Planetary ENA imaging: where we are, where to go

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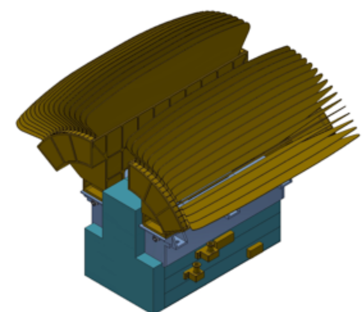
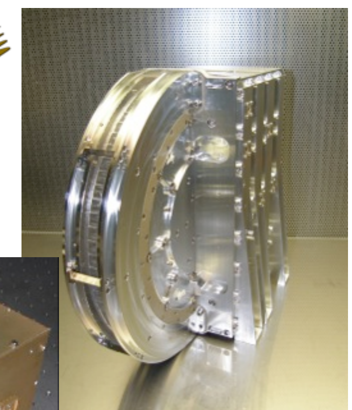
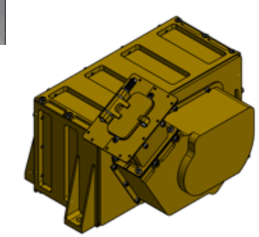
Planetary ENA imaging overview. Where we are now

Object	---------→ Difficulties: from non-dedicated detectors to full scale imagers -------→		
	Detection	Characterization	Imaging
Moon	Chandrayaan-1 (2009), IBEX (2009)	Chandrayaan-1 (2009)	Chandrayaan-1 (2009)
Saturn system	Voyager-1 (1981)	Cassini (2006 – 2008)	Cassini (2006 – 2008)
Mars, Venus	Mars Express (2006), Venus Express (2008)	Mars Express (2006), Venus Express (2008)	No relevant missions
Jupiter system	Voyager-1 (1981), Cassini (2003)	JUICE (2030)	JUICE (2030)
Mercury	BepiColombo (2021)	BepiColombo (2021)	BepiColombo (2021)
Comets	Not attempted	No relevant missions	No relevant missions

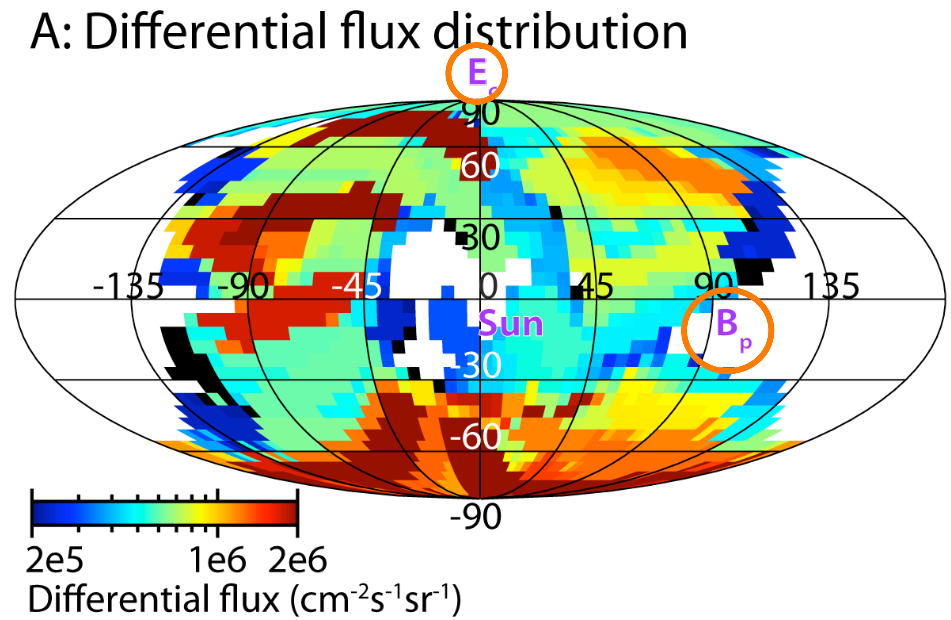
- Jupiter
  - JUICE (2022): 10 eV – 3 keV, nadir pointing slit imager
  - JUICE (2022): 1 keV – 300 keV, 2D imager
- Mercury (coming experiments)
  - BepiColombo / MMO (2015): 10 eV – 3 keV, full scape imager
  - BepiColombo / MPO (2015): 10 eV – 1 keV, nadir pointing slit imager
- Moon
  - Luna-Globe lander (2016): 10 eV – 10 keV, single pixel detector (pending approval)
  - Luna-Resource lander (2016): 10 eV – 3 keV, slit imager

