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Low-energy energetic neutral atom imaging of Io plasma and neutral tori

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ABSTRACT

Io's plasma and neutral tori play significant roles in the Jovian magnetosphere. We present feasibility studies of measuring low-energy energetic neutral atoms (LENAs) generated from the Io tori. We calculate the LENA flux between 10 eV and 3 keV. The energy range includes the corotational plasma flow energy. The expected differential flux at Ganymede distance is typically 10^3–10^5 cm^{-2} s^{-1} sr^{-1} eV^{-1} near the energy of the corotation. It is above the detection level of the planned LENA sensor that is to be flown to the Jupiter system with integration times of 0.01–1 s. The flux has strong asymmetry with respective to the Io phase. The observations will exhibit periodicities, which can be attributed to the Jovian magnetosphere rotation and the rotation of Io around Jupiter. The energy spectra will exhibit dispersion signatures, because of the non-negligible flight time of the LENAs from Io to the satellite. In 2030, the Jupiter exploration mission JUICE will conduct a LENA measurement with a LENA instrument, the Jovian Neutrals Analyzer (JNA). From the LENA observations collected by JNA, we will be able to derive characteristic quantities, such as the density, velocity, velocity distribution function, and composition of plasma-torus particles. We also discuss the possible physics to be explored by JNA in addition to the constraints for operating the sensor and analyzing the obtained dataset.

1. Introduction

1.1. Io neutral and plasma tori

Io, the innermost Galilean moon of Jupiter, introduces a large amount material of volcanic origin to the Jovian magnetosphere. As a result, the Jovian magnetosphere is composed of heavy ions (oxygen, sulfur, and their compounds). The strong and localized source of particles near Io creates characteristic spatial distributions of plasma and neutral particles in the Jovian magnetosphere, namely, the Io neutral and plasma tori (see, for example, reviews by Dessler, 1983; Thomas et al., 2004; Schneider and Bagenal, 2007; and references therein).

The Io neutral torus (called also as neutral cloud) is a dense concentration of atoms and molecules of volcanic origin that has formed around the Io orbit. These atoms are gravitationally bound to Jupiter. The composition is mainly sulfur (S) and oxygen (O) atoms as well as their compounds (e.g. Thomas et al., 2004). Hydrogen (H) atoms also exist, but the fraction thereof is small. Sodium (Na) atoms are also present. Na is bright because of its D-lines, but the fraction thereof is quite small; therefore the Na imaging is considered as a trace gas of more abundant compositions in the neutral torus (Mendillo et al., 2004). These atoms form a partial ring-like shape, which is associated with the short time scale of the loss of atoms via ionization (a few hours to tens of hours depending on the processes; see e.g. Schneider and Bagenal, 2007) compared to the filling time of the full torus (~150 h assuming 2.5 km s^{-1}, the escape velocity of Io).

When the neutral components in the Io neutral torus are ionized, the charged particles are accelerated by the motional electric field in the corotational flow in the magnetosphere. The accelerated ions form a plasma torus. The main components are (singly or multiply) charged O ions and S ions. H^+ ions are also present but the fraction thereof is less abundant. It is often assumed 10% (e.g. Thomas et al., 2004). However, there are several measurements showing much smaller fraction than 10% (e.g. Wang et al., 1998a,b; Zarka et al., 2001). The plasma in the torus is corotating with the Jovian magnetosphere. At the Io orbit, the corotational velocity of the plasma is ~74 km s^{-1}. The revolution speed of Io is ~17 km s^{-1} in the same direction as the corotational

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flow, so the relative plasma flow velocity is $\sim$57 km s^{-1} (e.g. Thomas et al., 2004). Even though the plasma source is more localized, because of the longer residence time (Schneider and Bagenal, 2007) compared with the rotation of the Jovian magnetosphere (9.925 h) the plasma torus is nearly axisymmetric in a plane, referred to as the centrifugal equator (Hill et al., 1974), defined by the rotation and magnetic dipole tilt. The tilt of the magnetic dipole is $\sim$9.6° (according to the so-called O4 model; Acuña and Ness, 1976), while that of the centrifugal equator is represented as 2/3 of the magnetic tilt (Hill et al., 1974).

After the Io neutral torus was discovered via the D-line emission of Na (Brown, 1974) and Io plasma torus via S^+ emission (Kupo et al., 1976), many observations on Io tori have been performed. Historically, investigations of the Io tori have been conducted via UV and IR spectroscopy (Herbert et al., 2001; Mendillo et al., 2004; Nozawa et al., 2004; Steffl et al., 2004a, 2004b, 2006, 2008; Yoneda et al., 2010, 2014) and in situ plasma observations (Bagenal, 1994, 1997; Bagenal et al., 1997; Frank and Paterson, 2001). Attempts for understanding the characteristics and the dynamics of Iogenic particles inside the Jovian magnetosphere are not only driven by the interests in magnetospheric science, but also the Io tori directly associate with the Io's volcanic activities (e.g. Herbert et al., 2001; Mendillo et al., 2004, 2007; Nozawa et al., 2004; Yoneda et al., 2010, 2014). The recent developed technique of energetic neutral atom (ENA) imaging has the potential to provide information concerning the Io plasma and neutral tori in an efficient manner.

