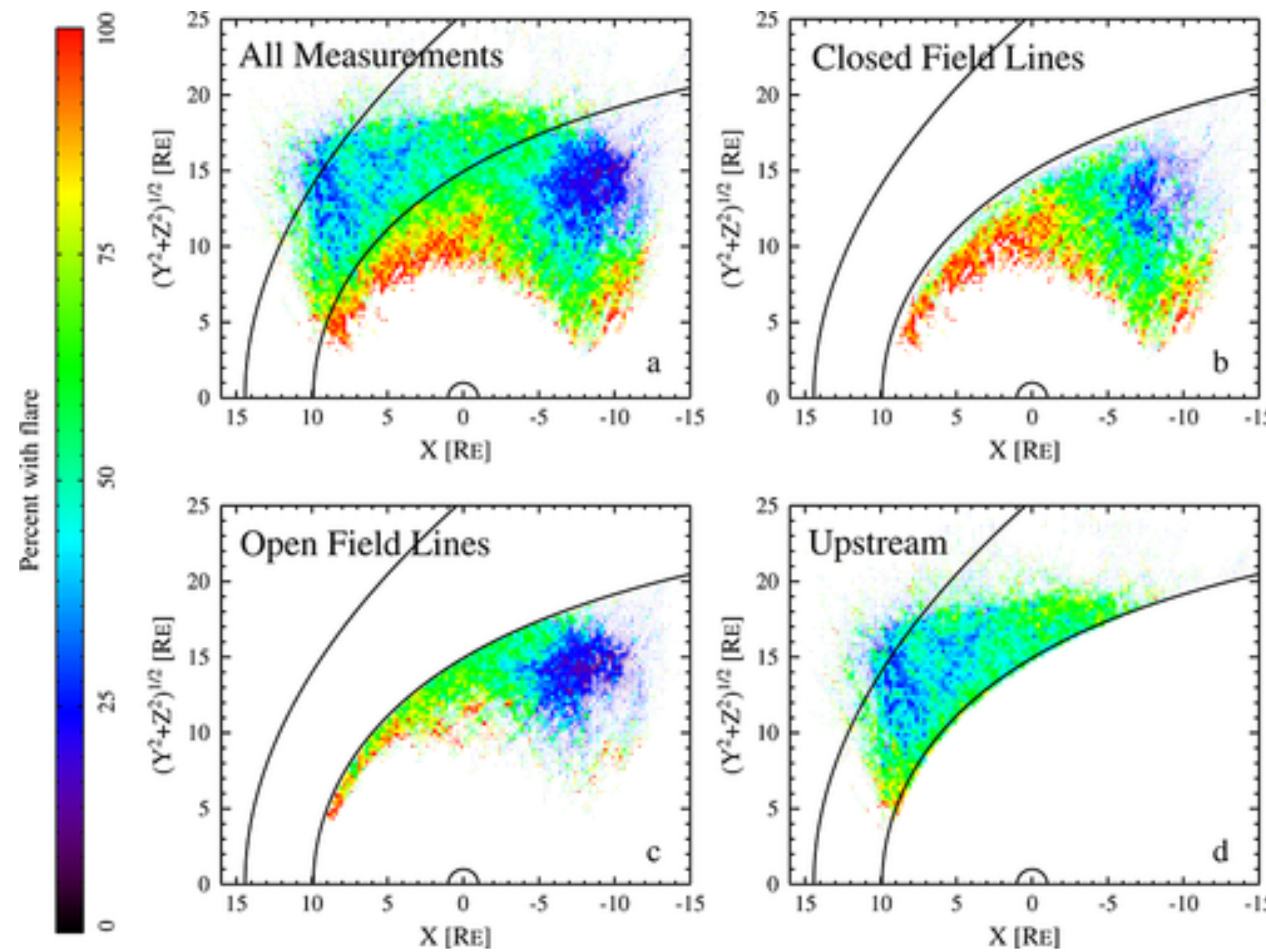
The GSFC GOF has tried to understand when SPFs occur in hopes of scheduling sensitive observations better.

With the help of our heliophysics collaborators, have determined that the SPF occur primarily on closed terrestrial field lines.