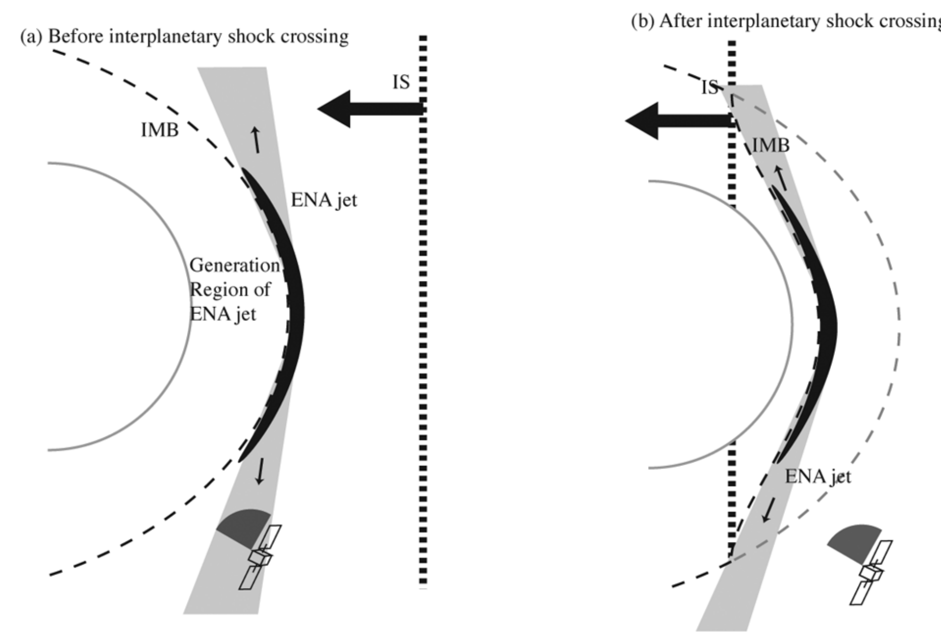



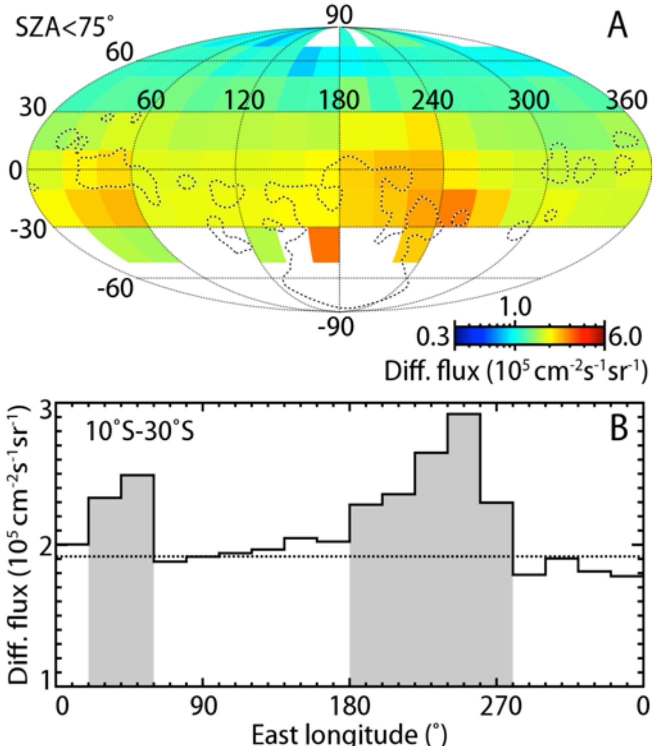
Non-magnetized atmospheric bodies. Mars

- CX ENAs from the magnetosheath and hydrogen backscattered from the exosphere measured
- Global ENA image constructed (*Wang et al., 2013)*
- ENAs was used to demonstrate fast response of the induced magnetosphere to the interplanetary bow shock (*Futaana et al., 2006)*
- Mars Express did not observed any ENAs resulted from escaping planetary ions. Likely due to too low exospheric densities during solar minimum (*Galli et al., 2008)*

