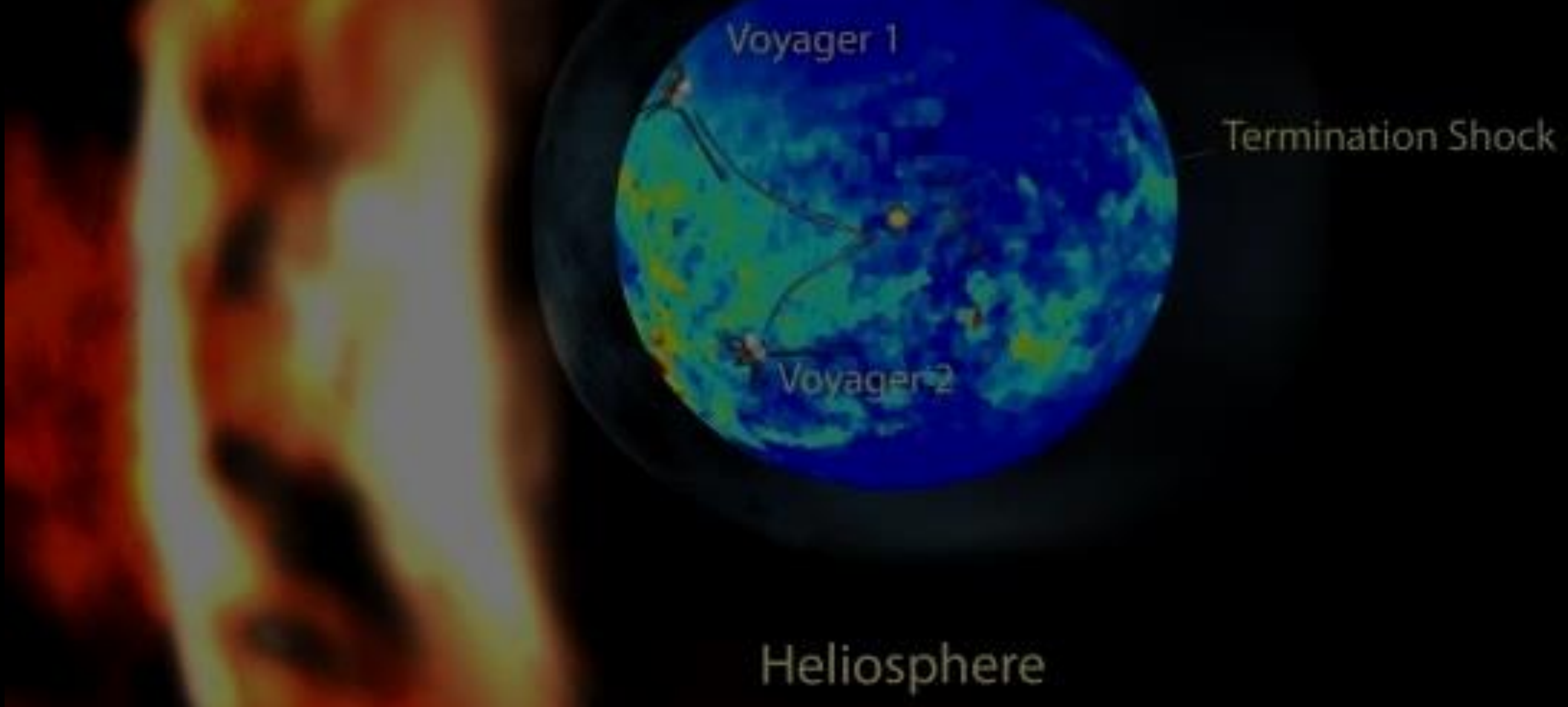
ACADEMY OF ATHENS / APPLIED PHYSICS LABORATORY

On the Origin of the 5-55 keV Heliosheath ENAs using Cassini/INCA measurements



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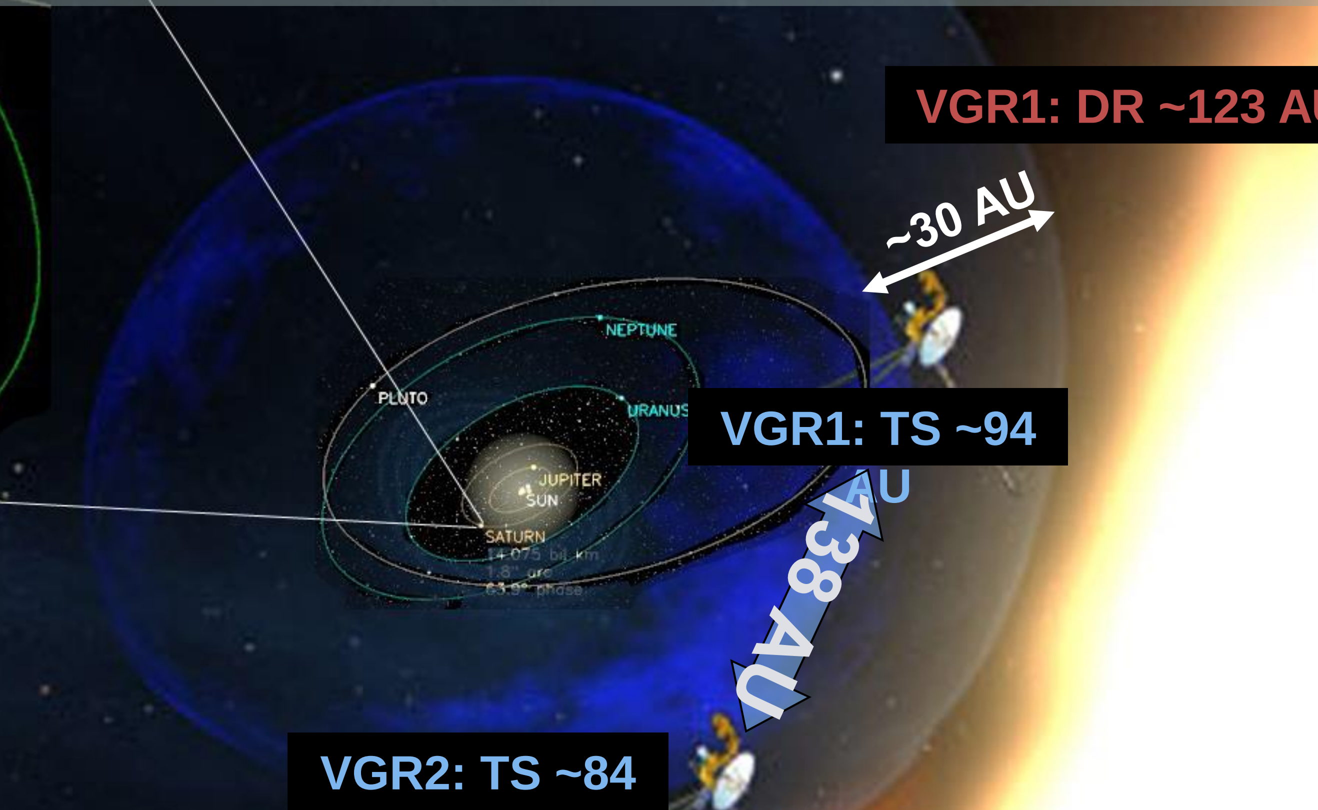
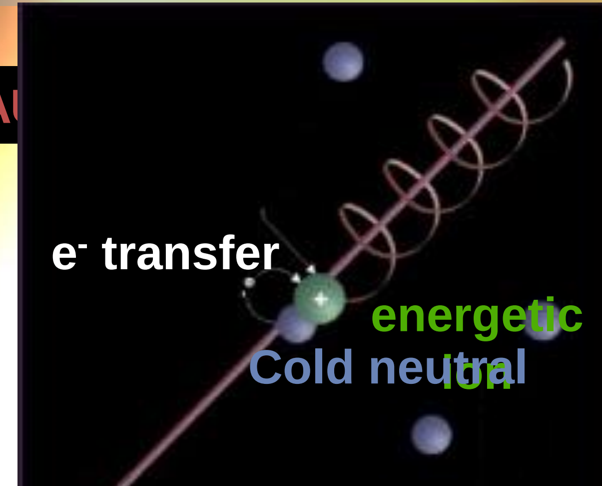
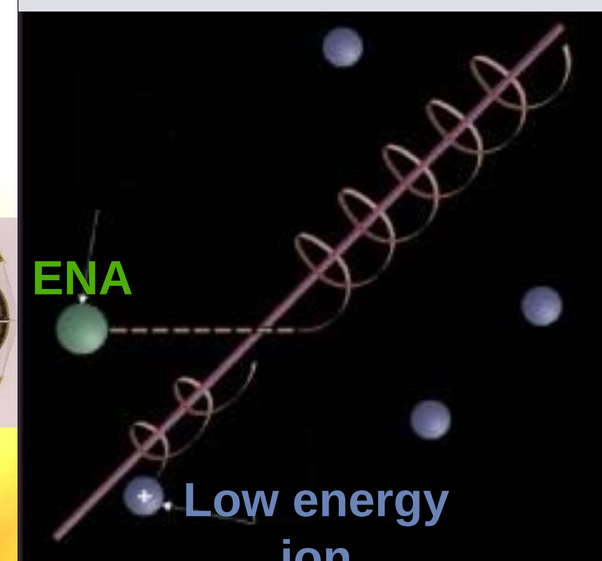
Charge-Exchange in the Heliosphere: Birth of ENAs

