JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

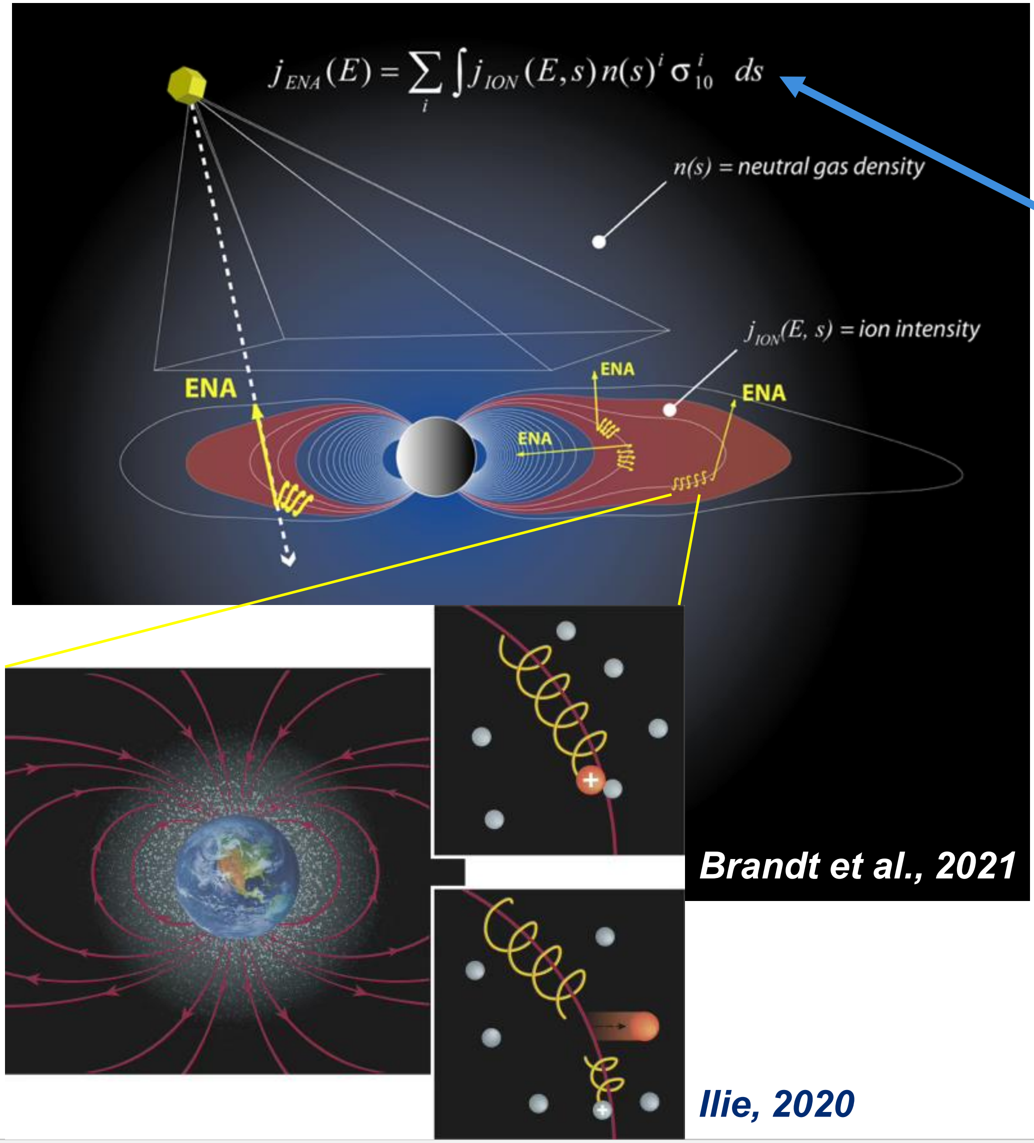
ENA Imaging of the Magnetosphere and Heliosphere from the Moon

Meeting of the Panel on Heliophysics, Physics, and Physical Science to Address Decadal-Level Science with Humans on the Moon

Matina Gkioulidou and Pontus Brandt
Johns Hopkins Applied Physics Laboratory

26 August 2025

Seeing is Believing: Energetic Neutral Atom (ENA) Imaging

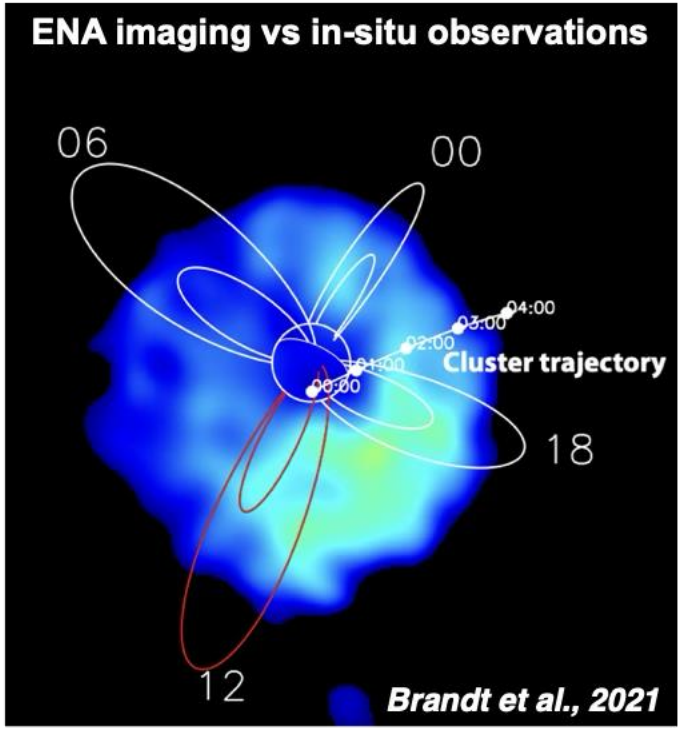


Brandt et al., 2021

Ilie, 2020

The ENA emissions from ring current and plasma sheet are optically thin and can be expressed as line integrals of underlying ion distribution as they experience charge exchange with the geocorona.