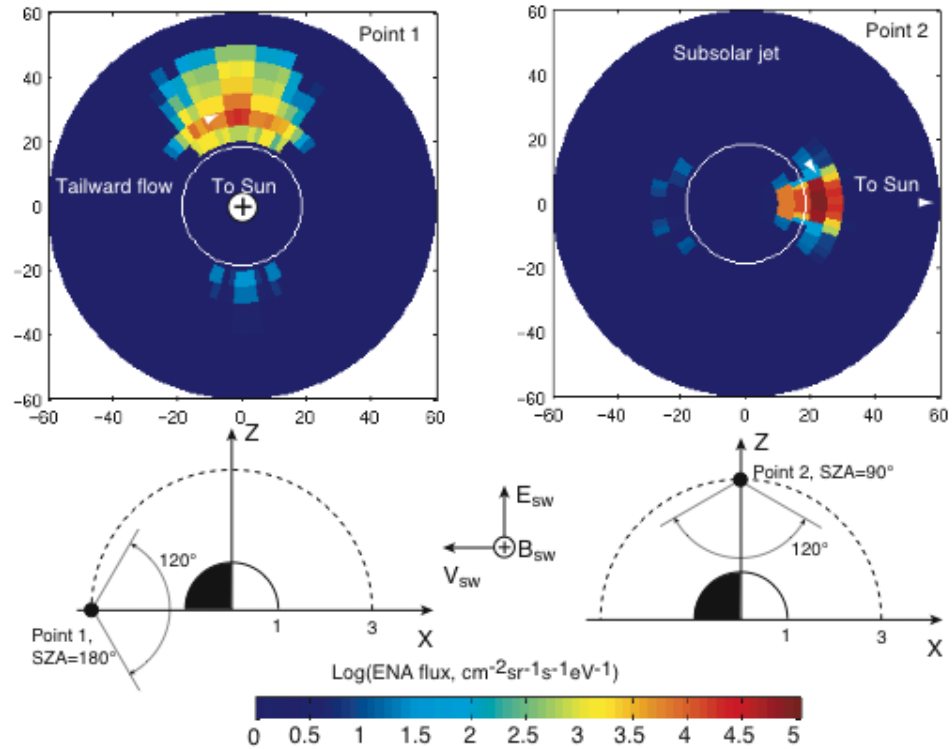




Non-magnetized atmospheric bodies. Next steps



Wang et al., 2013

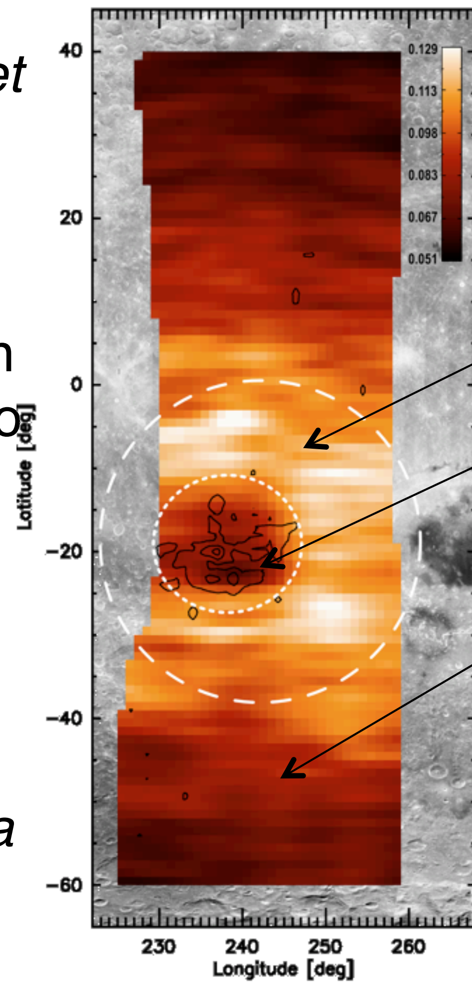


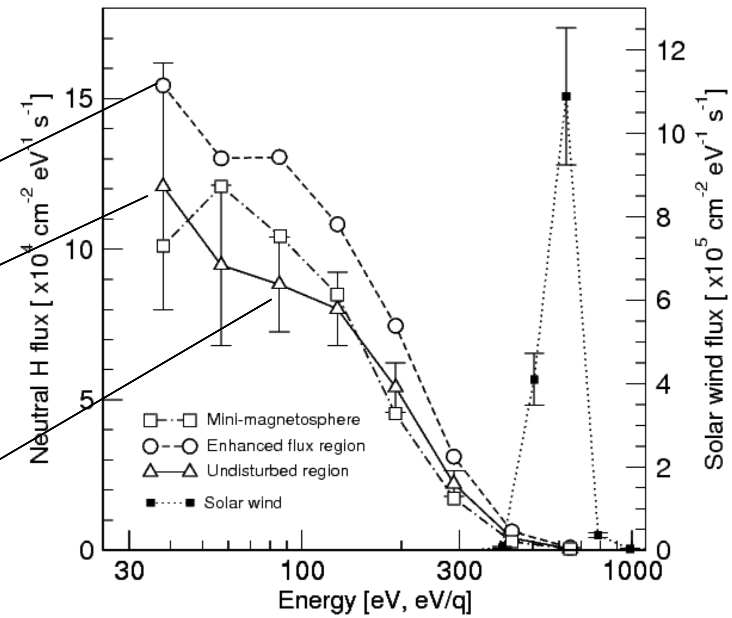
Barabash et al., 2002

- Global imaging of the magnetic anomalies on Mars. Only effects of the magnetic anomalies on the ENA signal identified(*Wang et al., 2013)*
- ENA Imaging of the escaping planetary ions (O → O+ → O (fast))
- Combination of in-situ solar wind monitoring and the induced magnetosphere response as seeing in ENA signal
- ENA imaging of comets (experiments)