1.2. Energetic neutral atom imaging in Jovian system

ENA imaging is a technique for the remote investigation of the interaction between space plasma and neutrals (e.g. Roelof and Williams, 1988; Gruntman, 1997; Wurz 2000). Several ENA instruments have been carried into space, and the data collected by these instruments have been used to study the interactions between space plasma and neutral gas (e.g. Burch, 2000, 2003; Krimigis et al., 2002; Mauk et al., 2003; Brandt et al., 2005; Futaana et al., 2011; Goldstein and McComas, 2013). More recently, ENA imaging has also been successfully applied to investigations of the interactions between space plasma and the Moon surface (e.g. Futaana et al., 2006; McComas et al., 2009; Wieser et al., 2009; Schaufelberger et al., 2011; Futaana et al., 2012).

ENAs near Jupiter were detected by the Voyager 1 Low-Energy Charged Particle (LECP) instrument. LECP is a sensor for high-energy plasma particles, (Krimigis et al., 1977) but Kirsch et al. (1981) concluded the energetic neutral atoms were a possible explanation of one of the observed signals. Cheng (1986) calculated the interaction between plasma and neutral atoms in the inner magnetosphere and concluded that the charge exchange makes a significant contribution to the fluxes of energetic neutral particles. Based on the dedicated ENA measurement performed by Cassini/INCA, Krimigis et al. (2002) reported the firm evidence of high-energy ENAs (HENAs; $>$10 keV) emitted from the Jupiter system. Later, Mauk et al. (2003) claimed that the observed ENAs in the range of 50–80 keV originated from a region slightly outside of the Europa orbit (trans-Europa gas tori).

These previous observations of ENAs in the Jupiter environment were only conducted in the high-energy regime ($>$10 keV). No low-energy ENA (LENA) instrument (with a typical energy range of 10 eV to a few keV) has been employed in the Jovian system, although there are some speculation for studying moon-plasma interactions (Plainaki et al., 2010; Milillo et al., 2013; Grasset et al., 2013). This unexplored energy range of LENAs is expected to provide us with valuable information regarding the characteristics of the Io tori, their formation and loss mechanisms, and associated transport mechanisms of Iogenic materials. Whereas a fraction of the energy is carried by high-energy particles in the Jovian system, the mass transfer, namely, the outward transport of Iogenic materials, is dominated by low-energy particles (Bagenal and Delamere, 2011). From this perspective, the low-energy particles are essential to the characterization of the Jovian plasma environment.

1.3. Low-energy energetic neutral atom imaging

Several LENA instruments have been used to investigate extraterrestrial environments. For example, the Neutral Particle Imager and Neutral Particle Detector were placed on board European Space Agency's (ESA's) Mars Express to establish a basic understanding of the ENA environment of Mars (Barabash et al., 2006). Replicas of these detectors were flown to Venus on the Venus Express mission (Barabash et al., 2007). IBEX-Lo has imaged the heliopause from the Earth orbit (McComas et al., 2009). The Chandrayaan-1 Energetic Neutrals Analyzer (CENA) was placed into Moon orbit (e.g., Kazama et al., 2006; Barabash et al., 2009), providing evidence of interaction between the solar wind and regolith surface. A replica of CENA, named Energetic Neutrals Analyzer (ENA), will be flown to Mercury with the ESA-JAXA joint mission, BepiColombo as a part of Mercury Plasma Particle Experiment (MPPE) on the Mercury Magnetospheric Orbiter (MMO) spacecraft (Saito et al., 2010). BepiColombo will also carry another LENA sensor, as part of the Search for Exospheric Refilling and Emitted Neutral Abundances (SERENA) package, on the Mercury Planetary Orbiter (MPO) spacecraft (Orsini et al., 2010). These aim to image Mercury-plasma interaction by LENAs (e.g. Grande, 1997; Barabash et al., 2001; Orsini et al., 2001; Massetti et al., 2003).

In 2022, ESA will launch its first Jupiter mission, JUpiter ICy moons Explorer (JUICE; Grasset et al., 2013). JUICE is equipped with a complete plasma package, Particle Environment Package (PEP), which includes a LENA sensor named Jovian Neutrals Analyzer (JNA). The measurement principle of JNA is identical to that of ENA and CENA (Kazama et al., 2006; Barabash et al., 2009).

In this paper, we estimate the LENA flux produced by charge-exchange reactions between particles in the Io neutral and plasma tori to demonstrate the feasibility of LENA observations from Ganymede orbit using existing LENA sensors. We assume simple models of the plasma and neutral tori. There are several reasons for using the simple models; first, such models require only a relatively short computational time for iterative calculation of the densities and velocity distribution functions of plasma and neutral tori; second, the line-of-sight integration for the LENA calculation will obscure details of small structures in any case; and third, simple models provide morphologic pictures that are useful for examining the application of this new technique of the LENA imaging to unexplored environment. The model is static, although the Io plasma and neutral tori are known to have temporal variations (e.g. Frank and Paterson, 2001; Herbert et al., 2001, 2003; Delamere et al., 2004; Nozawa et al., 2004; Yoneda et al., 2009; Steffl et al., 2004a, 2006). This is because this paper aims to understand the characteristics of LENA flux, particularly its intrinsic variations of the LENA flux due to the measurement technique and its limitations. In Section 4, environmental variations, which are important for understanding nature of the Io tori, will be discussed.

We calculate the LENA flux along the planned trajectory of the JUICE spacecraft (Grasset et al., 2013) and discuss the observation capabilities of JNA on board. In addition, we discuss the possible physics to be explored by JNA as well as the constraints for operating the sensor and analyzing the obtained dataset. We do not attempt to discuss the detailed physics of the Io tori in this paper.