Global Imaging of the Earth’s Magnetosphere with Energetic Neutral Atom (ENA) Detectors: Transforming Discoveries Demand Breakthrough Technologies

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Introduction: Why do we need global imaging?

The Earth’s magnetosphere is a complex system that interacts with the solar wind, ionosphere and neutral gases of atmosphere and geocorona. The complexity of these multiple interactions has been realized decades ago, with multiple missions and satellites operated to understand the details of these interactions and predict the state of the magnetosphere. Despite tremendous progress, the community is not at the stage where a reliable prediction and description of all desired variables can be achieved. One of the major problems is that local measurements are very sparse. Even with the new datasets available, it is difficult and sometimes impossible to reconstruct a global picture based just on a few local satellite measurements. Local satellite measurements often allow multiple interpretations, and consequently different solutions for the global state of the magnetosphere.

Recent attempts to solve this problem by using the state-of-the-art first-principles global models are very promising, and the models make it possible to causally link multiple satellite measurements to a global picture. However, global models are prone to problems, including numerical effects and empirical assumptions to cover the missing physics. An example could be local grid resolution-dependent dissipative processes. In the absence of a clear physical understanding of the corresponding physical processes, this could lead to a grid-dependent solution. A classic example is grid-dependent numerical resistivity in ideal MHD models, and the corresponding numerical reconnection in the geomagnetic tail.

Global imaging is a very effective way to understand the dynamics of the whole system, and constrain the global models. These two problems are crucial for the development of space-weather prediction tools. An example of such a constraint is the observations of post-midnight enhancement (PME) in ENA fluxes. After IMAGE s/c discovered the PME, it took a few years to realize that the PME is a consequence of skewing of the electric field equipotentials and a direct consequence of ring current shielding effect. The discovery of PME made it possible to realize the importance of Vasyliunas loop and the self-consistent electric field for the ring current dynamics and modeling.

Energetic Neutral Atom imaging: Proposed studies for the future missions

Previous missions dedicated to measure ENAs, IMAGE and TWINS, considerably improved the knowledge on the structure and dynamics of the Earth’s ring current. ENA imaging revealed complex dynamics of 3D ion distributions during geomagnetic storms, and demonstrated techniques for obtaining the global information on ion composition, pitch-angle distribution, and precipitating
ions. Studies have shown that ENA techniques are useful in obtaining pressure and current distributions in the inner magnetosphere.

The application of ENA imaging is not limited to studies of the ring current dynamics. It has been shown that under favorable conditions, TWINS and IMAGE could see the effects of bursty bulk flows and particle injections into the inner magnetosphere. A case study with IBEX data showed that ENA measurements could provide information on tail reconfiguration [McComas et al., 2011]. Using laboratory plasma diagnostic methods, it is possible to use TWINS data for reconstruction of plasma temperature maps in the tail [eg. Keesee et al, 2014].

Based on the results of the previously published studies, it is expected that future ENA missions will reveal information about the global magnetospheric reconfiguration, the location of the reconnection regions in the tail and at magnetopause, the energy flow pathways from the dayside to the tail, and to the ring current region.

It is anticipated that future ENA missions will be able to differentiate between different modes of magnetospheric behavior, that is, between different modes of ion transport from the tail to the ring current region: isolated substorms, sawtooth substorms, stormtime substorms, steady magnetospheric convection (SMC), sequential bursty bulk flows (auroral streamers), and substorm injections. In particular, future ENA detectors can track the intensity of energetic neutral atoms in the tail and the ring current evolving in time to quantify how individual injection events and prolonged intervals of nightside reconnection contribute to ring current intensities. With favorable viewing geometry, they can determine the depth to which reconnection-associated bursty flows and ion injections propagate into the ring current region, their azimuthal extent, the degree to which ions are energized, their spectral slopes, and H, O composition on a case-by-case and statistical basis for each event category.

Future ENA missions can also significantly advance the state of knowledge on the role of oxygen ions in the Earth’s magnetosphere. They can quantify how oxygen accumulates in the tail and test how oxygen regulates the storage and flow of energy, from the solar wind through the magnetotail and to the ring current region. Observations of the lower H and O ENA energies could be used to deduce the presence of lower energy outflow, both on the dayside and on the nightside of the magnetosphere. **Tracking lower energy populations versus higher energy populations will help determine the overall role of magnetospheric oxygen in controlling energy flow in the coupled solar wind-magnetosphere system.**

**Requirements for the future ENA detectors**

If successful, future ENA missions will answer many questions about magnetospheric dynamics that the community has been debating over the past decades. However, one might wonder why these questions have not already been answered with a long history of ENA measurements. Indeed, in addition to two ENA dedicated missions IMAGE and TWINS, there were ENA detectors onboard GEOTAIL, Astrid and CRRES s/c. The simple answer is that the ENA fluxes are very low, so a long integration time is necessary to obtain a good signal without statistical noise [Gruntman, 1997]. To solve this problem requires a large geometrical factor for the instrument, and also poses strict requirements to spatial and temporal resolution. For example, it took a few hours of observations to obtain a composed image in IBEX ENAs of the possible tail disconnection event [McComas, 2011]. For the TWINS mission, the best temporal resolution of 1 min and the spatial resolution of 1 x 1 degree could only be obtained with the technique known as “statistical smoothing”. Future ENA missions should have sufficient spatial and temporal resolution to resolve a required physical process. Recent progress in the development of next-generation ENA detectors suggests that these requirements will be met within the next decade(s). Westlake et al., 2016
presented a design for ENA detector to measure ENAs in the range 0.5-20 keV with angular resolution 48x2 deg x 2 deg and total geometrical factor per detector ~ 0.1 cm² sec. For comparison, TWINS ENA detectors have comparable spatial resolution, and total geometrical factor ~ 0.6-0.9 x 10⁻² cm² sec (McComas et al., 2009). Since the TWINS detectors already make it possible to measure the heating of the plasma in the tail associated with the bursty flows, an increase of about an order of magnitude for the geometric factor and therefore the sensitivity will allow to see the detailed picture of the reconnection related phenomena in the tail.

An example of what a future ENA detector would see is shown in the Figure 1. The image is generated with the output of a global MHD model, for a spacecraft located at 30 R_E from the Earth in the GSM Y direction. The image shows the location of the reconnecting current sheet, the structure of reconnection exhausts, both earthward and tailward, the location of magnetopause and cusps. Although actual images may be different from synthetic images, the information encoded in ENA images will constrain global models in the same way as ring current ENA images allowed to constrain inner magnetosphere models.

The synthetic image shows ‘instantaneous’ 2D ENA snapshot. Current technologies allow only a 1D image to be obtained ‘instantly’ for an energy range below ~10 keV, therefore a satellite motion or actuation system is required to obtain a 2D image (Goldstein and McComas, 2018). The 1D nature of low energy ENA detectors limits temporal resolution for measuring important processes in the tail. A significant advance would be the ability to obtain nearly simultaneous 2D images stereoscopically, from at least two ENA detectors viewing magnetospheric ENAs from two vantage points. **Future developments in stereoscopic missions with large geometrical factor 2D ENA detectors for the energy range 1-100 keV will significantly advance magnetospheric imaging, making possible the discoveries that will transform the field.**