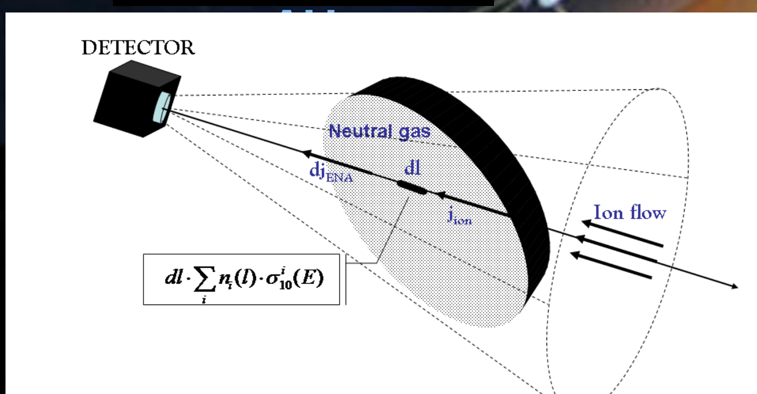




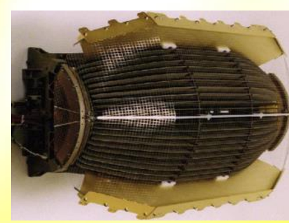
$$H^{+} + H \rightarrow H_{ENA} + H^{+}$$

$$(\Delta E \cong 0)$$



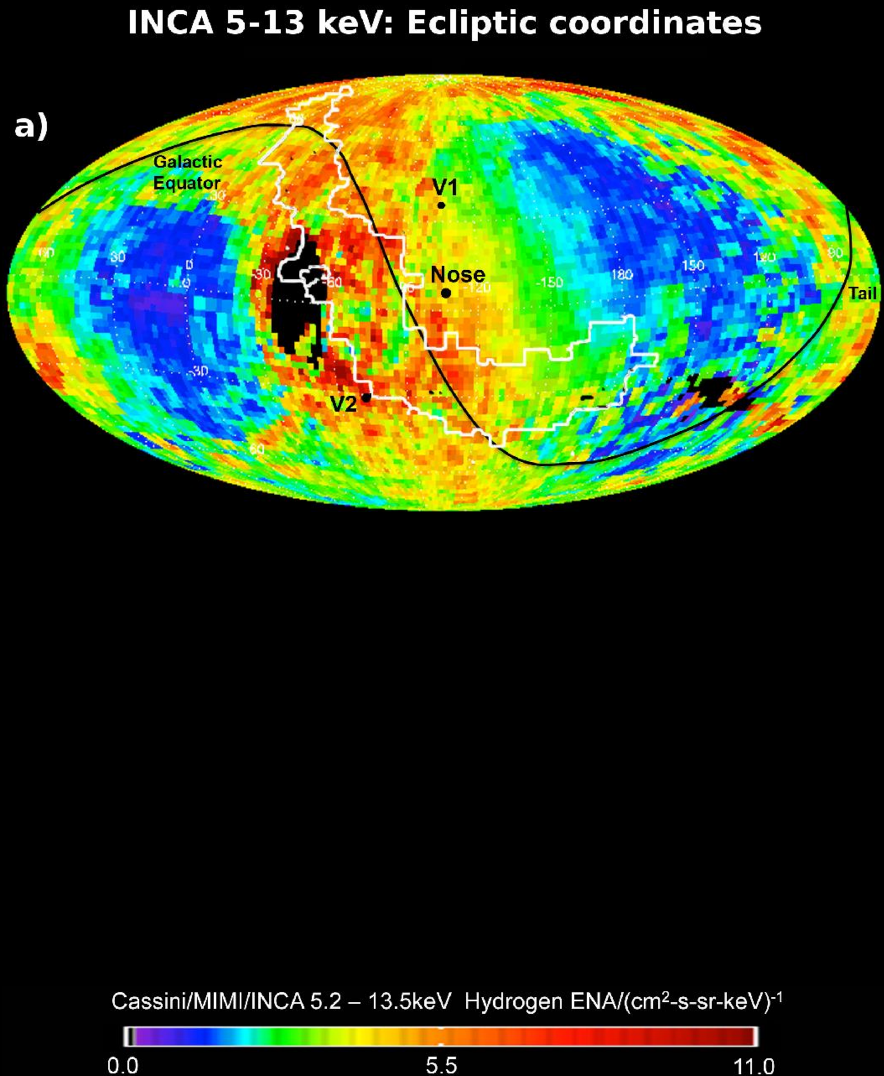


$$j_{ENA}(E) = \int_{0}^{\infty} dl \cdot \sum_{i} n_i(l) \cdot \sigma_{10}^{i}(E) \cdot j_{ion}(E,l)$$



Ion and neutral camera (INCA) onboard

IBEX Ribbon (white outline, McComas et al, Science, 2009) at 1.7 and 4.3 keV with Cassini/ MIMI/INCA Belt (Krimigis et al, Science, 2009) at 5.2-13.5 keV



Ribbon

External source or particles

+

"background" of ENA emissions (GDF)

Becomes increasingly important with increasing energy

At 4.29 keV it matches the

Belt

- A "reservoir" of particles that exist within the heliosheath, constantly replenished by new particles from the solar wind
- Enhanced particle pressure
- Stable as a function of energy

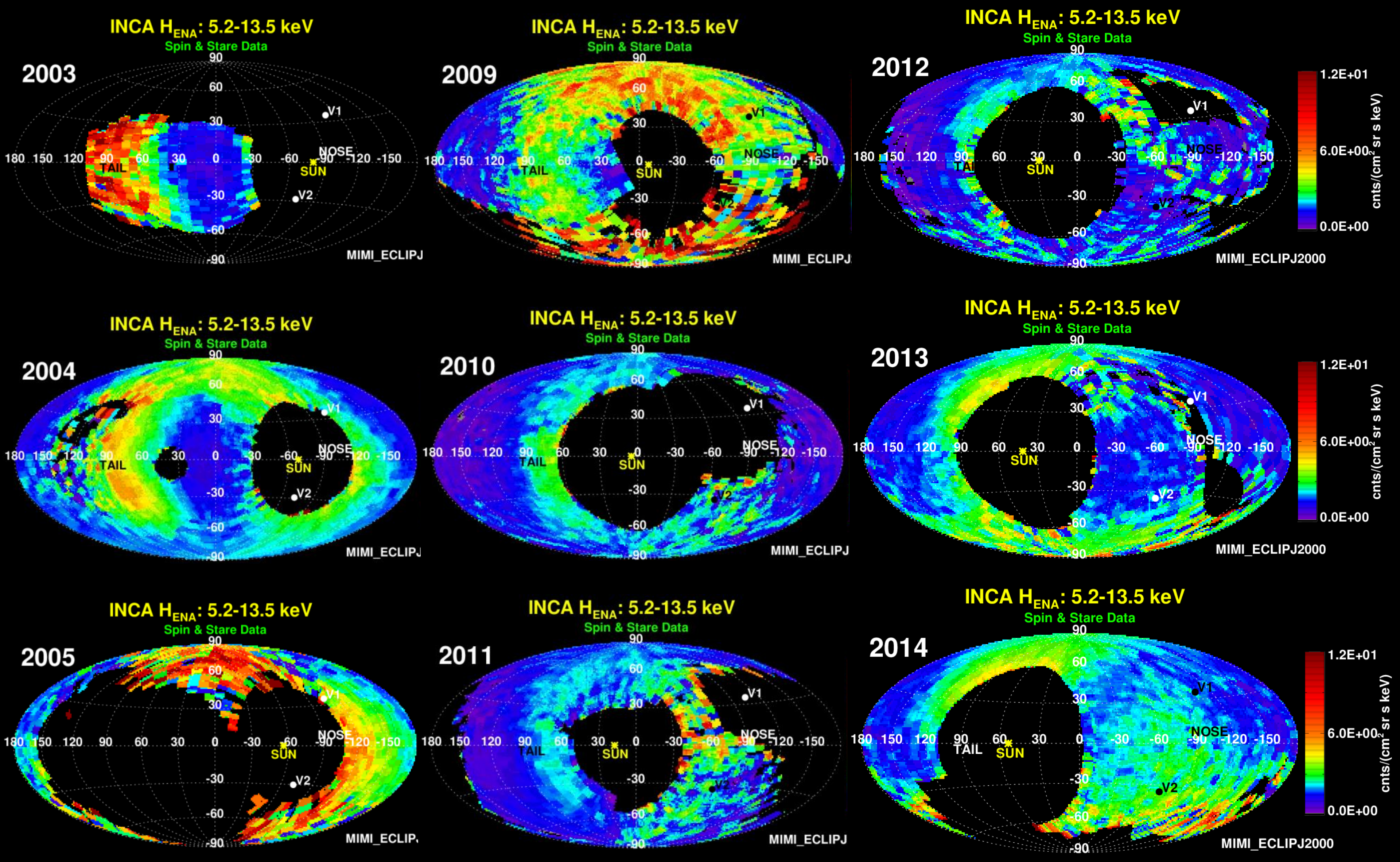
Symmetric heliosheath
Diamagnetic "bubble"

These interpretations depend on the reasonable assumption that *__the ENAs that INCA detects are sourced from the Heliosheath__*.

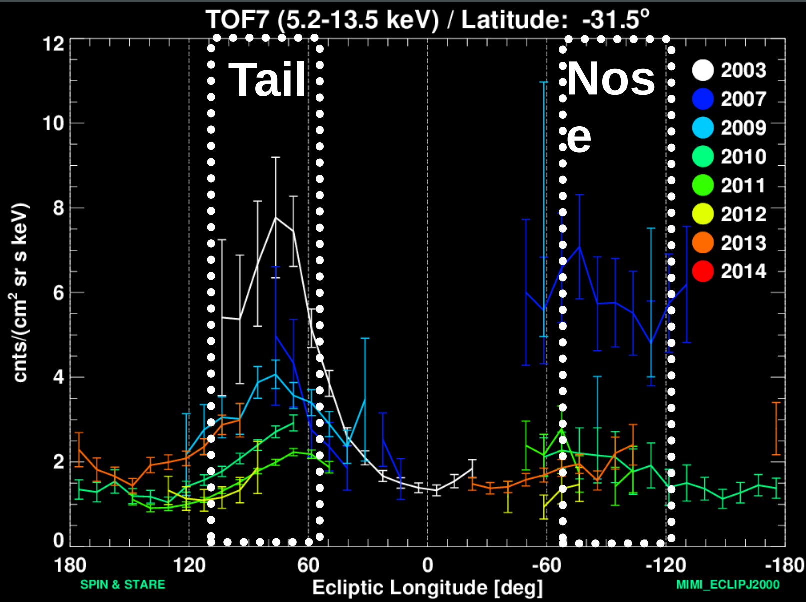
But, is that true?

