

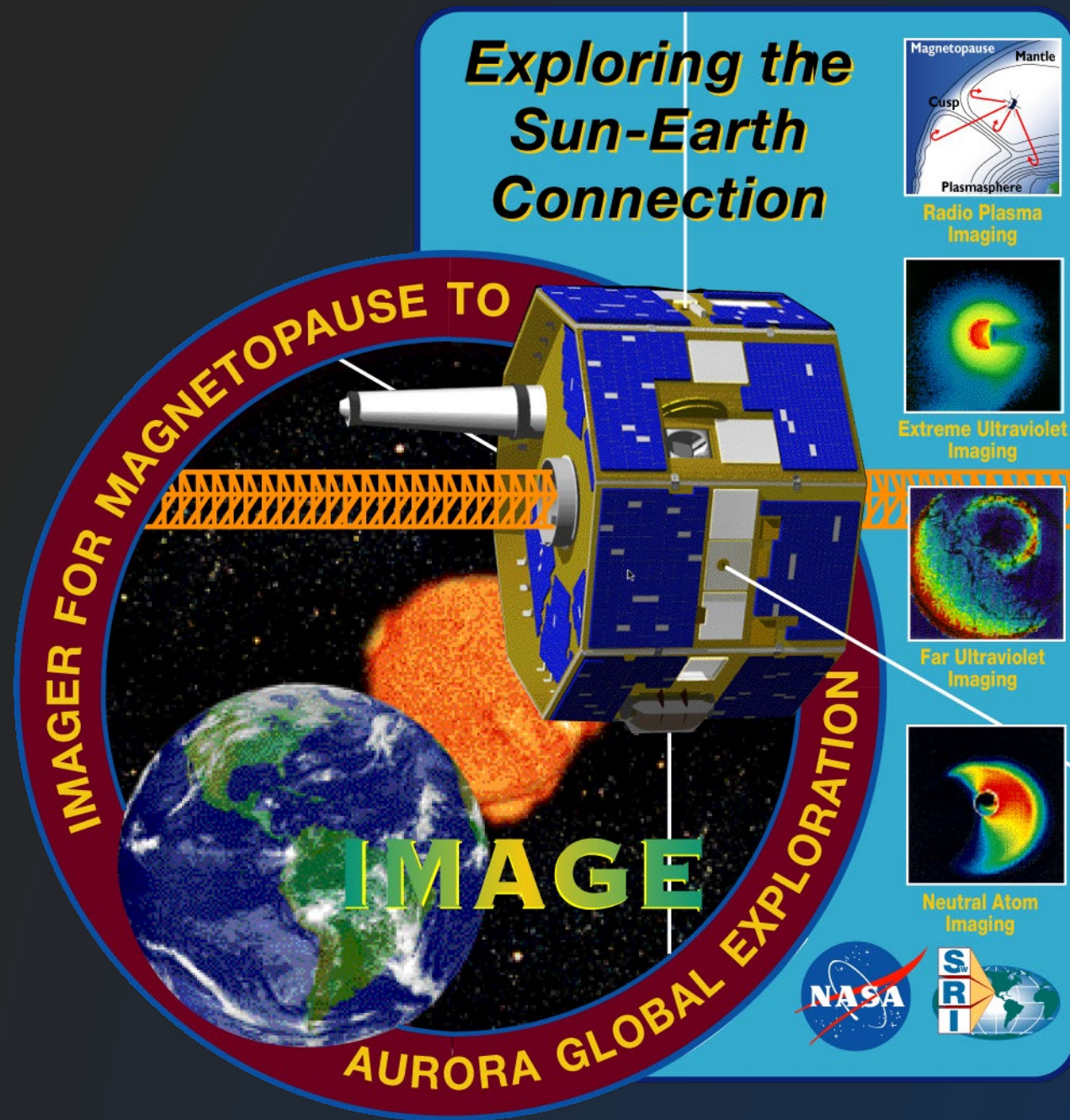
Mapping the Magnetosphere with Energetic Atoms

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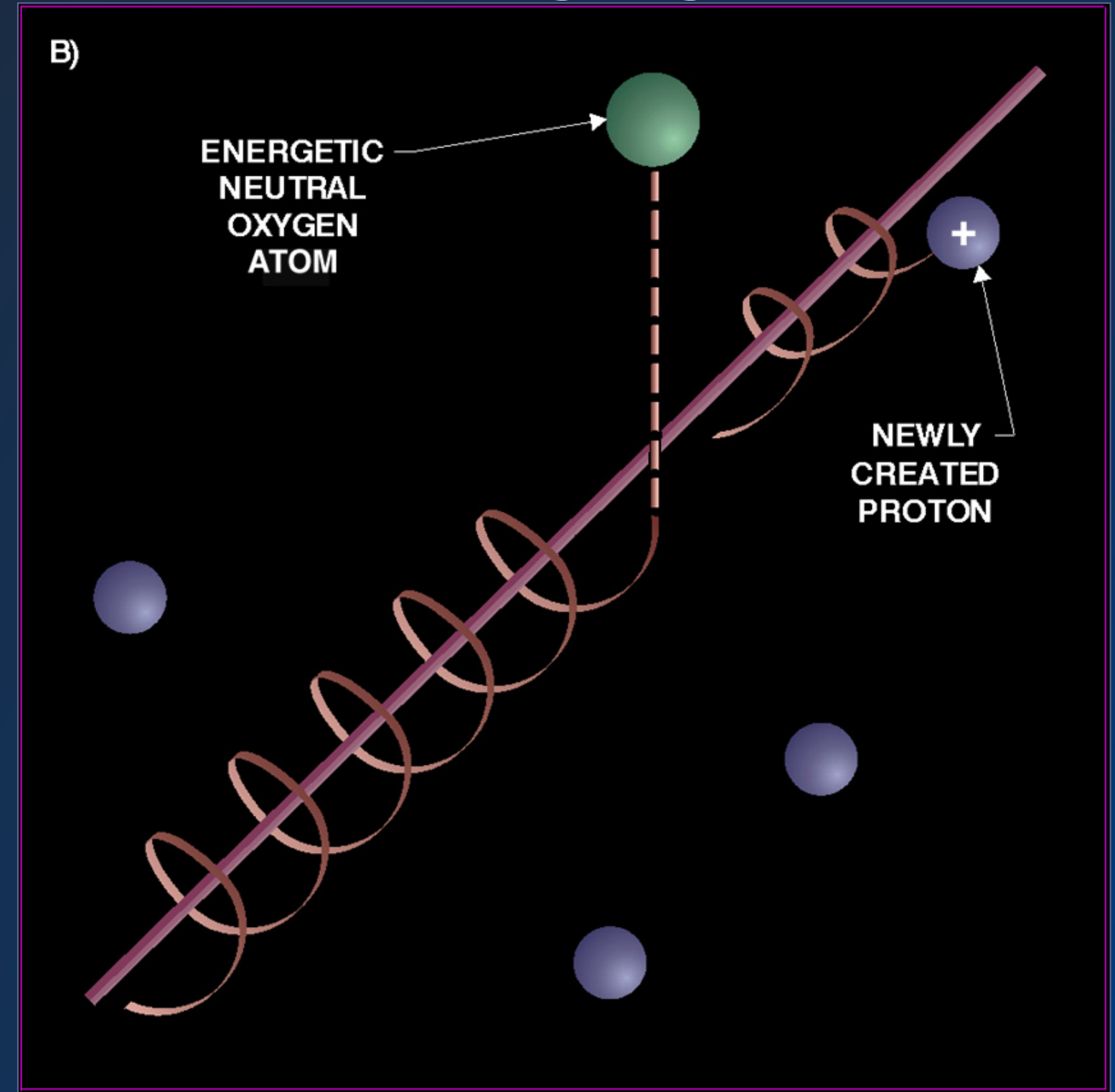
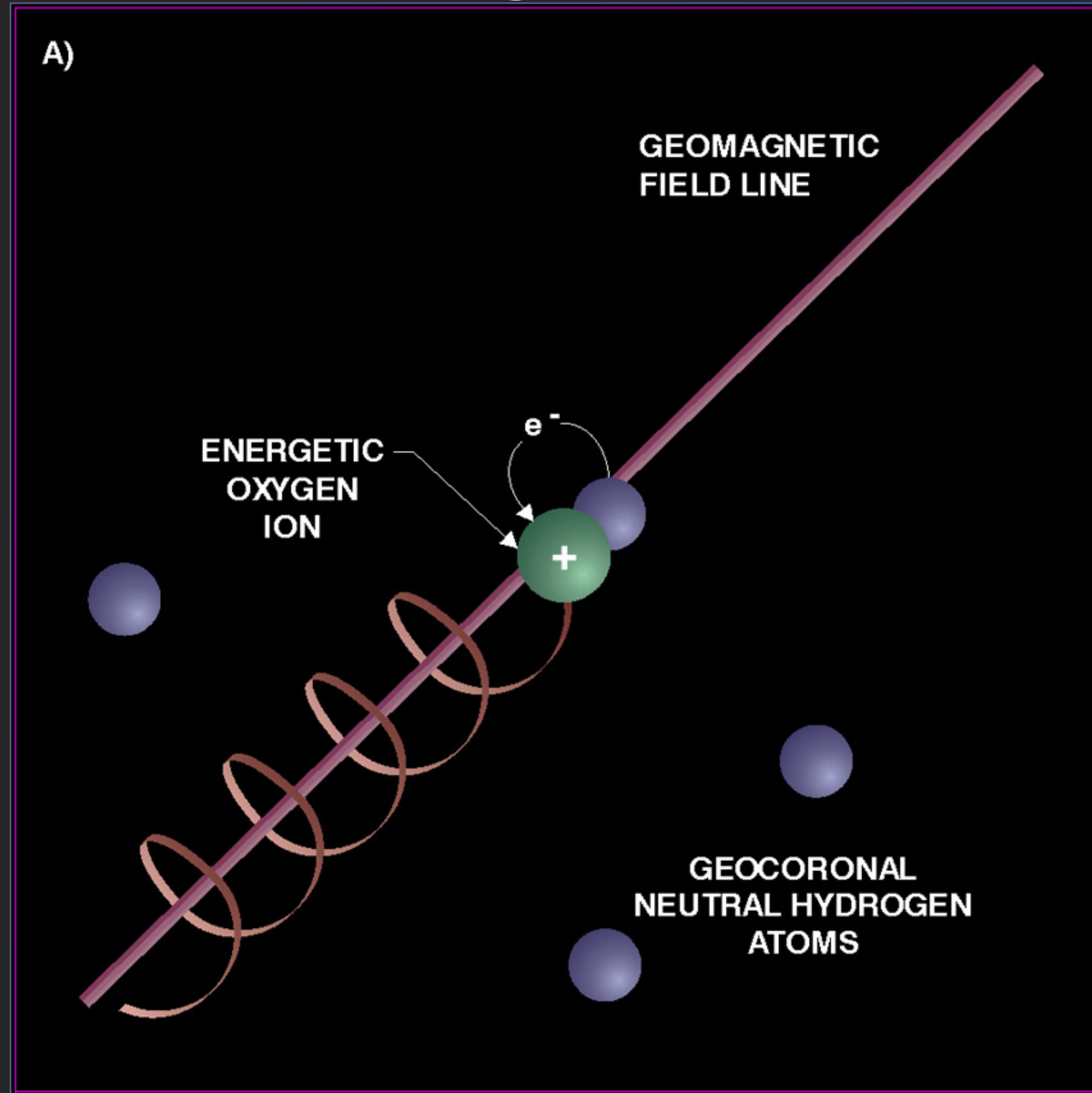