We can “see” plasmas with ENA imaging

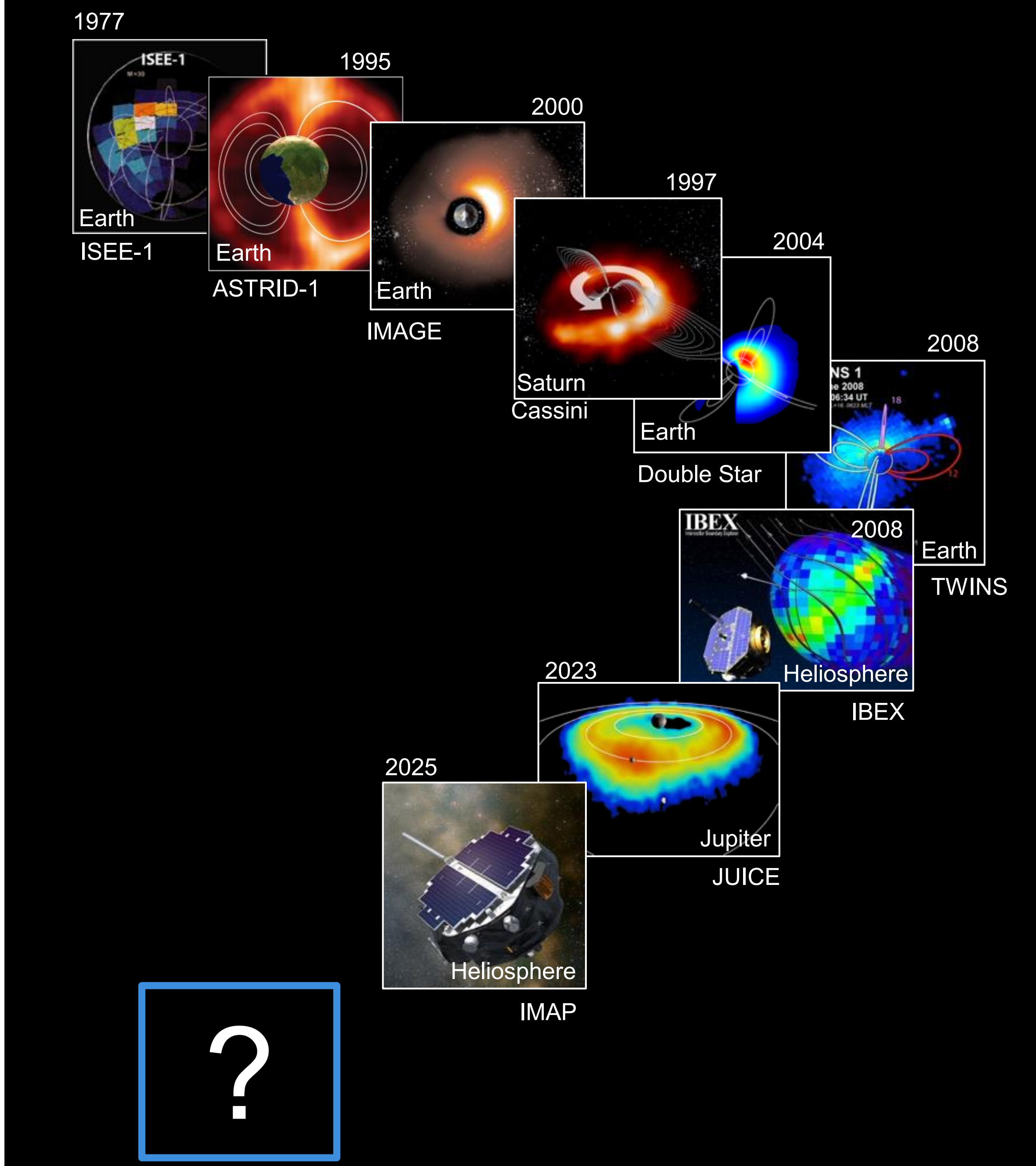


Brandt et al., 2021

ENAs provide not only a global image of the ion distribution but also compositional and spectral information about that distribution, just like photons reveal information about their source

History of ENA imaging

- ENA imaging is a powerful tool that allows us to “see” plasmas throughout our solar system and beyond.
- New instrumentation is pushing the envelope of high spatiotemporal resolution imaging
- Let’s see what the future holds for us!

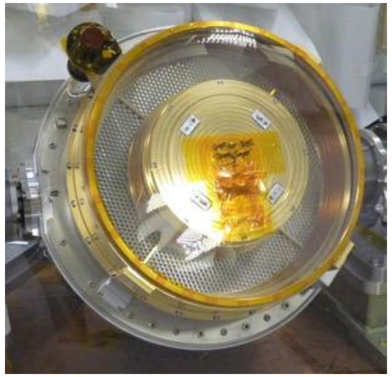


Overview of Current ENA Camera Technologies

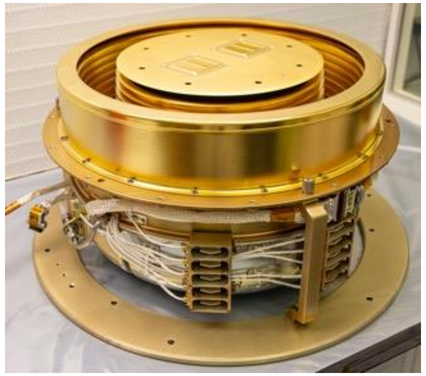
Single pixel ENA cameras based on ESA measurements

- Energy range few eV to few keV
- Using foils or surface interactions to convert ENAs into charged particles (low efficiency)
- Very narrow FOV (single pixel)
- HV to deflect charged particles

IMAP-Lo, Heritage: IBEX-Lo



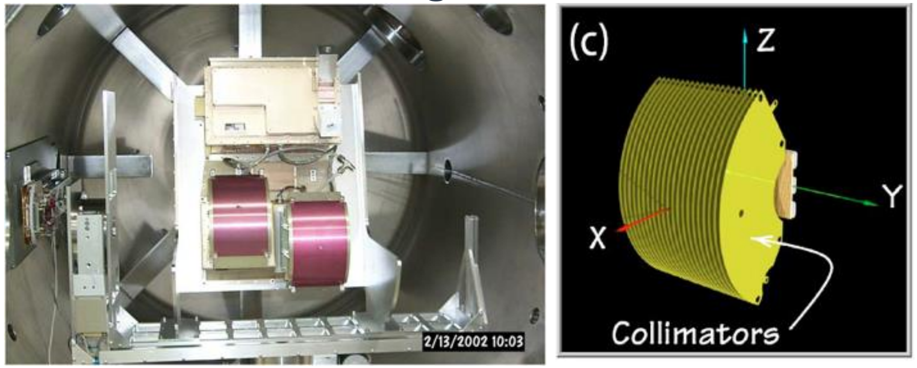
IMAP-Hi, Heritage: IBEX-Hi



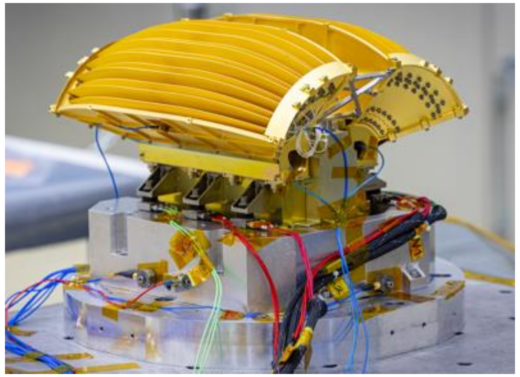
2D ENA cameras based on Time-Of-Flight measurements using foils

- Energy range keV to tens or hundreds of keV
- Wider FOV
- HV to deflect charged particles

TWINS, Heritage: MENA/IMAGE



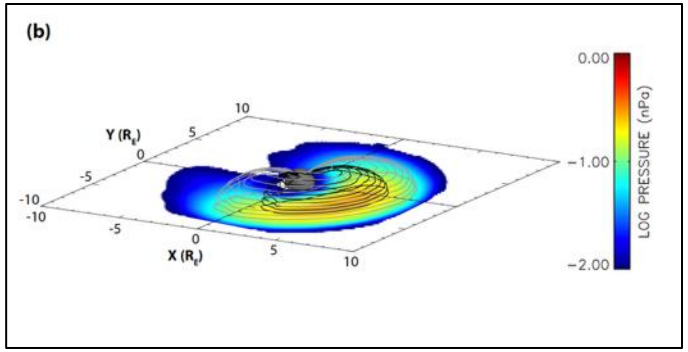
IMAP-Ultra, JUICE/JENI Heritage: HENA/IMAGE, INCA/Cassini



Magnetospheric ENA Imaging (Near-Side of the Moon)

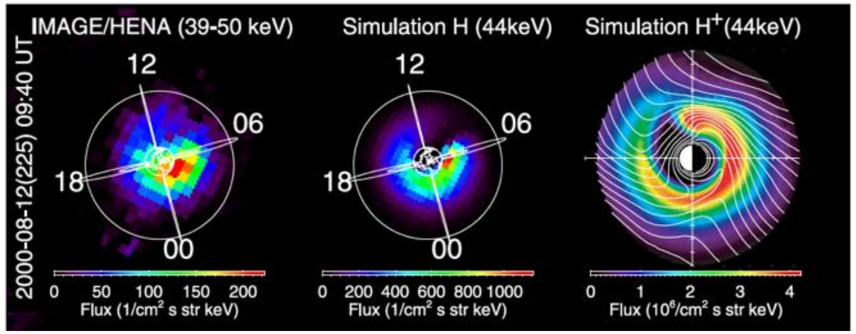
ENA Highlights – Much more than pretty pictures!

3D Current System



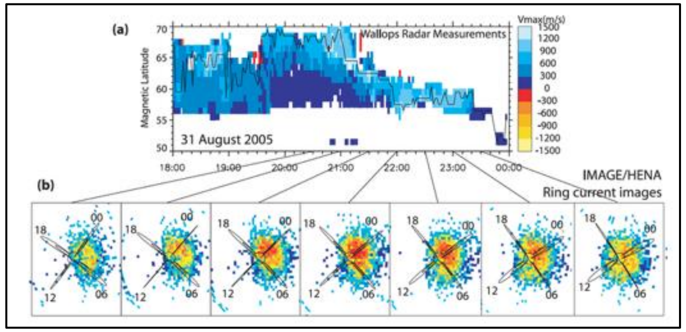
Using pressures derived from ENA images, Roelof et al. (1985) computed the associated 3D partial ring current system closing through the ionosphere.

MI-Coupling and Skewed E-Fields



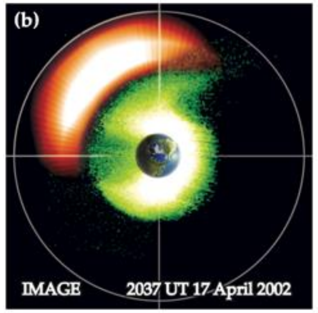
Ebihara and Fok (2004) concluded that the post-midnight enhancement of the PRC is consistent with a skewed convection electric field due to ionospheric closure.

