Enhancing In-house Computational Capability to Predict Low- and High-Energy Neutral Particles (LHENPs) Observations in Support of Planetary Exploration

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Introduction

Recent mission concepts, white papers, workshop proceedings, and decadal surveys have argued the merits of further exploring the magnetospheric systems of the gas and ice giants (Jupiter, Saturn, Uranus, and Neptune). The high-priority science observations and instrumentation for future planetary missions are under consideration. Energetic Neutral Atom (ENA) imaging — the technique of imaging various global plasma objects in space in fluxes of ENAs — is being considered, accounting for the remarkable science results from ENA imaging-based studies at Earth, Mars and Saturn.

With respect to the upcoming JUICE mission at Jupiter, the science community is actively refining their investigation plan to optimize the mission science return, including observations from the JENI (Jovian Energetic Neutrals and Ions) camera. Advanced prediction tools are needed to assist in the planning and interpretation of observations for future and ongoing missions.

Objective

Project R6611 aimed to further expand the worldwide recognition of Southwest Research Institute in developing state-of-the-art prediction tools as a pathway to assist in the science planning of the JUICE mission and future exploration of the ice giant systems (e.g., Uranus and Neptune Odyssey Flagship missions).

The outcomes of Project R6611 provide new opportunities to broaden the use of a new Low to High Energy Neutral Atoms (LHENA) prediction tool to study other planetary systems (e.g., Mercury, Earth, Mars) and objects (e.g., the Moon) of our solar system.

	ORIGINAL CODE	ENHANCED TOOL
Energy Range	• 10 keV - 1 MeV	600 eV - 1 MeV
Magnetospheric Field Models	• **Jupiter:** JRM09+CON2020 (Connerney et al., 2020)	Unchanged
	• **Saturn:** KMFM (Khurana et al., 2006, 2009)	Unchanged
	• **Uranus:** Q3 (Connerney et al., 1987)	Unchanged
	• **Neptune:** O8 (Connerney et al., 1991)	Unchanged
Neutral Distribution Models	• **Jupiter:** O, O_2, SO_2, SO, H_2, H	Unchanged
	• **Saturn:** H_2O, OH, O, H	Unchanged
	• **Uranus:** Atomic hydrogen (H) Corona (after Herbert & Hall, 1996)	H, H_2, O, O_2, OH, H_2O (after Herbert & Hall, 1996; Eviatar & Richardson, 1986; Naylor et al., 2025)
	• **Neptune:** Triton's neutral Hydrogen torus (after Cheng, 1990)	Unchanged
Ion Distribution Models	• **Jupiter:** Galileo-based model of H^+ (Santos-Costa et al., 2024)	H^+, O^+, S^{++} distributions from Juno JADE & JEDI data (after Liu et al., 2024)
	• **Saturn:** Voyager-based model of H^+ (Santos-Costa et al., 2003)	H^+ & O^+ distribution from Cassini MIMI CHEMS & LEMMS data (from Dialynas et al., 2013)
	• **Uranus:** Physics-based model of H^+ (adapted from Santos-Costa et al., 2003, 2024)	Physics- & Voyager 2-based model of H^+ (adapted from Garrett et al., 2015; Santos-Costa et al., 2003)
	• **Neptune:** Physics-based model of H^+ (adapted from Santos-Costa et al., 2003, 2024)	Physics- & Voyager 2-based model of H^+ (adapted from Garrett et al., 2017; Santos-Costa et al., 2003)