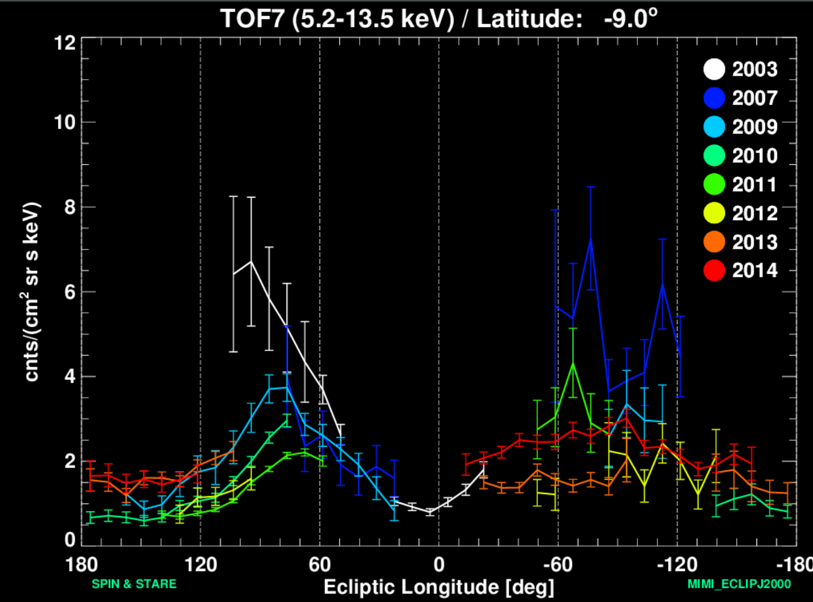
TOF7 channel (5.2-13.5 keV) ENA intensities

ENA intensities in the Belt become comparable to the intensities in the Basin by the end of 2011 and recover during 2013.

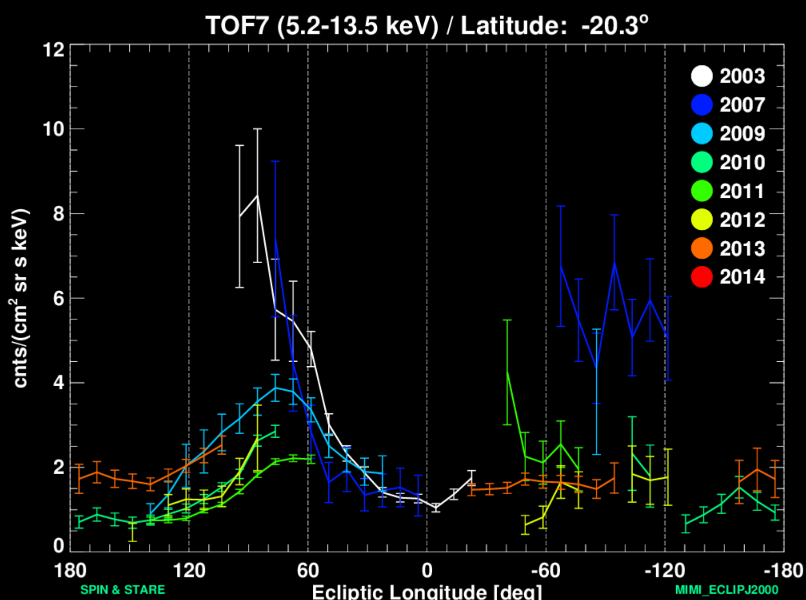


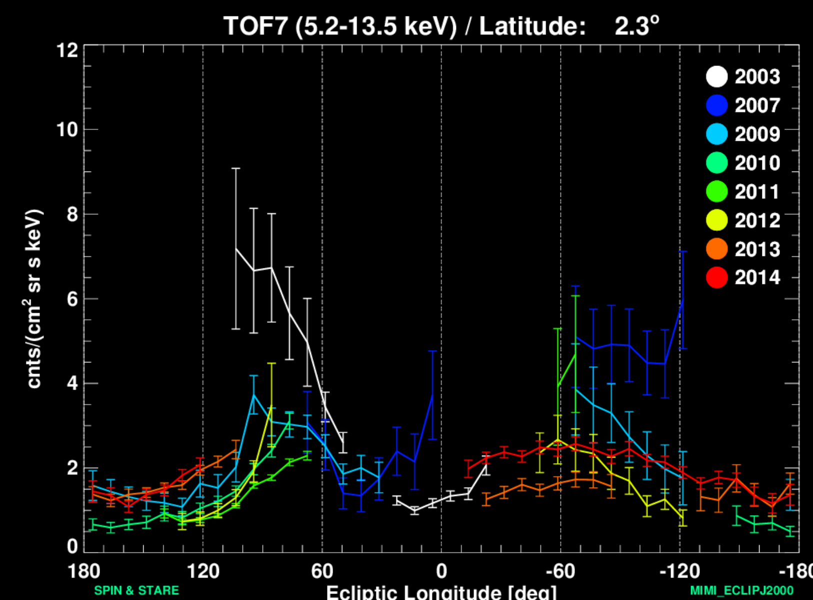
ENA Intensity profiles at selected latitudes, 2003-2014 (5-13 keV)





Average of INCA/ENA intensities over 11.25 x 9.0 deg (ecl. long x ecl. lat.)





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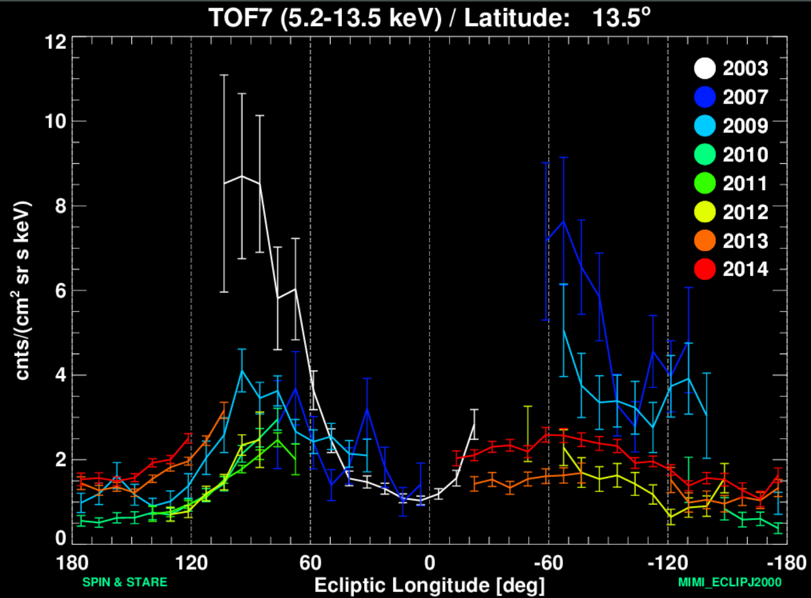
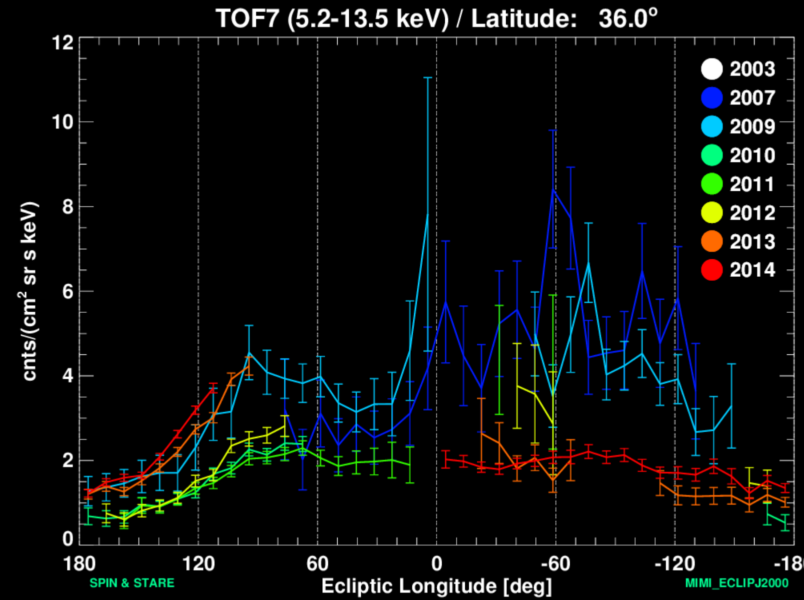
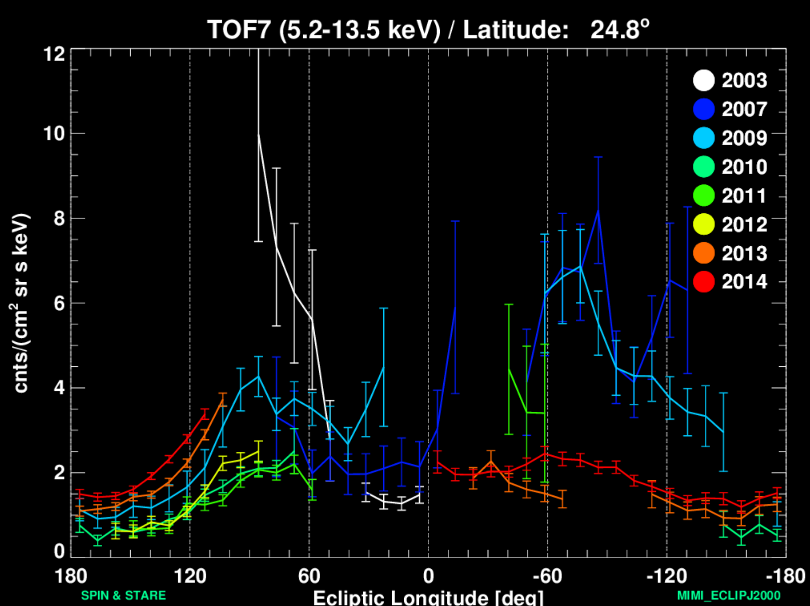
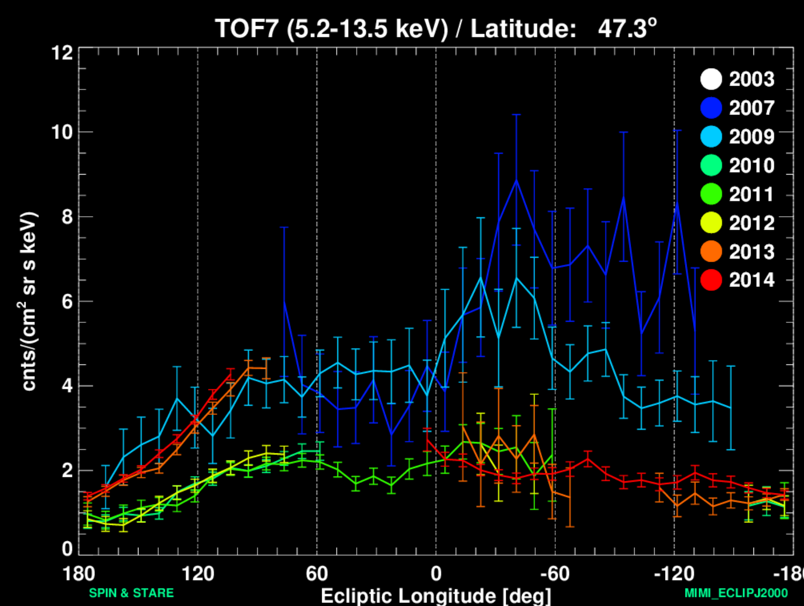
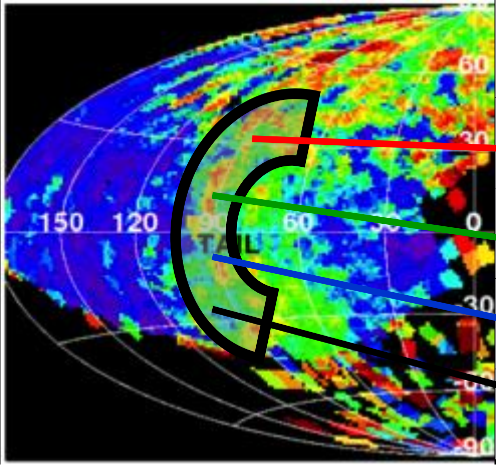