SAPS and PRC



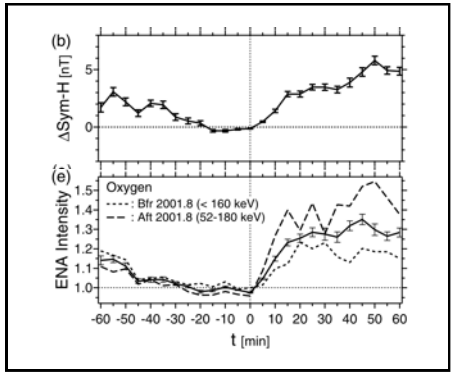
The PRC enhancement is correlated with the SAPS flow velocities consistent with the increased region-2 current (Brandt et al., 2008).

Plasmasphere Dynamics



Goldstein et al. (2004) reported undulations in the plasmapause attributed to a ring current injection.

Substorm Injection Triggers SYMH Recovery



Ohtani et al. (2005) used HENA O and H ENA images to conclude that the substorm-associated tail current disruption is responsible for the SYMH recovery, not fast ring current decay.

Injections and Planetary Rotation Periods

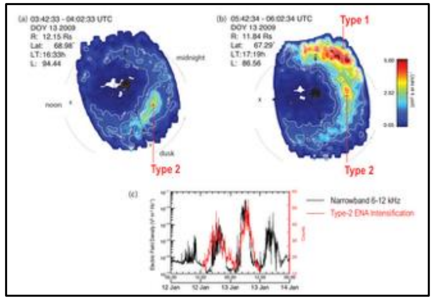
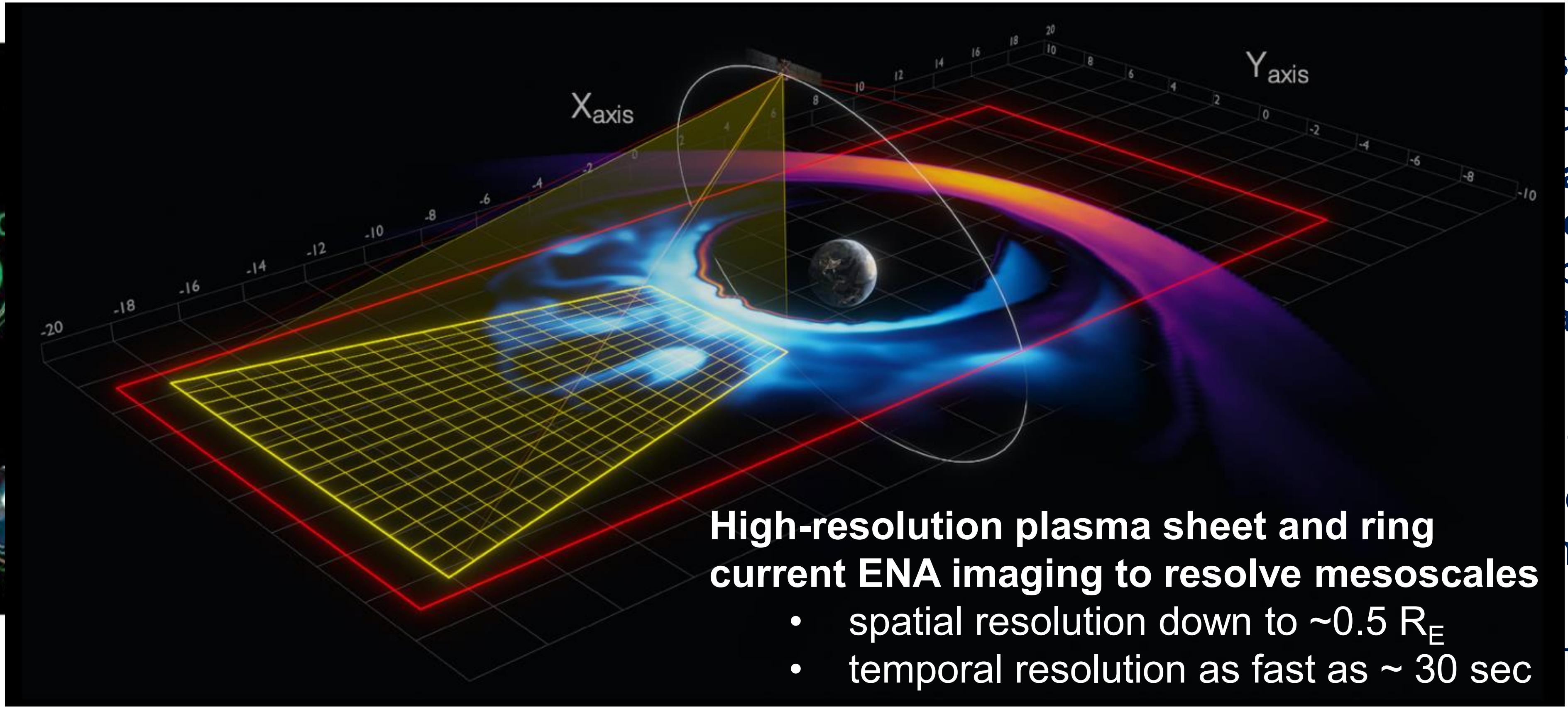


IMAGE and Cassini ENA and radio observations of Earth and Saturn reveal that periodic substorm injections drive the periodic radio emissions at Saturn that have been used to define the planetary rotation period in the past (Mitchell et al., 2009).

Decadal Survey’s Links mission concept: Global imaging at mesoscale resolution & in-situ measurements from different platforms



spacecraft at a
orbit of 8 R_E
al and
esolution
pheric ENA
al FUV imaging

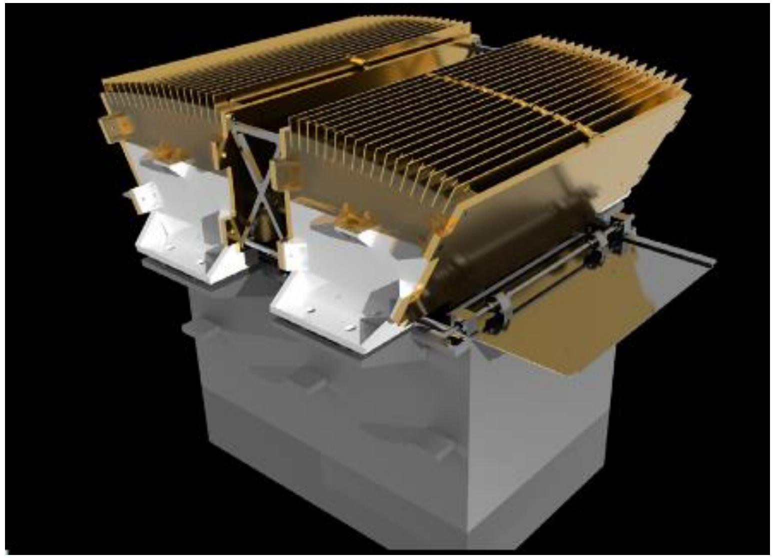
almost
ts with with
es (~8, ~11,
measuring
etic particles
fields in-situ

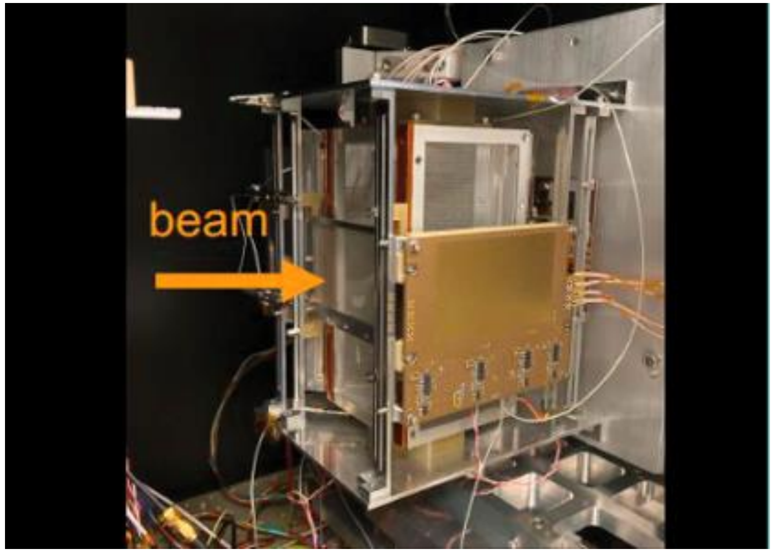
Current Capabilities and Resources

Energy	Angular Resolution	Geometric Factor (cm^2 sr)	Instantaneous FOV	Instruments
3 – 300 keV	2˚ E≥ 40 keV (H)	0.152	120º x 90º	IMAP-Ultra JUICE/JENI
1 - 30 keV	4 deg	8 x 10^{-3}	70˚	TWINS
5 – 1000 eV	6 deg	~10^{-4}	9º x 9º	IMAP-Lo
500 eV – 15 keV	4 deg	0.0011 – 0.014	4º x 4º	IMAP-Hi