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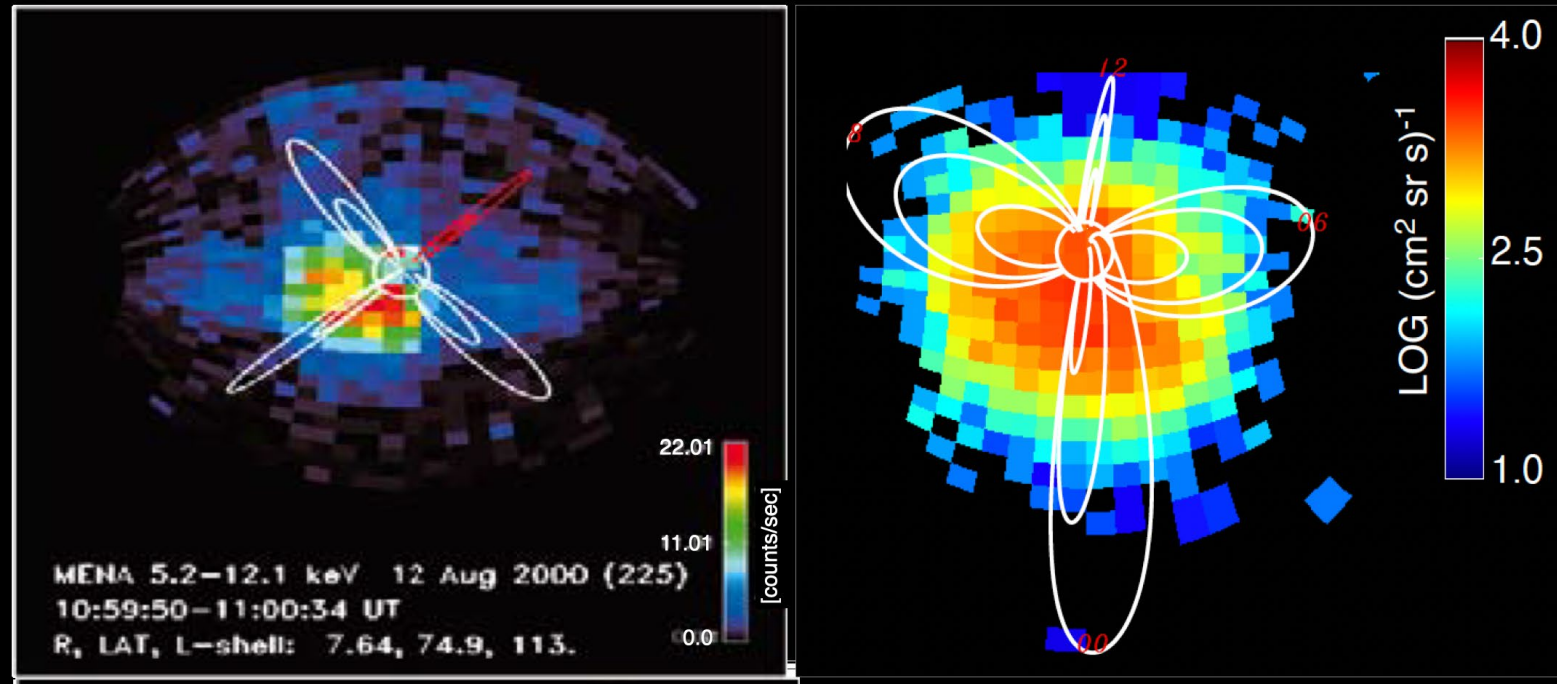
What is Energetic Neutral Atom (ENA) Imaging?