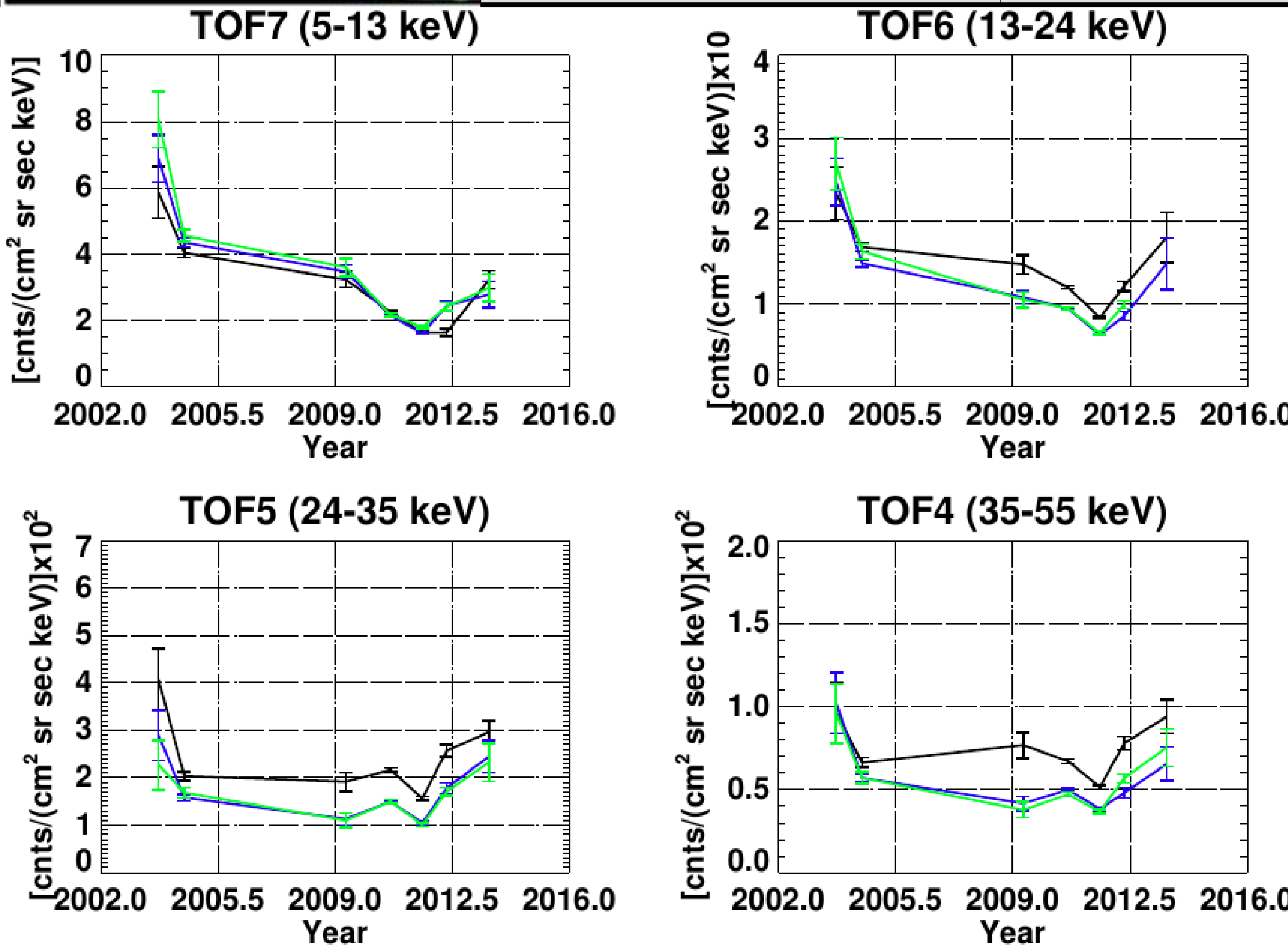
Average of INCA/ENA intensities over 11.25 x 9.0 deg (ecl. long x ecl. lat.)







Ecl. Lon.	Ecl. Lat.	Missing data
100º --> 80º	*20º --> 40º*	*NO DATA*
100º --> 80º	*0º --> 20º*	*2005, 2014*
100º --> 80º	*-20º --> 0º*	*2005, 2014*
100º --> 80º	*-40º --> -20º*	*2005, 2014*