Instrument	Power	Mass
IMAP-Ultra	N/A, but similar to JENI	N/A, but similar to JENI
JUICE/JENI	7.6 W	7.4 kg (sensor) 7.0 kg (shielding)
TWINS	25.3 W	18.7 kg
IBEX-Lo	3.46 W (sensor only)	11.5 kg
IBEX-Hi	0.65 W (sensor only)	7.4 kg)
IMAP-Lo	N/A	N/A
IMAP-Hi	N/A	N/A

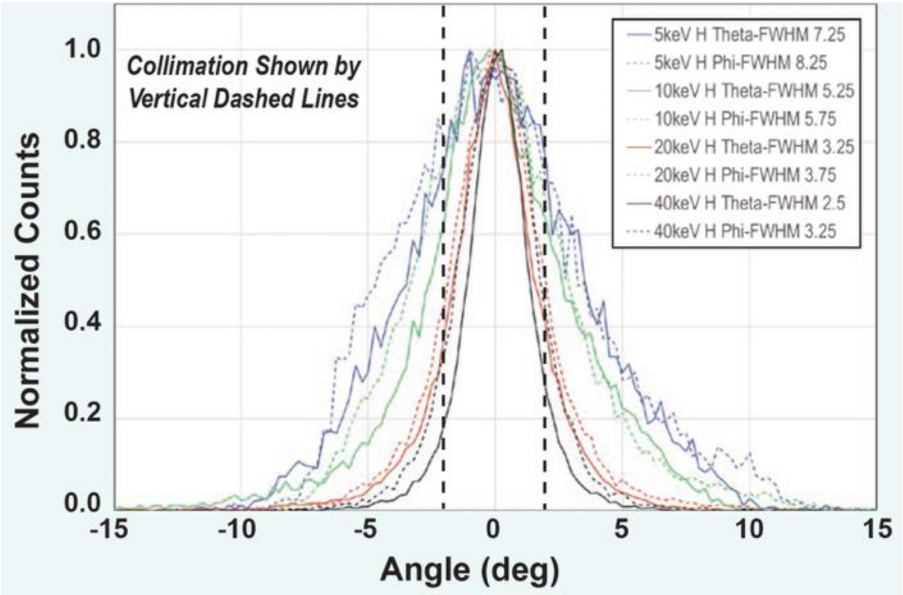
Capabilities in Development





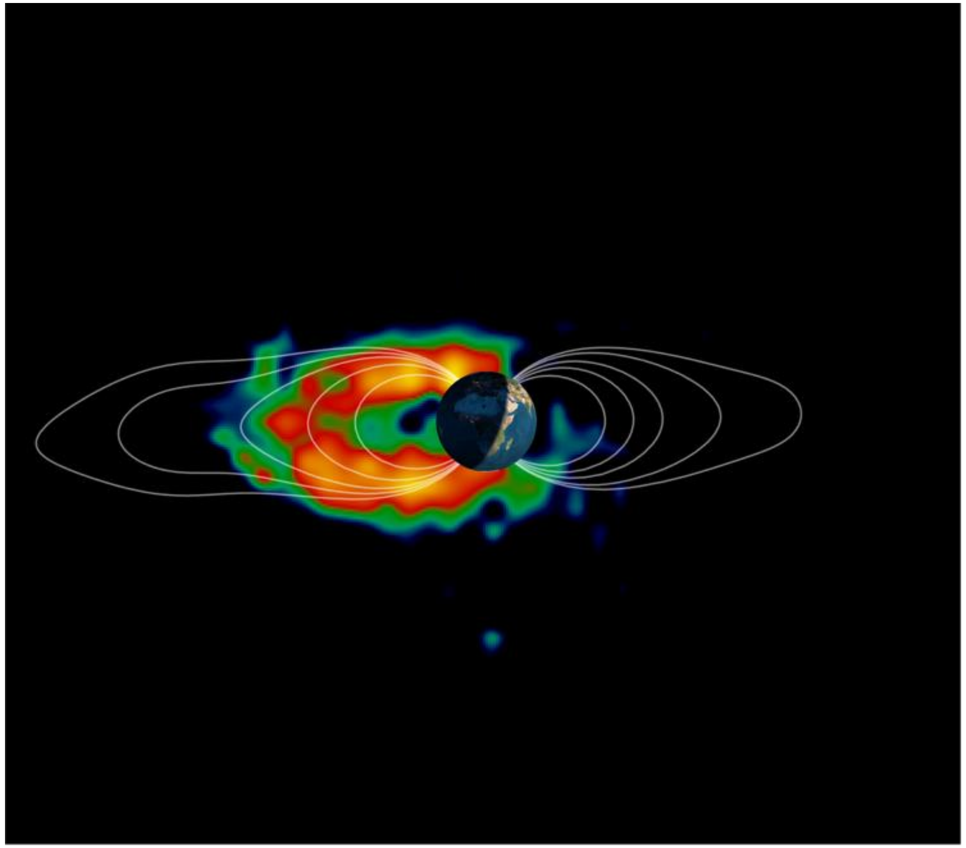
- APL's 3rd generation ENA camera with larger and collimated aperture
- Enables larger GF and higher angular resolution for lower energies
- 50˚ x 50˚ FOV

Angular resolution



Science Requirements and Return from the Moon

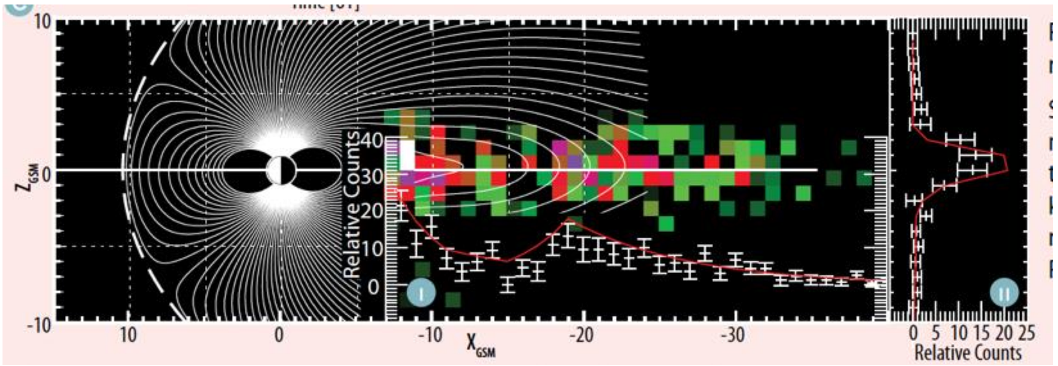
- **Ring current strength and evolution**
  - Achievable with current technologies, but larger GF needed for 20 min cadence
  - 2˚ resolution (~2 R_E) sufficient to assess ring current energy content (10-200 keV) and composition (H^+ and O^+)
- **Plasma sheet energization pathways**
  - High time (≤1 min) and high angular/spatial resolution (≤1˚/1 R_E) and low-energy (~1 keV) threshold to meet Decadal concept, but does not provide polar views
  - Oxygen ENAs are very sensitive to acceleration processes and require particular attention due to their large scattering in the instrument
  - Therefore, also high GF, meaning large instrumentation while maintaining high UV background rejection
- **Ionospheric outflow**
  - High angular resolution to resolve Earth polar regions <1 R_E (~1˚)
  - Large GF and low-energy threshold down to 10’s eV, meaning high conversion efficiency using conversion surfaces
- **Magnetosheath location and dynamics**
  - High angular resolution and large GF to resolve magnetosheath location to <0.5 R_E



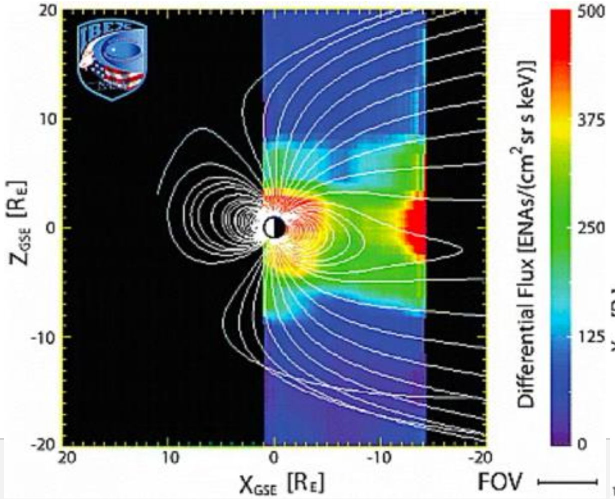
Example hydrogen ENA image in 10-50 keV range, 20 min integration taken by IMAGE/HENA 22 January 2004 in the equatorial plane from about 8 R_E distance.