Kuntz & Snowden 2008

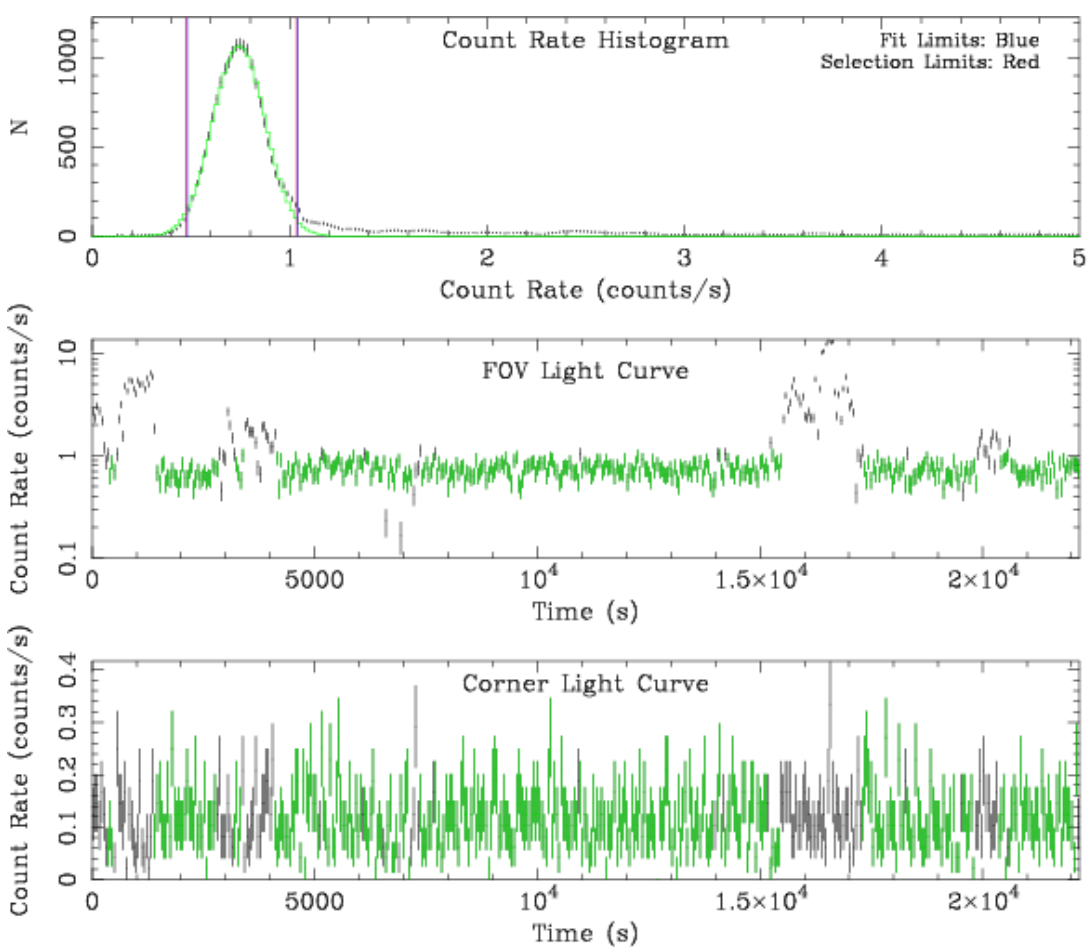


Walsh et al. 2014



Back to the Beginnings: SPF

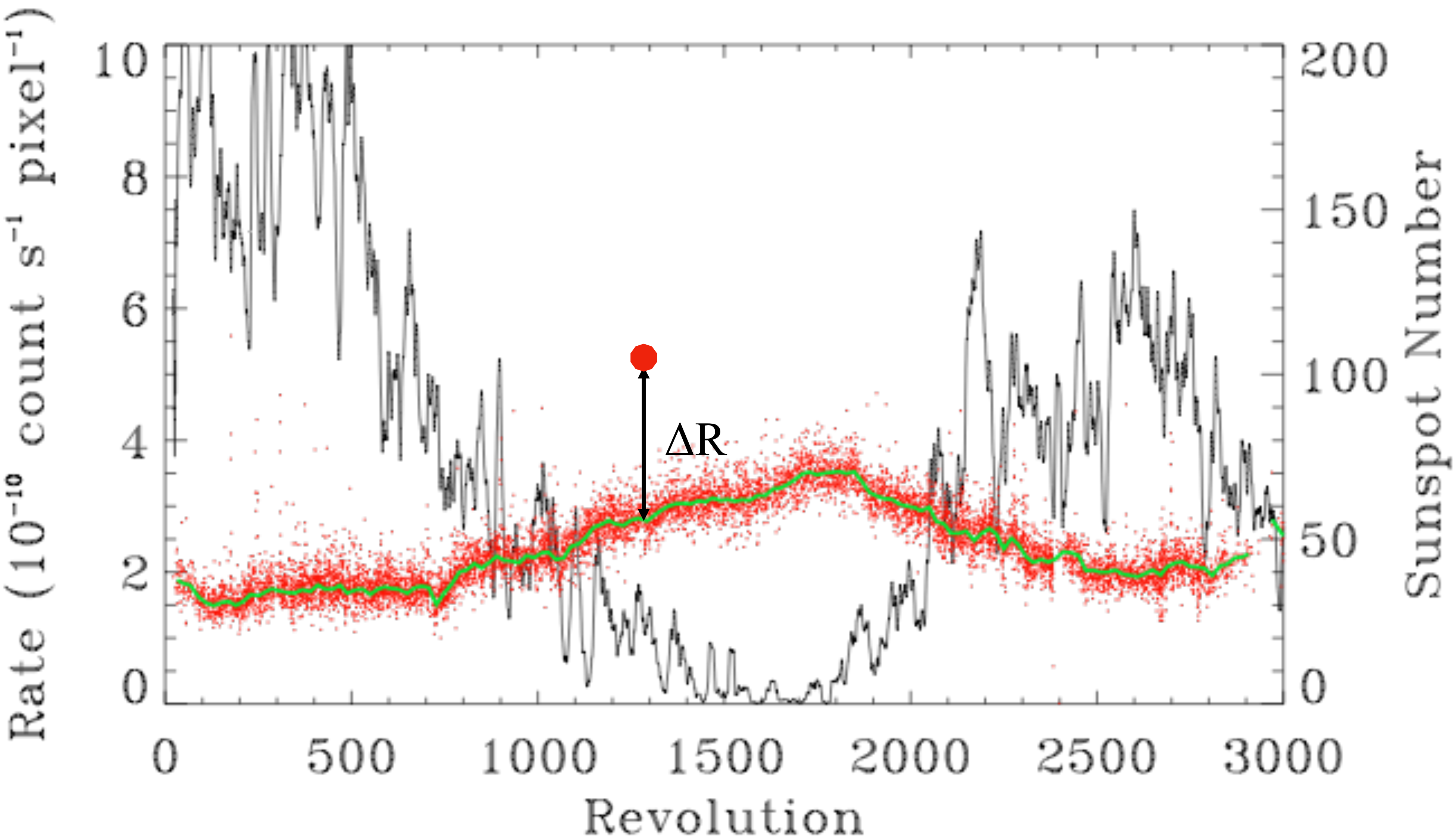
In 2018 Gastaldello formed an ISSI team to study the SPF problem in XMM in order to plan for Athena.
The ISSI team is half astro- and half helio-physics.
The heliophysics side is very interested since XMM is such a sensitive monitor of low energy protons that it is providing new insights into the distribution of particle populations in the magnetosphere and magnetosheath.
XMM GOF is providing "trend" data to heliophysics to support this effort



Back to the Beginnings: QPB

Similarly, GSFC GOF work with both the local interdisciplinary group and the ISSI team lead to a new view of the QPB:

If we measure the mean QPB light-curve over the mission and take ΔR to be the difference between the instantaneous QPB rate and the mean light curve:



