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Planetary ENA imaging: where we are, where to go

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Abstract

Energetic Neutral Atom (ENA) imaging is a remote plasma and neutral gas diagnostic technique based on measurements of fast (>10 eV) atoms originating from interaction of plasma with background neutral gas or solids (surfaces, dust grains). We review applications of ENA imaging to study the magnetospheres of the Earth, Jupiter, and Saturn, and the solar wind interaction with non-magnetized Mars, and airless Moon. The new frontiers for ENA imaging in planetary research are in further advancing imaging of the high latitude / low altitude region of the terrestrial magnetosphere, imaging of backscattered and sputtered ENAs, application of ENA imaging to characterize neutral gas distributions, and ENA imaging of giant/ icy giant planetary systems. The prioritized design drivers for future ENA instruments would be higher angular resolution down to 1° and mass resolution (for plasma – surface interaction studies) at the already achieved sensitivity.

1. Bases of ENA imaging

Energetic Neutral Atoms (ENA) are fast atoms of energies much higher than the respective escape energy. Due to neutrality ENAs are not affected by electromagnetic forces. Due to high energy the gravitational banding of their trajectories is negligible. ENAs thus propagate as photons and can be used for remote diagnostic. ENAs are produced via charge – exchange reactions between ions constituting the plasma and background gas. Scattering and neutralization of ions impinging surfaces or exobases of atmospheres, and sputtering of solids also result in ENA production. Due to different measurement techniques ENAs in the energy range 10 eV – few keV are called LENA (low energy ENAs) and in the range 10 keV – 100s keV HENA (high energy ENAs).

The charge – exchange ENA fluxes are given by line-of-sight integrals over the ion differential fluxes and neutral gas density weighted with the respective cross sections. The backscattered ENA fluxes are given by the plasma fluxes at the surface multiplied by the respective yield and scattering function.

ENA imaging resembles photon imaging. However, there is a fundamental difference. The local ENA emission function is not isotropic because normally plasma distribution functions are anisotropic. An ENA image at a fixed vantage point is not an image of the ENA emitting plasma but an image of a plasma population with velocities towards the observer.

2. Scope of the review

We consider ENA imaging of the solar system bodies only. Imaging heliospheric ENA originating beyond the termination shock is out of scope of this review. Only experimental results are reviewed. As experience shows, in the ENA imaging field computer simulations may not always provide reliable predictions although they are the key in de-convolution and interpretation of ENA observations.

3. The Earth magnetosphere

The initial prove-of-concept of ENA imaging was performed by *Edmond Roelof* analysing ISEE 1 data (1987). The IMAGE mission (2000-2005), Imager for Magnetopause-to-Aurora Global Exploration, carrying three ENA instruments performed most comprehensive to-date ENA imaging of the Earth's magnetosphere. Other missions carrying dedicated ENA instrumentation include Astrid-1 (1995), TWINS (Two Wide-Angle Imaging Neutral-Atom Spectrometers, 2008-present), and IBEX (Interstellar Boundary Explorer, 2008-present). The focus was on ENA imaging of the ring current but there have been also obtained ENA images of the tail, magnetosheath, and the polar region both in the HENA and LENA energy ranges.

4. The Giant planets

Cassini (1997-present) carries a dedicated HENA instrument INCA for imaging the Saturn magnetosphere. During Jupiter fly-by Cassini also performed imaging of the Jupiter magnetosphere from 200 Jovian radiaa revealing a Europa torus as a powerful source of material inside the Jovian system.

At Saturn, combining ENA imaging of large – scale injections with high-resolution in-situ measurements has been a very successful technique to probe the global behavior and detailed physical heating and transport mechanisms during large scale injections. Monitoring magnetospheric activity via ENA imaging and simultaneously sampling the solar wind estabslished that Saturn's magnetospheric energization processes are strongly influenced by the solar wind.

5. Non-magnetized bodies. Mars

ENA imaging of Mars was performed by the ASPERA-3 instrument onboard Mars Express mission (2003 – present). The similar instrument was flown to Venus onboard Venus Express (2005-present). Charge – exchange ENA fluxes from the magnetosheath and ENA backscattered from the exobase were recorded. The magnetosheath ENA fluxes are highly anisotropic with an enhancement close to the plane perpendicular to the solar wind direction that forms a layer- or wall-like structure. Such morphology makes ENA imaging of the entire generation region from a single orbit difficult. Only statistically averaged picture from multiple vantage points can be obtained. The intensity and direction of the fluxes is highly variable, instanteneoulsy following changes in the upstream conditions, i.e., interplanetary shocks, and/or internal dynamics of the induced magnetosphere. Despite strong expectations no oxygen ENAs were recorded on Mars Express, likely due to unusually thin exosphere during the solar minimum in 2009 resulting in very low background gas densities.

6. Airless bodies. The Moon

Chandrayaan-1 (2008-2009) and IBEX discovered completely unexpected strong fluxes of backscattered hydrogen originating from neutralization of the impinging solar wind protons on the lunar surface. The typical hydrogen ENA fluxes are of 10-20% of the solar wind. The backscattered hydrogen was used to image a mini-magnetosphere related to the lunar anomaly. The spectrum of backscatters is Maxwellian with a temperature of 60 – 160 eV proportional to the impinging proton velocity. Measurements of the spectra turned out to be a usefull diagnostic tool to investigate the parent ion distribution right at the surface. The neutralization of precipitating protons on surfaces is the common process throughout the solar system. The imaging of airless bodies in backscatters can thus be widely applied.

7. Future ENA experiments

Mission	Target	Instr. ENA energy
BepiColombo/ MMO (2015)	Mercury	ENA 10 eV – 3 keV
BepiColombo/ MPO (2015)	Mercury	ELENA <20 eV–5 keV
Luna-Resource (2017)	Moon	LINA 10 eV – 3 keV
JUICE (2022)	Jupiter	PEP/JNA 10 eV – 3 keV PEP/JENI 0.5 – 300 keV

8. Frontiers for ENA imaging

We identified the following fields where we expect most promising applications of ENA imaging:

- ENA imaging of backscattered hydrogen and sputtered atoms at airless bodies;

- ENA imaging of high latitude / low altitude region of the terrestrial magnetosphere;

- ENA imaging of giant/icy giant planetary systems due to their vast size, inaccessibility of many regions for in-situ measurements, complex satellite – magnetosphere interactions

We also expect further developments in application of ENA diagnostic to investigate the background gas (plasma distribution is assumed to be known). Measurements of the integrated ENA flux variability combined with local upstream measurement of the solar wind will provide insights in the dynamics of induced magnetospheres at non-magnetized bodies. To achieve these frontiers the developments in the experimental techniques should be focused on higher angular resolution, down to 1°, and higher mass resolution to resolve elemental composition of regolith on airless bodies.