ENA imaging takes advantage of charge-exchange collisions

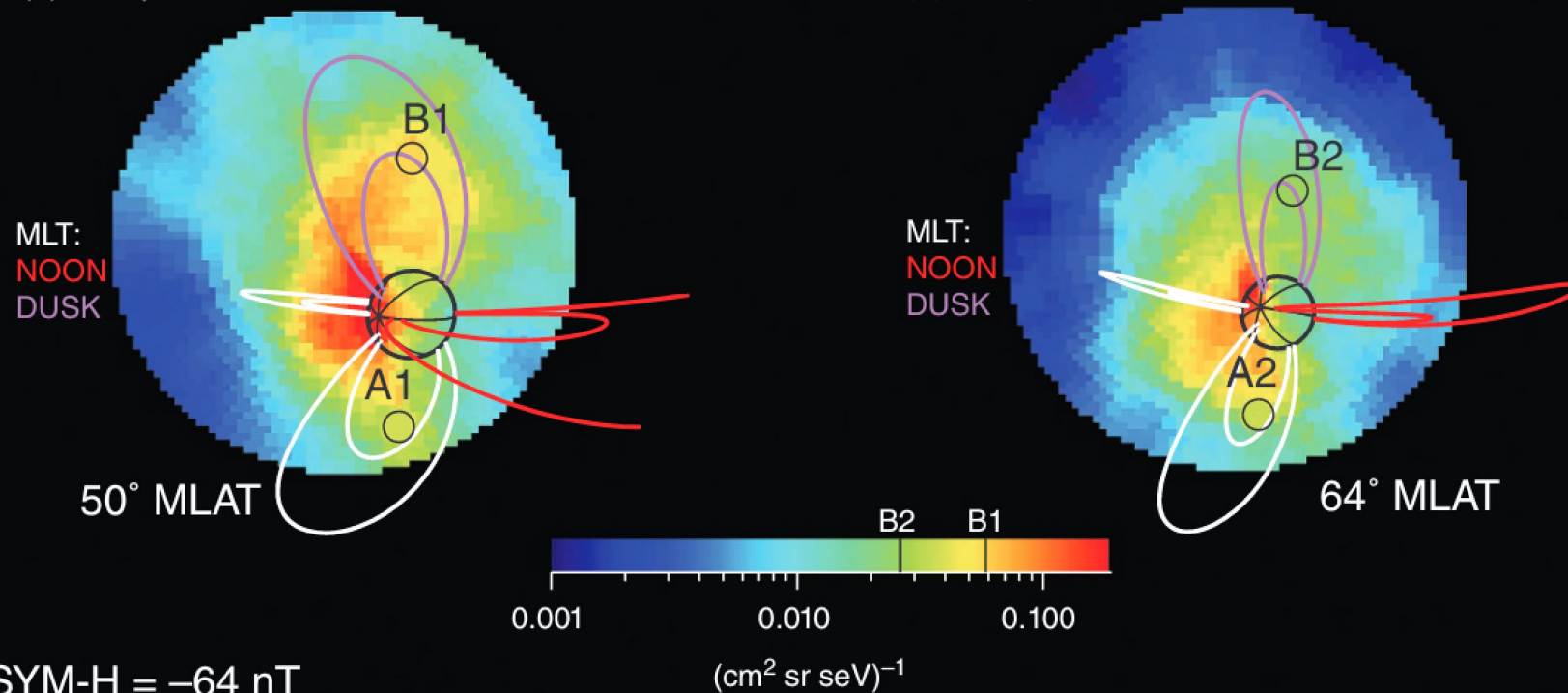
What are the benefits of ENA Imaging?

Energetic neutral atom (ENA) imaging is a remote measurement that can provide a global view of the ions in the magnetosphere



TWINS 1 12 keV
(c) 06 Apr 2010 12:16–12:30 UT

TWINS 2 12 keV
(d) 06 Apr 2010 12:15–12:31 UT



Skymap images of ENA flux from MENA (upper left) (Fok et al, 2003), HENA (upper right) (Brandt et al, 2002), and both TWINS (bottom) (Maggiolo et al, 2021)

What do ENA instruments measure?

Diagram illustrating the components of the ENA flux equation:

$$j_{ENA}(E) = \int_0^\infty \underbrace{j_{ion}(E, s)}_{\text{ion flux}} \underbrace{n_n(s)}_{\text{Neutral density}} \underbrace{\sigma_{cx}(E)}_{\text{Charge exchange cross section}} \underbrace{\exp \left[-\sigma_{cx}(E) \int_0^\infty n_n(s') ds' \right]}_{\text{Loss due to additional cx collisions}} ds$$

The diagram shows the following components and their corresponding labels:

- ENA flux**: Points to the left side of the equation, $j_{ENA}(E)$.
- LOS integral**: Points to the integral symbol $\int_0^\infty$.
- ion flux**: Points to $j_{ion}(E, s)$ (circled in the original image).
- Neutral density**: Points to $n_n(s)$.
- Charge exchange cross section**: Points to $\sigma_{cx}(E)$.
- Loss due to additional cx collisions**: Points to the exponential term $\exp \left[-\sigma_{cx}(E) \int_0^\infty n_n(s') ds' \right]$.

Energetic neutral atom (ENA) measurements help us get information about the ion population

What else do we have to consider?

ENA flux

LOS integral

Neutral density

ion flux

Charge exchange cross section

Loss due to additional cx collisions

$$j_{ENA}(E) = \int_0^\infty \underbrace{j_{ion}(E, s)}_{\text{ion flux}} \underbrace{n_n(s)}_{\text{Neutral density}} \underbrace{\sigma_{cx}(E)}_{\text{Charge exchange cross section}} \exp \left[-\sigma_{cx}(E) \int_0^\infty n_n(s') ds' \right] ds$$

The diagram illustrates the components of the ENA flux equation. The equation is shown in a white box. Arrows point from labels to parts of the equation: 'ENA flux' points to the left side; 'LOS integral' points to the integral sign; 'ion flux' points to $j_{ion}(E, s)$; 'Neutral density' points to $n_n(s)$; 'Charge exchange cross section' points to $\sigma_{cx}(E)$; and 'Loss due to additional cx collisions' (circled) points to the exponential term. A bracket also groups the exponential term and the final ds term.

Additional charge exchange collisions need to be considered for low altitude emissions (LAE)

What else do we have to consider?

ENA flux

LOS integral

Neutral density

ion flux

Charge exchange cross section

Loss due to additional cx collisions

$$j_{ENA}(E) = \int_0^\infty \underbrace{j_{ion}(E, s)}_{\text{ion flux}} \underbrace{n_n(s)}_{\text{Neutral density}} \underbrace{\sigma_{cx}(E)}_{\text{Charge exchange cross section}} \exp \left[-\underbrace{\sigma_{cx}(E)}_{\text{Charge exchange cross section}} \int_0^\infty \underbrace{n_n(s')}_{\text{Neutral density}} ds' \right] ds$$

The charge exchange cross section, measured in laboratory experiments, decreases with increasing energy

What else do we have to consider?