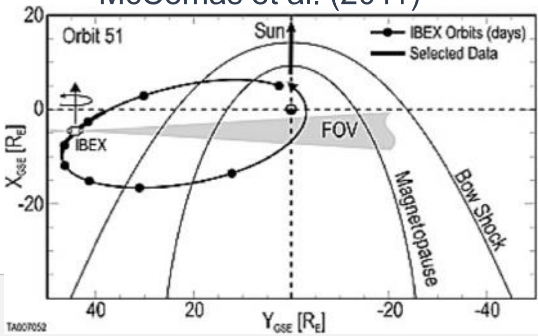
Science Requirements and Return from the Moon

- **Ring current strength and evolution**
  - Achievable with current technologies, but larger GF needed for 20 min cadence
  - 2˚ resolution (~2 R_E) sufficient to <u>assess</u> ring current energy content (10-200 keV) and composition (H^+ and O^+)
- **Plasma sheet energization pathways**
  - High time (≤1 min) <u>and</u> high angular/spatial resolution (≤1˚/1 R_E) <u>and</u> low-energy (~1 keV) threshold to meet Decadal concept, but does <u>not</u> provide polar views
  - Oxygen ENAs are very sensitive to acceleration processes and require particular attention due to their large scattering in the instrument
  - Therefore, also high GF, meaning large instrumentation while maintaining high UV background rejection
- **Ionospheric outflow**
  - High angular resolution to resolve Earth polar regions <1 R_E (~1˚)
  - Large GF and low-energy threshold down to 10's eV, meaning high conversion efficiency using conversion surfaces
- **Magnetosheath location and dynamics**
  - High angular resolution and large GF to resolve magnetosheath location to <0.5 R_E



Simulated ENA image of the plasma sheet from 30 R_E integrated over 20 min as proposed for the STORM MIDEX mission, using APL's **3rd generation ENA camera**. While the lunar surface offers a good platform, higher GF and angular resolution are required.





~2-day averaged images of the Earth's plasma sheet from IBEX
McComas et al. (2011)

Science Requirements and Return from the Moon

- **Ring current strength and evolution**
  - Achievable with current technologies, but larger GF needed for 20 min cadence
  - 2˚ resolution (~2 R_E) sufficient to assess ring current energy content (10-200 keV) and composition (H^+ and O^+)
- **Plasma sheet energization pathways**
  - High time (≤1 min) and high angular/spatial resolution (≤1˚/1 R_E) and low-energy (~1 keV) threshold to meet Decadal concept, but does not provide polar views
  - Oxygen ENAs are very sensitive to acceleration processes and require particular attention due to their large scattering in the instrument
  - Therefore, also high GF, meaning large instrumentation while maintaining high UV background rejection
- **Ionospheric outflow**
  - High angular resolution to resolve Earth polar regions <1 R_E (~1˚)
  - Large GF and low-energy threshold down to 10's eV, meaning high conversion efficiency using conversion surfaces
- **Magnetosheath location and dynamics**
  - High angular resolution and large GF to resolve magnetosheath location to <0.5 R_E

IMAGE/LENA

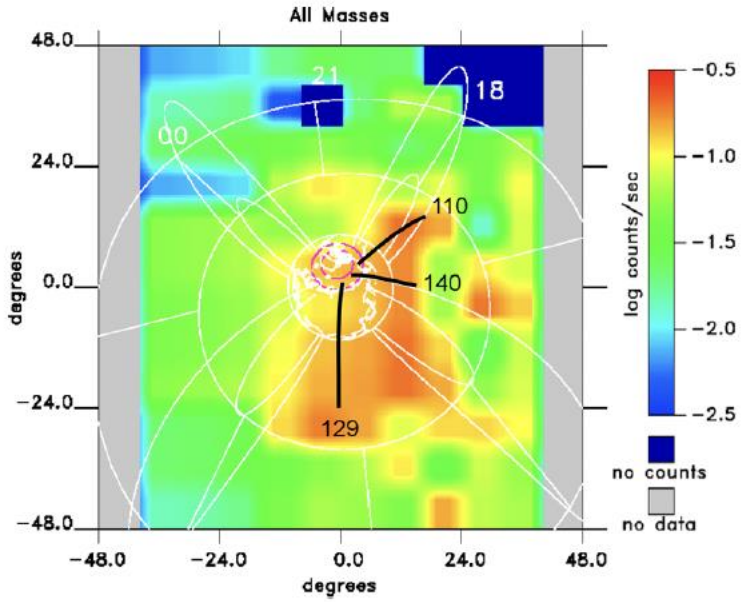


Figure 3. Neutral atom image from the IMAGE spacecraft. Noon (dawn) is in the lower right (left) hand corner. The neutral flux peaks over the entire dayside off the direction to the Earth. Three magnetic field lines from 72° latitude and from 0900, 1200, and 1500 MLT are identified by the pitch angle (129°, 140°, and 110°, respectively) for charge exchange at three different altitudes.

Fuselier et al. (2006)

Science Requirements and Return from the Moon

- **Ring current strength and evolution**
  - Achievable with current technologies, but larger GF needed for 20 min cadence
  - 2˚ resolution (~2 R_E) sufficient to assess ring current energy content (10-200 keV) and composition (H^+ and O^+)
- **Plasma sheet energization pathways**
  - High time (≤1 min) and high angular/spatial resolution (≤1˚/1 R_E) and low-energy (~1 keV) threshold to meet Decadal concept, but does not provide polar views
  - Oxygen ENAs are very sensitive to acceleration processes and require particular attention due to their large scattering in the instrument
  - Therefore, also high GF, meaning large instrumentation while maintaining high UV background rejection
- **Ionospheric outflow**
  - High angular resolution to resolve Earth polar regions <1 R_E (~1˚)
  - Large GF and low-energy threshold down to 10's eV, meaning high conversion efficiency using conversion surfaces
- **Magnetosheath location and dynamics**
  - High angular resolution and large GF to resolve magnetosheath location to <0.5 R_E

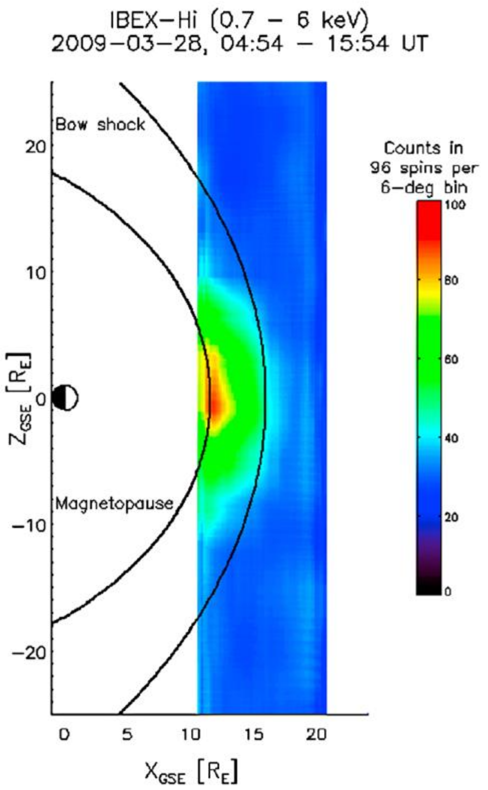


Figure 1. Hydrogen ENA countrate integrated from 0.7–6 keV on 28 March 2009 from 04:54–15:54 UT. The peak is centered on the subsolar magnetopause. Significant flux extends to nearly ±10 R_E in the Z_{GSE} direction.