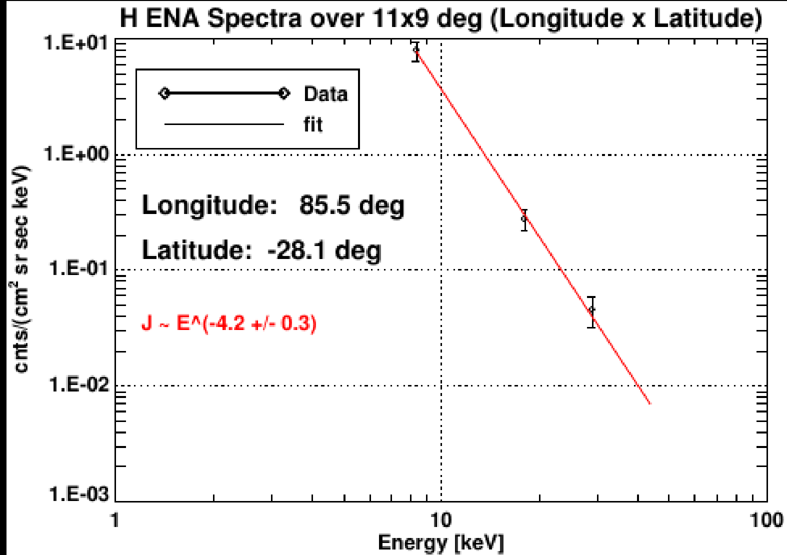
2003-2011 ENA decrease

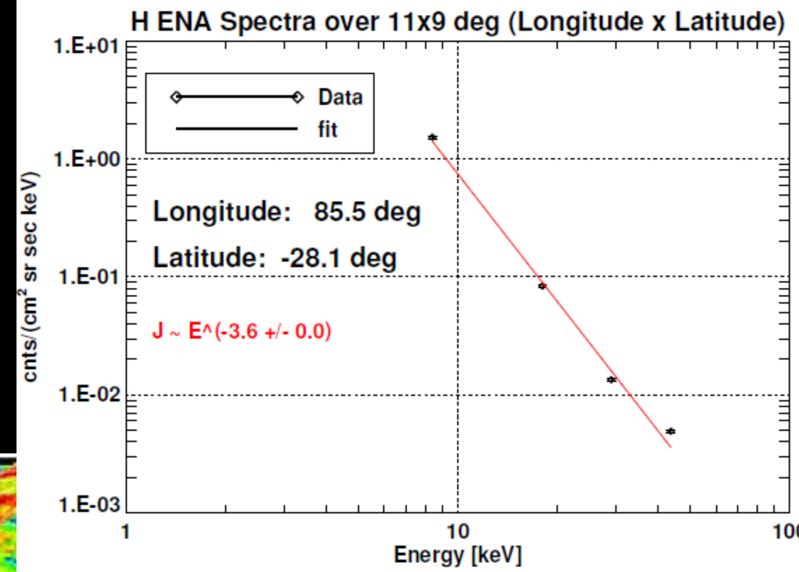
5-13 keV : factor of ~4

13-24 keV: factor of ~3

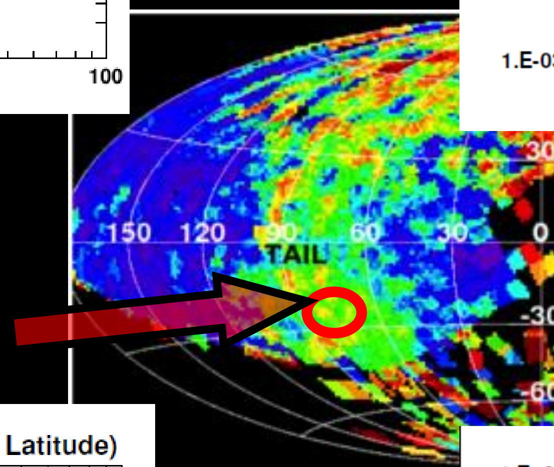
24-35 keV: factor of ~3

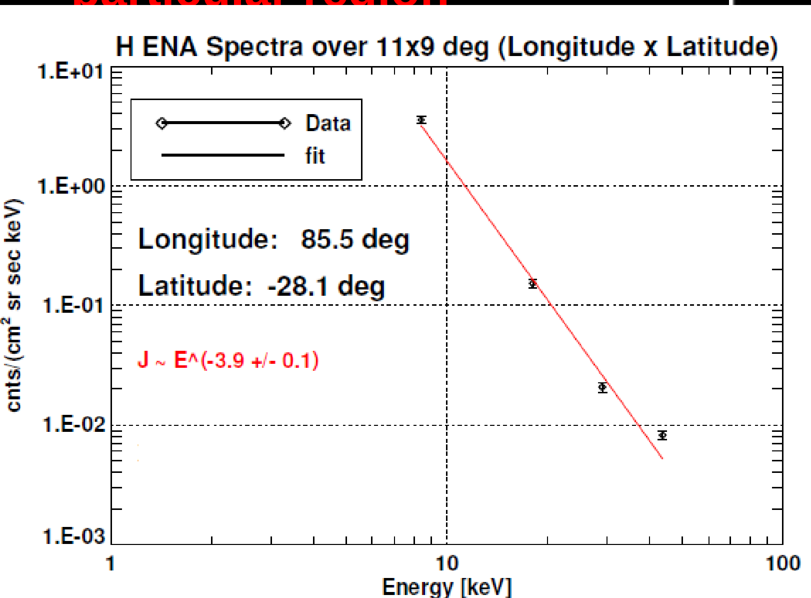
35-55 keV: factor of ~2

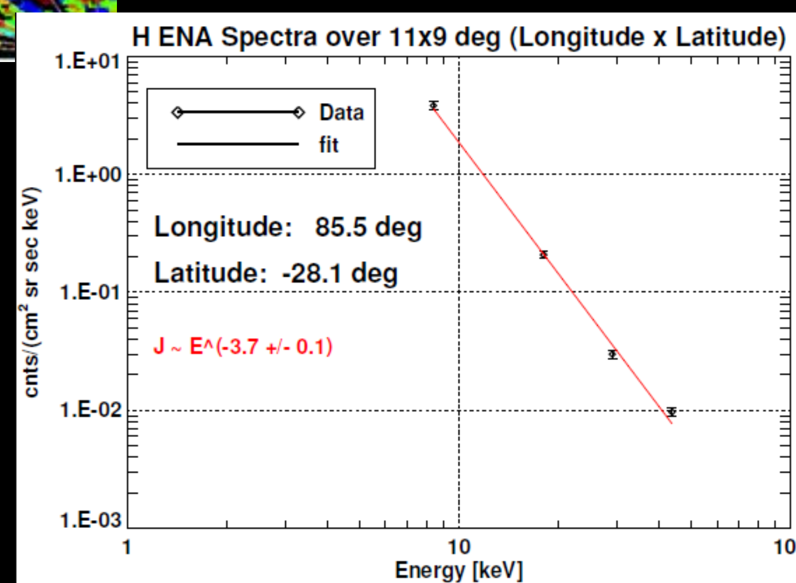




Here are some typical examples of the energy spectra and the fits, sampled from **this particular region**

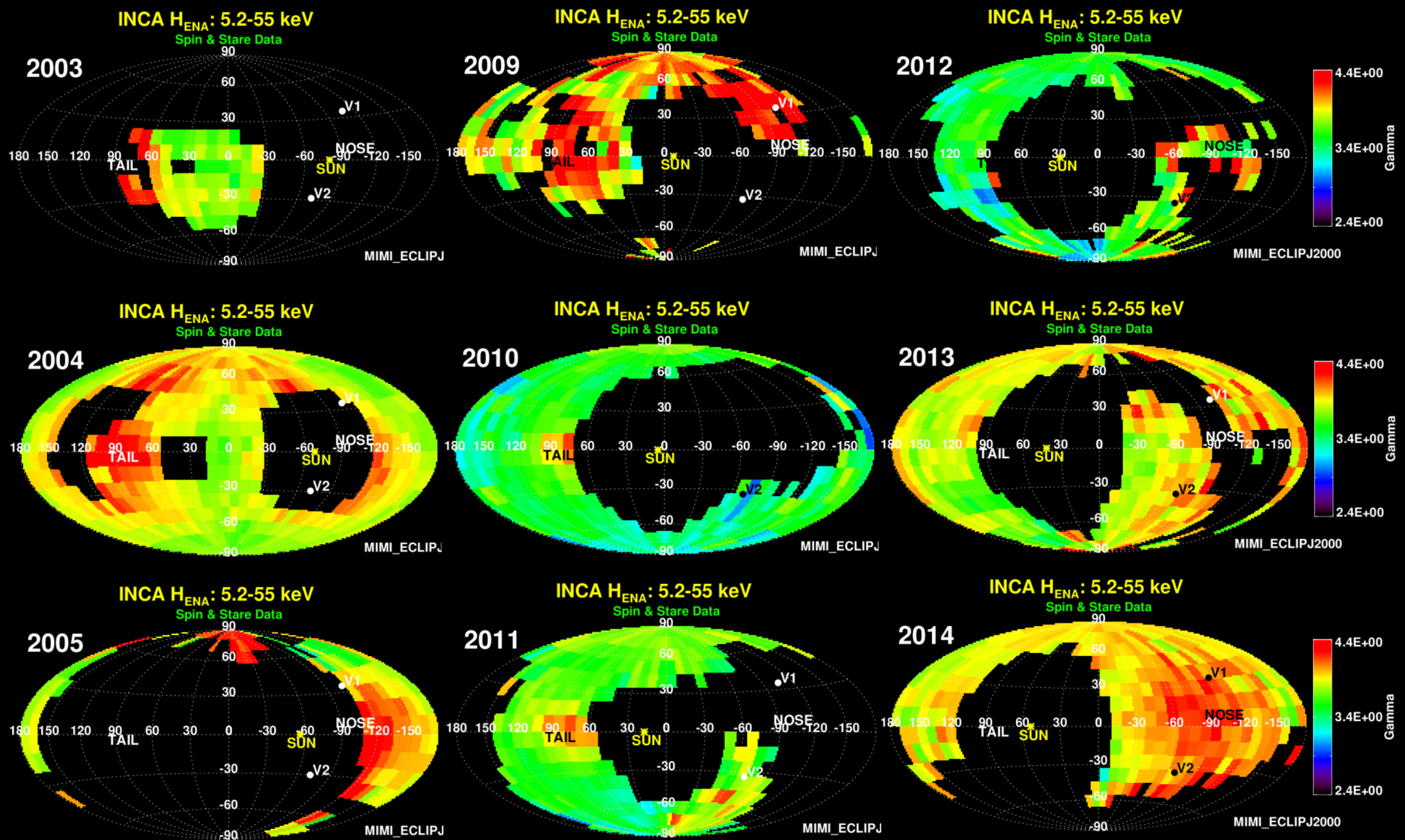




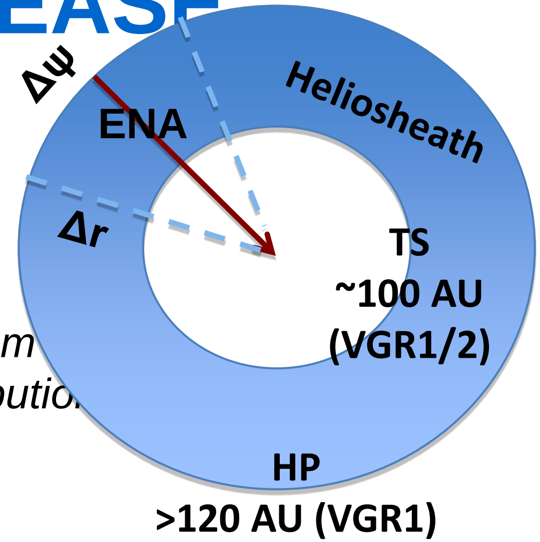


ENA Spectral Index Maps

Spectral index maps during 2003 to 2014 produced with Power Law fits (J_{ENA}~$E^{-\gamma}$) in the 5-55 keV energy range



MECHANISMS FOR H_{ENA} DECREASE



At 5-55 keV (INCA energies), the ENA emission is optically thin, i.e. j_{ENA} cannot be significantly reduced between the heliosheath and INCA.

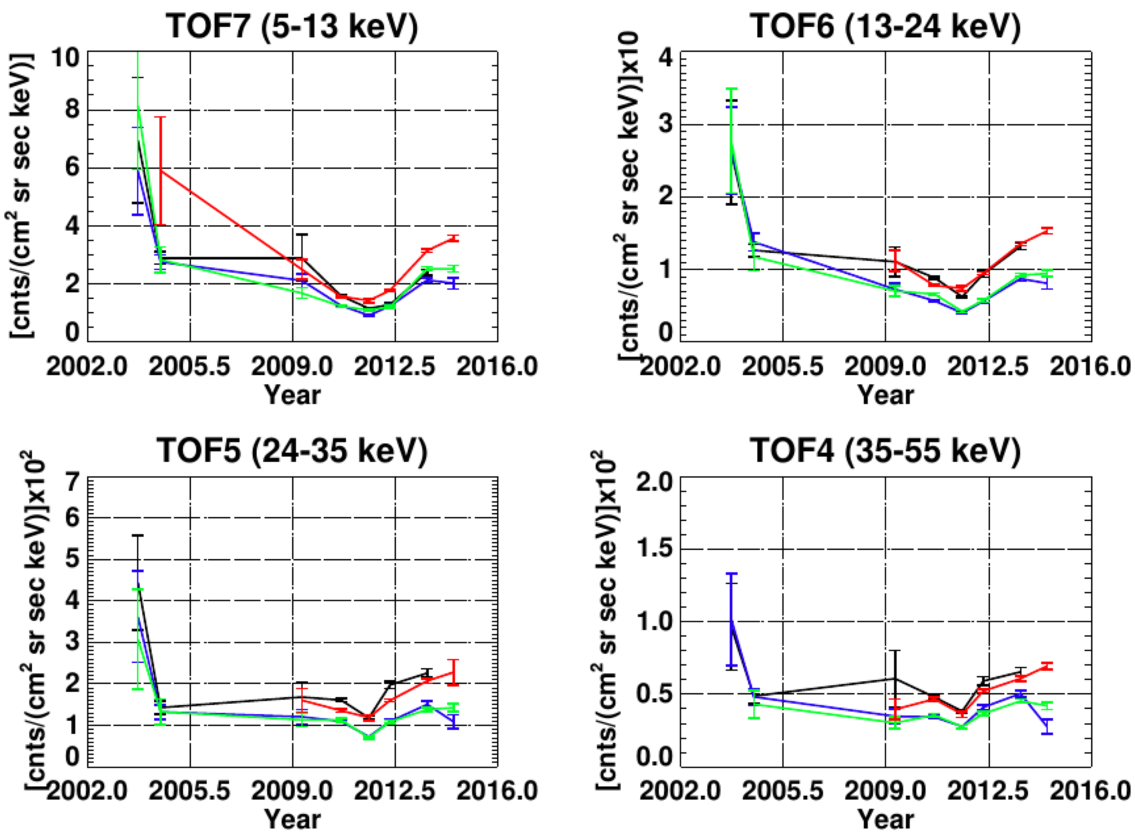
THE QUESTION IS: *How rapidly can the ENA emission change from volume with thickness Δr, that contains a ~0.1 cm^{-3} neutral H distribution and an energetic ion population with velocity v?*