ENA flux

LOS integral

Neutral density

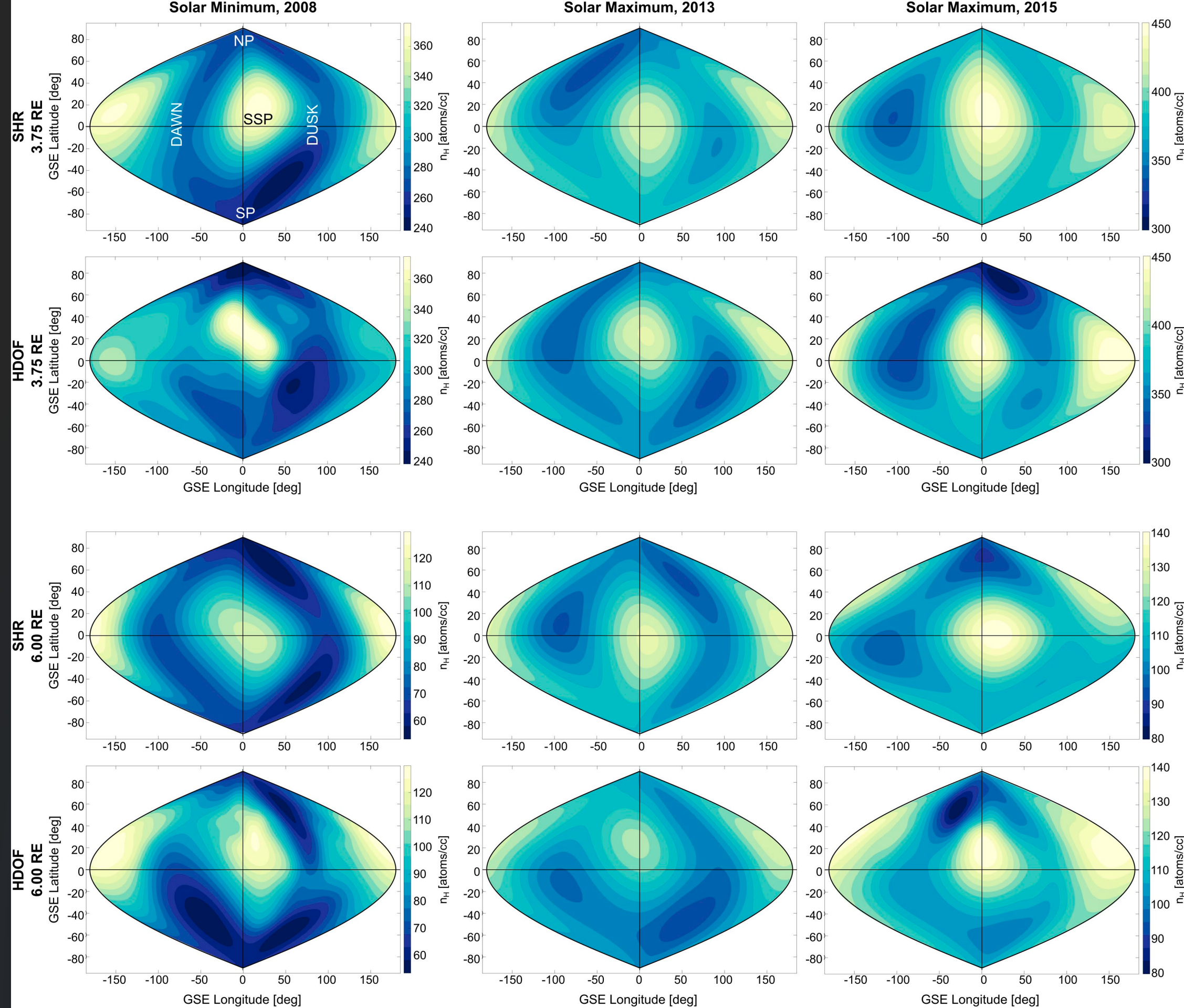
Loss due to additional cx collisions

$$j_{ENA}(E) = \int_0^\infty \underbrace{j_{ion}(E, s)}_{\text{ion flux}} \underbrace{n_n(s)}_{\text{Neutral density}} \underbrace{\sigma_{cx}(E)}_{\text{Charge exchange cross section}} \exp \left[-\sigma_{cx}(E) \int_0^\infty n_n(s') ds' \right] ds$$

ion flux

Charge exchange cross section

The density of neutrals in the exosphere decreases with distance from the Earth, but has been shown to be dynamic



Lyman- α measurements
of Hydrogen geocorona
using TWINS show spatial
and temporal variations

Zoennchen JH et al. (2024)
doi: 10.3389/fspas.2024.1409744

What else do we have to consider?

Diagram illustrating the components of the ENA flux equation:

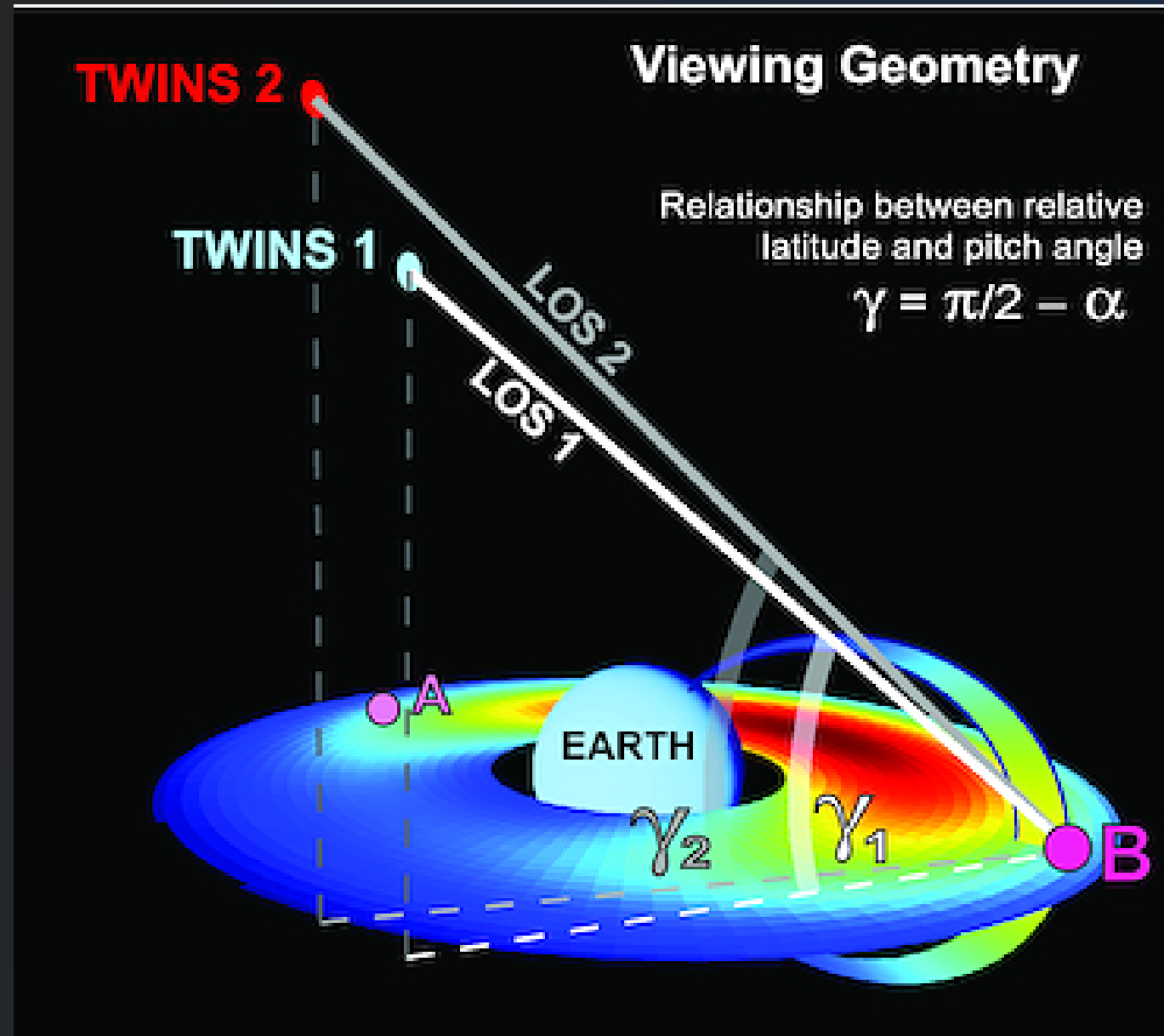
$$j_{ENA}(E) = \int_0^\infty \underbrace{j_{ion}(E, s)}_{\text{ion flux}} \underbrace{n_n(s)}_{\text{Neutral density}} \underbrace{\sigma_{cx}(E)}_{\text{Charge exchange cross section}} \exp \left[-\sigma_{cx}(E) \int_0^\infty n_n(s') ds' \right] ds$$

The diagram includes the following annotations:

- ENA flux**: Points to the left side of the equation, $j_{ENA}(E)$.
- LOS integral**: A blue circle around the integral symbol $\int_0^\infty$ at the beginning of the equation.
- ion flux**: Points to the $j_{ion}(E, s)$ term.
- Neutral density**: Points to the $n_n(s)$ term.
- Charge exchange cross section**: Points to the $\sigma_{cx}(E)$ term.
- Loss due to additional cx collisions**: A bracket points to the exponential term $\exp \left[-\sigma_{cx}(E) \int_0^\infty n_n(s') ds' \right]$.