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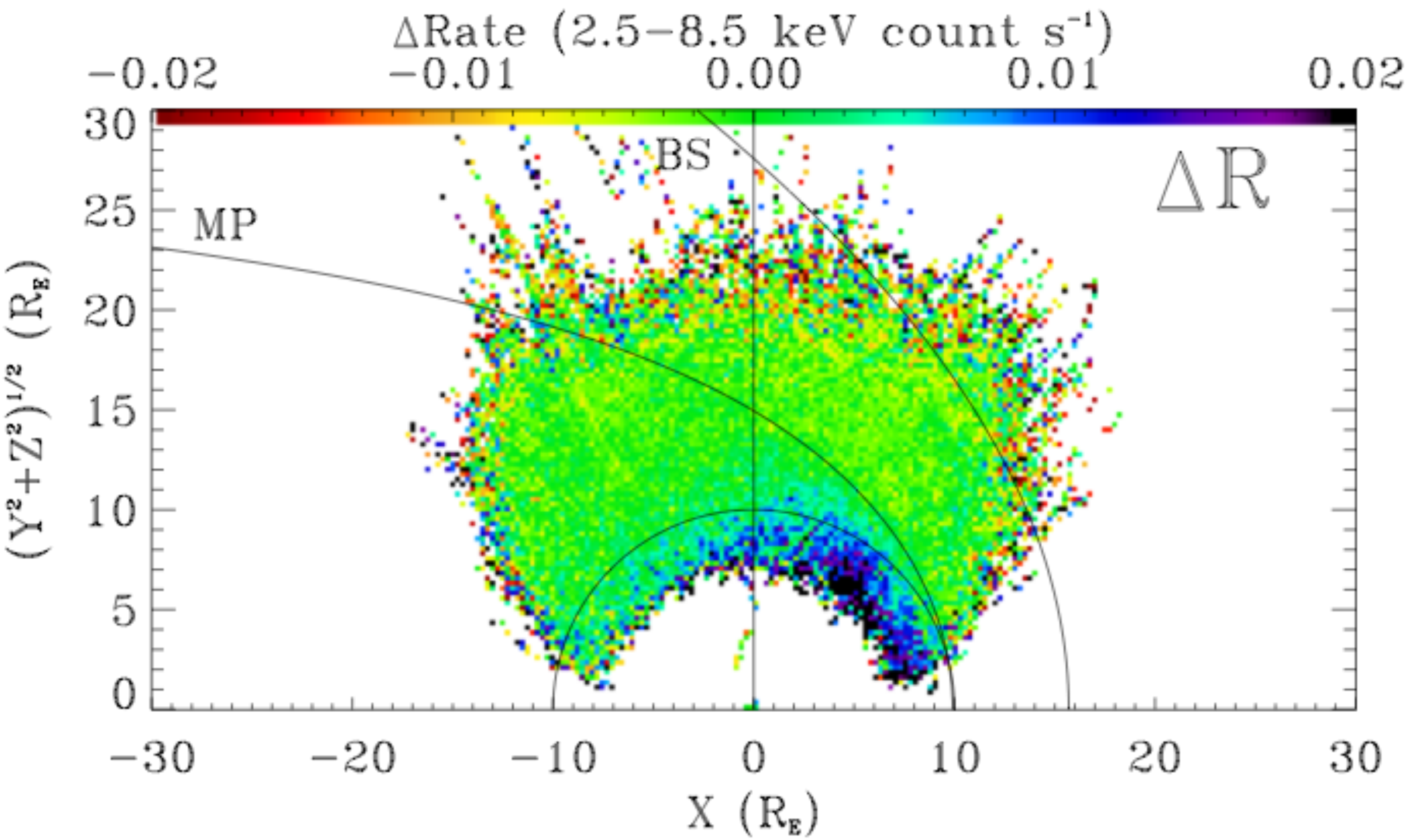
Then we find ΔR is a function of the spacecraft location