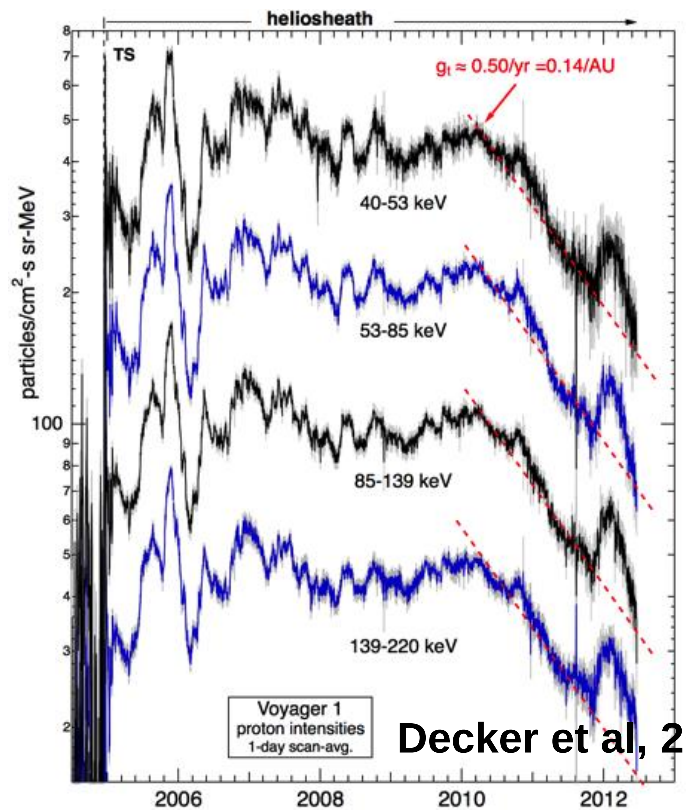
1) Ionization of interstellar neutral H-atoms within the heliosheath: Assuming that the Heliosheath is ~30 AU thick, it will take the **neutral H-atoms >6 yrs to flow through the heliosheath** (velocity of 23.5 km/s, i.e. 5 AU/year). **This mechanism is too slow to explain the observed ENA decrease.**

2) Charge-exchange decay rate for energetic heliosheath protons: The rate at which a stagnant 10 keV H^+ population (no flow-through) would be extinguished (in place) by C. E. is **~1/(2.25 yr)** corresponding to a **>60% stagnation loss in 2 yrs** (but only **22% at 45 keV**). **This mechanism also cannot explain the observed ENA decrease (at least not alone), because it fails to explain the >35 keV ENA decrease.**

3) Evacuation rate for energetic heliosheath protons: A 10 keV H^+ population will be evacuated at a distance of 100 AU in **T = L/v = 0.34 yrs** (the shortest possible time). However, the field aligned streaming velocities are <100 km/s (VGR1/2). Thus, **a lower limit to the evacuation time would be >4.7yrs** (so that **~50% of the population** could be moved out of the volume even **in 2 yrs**). For **a >40 keV H^+** (twice as fast as a 10 keV H^+ population), the **evacuation rate is >2 yrs**.

QUESTION #1: ***How do these INCA/ENA measurements compare with in-situ ion measurements from VGR1 (and VGR2)?***



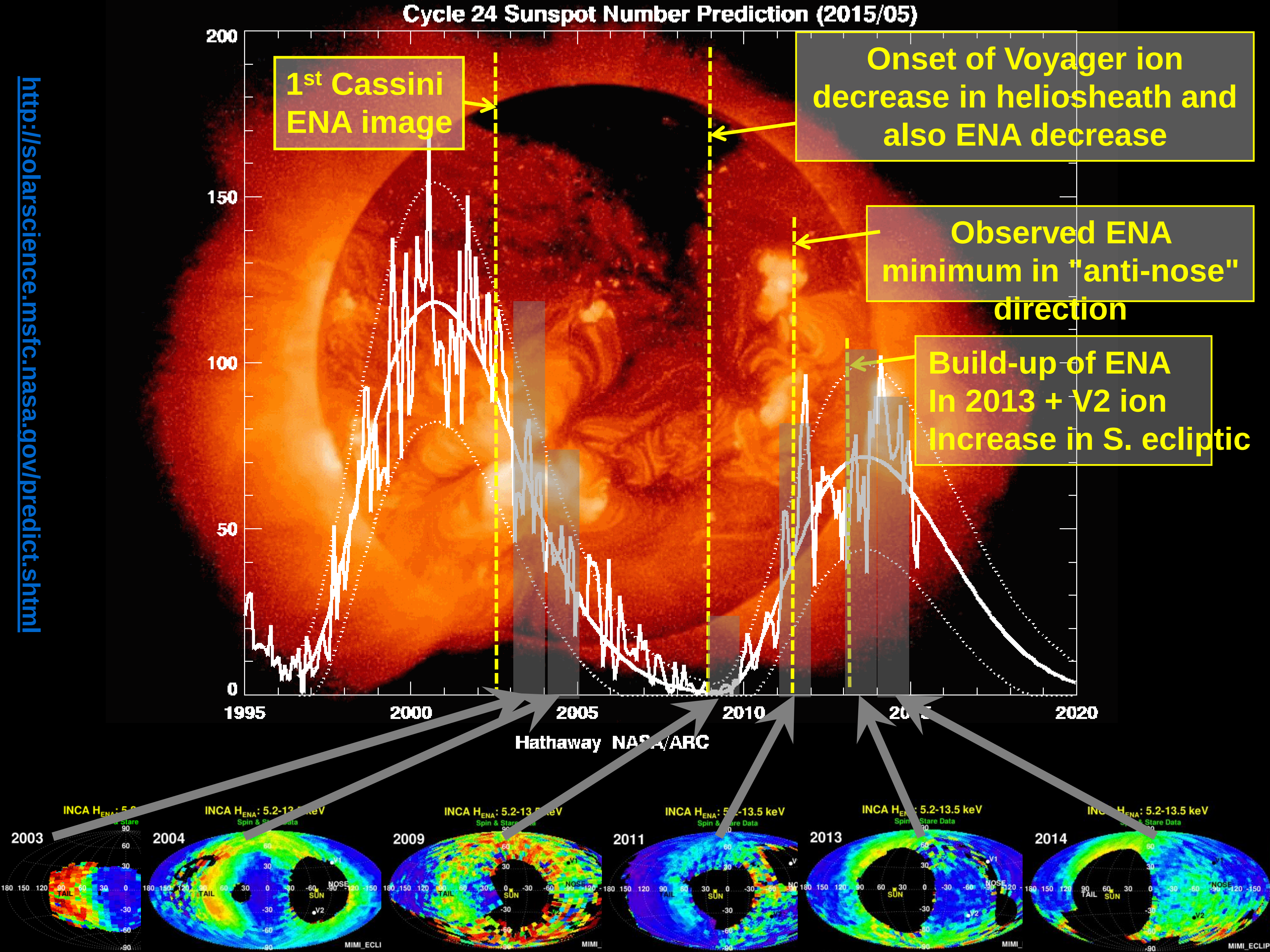


Decker et al, 201

The ENAs that we observe with INCA decreased by a factor of ~3 in ~ 8 years and by a factor of ~1.5-2 in the time period from 2009 to the end of 2011;
At about the same time period, VGR1 (and VGR2) detect an ion decrease by a factor of ~3 in the heliosheath;

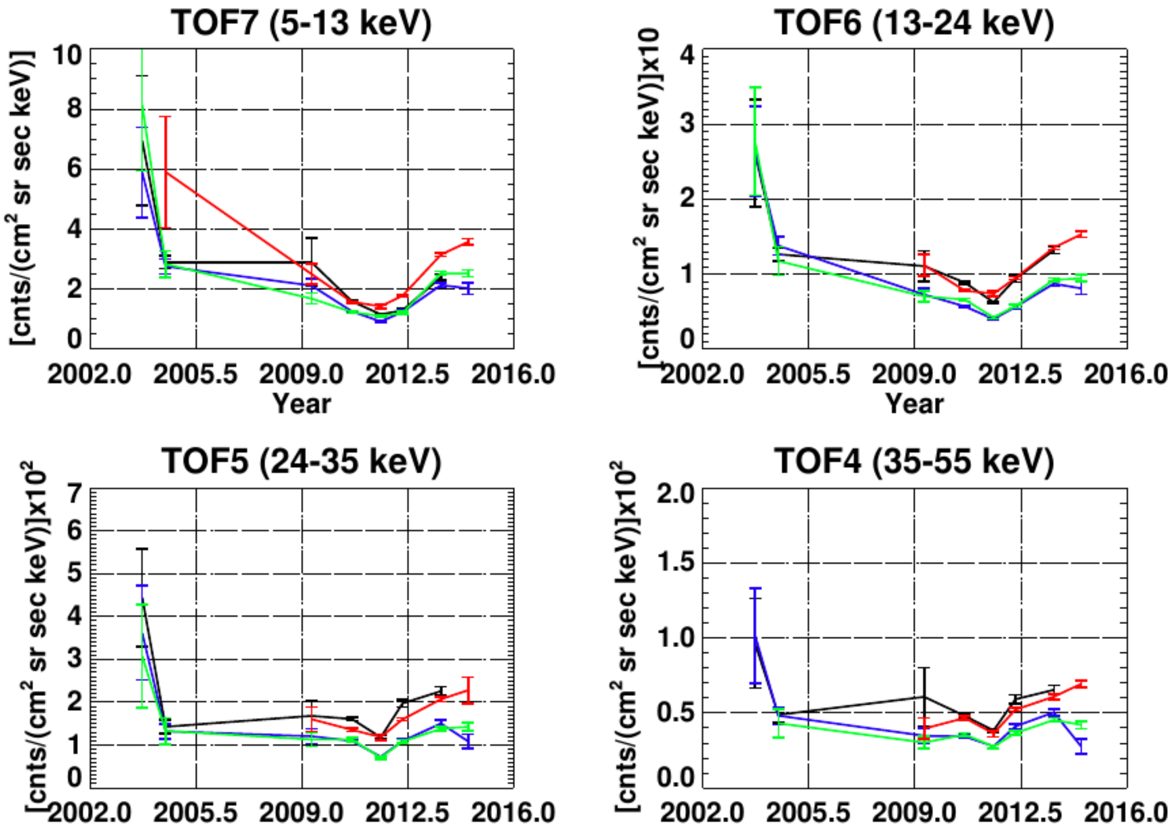
The decrease in H ENAs could be due to decrease in heliosheath ion population during the declining phase of SC23 and the recovery during the onset of the new solar cycle (SC24).