Fuselier et al. (2010)

Science Requirements Summary

Science Objective	Science Requirement	Measurement Requirement	Mission Requirements	Development Needed
Ring current evolution in response to solar drivers	ENAs covering the energy range and species that dominates the ring current energy density at ring current evolution time scales	H and O 10-200 keV ~20 min cadence 2RE resolution → ~2˚ FOV to cover R = 10 R_E -> 20˚	Most vantage points	TRL=5 Technology exists, but larger geometry factor (size) needed
Energization and injections from plasma sheet to ring current	ENAs covering the energy pathway of ions from plasma sheet to ring current at injection timescales	H and O 1-100 keV ~1 min cadence ≤1 RE → ≤1˚ FOV to cover R = 30 R_E → 50˚	Dusk and dawn vantage points Decadal Links concept requires polar view that cannot be achieved from the Moon	TRL=3-4 Large GF instrumentation with high angular resolution. Physical collimation, or other means to improve on electron optics limit.
Ionospheric outflow	ENAs covering the low energy range from the ionosphere	O ~10's eV - 10 keV ~20 min cadence ~1RE resolution -> ~1˚ FOV to cover R = 5 R_E → 10˚	Most vantage points	TRL=3-4 Much higher GF and efficiencies needed, meaning high conversion surface efficiencies
Magnetosheath location and solar wind response	ENAs from sub-solar point	H and O 100 eV - 10 keV ~10 min <0.5 R_E → 0.5˚ FOV to cover subs-solar point R = 1 R_E → >degrees	Dusk and dawn vantage points	TRL=4 Large GF and high-angular resolution

Site and Operational Requirements

- **Site where an Earth-facing ENA camera can be deployed**
  - Equatorial sites preferred. Higher latitude would view too close to the lunar horizon that might be obscured by dust
- **Regular communication of health and science data**
  - Daily to weekly to monitor health of instrument, command uplink and science data downlink
- **Lifetime should ultimately be several years**
  - Sufficient for pathfinders to operate several months for proof-of-concept and technology maturation
- **Likely not much human on-site support possible once deployed**
  - Instrumentation to sensitive to be manipulated on the surface
  - Satellite-borne instrumentation operates autonomously up to a year

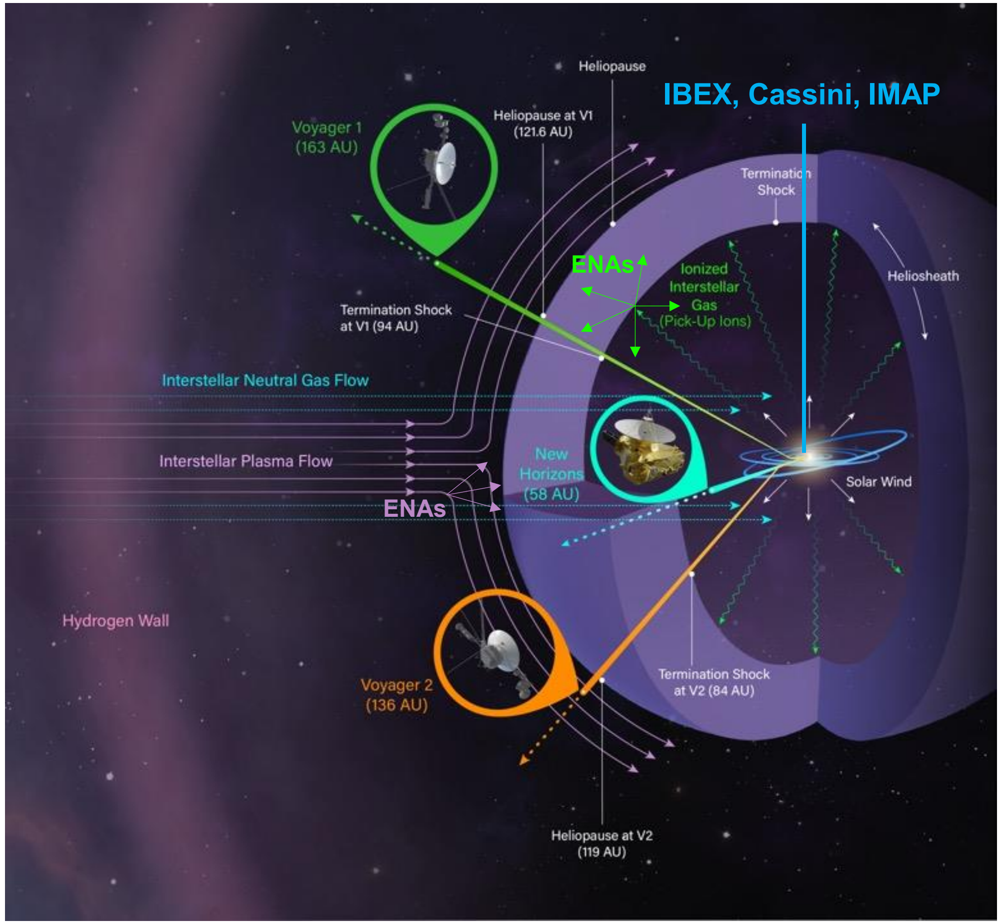
Technical Challenges and Considerations

- **High voltage**
  - Instrumentation relies on several kV HV for deflecting ambient charged particles
  - Presence of dust and photo electrons may lead to unwanted discharges
- **Sun cover**
  - Instrumentation cannot have the Sun within FOV
  - Moveable occulting aperture required
- **UV background rejection**
  - Lyman-alpha from Earth and geocorona dominates background
  - Rejection must be maintained with increased GF

Heliospheric ENA Imaging
(Far-Side of the Moon)

Overview of Heliospheric ENA Imaging

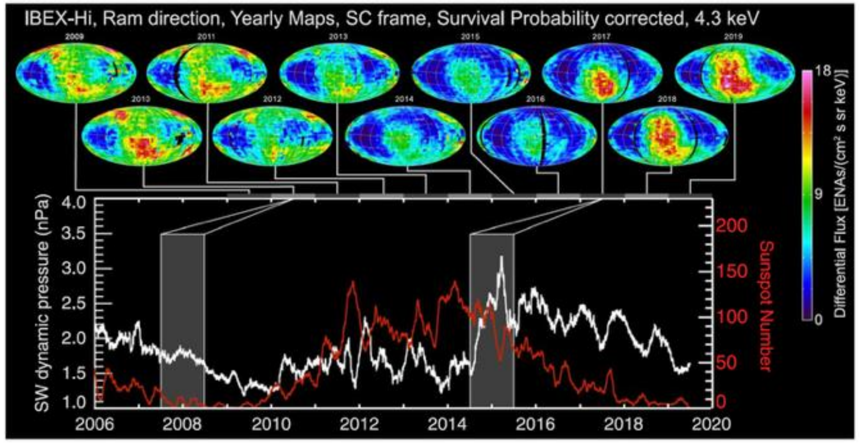
- **ENAs are emitted from**
  - energetic ions at the boundary of the heliosphere
  - interstellar neutral and plasma flow interacting with the heliosphere
- **Puzzling ~1 – 40 keV ENA images of the boundary (IBEX, Cassini, IMAP)**
  - Provides insight into the heliospheric interaction with the Very Local Interstellar Medium
  - Indicative of heliospheric morphology and connection to interstellar magnetic field
  - Dynamics on months to year timescales
  - See McComas et al. (2020) and Dialynas et al. (2017)
- **High angular detection of interstellar neutrals reveals interstellar cloud environment**
  - Swaczyna et al. (2022) concluded that the Sun is nearing the transition region between the Local Interstellar Cloud and the G-Cloud
- **ENA intensities are weak and require several days to week integration time**
  - Observations are accomplished by wide FOV or telescope on spinning platform



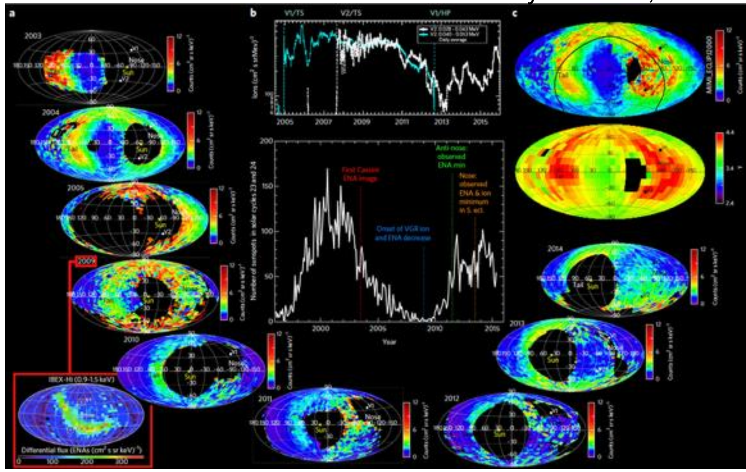
Overview of Heliospheric ENA Imaging

- ENAs are emitted from
  - energetic ions at the boundary of the heliosphere
  - interstellar neutral and plasma flow interacting with the heliosphere
- **Puzzling ~1 – 40 keV ENA images of the boundary (IBEX, Cassini, IMAP)**
  - Provides insight into the heliospheric interaction with the Very Local Interstellar Medium
  - Indicative of heliospheric morphology and connection to interstellar magnetic field
  - Dynamics on months to year timescales
  - See McComas et al. (2020) and Dialynas et al. (2017)
- High angular detection of interstellar neutrals reveals interstellar cloud environment
  - Swaczyna et al. (2022) concluded that the Sun is nearing the transition region between the Local Interstellar Cloud and the G-Cloud
- ENA intensities are weak and require several days to week integration time
  - Observations are accomplished by wide FOV or telescope on spinning platform

McComas et al., 2020



Dialynas et al., 2017



IBEX-Hi (top) and Cassini/INCA (bottom) ENA observations of the heliosphere showing emission structure across the sky originating from the heliosheath or beyond. Solar cycle variations are attributed to solar wind pressure variations impacting the energization in the heliospheric boundary.

