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Energetic neutral particles detection in the environment of Jupiter's icy moons: Ganymede's and Europa's neutral imaging experiment (GENIE)

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ABSTRACT

The detection of Energetic Neutral Particles (ENP) above 10 eV can unequivocally relate a surface-bound exosphere to surface features and can monitor instantaneously the effect of plasma precipitation onto the surface. In the framework of a mission to Jupiter's moons, 2D imaging of plasma precipitation will provide important information on the plasma circulation at the orbits of the moons. Furthermore, a joint measurement of precipitating ions will permit an estimation of the efficiency of the release process. Coupled measurements of ENP and gas composition will improve our knowledge of surface release mechanisms. Ganymede's and Europa's Neutral Imaging Experiment (GENIE) is a high-angular-resolution detector, based on the ToF (Time of Flight) technique, that can detect ENP (energy range >10 eV–few keV) in the Jupiter environment thanks to an innovative design and technology. Its objective is to map the sites of origin of the ENP of the icy moons' exospheres to investigate the interaction between the surface and the environment. Finally, coupling GENIE with an ion sensor and a mass spectrometer will be an outstanding opportunity to better understand the magnetosphere–moon coupling within the Jupiter system and compare the surface interaction with plasma in the diverse moons. In this paper, the scientific objectives and requirements of ENP detection are summarized and the description of the innovative design concept of GENIE is given, together with the signal and background noise simulation.

1. Introduction. Icy moons environment

The study of the interactions between a solid body and its environment is fundamental for determining realistic scenarios for the evolutionary history of the body itself and the bodies strongly linked to it. The term "environment" refers to electromagnetic radiation (from thermal-IR to UV), plasma, neutral particles and dust in the vicinity of the body. In fact, understanding the details of the body–environment interaction mechanisms permits the evaluation of the exchange of energy and material, hence the extrapolation of the present conditions to the past can reveal important aspects of the body evolutionary history. In case of

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bodies that neither possess a dense atmosphere nor a strong intrinsic magnetic field, the surfaces are directly exposed to solar radiation and plasma (Milillo et al., 2011). The overall alteration of the surfaces due to these agents is referred to as space weathering (Hapke, 1986, 2001).

Among the diverse bodies of our Solar System, the icy moons of Jupiter experience a strong interaction with the Jovian magnetosphere; in fact, the Galileo mission data analysis showed that these moons are continuously irradiated by energetic ions (H^+, C^+, O^+ and S^+) and electrons in the energy range from keV to MeV (Cooper et al., 2001; Paranicas et al., 2002). The effects of this intense irradiation on ice could be of crucial importance to the ocean below the icy crust. However, the details of the surface processes and their impact on the immediate environment are still to be investigated.

Since the end products of each specific particle-release process are difficult to discriminate and to measure in the real in situ environment of Solar System bodies, laboratory data are of essential for these investigations. Laboratory ice experiments (Brown et al., 1982, 1984; Johnson et al., 1982 and references therein) demonstrated that ion impact upon ice produces particle release and surface chemical alteration. The mechanism producing this release is a complex combination of diverse processes involving ion sputtering and radiolytic dissociation, which will be described in Section 2. Nevertheless, the real conditions have never been observed and verified in situ. In fact, it is not straightforward to reproduce accurately in the lab the aggregation status of ice, considering the factors that determine the surface release efficiency (e.g., temperature, pressure, purity and history of the water molecules).

On the other hand, to understand the laboratory measurements on sputtering, modeling and simulations are equally important. The Europa Global model of Exospheric Outgoing Neutrals (EGEON) model (Plainaki et al., 2012), simulating the generation of the exosphere at Europa, shows that the origin of the dense-exosphere/thin-atmosphere (referred to as *exosphere* in this paper) is the magnetospheric ion impact on the moon's surface. The estimated exospheric densities agree with previous estimations and models (Johnson et al., 2004; Shematovich et al., 2005; Cassidy et al., 2007) and the simulated O_2 component of Europa's exosphere is in accordance with the oxygen density derived by the observed OI intensity by HST (Hall et al., 1998; Saur et al., 2011).

The expected exospheric generation mechanisms at the other Galilean moons are similar to the Europa case. The exospheric generation geometry at Callisto is expected to be similar to that of Europa, since the absence of an intrinsic magnetic field leaves the surface unshielded from the impacting ion fluxes. However, the intensity of these ion fluxes is lower, collisions could not be negligible, at least locally (Kliore et al., 2002) and the moon's surface is darker (e.g., Johnson et al., 1983), largely mantled by a veneer of non-water-ice material rich in CO_2, hydrates and organics (McCord et al., 1997, 1998; Hibbitts et al., 2002). The expected surface release due to ion impact should be less effective; instead, higher temperatures could produce a significant contribution from sublimation during the day and the exosphere is expected to be colder and thinner.