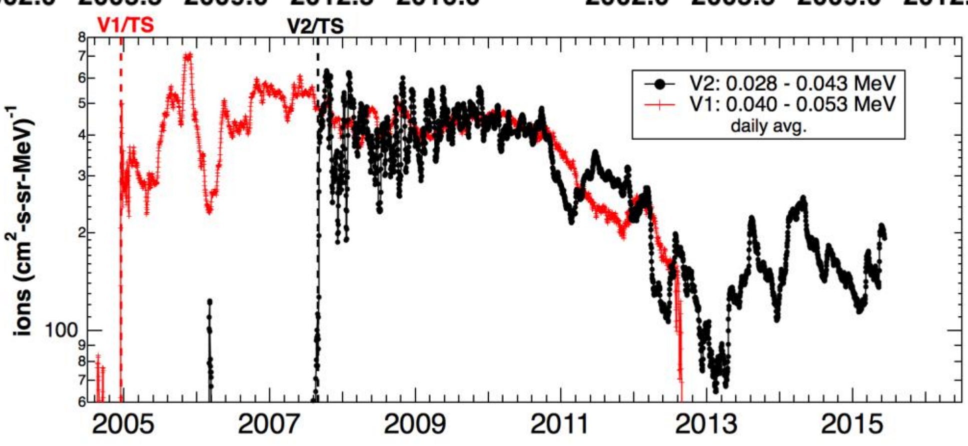
But how does evolution of the Solar Cycle compares with the ENA measurements?



Cycle 24 Sunspot Number Prediction (2015/05)
1st Cassini ENA image
Onset of Voyager ion decrease in heliosheath and also ENA decrease
Observed ENA minimum in "anti-nose" direction
Build-up of ENA In 2013 + V2 ion Increase in S. ecliptic
200
150
100
50
0
1995
2000
2005
2010
2020
Hathaway NASA/ARC
http://solarscience.msfc.nasa.gov/predict.shtml
2003
2004
2009
2011
2013
2014
Spin & Stare Data
TAIL
SUN
NOSE
V1
V2
MIMI_ECLI

QUESTION #2: *How do we explain the turn-up in the ENA intensities from 2012 and beyond?*





Although VGR1 has left the heliosheath, the ion intensities, as measured by VGR2 (still surveying through the heliosheath), are increasing since early 2013 up to date, consistent with the increase in ENA intensities as measured by INCA during the same time period.

But our ENA measurements show an increase from 2011 and beyond, whereas the VGR2 ions increase after 2013. Furthermore, these ENA time histories represent the "anti-nose" (heliotail) region and not the location of VGR2.

So, what do the INCA/ENA measurements look like at the VGR1 and VGR2 location?

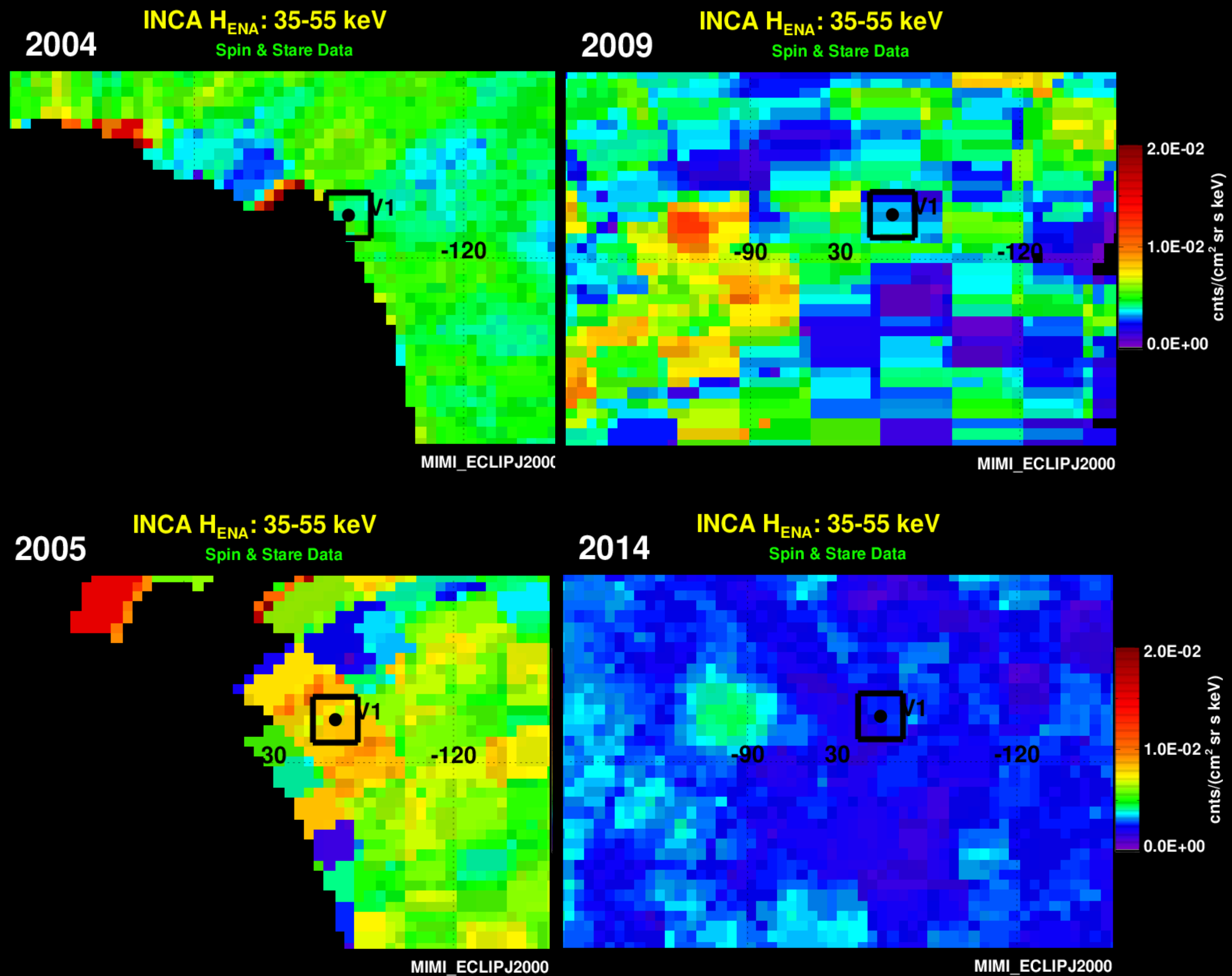
CLOSEUP IN INTENSITIES TOWARDS THE Voyager 1 LOCATION