Non-magnetized airless bodies. The Moon

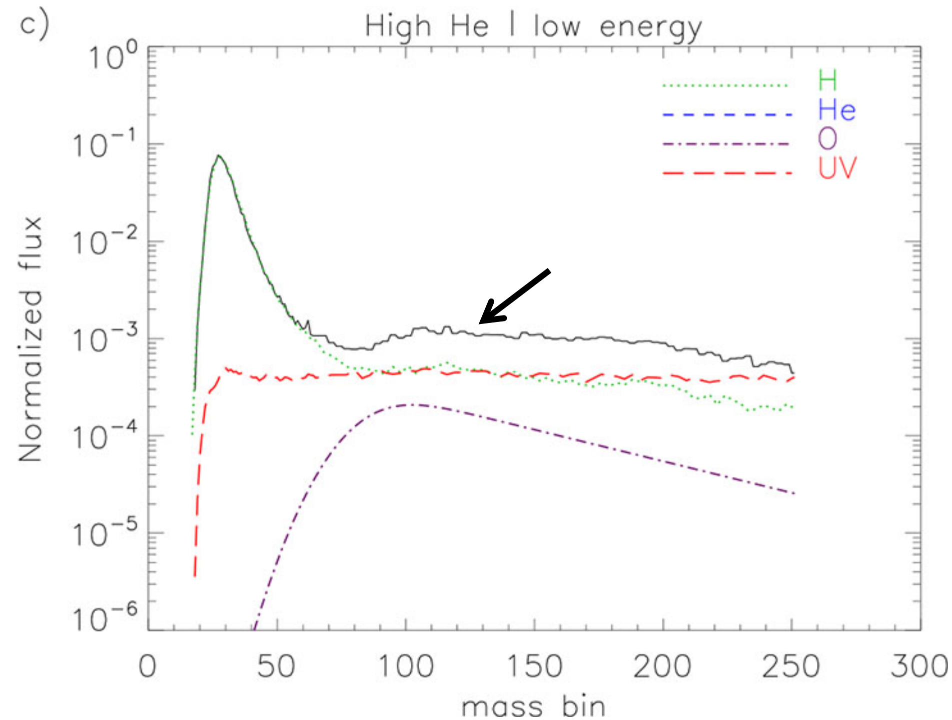
- High backscattered hydrogen flux (20% reflection) measured (*Wieser et al, 2009; McComas et al., 2009*)
  - Solar wind - regolith interaction is very complex
  - Implications for the hydrogen absorption and release still to be investigated
- Mini-magnetospheres exist (*Wieser et al., 2009)*
- Backscattered ENA spectrum variations allow remote sensing of the surface potential (*Futaana et al., 2013):*
  - $T_{ena} \sim V_{plasma} = f\,(U_{surface})$

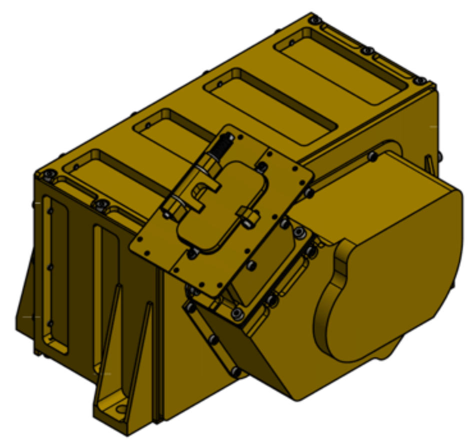




Non-magnetized airless bodies. Next steps

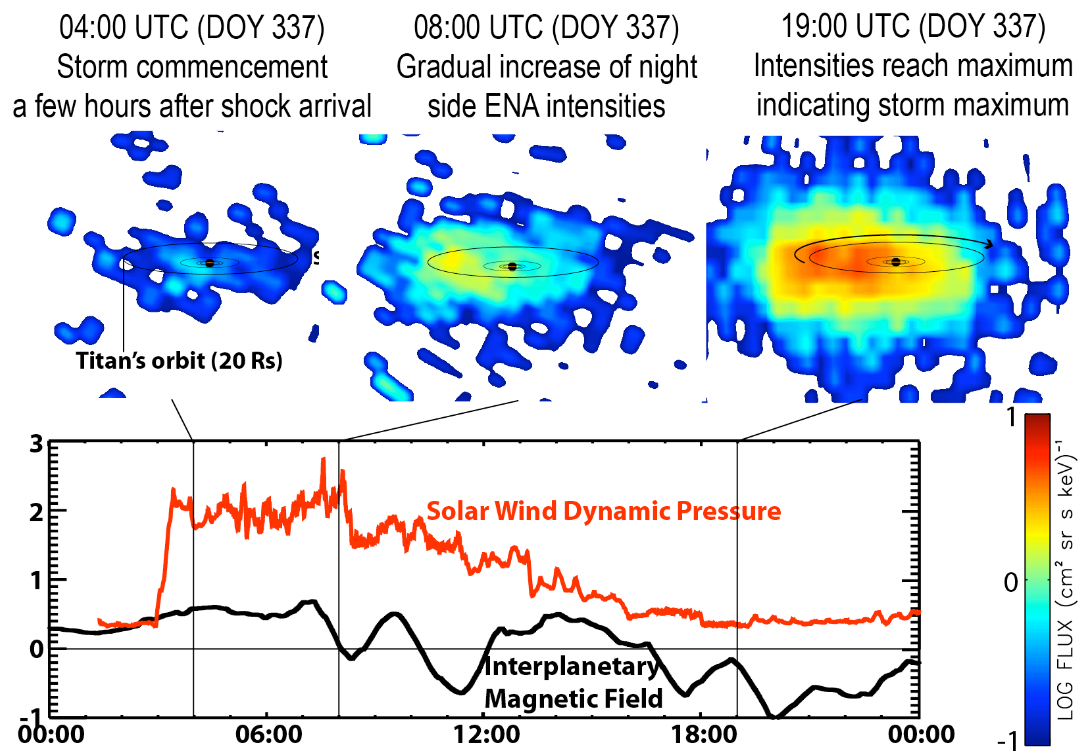
- Imaging via sputtered atoms to investigate the exosphere sources and responses to the external conditions
  - First detection of sputtered oxygen on Chandrayan-1 during helium enriched solar wind conditions (*Vorburger et al., 2013)*
- Understanding of microphysics of the plasma – surface interaction
  - Dependence of the backscattered flux on minerology, topography, and regolith physical properties
  - ENA measurements from a lander