Overview of Heliospheric ENA Imaging

- **ENAs are emitted from**
  - energetic ions at the boundary of the heliosphere
  - interstellar neutral and plasma flow interacting with the heliosphere
- **Puzzling ~1 – 40 keV ENA images of the boundary (IBEX, Cassini, IMAP)**
  - Provides insight into the heliospheric interaction with the Very Local Interstellar Medium
  - Indicative of heliospheric morphology and connection to interstellar magnetic field
  - Dynamics on months to year timescales
  - See McComas et al. (2020) and Dialynas et al. (2017)
- **High angular detection of interstellar neutrals reveals interstellar cloud environment**
  - Swaczyna et al. (2022) concluded that the Sun is nearing the transition region between the Local Interstellar Cloud and the G-Cloud
- **ENA intensities are weak and require several days to week integration time**
  - Observations are accomplished by wide FOV or telescope on spinning platform

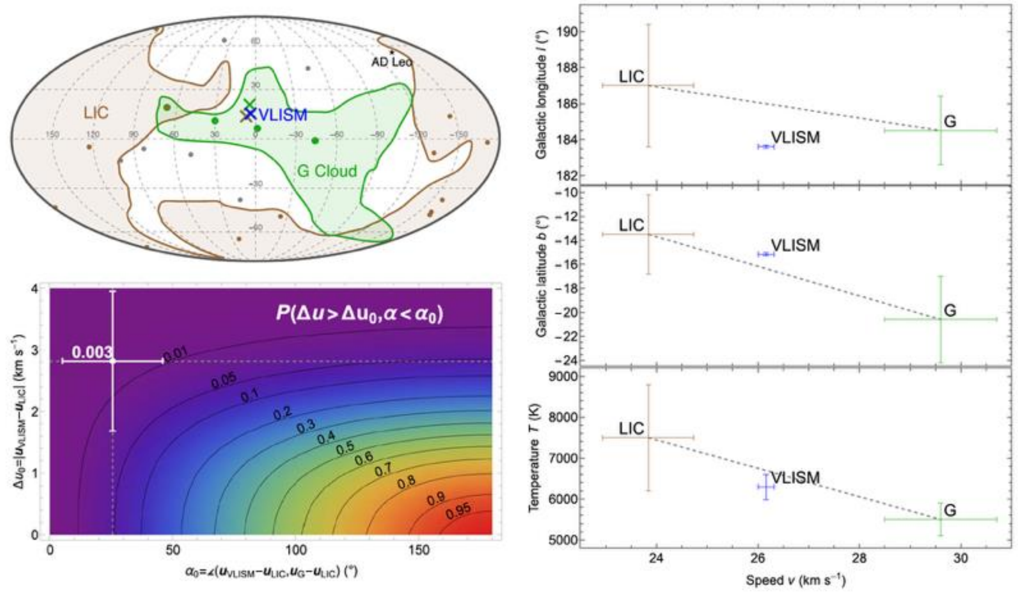


Figure 2. Top left panel: spatial extent of the LIC (brown) and G cloud (green) projected on the sky in Galactic coordinates from Redfield & Linsky (2008). The stars within 10 pc from the Sun with identified absorption from nearby interstellar clouds are shown as filled circles (brown—LIC; green—G cloud; gray—other clouds); the crosses indicate the inflow directions of the LIC, G cloud, and pristine VLISM. Bottom left panel: color-coded cumulative distribution function of random bulk flow fluctuations inside the LIC (see text). Speed fluctuation is shown on the ordinate and angle away from the G–LIC relative flow vector on the abscissa. The observed speed and angle of the VLISM are marked as a white point with error bars. Right panels: comparison of the flow properties of the LIC and G cloud with the pristine VLISM organized by their speed in the solar frame (top to bottom): Galactic longitude, Galactic latitude, and temperature.

Swaczyna et al., 2022

Site and Operational Requirements

- **Far side of the Moon to avoid ENA and EUV foregrounds from the terrestrial magnetosphere**
  - Line of sights cutting through L≤40 can contain ENAs from the terrestrial magnetosphere
  - Equatorial site has the benefit of panning the sky in one month, but requires larger GF
  - Near-polar sites, has the benefit of more continuous observations of one part of the sky and more counts, but is limited to the polar sky
- **Regular communication of health and science data**
  - Daily to weekly to monitor health of instrument, command uplink and science data downlink
- **Lifetime should ultimately be several years**
  - Sufficient for pathfinders to operate several months for proof-of-concept and technology maturation
- **Likely not much human on-site support possible once deployed**
  - Instrumentation to sensitive to be manipulated on the surface
  - Satellite-borne instrumentation operates autonomously up to a year