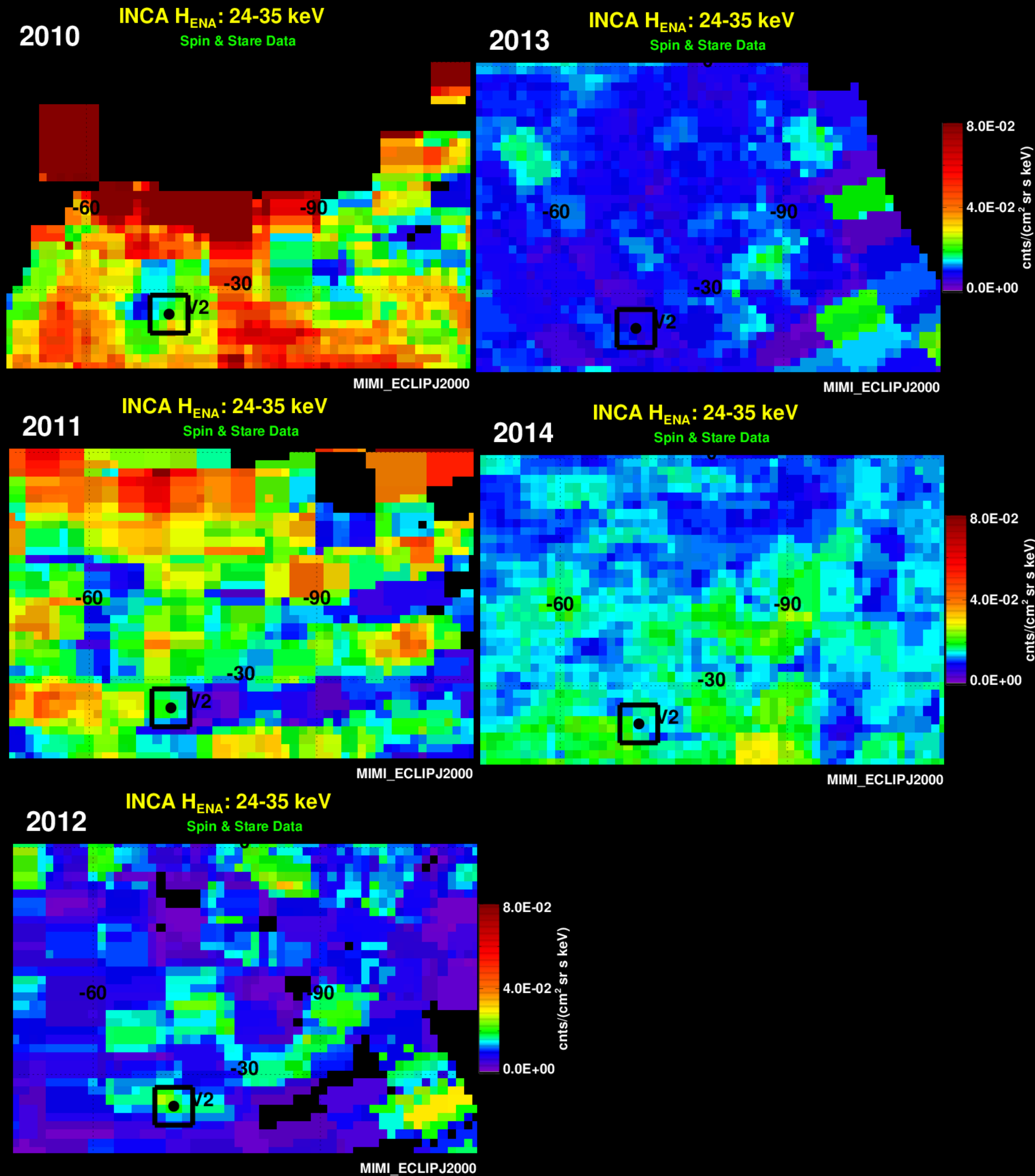
TOF4 CHANNEL

35-55 keV

ENA intensities averaged over 5 x 5 deg (long x lat).

TOF4 channel (35-55 keV) -almost- directly compares with the 40-53 keV Voyager 1 channel.



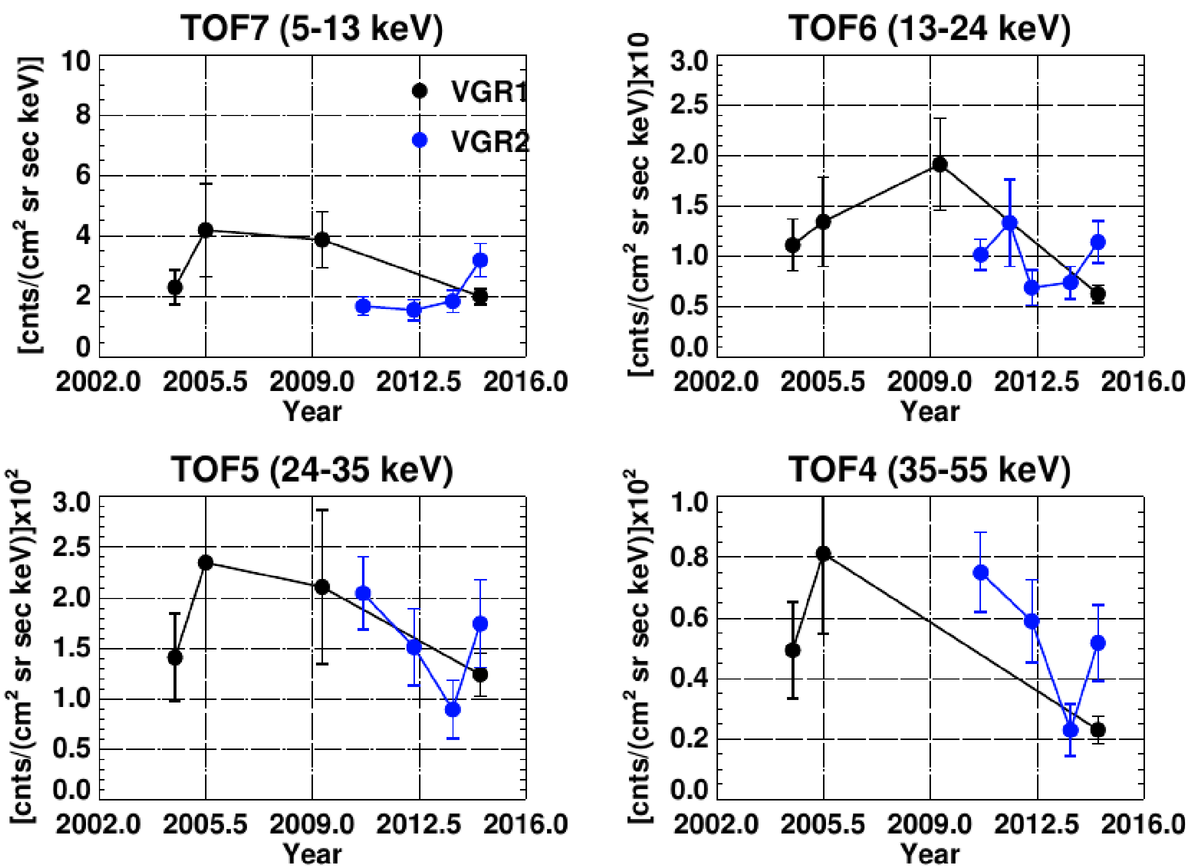


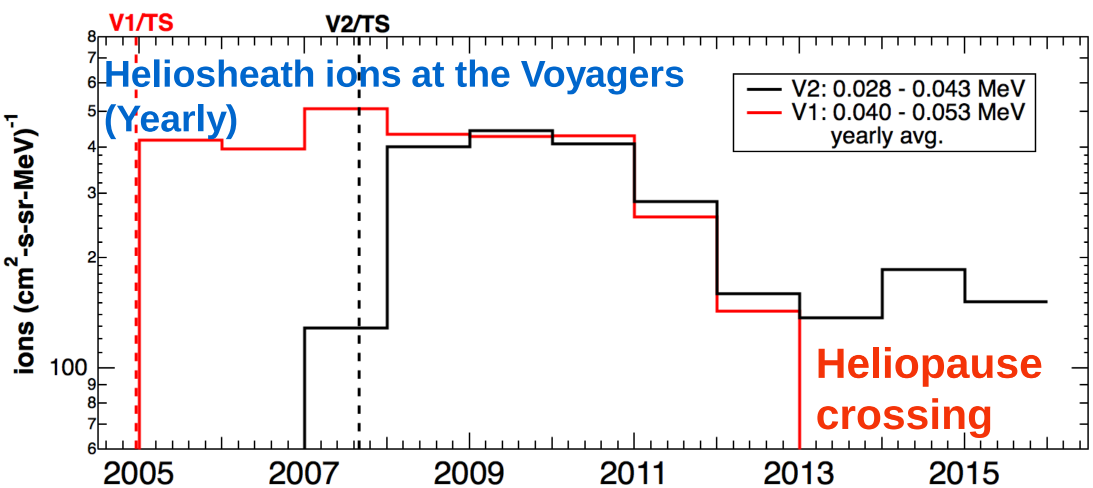
CLOSEUP IN INTENSITIES TOWARDS THE Voyager 2 LOCATION

TOF5 CHANNEL 24-35 keV

ENA intensities averaged over 5 x 5 deg (long x lat).

TOF5 channel (24-35 keV) -almost- directly compares with the 28-43 keV Voyager 2 channel.





TOF (5-55 keV) channels ENA intensities vs. time, at the VGR2 location

As shown in the previous slides and is also highlighted here, *the* ***5-55 keV ENAs decrease up to 2013 but recover during 2014.***

The ***>30 keV H^+ intensities at VGR2 increase by a factor of 1.5-2*** during 2014, while the ***>24 keV H_{ENA} intensities increase by a factor of 1.8-2*** during the same time period.

The overall ***similarity*** between the detailed time histories ***of V2 ions (lower panel) and ENAs*** is striking! If V1 was still inside the HS, ion intensities at that location at >30 keV may well have shown the same behavior.

Such convergence in time dependence between ENAs and V1/2 measured ions, suggests strongly that ***the source of ENAs is the Heliosheath***

Summary and Conclusions

• The **beginning of the declining phase (year 2003) of SC23,** where solar activity is high enough (SSN~70) is associated with **high ENA intensities in the Belt** (e.g. *~5-8 (cm^2 sr sec keV)$^{-1}$* for the 5-13 keV energy range) **from the direction of the heliospheric tail**, relative to solar minimum.

• The **ENA intensities gradually decrease** by a factor of ~3 in all INCA TOF channels from 2003 to 2011, the observed minimum, i.e. ~1 yr after the minimum in solar activity of SC23 (where SSN~20).

• The **decrease of heliotail ENA fluxes by >2** could be accounted for by a decrease of either (or both) **J_{ION} or n_H**. Calculations using standard parameters showed that **>50% of a 5-55 keV H^+ population can be evacuated from the Heliosheath (at 100 AU) within a <2 year time period.**

• The **decrease in 5-55 keV heliotail ENAs** during the years 2009 to 2011 is **consistent with the decrease in the >40 keV ion intensities (by a factor of 2-3)** during the same time interval, as measured by VGR1 and VGR2 in the heliosheath, and the onset of the new solar cycle (SC24).

• ENA **spectra** (~5-55 keV) are described by **power laws in energy** with typical γ ~ 4, are **softest at the ecliptic equator** and in the direction of the heliotail and **become harder in 2003-2011 period**.

• The **solar cycle controls the ion population in the heliosheath with a delay of ~1-1.5 yrs (on average)**, which in turn controls the **ENA production seen in the inner heliosheath (as detected by INCA) in ~2 to 4 months**. Consequently, changes that occur in the heliosheath due to the solar wind, will be seen in INCA ENAs with **a ~1.5-2 yrs delay**.

• The **increase in the Belt intensities during 2013 and 2014** (tailwards and at the position of V2), is consistent with the **increase in ion intensities at the VGR2 position**, is possibly connected to the **onset of SC24 and the solar wind changes through the new solar cycle**. No recovery has been seen at V1.

• Although V1 and V2 are located towards the nose, the **congruence of ion time histories at V1&V2 and the ENA profiles** with time argues strongly that **the source of the> 5 kev ENA is the Heliosheath** and that the ion intensity change measured in-situ by the Voyagers during the 2007-2014 is **global throughout the heliosheath**.

Thank you!