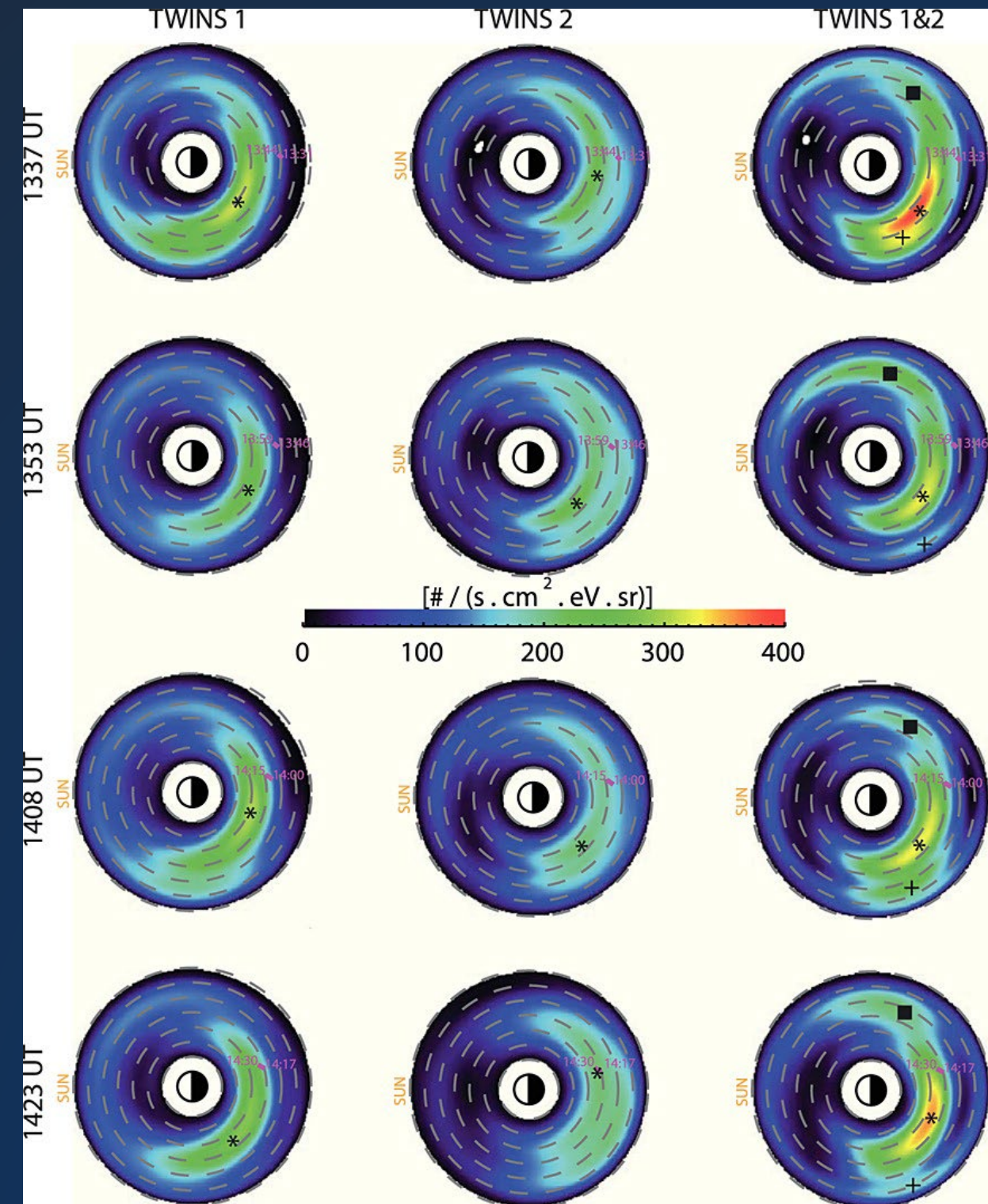
The measurement combines everything along the line of sight (LOS)

TWINS studies utilized dual vantage points



Goldstein et al, 2012

<https://doi.org/10.1029/2012JA017804>



Perez et al, 2014

<https://doi.org/10.1002/2014JA020662>

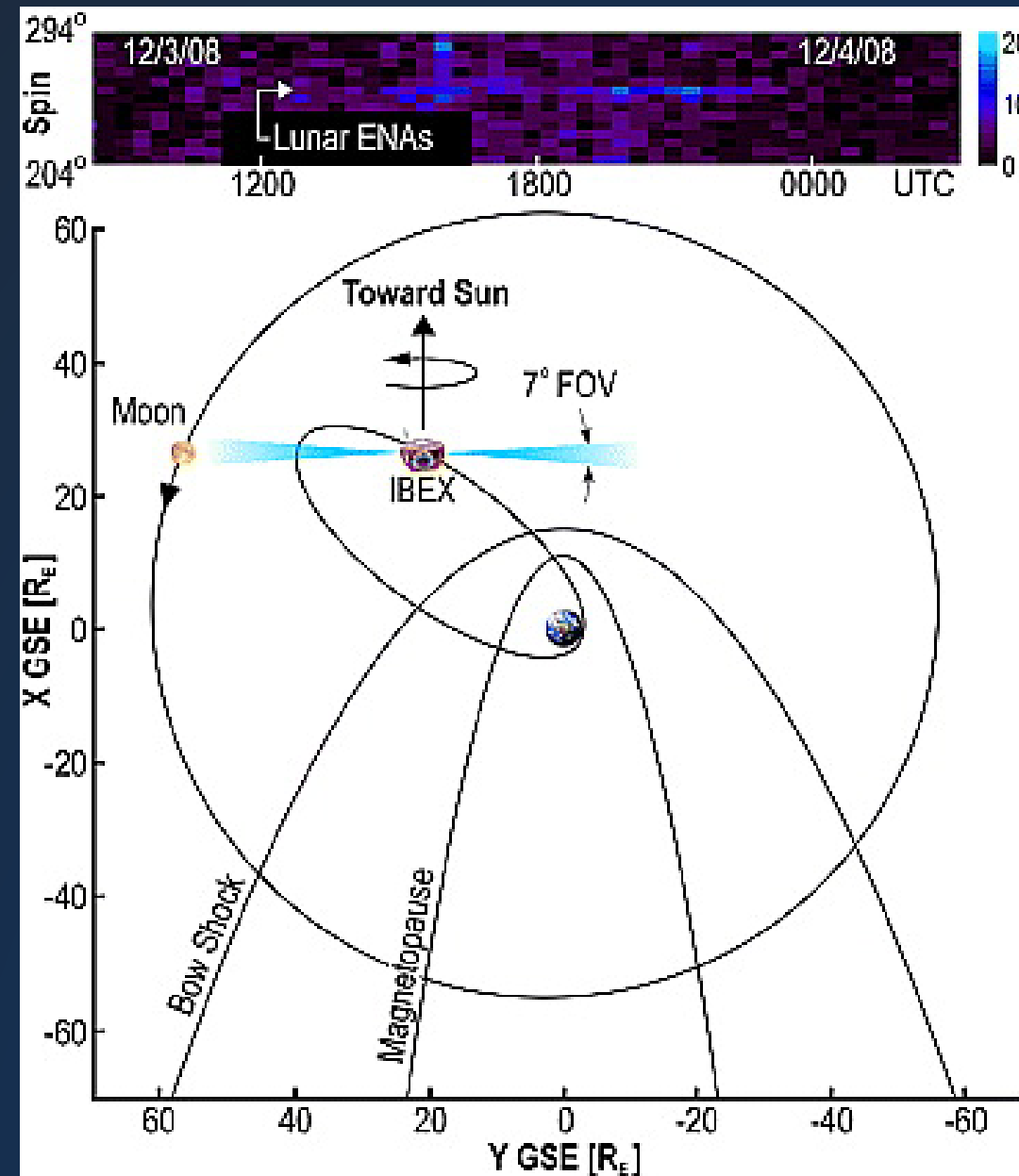


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What if we put an ENA
imager on the moon?

What did the Interstellar Boundary EXplorer (IBEX) do?

- Designed to observe ENAs from ~ 100 AU
- Observed ENAs of lunar origin
- Relevant to solar wind-moon interactions throughout solar system and other space plasma/small body interactions
- A consideration as background signal in moon-based measurements