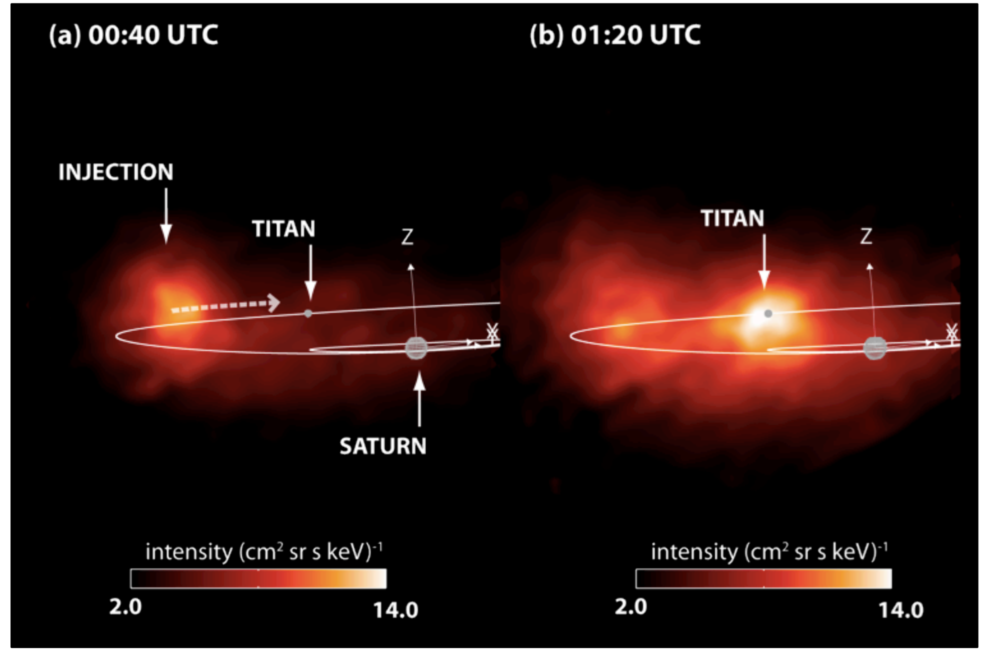
ENA sensor for Luna-Globe (2016)

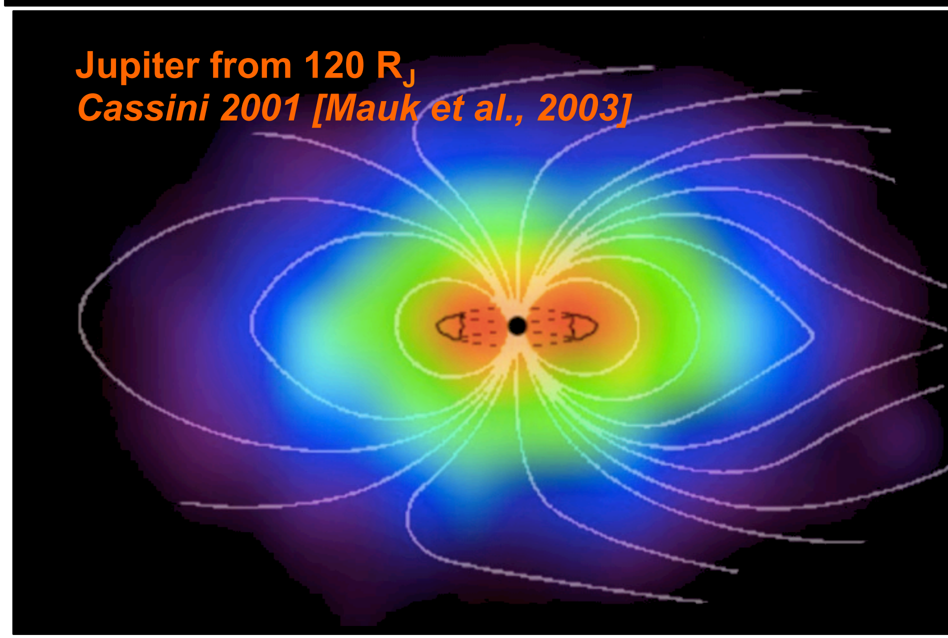
- CX ENAs from the energetic ions in the Saturn magnetosphere
- Discovery of periodic, global injections and plasma acceleration (*Paranicas et al., 2005; Mitchell et al., 2005, 2009; Carbary et al., 2008*)
- Global ion transport and dispersion (*Brandt et al., 2008*)
- Periodic field perturbations from a rotating partial ring current (*Khurana et al., 2008; Provan et al., 2009; Brandt et al., 2010)*
- Solar wind control of the magnetosphere dynamics (*Brandt et al., 2006*)