The interaction of Ganymede with Jupiter's magnetospheric plasma (Paranicas et al., 1999) is particularly interesting and complex since its intrinsic magnetic field – unique for a moon – reconnects to the external Jovian magnetic field, partially shielding the surface from ion impact, especially at the equatorial regions (Kivelson et al., 1997). In fact, it has been demonstrated that there is a very close correspondence between the observed higher-albedo polar cap boundary and the open/closed field lines boundary (Khurana et al., 2007). Furthermore, the OI auroral emission observed with HST (McGrath et al., 2003, 2013) was a signature of the complex interaction of the plasma with the exosphere of the moon. The configuration of the reconnection of the intrinsic and external magnetic field of Ganymede depends on the position of the moon with respect to the Jovian magnetic equator. In fact, the 10° tilt of Jupiter's magnetic field relative to the spin axis results in a configuration modulation at Jupiter's rotation period of 10.5 h (Jia et al., 2009). The plasma conditions vary slowly with respect to the plasma flow across Ganymede (some minutes); nevertheless, faster variatons (40 s) have been seen by the Galileo magnetometer (Kivelson et al., 1998) and explained by the intermittent magnetic reconnection at the magnetopause, which produces fast transfer events (Jia et al., 2010). The dynamics of the Jovian magnetospheric plasma determine the dynamics of plasma entry and circulation inside Ganymede's magnetosphere and eventually the precipitation towards the surface (Johnson, 1997).

The possibility of studying the dynamics, effectiveness and configuration of the interaction between Jupiter and its moons is the first priority for understanding how the Jupiter system works today and how it evolved. This could be done by characterizing the plasma and electromagnetic field environment, the surface, as well as the global exospheric composition and distribution. But only the mapping of the surface release regions can provide a link between the agents (plasma, electromagnetic radiation), the target (surface) and the products (exosphere).

A second type of interaction between magnetospheric plasma and moons is the charge exchange process acting at the Europa's and Io's tori and exospheres (Krimigis et al., 2002; Mauk et al., 2003; Mitchell et al., 2004). An energetic ion captures an electron from the gas, becoming an Energetic Neutral Atom (ENA) with the same energy and direction (e.g., Roelof and Williams, 1988; Orsini and Milillo, 1999). The efficiency of the charge-exchange process depends on the (energy-dependent) cross section. Finally, the ENA energy distribution peaks at the parent ion distribution weighted by the cross section. In the Jupiter environment, the energy distribution of ENA can extend at lower energies below the keV range (referred in this paper as Low-Energy Neutral Atom – LENA).

The detection of charge-exchange ENA, integrated along the line of sight, from many successful missions like IMAGE (Burch et al., 2001), Cassini (Krimigis et al., 2004), MEX (Barabash et al., 2006) and VEX (Barabash et al., 2007), demonstrated the potential of global remote sensing the plasma distribution and dynamics via ENA.

Milillo et al. (2011) pointed out the potential of mapping the surface release processes in the Solar System bodies exposed to the environment, through Energetic Neutral Particles (ENP) detection, a method for the in situ investigation of the environmental interaction between bodies without a thick atmosphere. In fact, recently, an ENP detector has been operated in the Moon environment on the Chandra Yaan-1 mission (Goswami and Annadurai, 2009), detecting the neutralized and back-scattered solar wind from the surface (Wieser et al., 2009). Furthermore, the SERENA-ELENA sensor (Orsini et al., 2009, 2010), devoted to detecting and mapping the Sputtered High Energy Atoms (SHEA) and neutralized and back-scattered ions in the Mercury environment, is included in the payload of the BepiColombo/MPO spacecraft to be launched in 2015 (Benkhoff et al., 2010). Moreover, an ENP detector is included in the model payload of the ESA JUICE mission to Jupiter's moons (Grasset et al., in press).

In summary, the detection of ENP at Jupiter's moons becomes the key to determine the surface–exosphere–magnetosphere system and to reveal information on the relevant energetic processes. The Scientific Goals of the measurements are the following:

1. To characterize, in space and in energy, the radiating component of the exospheres.
2. To study the interactions of the moons with the Jovian magnetosphere.
3. To discriminate and depict the exosphere generation mechanisms.
4. To study the global plasma distribution and circulation at the Europa and Io orbits.