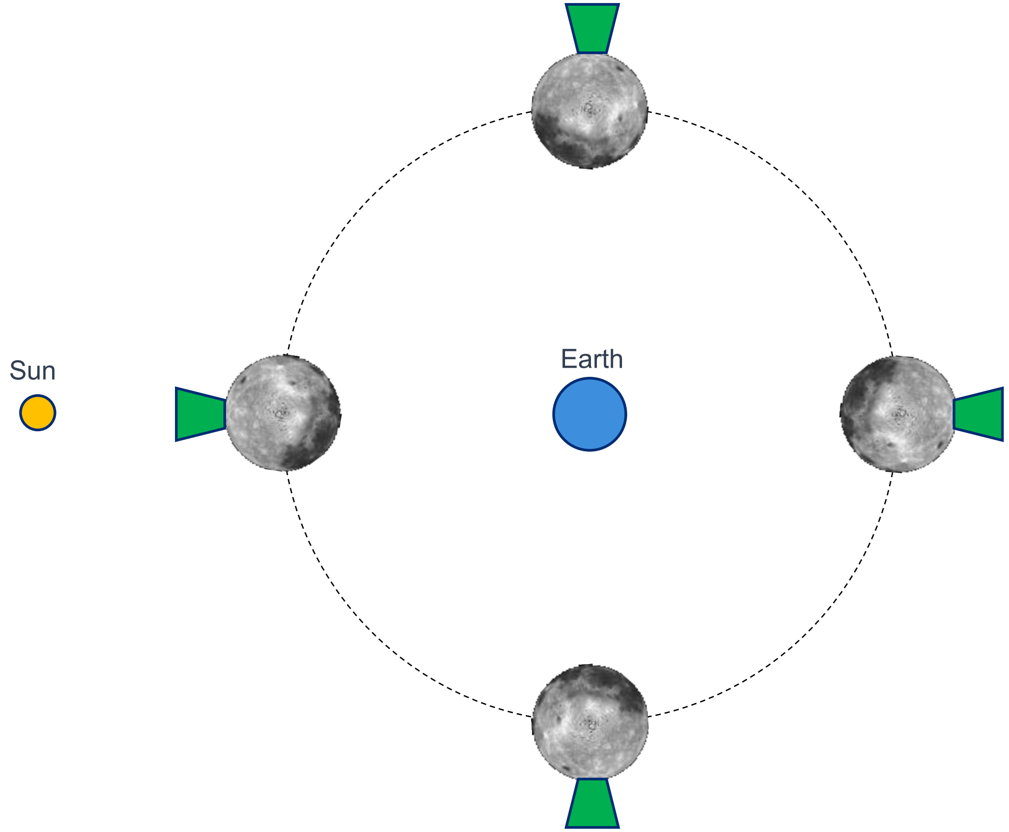


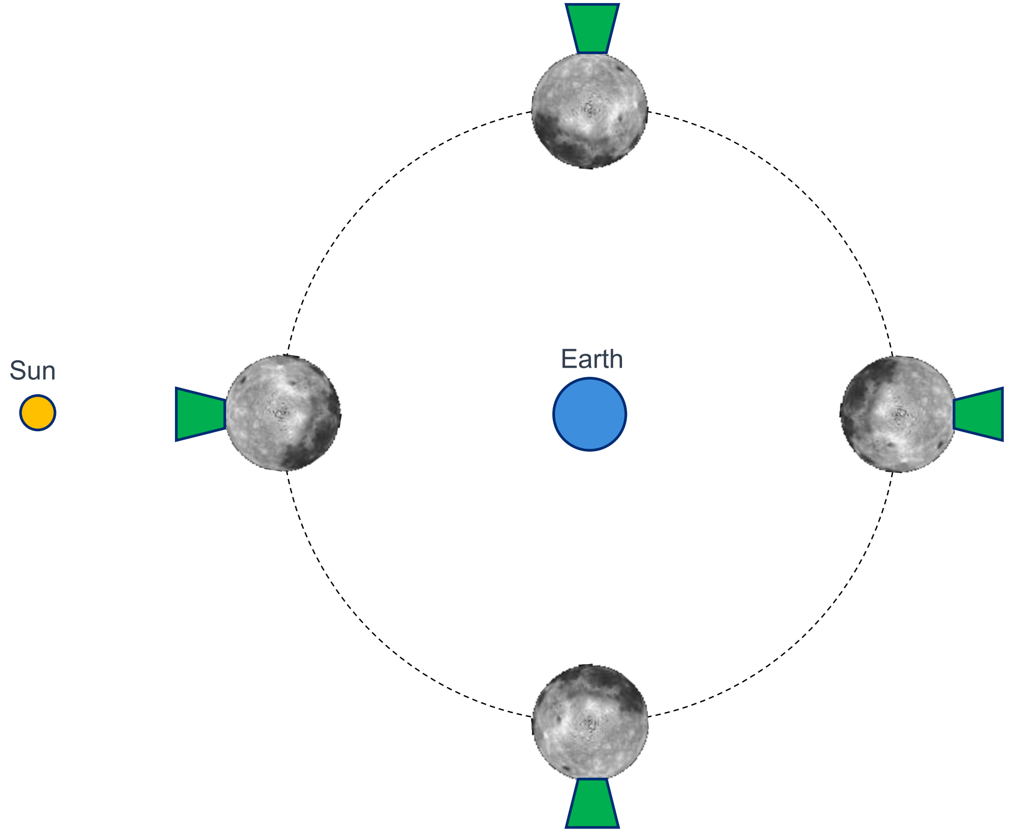
Image credit to USGS, Flagstaff, AZ

Science Return

- **<u>Equatorial Site:</u> Monthly latitudinal swath images and energy spectra of all heliospheric longitudes**
  - Because of the Moon's orbit, a fixed ENA camera would pan across all heliospheric longitudes in one sidereal period (27d), with the exception of a Sun exclusion zone when the camera is taring in the direction of the Sun
  - Latitudinal coverage and integration time of one region of sky depend on instantaneous FOV (or number of telescopes)
  - Therefore, temporal variations on a monthly timescale should be achievable
- **<u>Polar Site:</u> Continuous staring images at polar sky and energy spectra**
  - A polar-looking camera would stare at the same part of the sky and hence could obtain continuous time series of temporal variability, even for a relatively small FOV
  - It would not suffer from sun pointed periods, but could be subjected to more ENA and EUV terrestrial backgrounds
- **Composition and distribution of primary and secondary interstellar neutral streams**
  - One observation per month as the ENA detector passes through the interstellar neutral streams
  - Exception, again for a Sun exclusion zone when detector is looking towards the Sun

Technical Challenges and Considerations

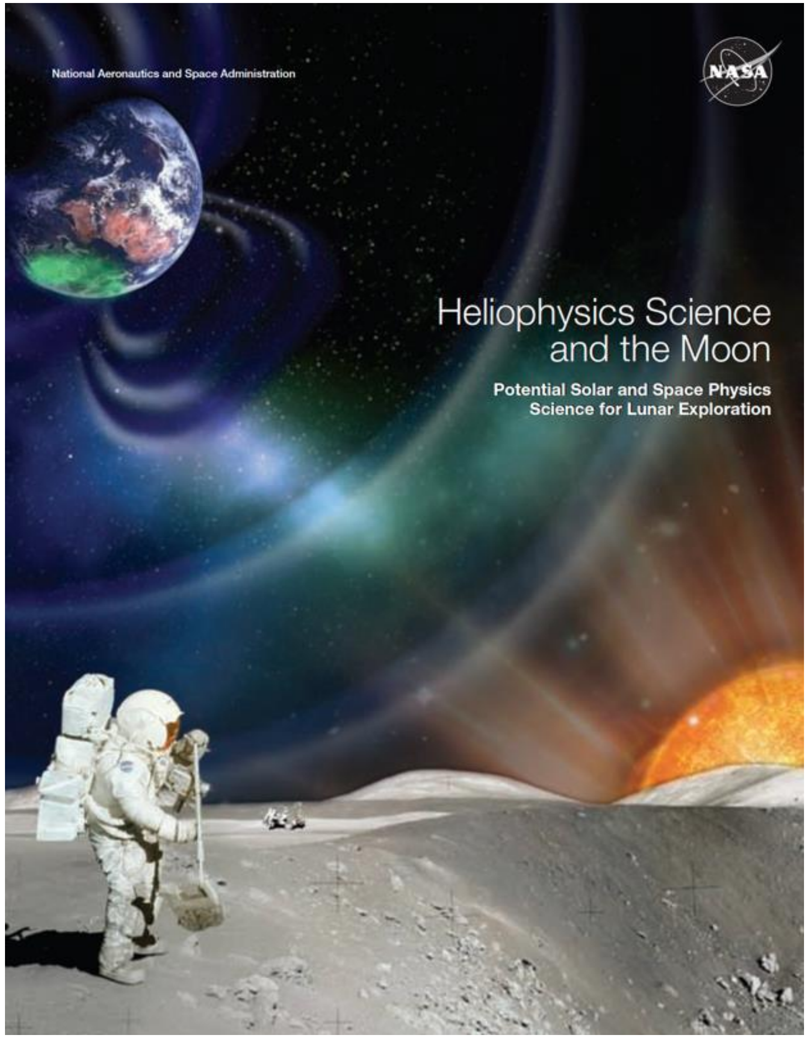
- **High voltage**
  - Instrumentation relies on several kV HV for deflecting ambient charged particles
  - Presence of dust and photo electrons may lead to unwanted discharges
- **Sun cover**
  - Instrumentation cannot have the Sun within FOV
  - Moveable occulting aperture required
- **Wide FOV**
  - In order to resolve ~monthly temporal variations, the camera must collect sufficient counts once per orbit from one pixel in the sky
  - Therefore, a wide FOV, or multiple heads are needed
  - Current solutions in the <10 keV range (IMAP-Lo and IMAP-Hi) rely on telescope design and spinning spacecraft
  - IMAP Ultra does have wide FOV and covers ~1 – 100 keV, but has degraded angular resolution below 10 keV



Concluding Remarks

Heliophysics Science and the Moon – almost two decades ago

- **Subpanel for Heliophysics Science and the Moon**
- **Report to the NASA Advisory Council Heliophysics Subcommittee, September 2007**
  - Heliophysics and space weather of the Moon
  - Moon as a historical record
  - The Moon as a Heliophysics Science Platform, including both magnetospheric and heliospheric imaging
- **But, not much has happened…Why?**
- **No thrust due to lack of technology development, pathfinder investigations of perhaps need**



Concluding Remarks on Path Forward

- **The Moon as a platform potentially offers higher landed mass resources than satellites do, allowing for new realms of large instrumentation (geometry factor)**
- **The large distance and location of the Moon imposes strict requirements on angular resolution and geometry factor to resolve the magnetosphere at Decadal-level recommendations**
  - ~1˚ resolution corresponds to about 1 R_E spatial resolution (0.5 R_E resolution desired). This is hard!
  - The Moon only offers side-views (meridional) of the terrestrial magnetosphere, whereas the Decadal Links concept requires also polar views to resolve injections.
  - Higher mass enables new instrument design that can tackle higher angular resolution and larger geometry factor
  - Even with less strict requirements, the Moon provides the big advantage of near-continuous imaging of ring current and plasma sheet activity, which is the one of key space weather responses of the magnetosphere
- **However, the lunar plasma and dust environment must be better understood before any space physics instrumentation can be deployed and reliably operated**
- **Many NASA lunar opportunities are mostly focused on supporting Moon to Mars program and not so much remote science observations of the magnetosphere or plasma environement**
  - It would be good have some emphasis also on science to be conducted from the Moon
- **High-energy (~1 – 200 keV) ENA imaging from the lunar surface requires ideally**
  - Large GF instrumentation
    - Development to increase GF and instrument size, while maintaining UV background rejection
  - High (<2˚) angular resolution using, for example physical collimation, but equatorial vantage point makes it difficult to meet Decadal recommendations on imaging injections
    - Coupled with large GF
- **Low-energy (10's eV – few keV) ENA imaging from the lunar surface requires ideally**
  - Higher GF and efficiencies
  - Higher angular resolution to resolve terrestrial ionospheric outflow
  - Wide-FOV, or multi-head solutions for the moon