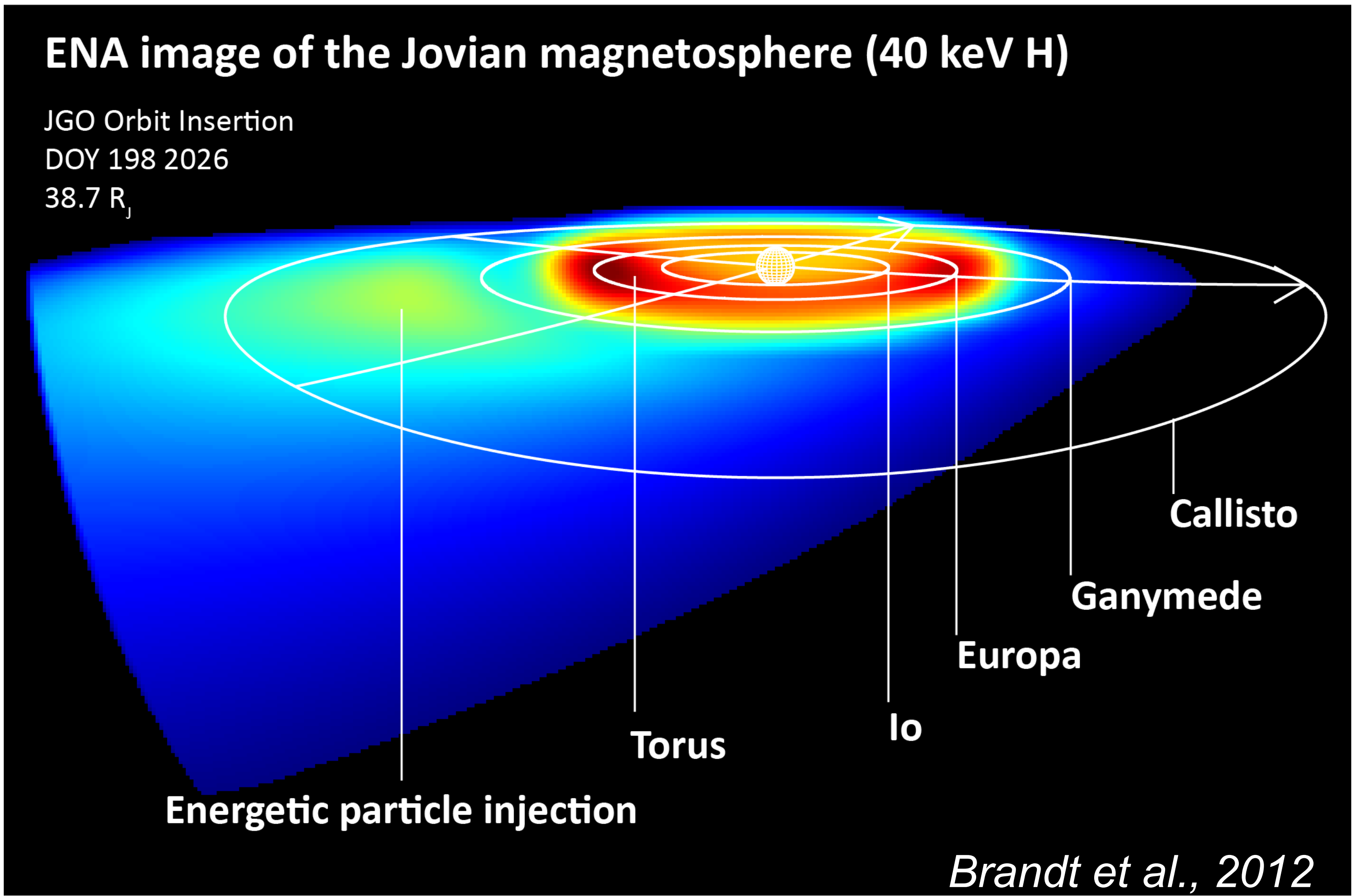
Giant planets. Imaging satellite's tori

- Imaging of the Titan exosphere/ upper atmosphere (*Brandt et al., 2010)*
  - Neutral density profile and dynamics. The exospheric extension up to 50000 km
  - Lighting up plasma injections
- Imaging of the Europa torus and detection of the neutrals nebular around Jupiter (*Krimigis et al., 2002; Mauk et al., 2003).*