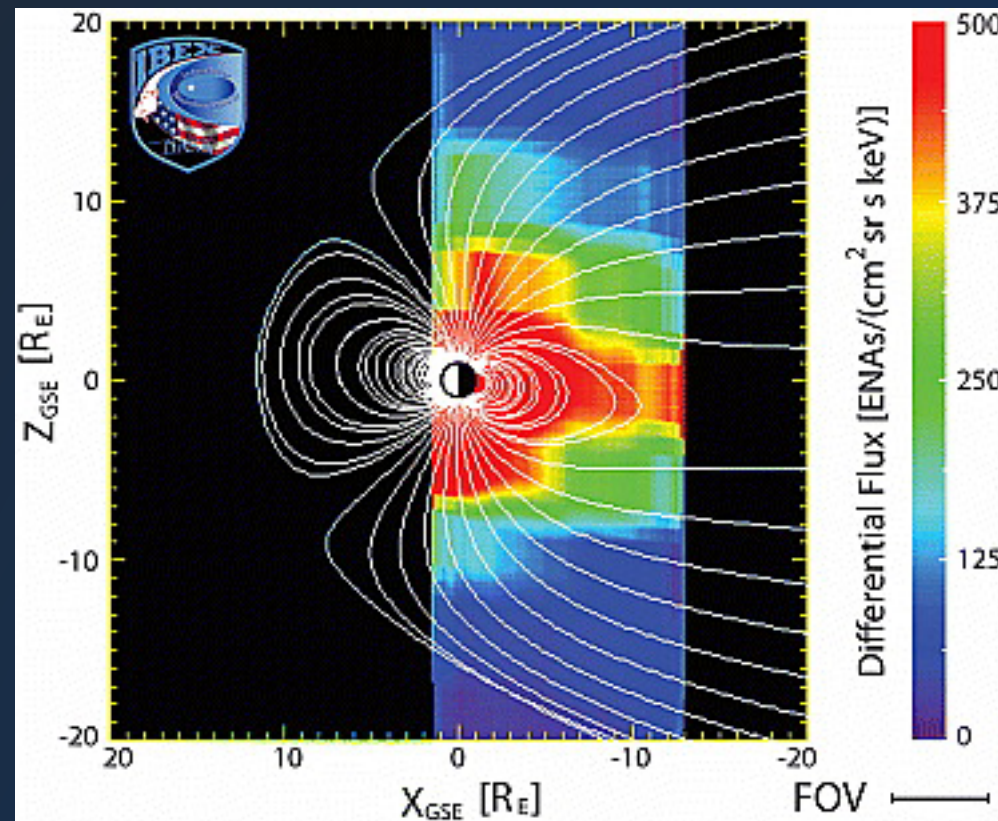
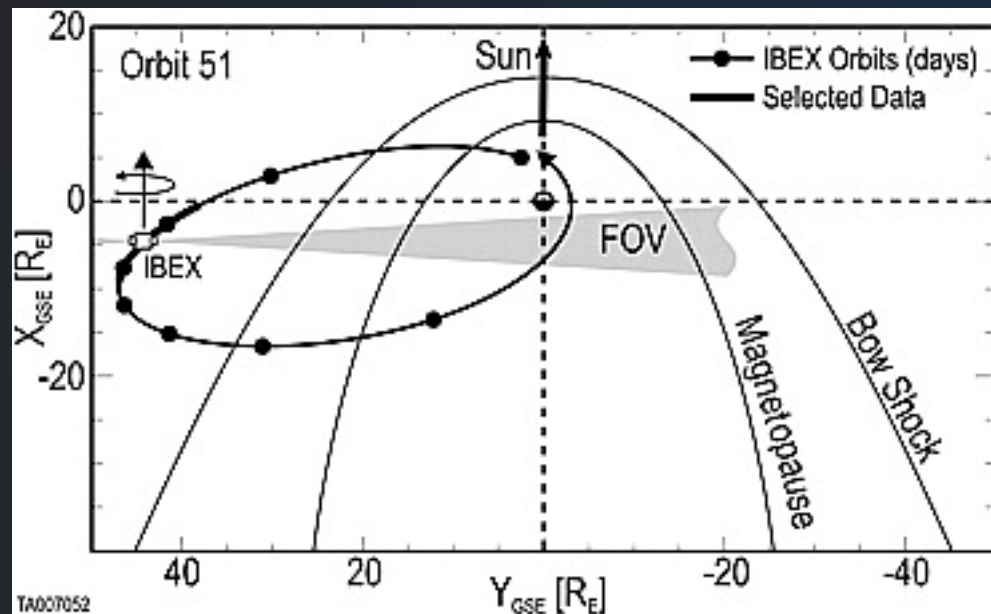


McComas et al, 2009

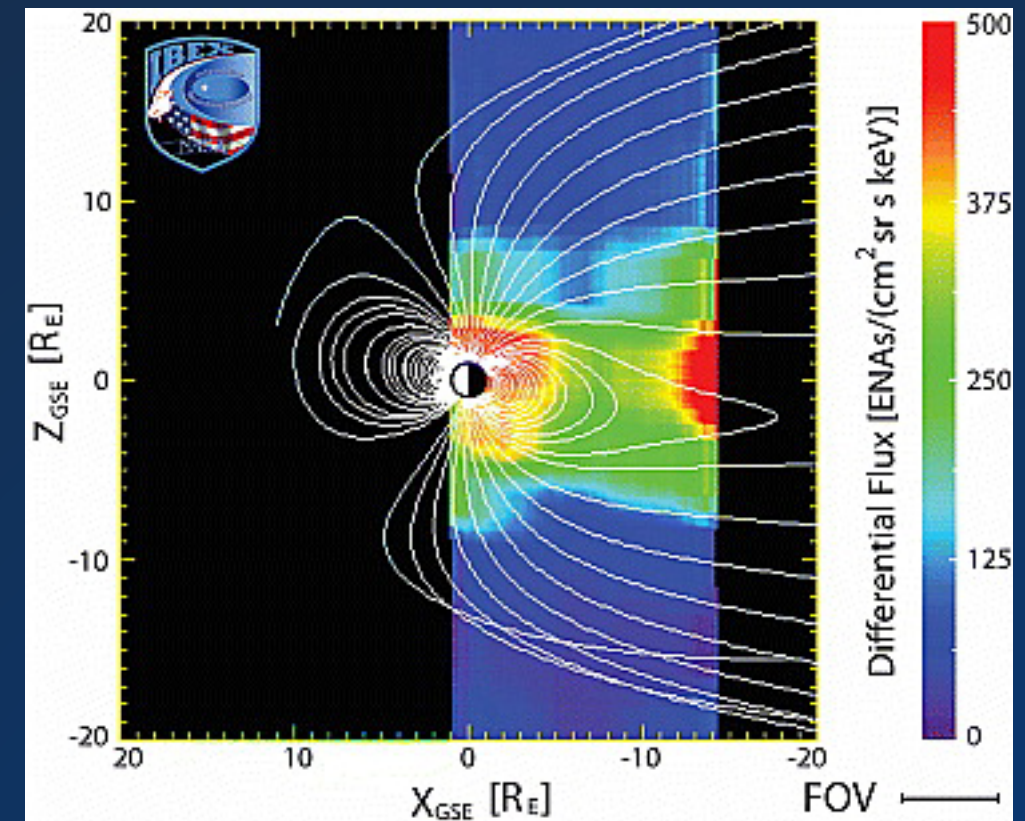
<https://doi.org/10.1029/2009GL038794>

What did the Interstellar Boundary EXplorer (IBEX) do?

Observations of the magnetotail/plasma sheet:
Observations of downtail intensification