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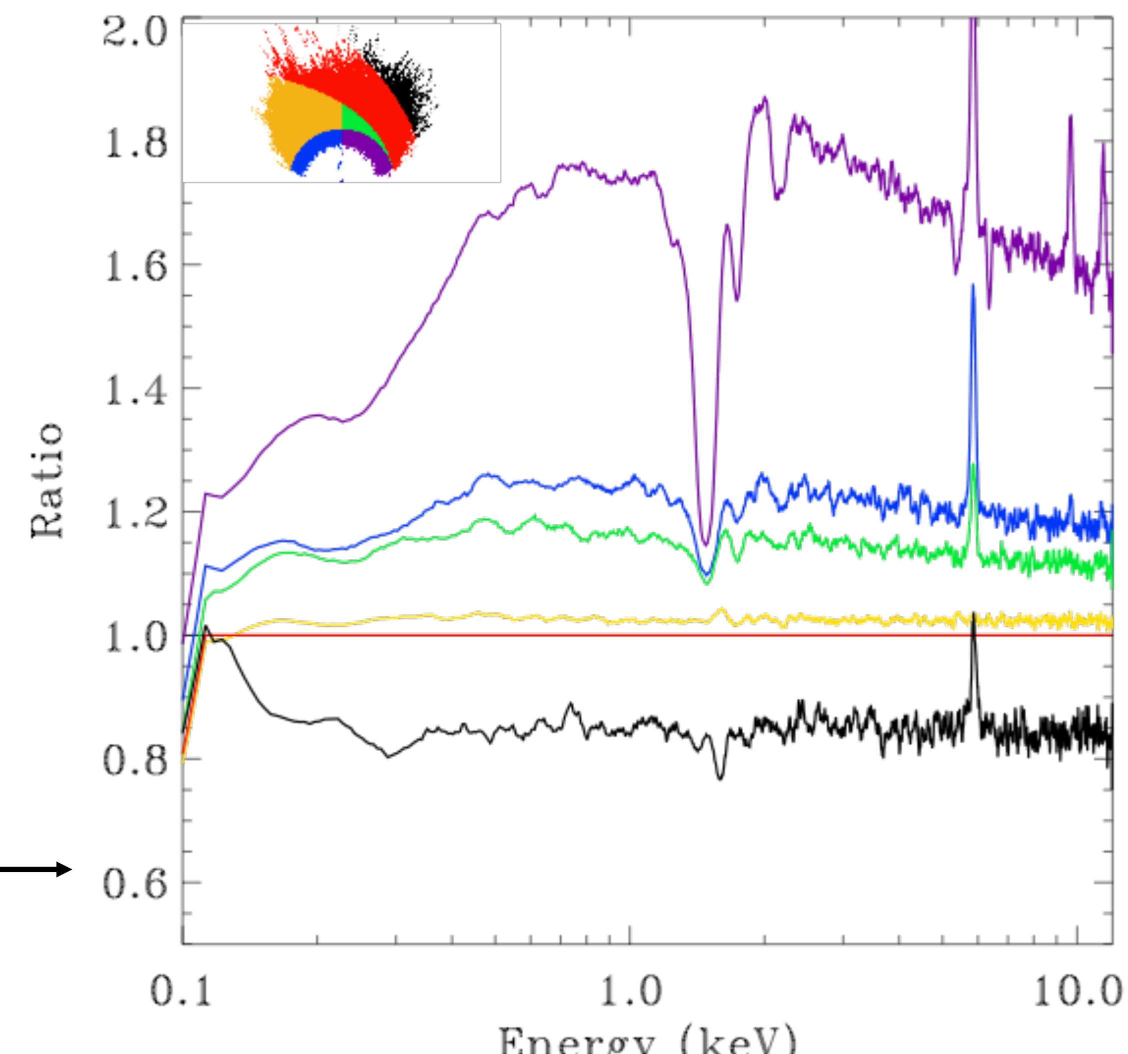
Then we find ΔR is a function of the spacecraft location and that the spectral shape is a function of ΔR.

This is also of interest to the space physics community, but it is less clear what we are measuring here.



Ratio of the spectrum for each region to that measured in the magnetosheath.