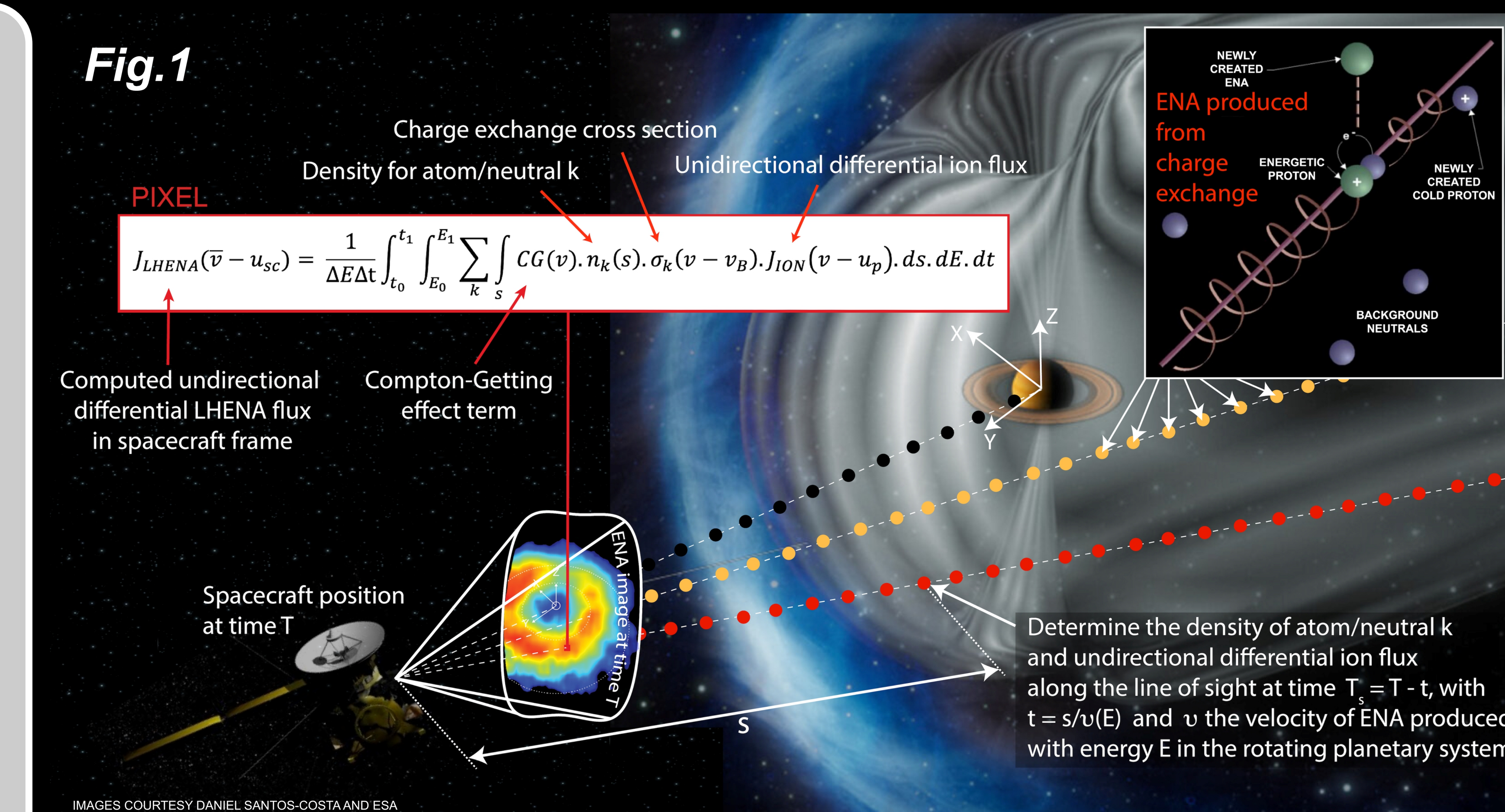

Figure 1: Composite image illustrates the ENA imaging technique to study planetary systems. This figure also shows our methodology for predicting distribution maps of energetic neutral atoms — which, in this case, are here originated from charge exchange between singly charged ions and neutral environments present within magnetospheric systems, from a spacecraft viewpoint.

Technical Approach

Project R6611 specifically focused on enhancing the computational capability of an existing in-house model of ENA production to predict and interpret the observation of LHENA, which are here resulting from charge-exchange interactions between charged and neutral particles populating the magnetospheric systems of the outer planets (encapsulated image of Figure 1).

In addition to carrying out code optimization, the key steps to enhance the capability of our in-house tool to predict and analyze the detection of LHENAs were to generalize the theoretical approach to low- and high-energy populations for a moving reference frame (Fig. 1), account for various fast neutral atoms (hydrogen, oxygen, and sulfur), broaden the energy ranges of neutral atoms to 600 eV – 1 MeV, improve the models of ion distributions from planetary missions, and implement post-processing of synthetic LHENA flux maps to permit meaningful comparisons between modeled images and imager observations.

Results

- **Code optimization:** The time computation of a synthetic LHENA map - with hundreds of thousands of pixels for a resolution of 0.25°x0.25° and a field of view of 120°x90° - takes now a few minutes instead of hours, making our LHENA prediction tool highly efficient to (1) predict global ENA observations of a magnetospheric system from a spacecraft viewpoint along a given trajectory, and (2) analyze observations from ENA imagers.