1048 UT on 5 November -
0223 UT on 7 November
2009

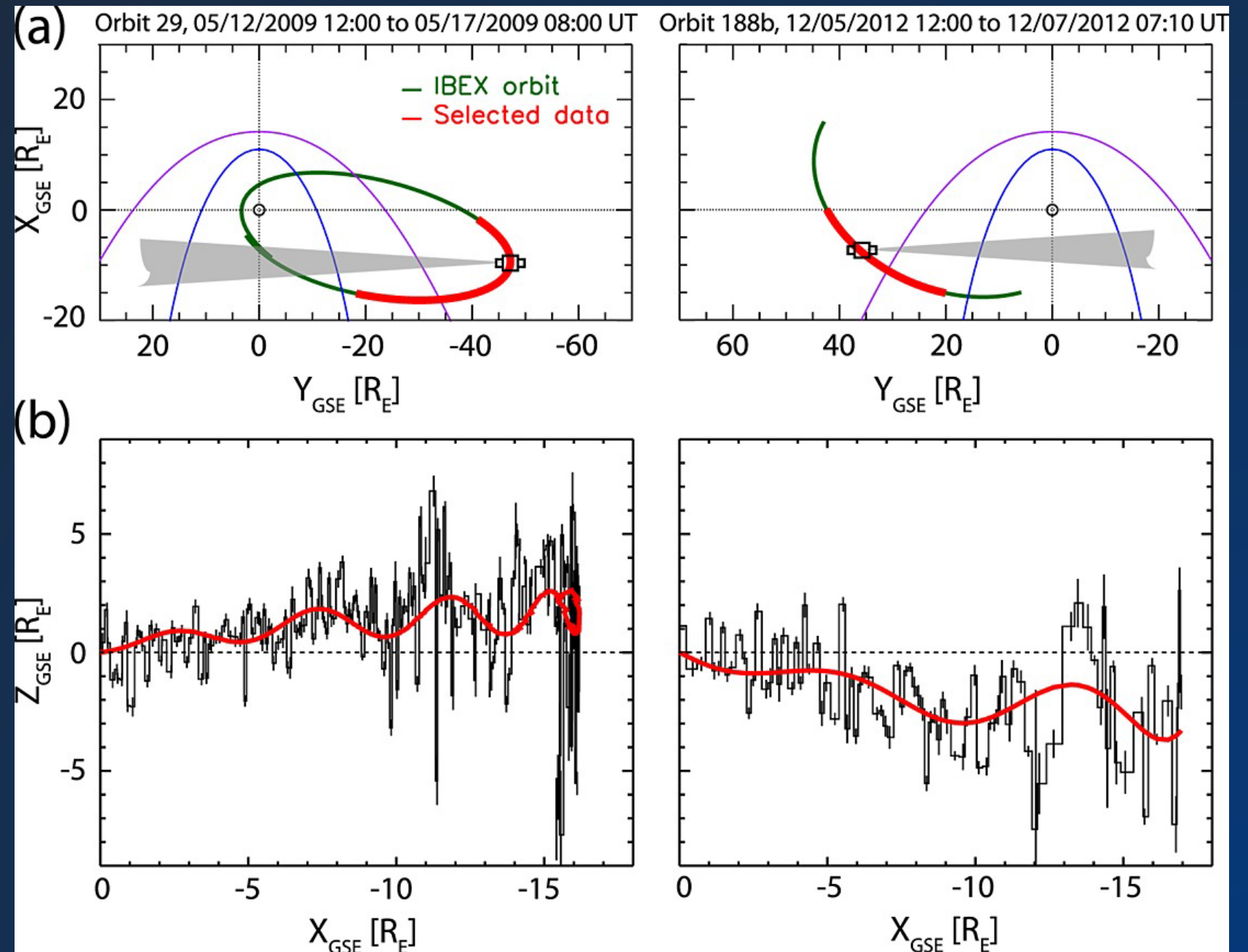


2121 UT on 27 October -
1340 UT on 29 October
2009

McComas et al, 2011
<https://doi.org/10.1029/2010JA016138>

What did the Interstellar Boundary EXplorer (IBEX) do?

Observations of the magnetotail/plasma sheet:
Observations of plasma sheet diurnal motion and short time-scale flapping



Dayeh et al, 2015

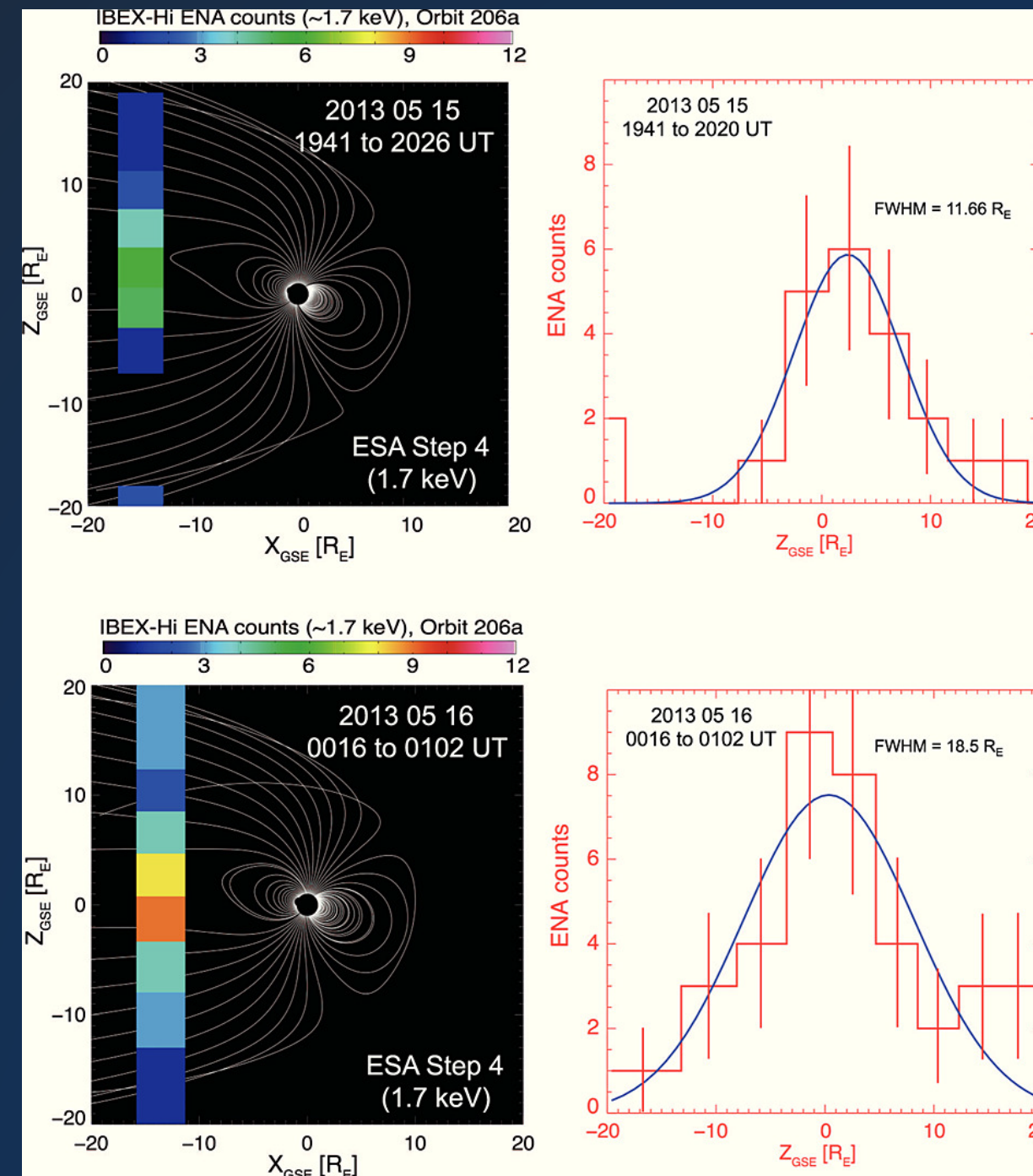
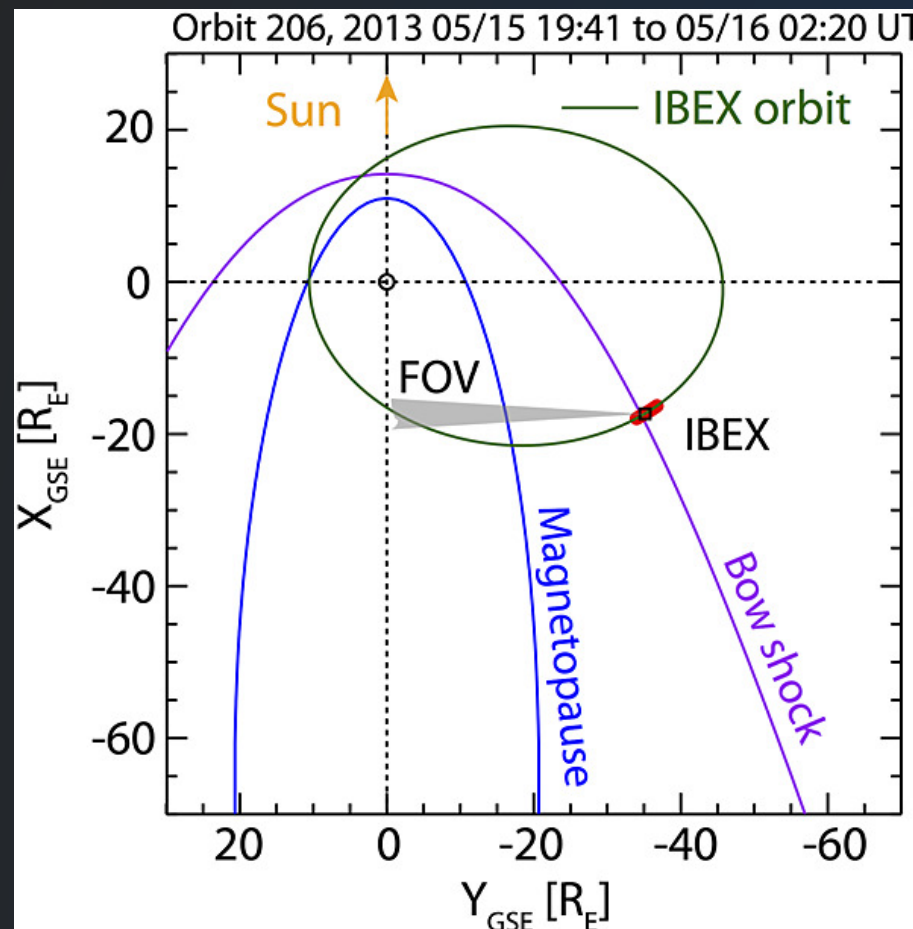
<https://doi.org/10.1002/2015GL063682>



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What did the Interstellar Boundary EXplorer (IBEX) do?