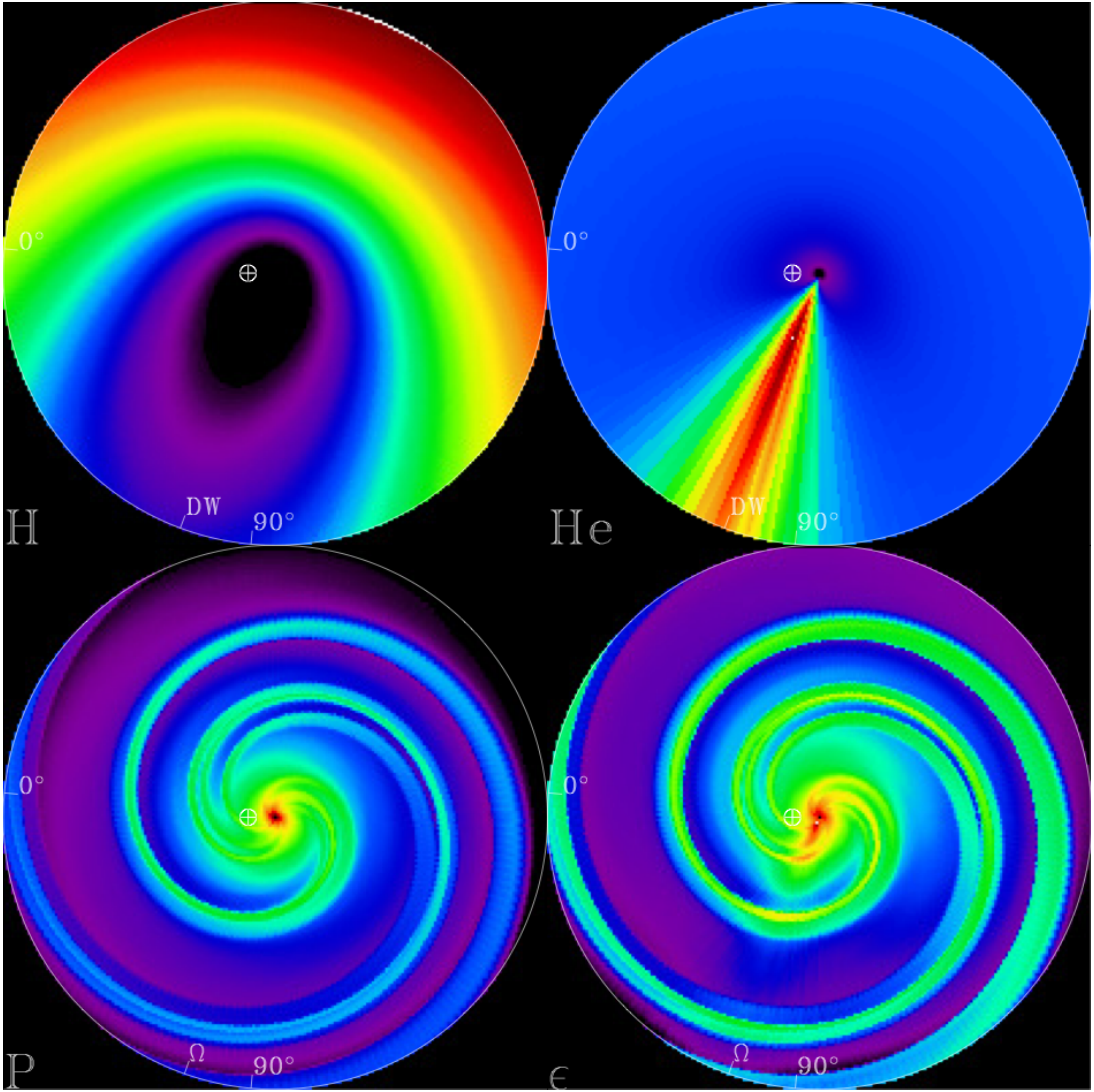
Summary

HEO spacecraft are subject to many backgrounds avoided in LEO.