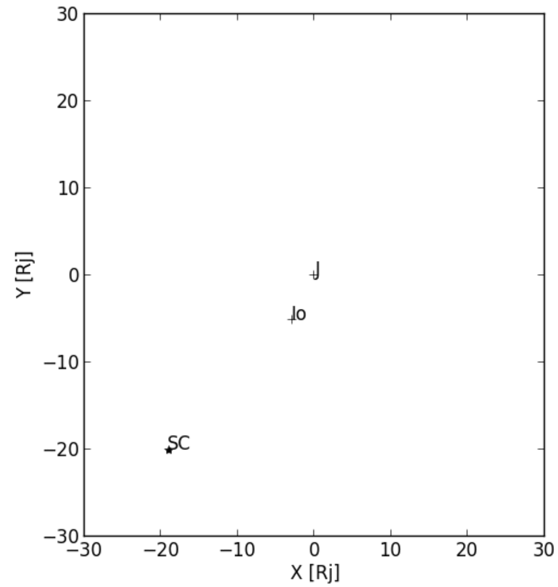


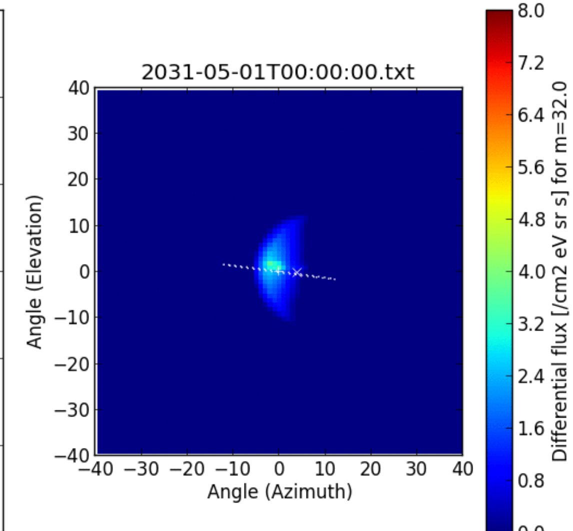


- Imaging of the Jupiter magnetosphere
  - Global dynamics and periodicities of the injections
  - External drivers (any effects?)
  - Plasma transport and energization

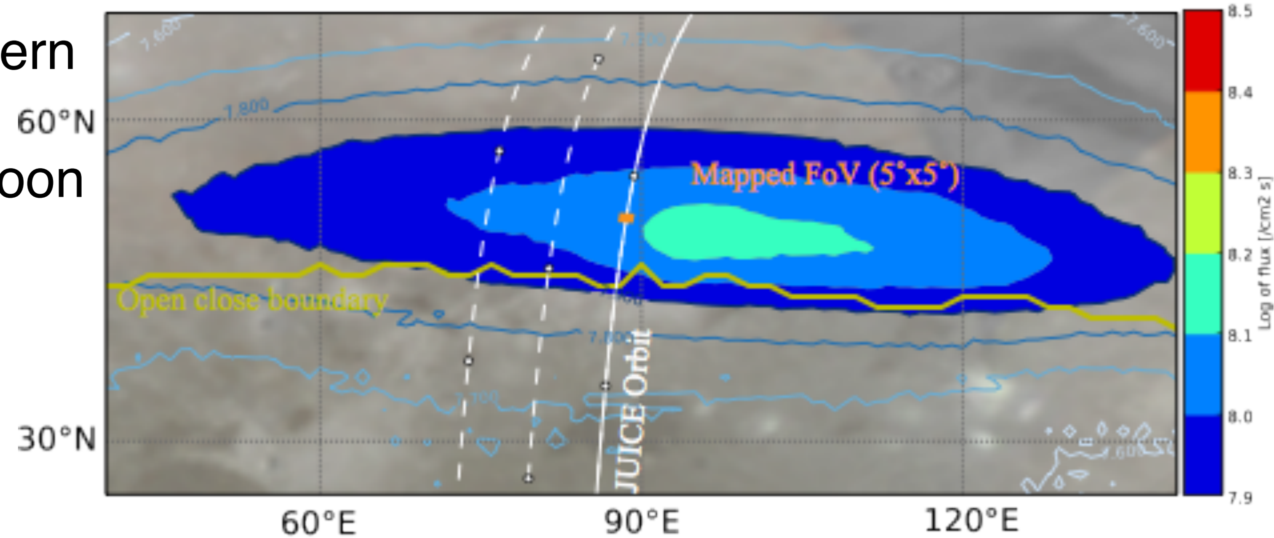


- Europa and Io tori imaging
  - Europa torus is weak in UV
  - Io torus is weak in energetic ENAs (low ion flux). Imaging in the corotation plasma energy range required (100s eV – keV) (*Futaana et al., 2013)*