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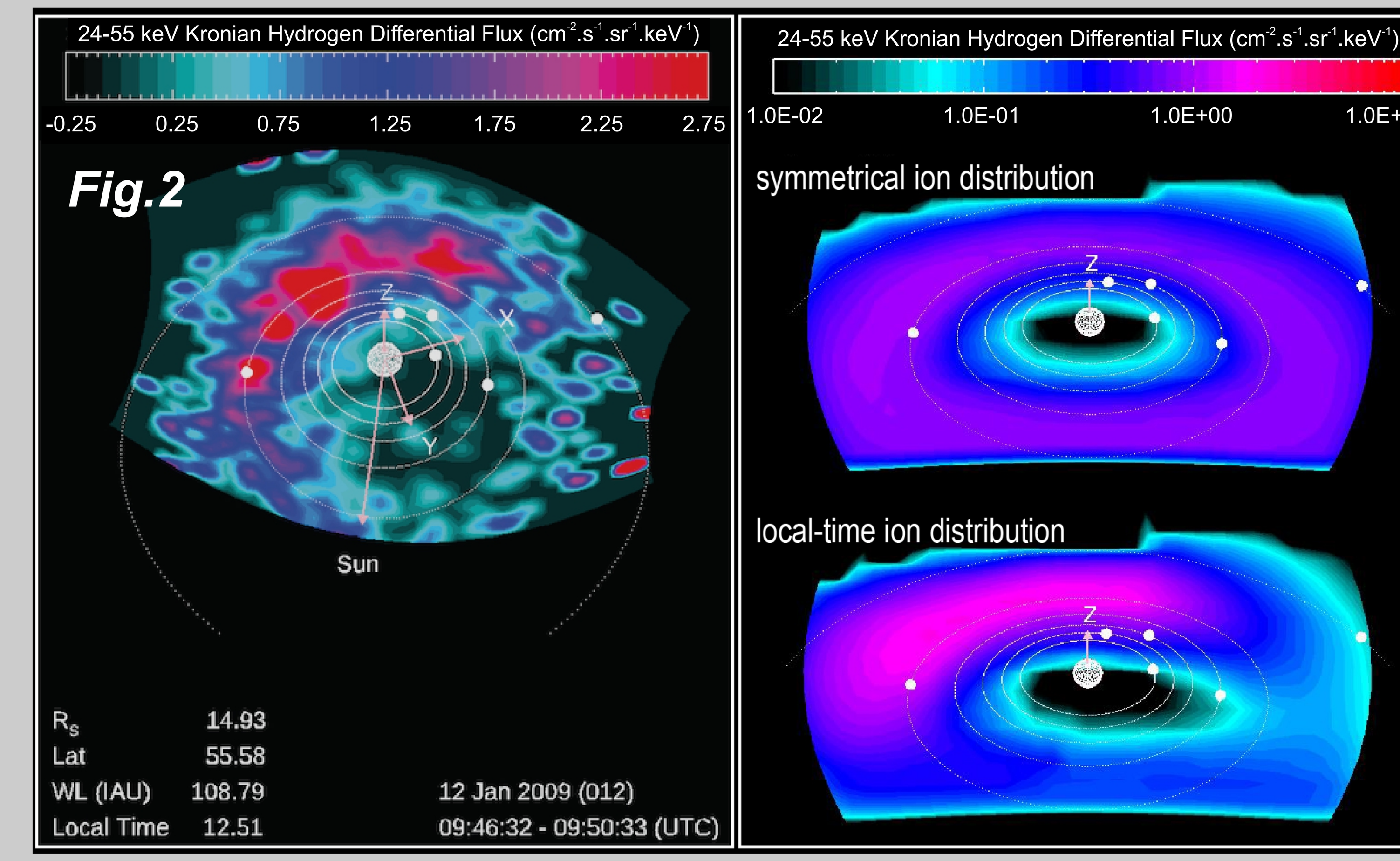
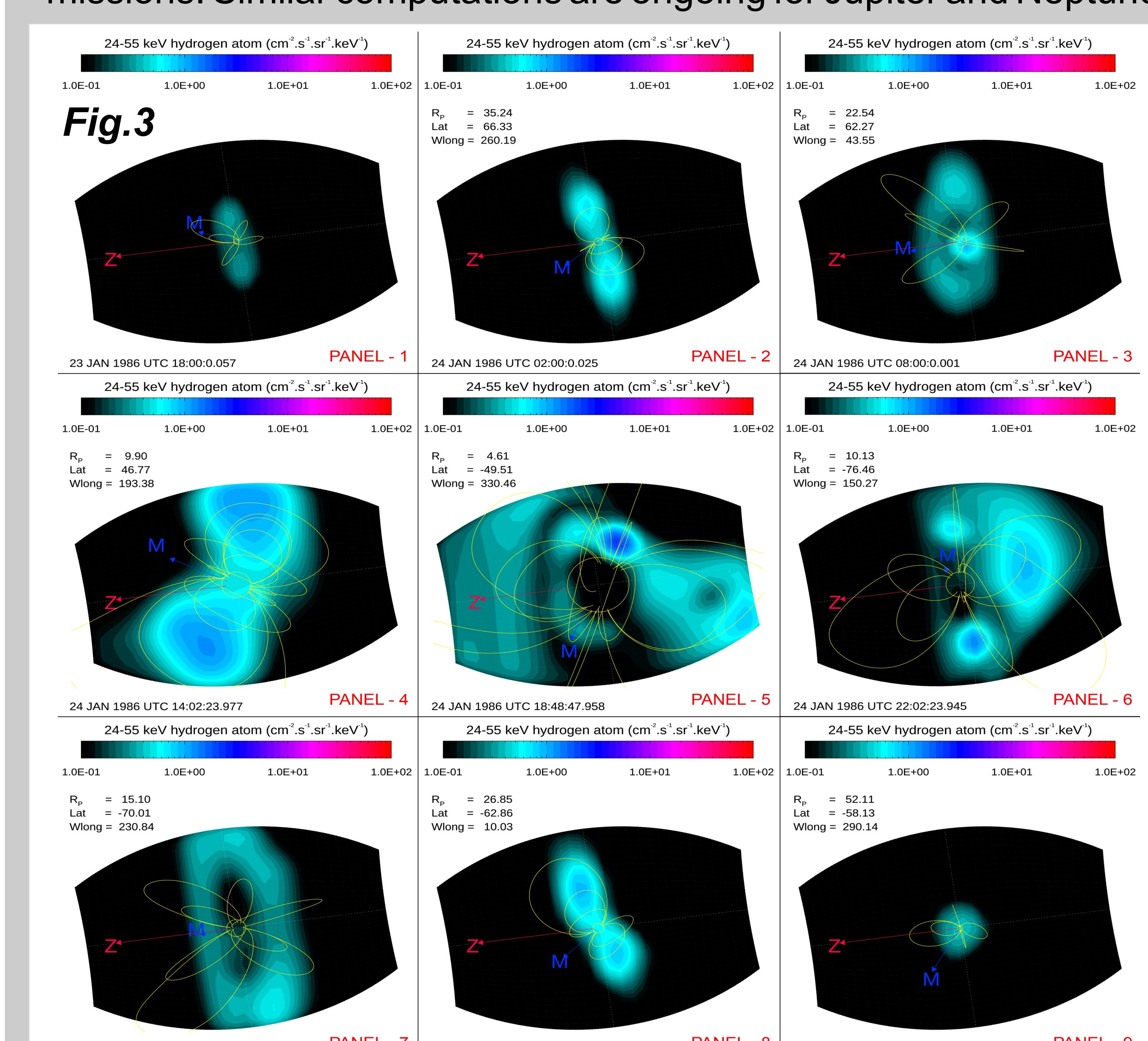
Results (continued)

- **Proof of concept validation:** Comparisons between our simulator outputs and past ENA observations were carried out to conduct a proof of concept (Fig.2). Results not only validated our improved computational prediction tool but also provided insights into the local time distributions of ENA fluxes observed at Saturn during the Cassini mission in 2004-2017.



- **Case study results:** A set of simulations permitted to gauge the detectability of LHENA fluxes at Uranus by simulating what an imager would have observed during Voyager 2 flyby in 1986 (Fig.3). Our predictions provide invaluable information regarding unexplored regions of Uranus and instrument design mitigation for future missions. Similar computations are ongoing for Jupiter and Neptune.



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