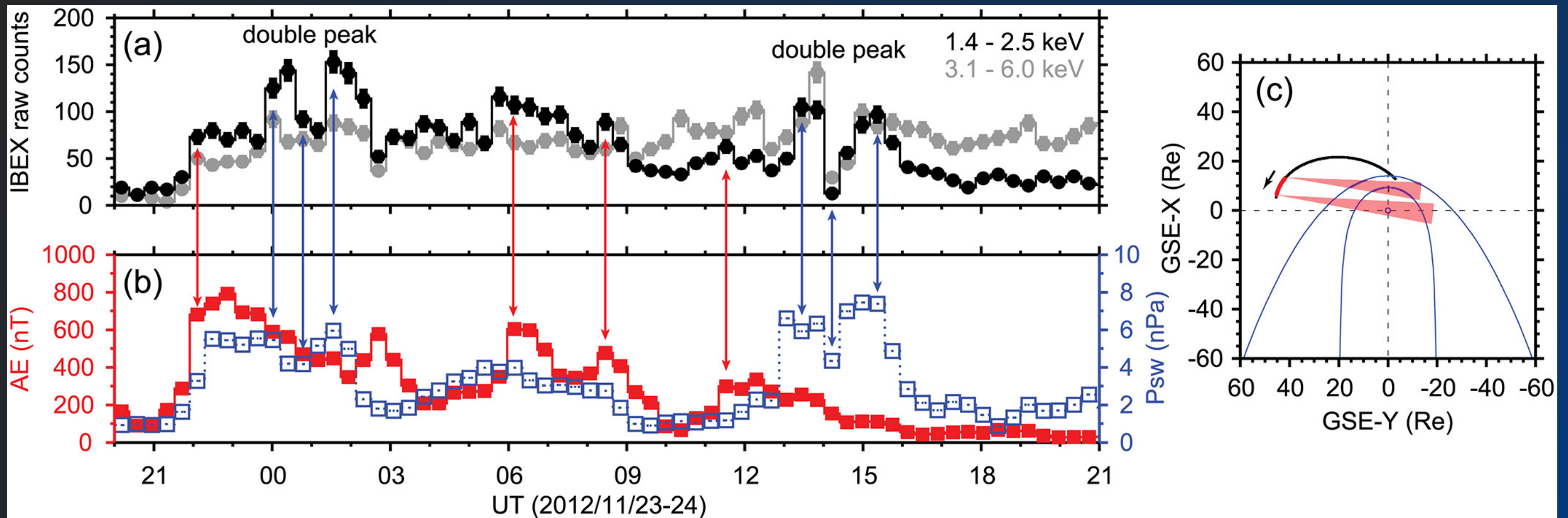
Observations of the magnetotail/plasma sheet:
Development of cold dense plasma sheet during northward IMF



Fuselier et al, 2015
<https://doi.org/10.1002/2015GL065716>

What did the Interstellar Boundary EXplorer (IBEX) do?

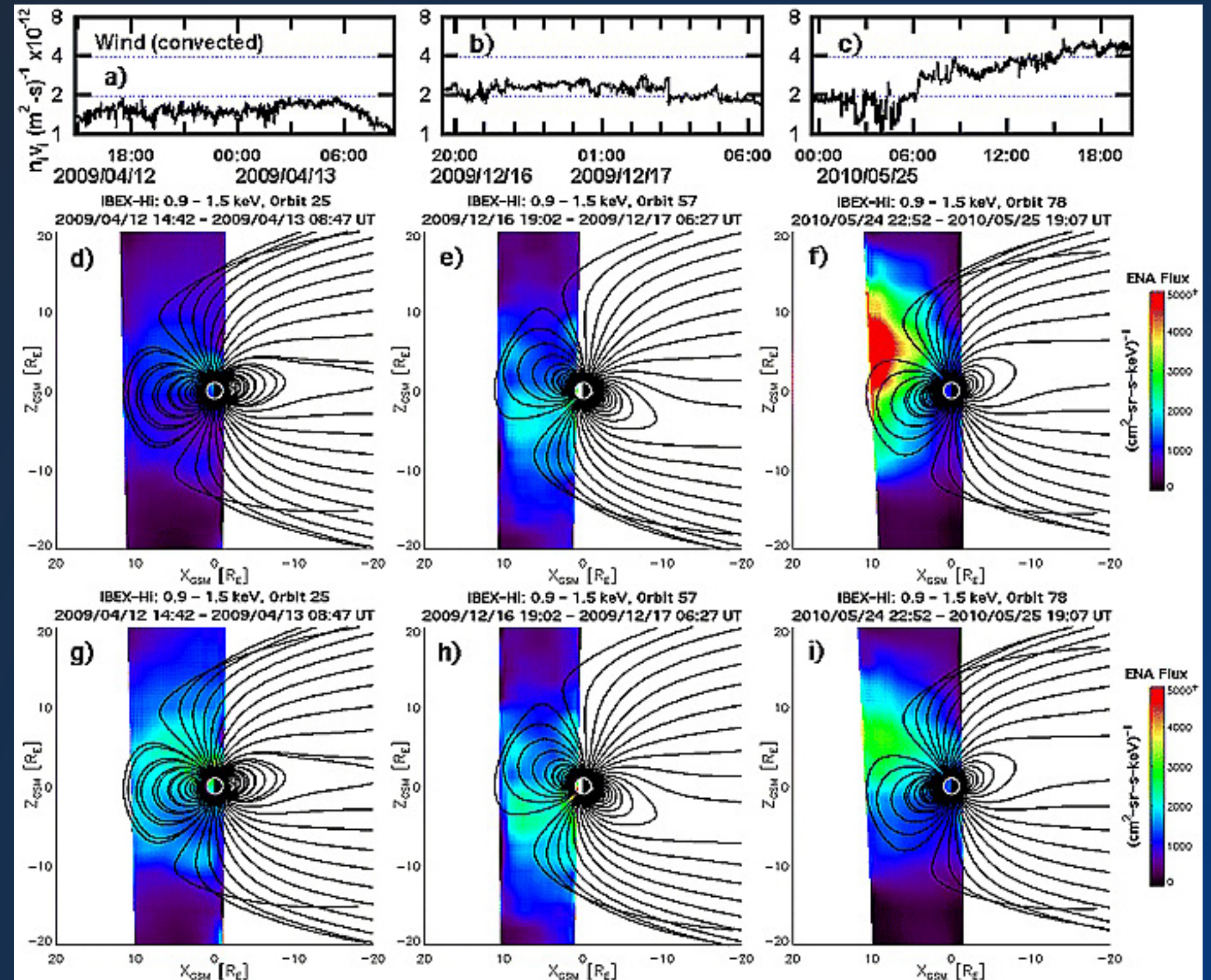
Observations of the inner magnetosphere:
Correlations with the AE index indicating strong emission during FAC formation



Ogasawara et al, 2019
<https://doi.org/10.1029/2019JA026976>

What did the Interstellar Boundary EXplorer (IBEX) do?

Observations of the dayside cusps:
Cusp ENA emission related to magnetopause reconnection locations



Petrinec et al, 2011

<https://doi.org/10.1029/2010JA016357>

What should be considered for a lunar ENA imager?

- Spatial and temporal resolution
- Energy range
- Time delays

Increase counts with active ENA experiments

- Artificially increase neutral density to increase ENA flux
- Release could be at a modulated frequency for improved detection
- Releases of unused fuel from rockets could be used for such experiments

ENA flux

Neutral density

$$j_{ENA}(E) = \int_0^\infty j_{ion}(E, s) n_n(s) \sigma_{cx}(E) \exp \left[-\sigma_{cx}(E) \int_0^\infty n_n(s') ds' \right] ds$$

Scime and Keese, 2019

<https://doi.org/10.3389/fspas.2019.00009>

What should be considered for a lunar ENA imager?

- Spatial and temporal resolution
 - Energy range
 - Time delays
-
- Combine with measurements from other sources