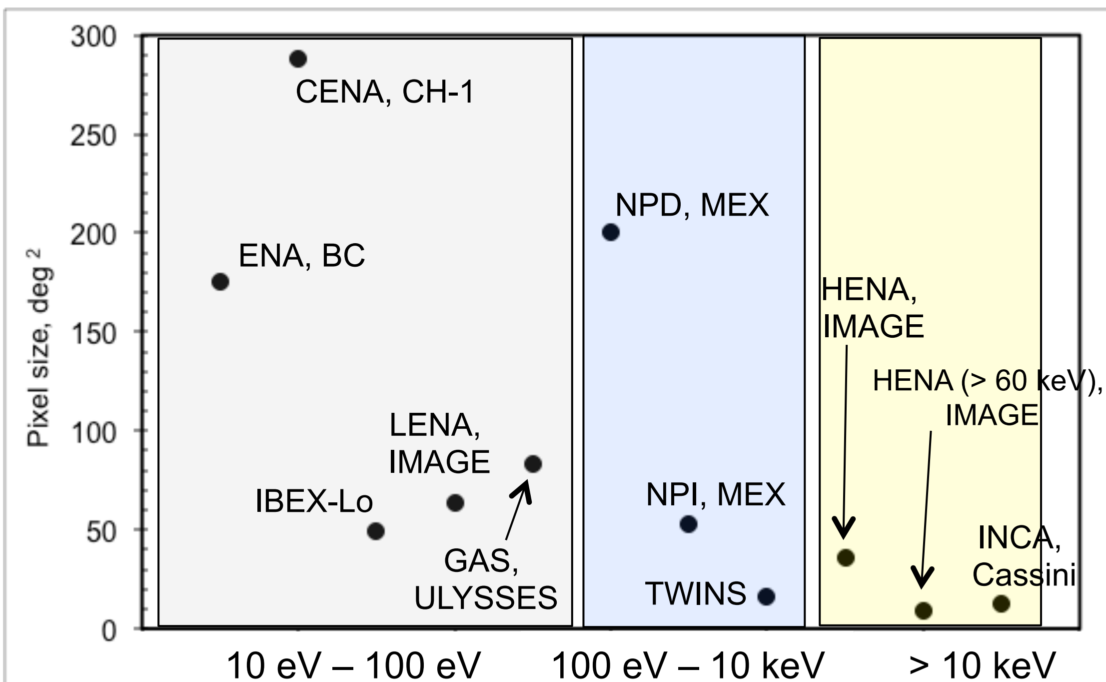


- Backscattered and sputtered neutrals from Ganymede to identify the precipitation pattern (*Futaana et al., 2013)*. The technique is similar to the Moon and Mercury.

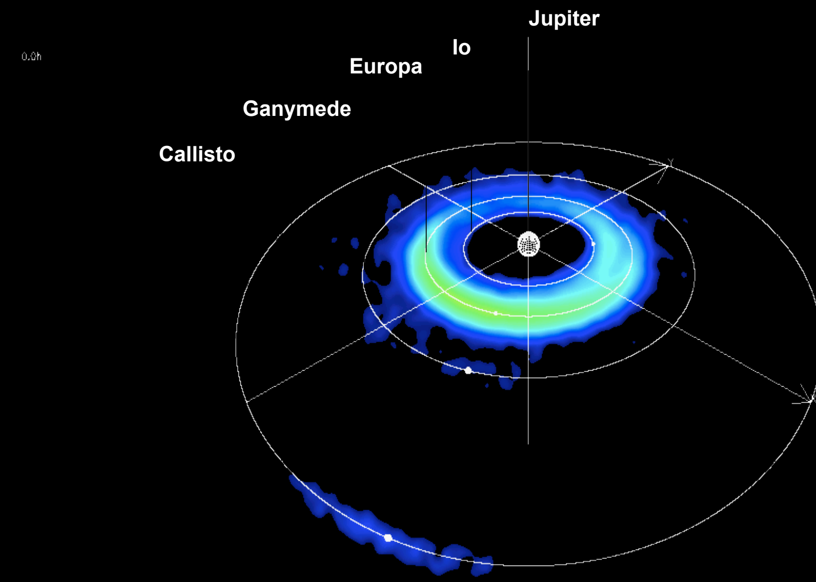


ENA instrumentation. Next steps

- Higher angular resolution to resolve finer structures (achieved 10 deg^2 pixel for energies > 60 keV , goal 1-2 deg^2 for energies < 1 keV
  - Fundamental problem 1: how to overcome ENA velocity vector degradation in the interaction with surfaces / foils
  - Fundamental problem 2: how to achieve sufficient G-factor / pixel?
  - Single pixel large detectors?
- Ultra-low energies (< 10 eV) and large G-factor detectors with high ($M/\Delta M$ > 10) mass resolution for measurements of sputtered atoms



JUICE/PEP, 2031



Simulations by Brandt, 2012

Roelof, 1987

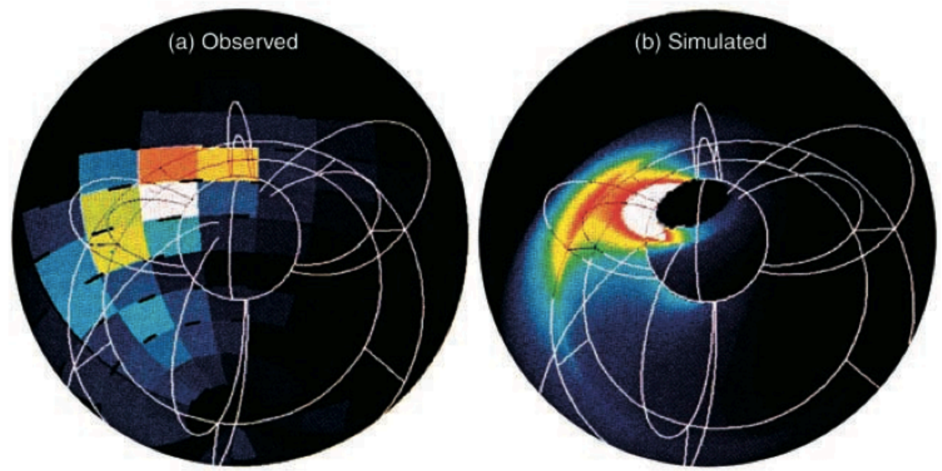


Figure 3. (a) First ENA image constructed from data obtained by the MEPI detector onboard ISEE-1. (b) Simulated image using a parametric ring current and exospheric model. (Reproduced from Ref. 5, © 1987, AGU.)