- the spacecraft samples many different environments and particle populations
- this leads to more complex data analysis but
- the XMM SPF data is of interest to the space physics community (as is the QPB data)

Soft X-ray missions are plagued by SWCX emission

- modelling is very difficult because the input SW data does not exist
- currently concentrating on mitigation strategies informed by heliospheric and magnetospheric science
- XMM makes observations to help mitigate SWCX emission
- XMM makes observations to address space physics questions
- XMM sparked the development of a new cross-disciplinary field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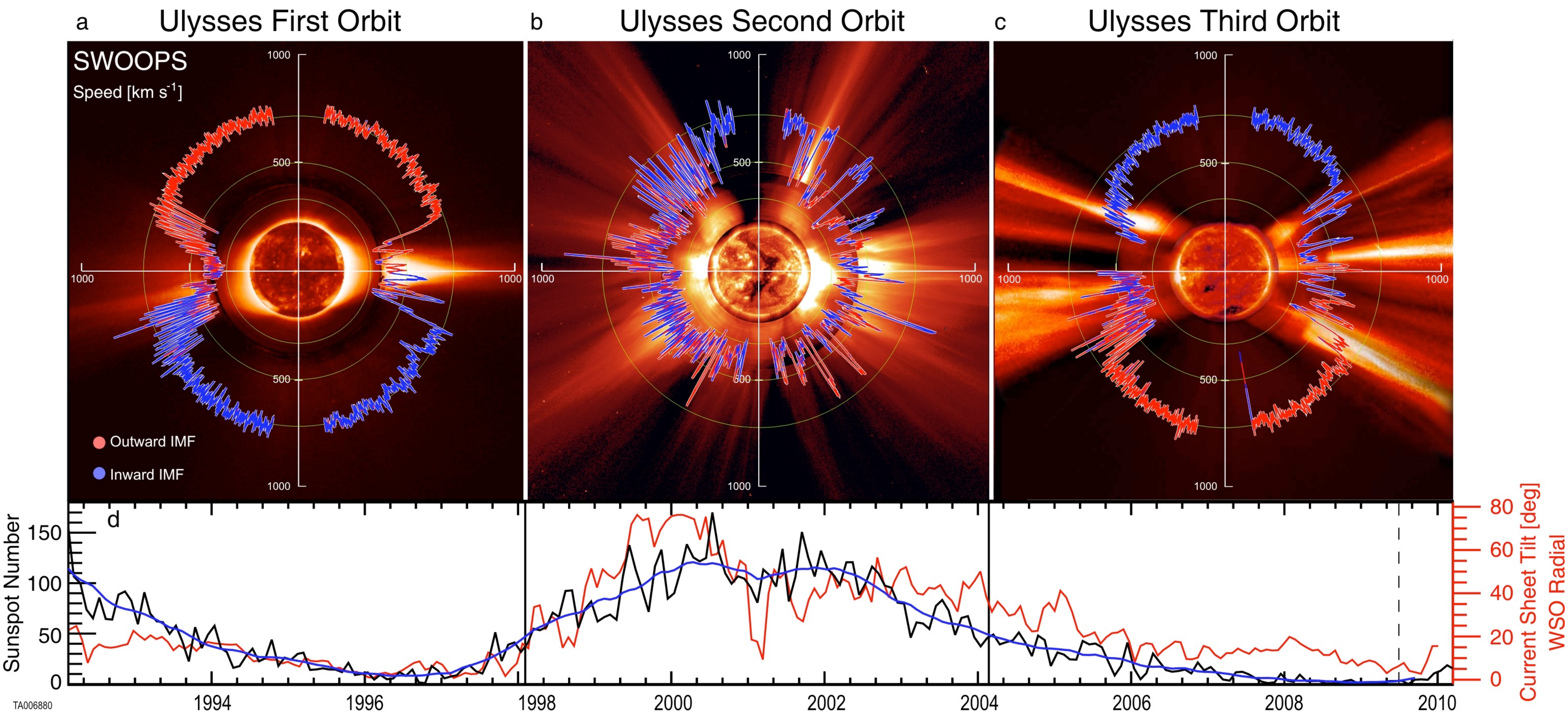

a
Ulysses First Orbit
b
Ulysses Second Orbit
c
Ulysses Third Orbit
SWOOPS
Speed [km s-1]
Outward IMF
Inward IMF
d
Sunspot Number
Current Sheet Tilt [deg]
WSO Radial
1994
1996
1998
2000
2002
2004
2006
2008
2010
TA006880