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Radar signal propagation through the ionosphere of Europa

Cyril Grima[a,*], Donald D. Blankenship[a,1], Dustin M. Schroeder[b,2]

[a] Institute for Geophysics, University of Texas at Austin, TX 78758, USA
[b] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

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ABSTRACT

We review the current state of knowledge of the Europan plasma environment, its effects on radio wave propagation, and its impact on the performance and design of future radar sounders for the exploration of Europa's ice crust. The Europan ionosphere is produced in two independently-rotating hemispheres by photo-ionization of the neutral exosphere and interaction with the Io plasma torus, respectively. This combination is responsible for temporal and longitudinal ionospheric heterogeneities not well constrained by observations. When Europa's ionosphere is active, the maximum cut-off frequency is 1 MHz at the surface. The main impacts on radar signal propagation are dispersive phase shift and Faraday rotation, both a function of the total electron content (up to 4×10^{15} m^{-2}) and the Jovian magnetic field strength at Europa ($\sim$420 nT). The severity of these impacts decrease with increasing center frequency and increase with altitude, latitude, and bandwidth. The 9 MHz channels on the Radar for Icy Moons Exploration (RIME) and proposed Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON) will be sensitive to the Europan ionosphere. For these or similar radar sounders, the ionospheric signal distortion from dispersive phase shift can be corrected with existing techniques, which would also enable the estimation of the total electron content below the spacecraft. At 9 MHz, the Faraday fading is not expected to exceed 6 dB under the worst conditions. At lower frequencies, any active or passive radio probing of the ice shell exploration would be limited to frequencies above 1–8 MHz (depending on survey configuration) below which Faraday rotation angle would lead to signal fading and detection ambiguity. Radar instruments could be sensitive to neutrals and electrons added in the exosphere from any plume activity if present.

1. Introduction

Europa's global ocean is in contact with a potentially active silicate floor and lies below a geologically dynamic ice crust up to 30-km thick (e.g., Billings and Kattenhorn, 2005; Nimmo et al., 2005). The shape and composition of Europa's surface are the result of multiple processes, most of which involve direct and indirect interactions between the ocean and ice shell (e.g. Kattenhorn and Hurford, 2009; Collins and Nimmo, 2009). Surface chemistry is governed, in part, by material exchanged with the sub-surface ocean (Carlson et al., 2009), and formation models for observed chaotic terrains of disrupted ice also suggest shallow water lenses and brines could reside within the ice crust (Schmidt et al., 2011) providing a mechanism for material exchange between the surface and shallow subsurface of the ice shell. These signatures of vertical material and energy exchange within a massive liquid/solid hydrosphere make Europa a leading planetary candidate for habitability (Hand et al., 2009).

Investigation of Europa's icy crust from the ocean to its surface is a programmatic goal for the Europa Space Agency (ESA) and the National Aeronautics and Space Administration (NASA). The ability to directly probe the subsurface makes orbital radar sounders (1–100 MHz) key instruments for ice-ocean detection (Blankenship et al., 2009). The extensive heritage of the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) (Orosei et al., 2014) and the Shallow Radar (SHARAD) (Seu et al., 2007) at Mars as well as countless of ground and airborne radar experiments in terrestrial icy terrains (e.g. Peters et al., 2007; Fretwell et al., 2013; MacGregor et al., 2015) demonstrated the capabilities of radio waves to penetrate the ice down to several kilometers deep, sampling its macro-structure and composition. The Radar for Icy Moons Exploration (RIME) (Bruzzone et al., 2011) is a selected instrument for the European Space Agency's (ESA) JUpiter ICy moons Explorer (JUICE) (Grasset et al., 2013). JUICE is to be launched in 2022 to fly-by Europa, Callisto and orbit Ganymede from 2030. The Radar for Europa Assessment and Sounding: Ocean to

* Corresponding author. Tel.: +1 512 471 0377.
E-mail addresses: cyril.grima@gmail.com (C. Grima), blank@ig.utexas.edu (D.D. Blankenship), dustin.m.schroeder@jpl.nasa.gov (D.M. Schroeder).
[1] Tel.: +1 512 471 0489.
[2] Tel.: +1 818 354 1206.

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Near-surface (REASON) has also recently been selected by the National Aeronautics and Space Administration (NASA) for a dedicated mission to Europa (Blankenship et al., 2009).

Radar sounders are active instruments, so the transmitted electromagnetic signal travels twice into the space environment before reception. The space environment at Europa is dynamic with a complex plasma topology of multiple sources (Kivelson et al, 2004, 2009). Its orbit is located within the inner magnetosphere of Jupiter and resides at the outer edge of the Io plasma torus. A dynamic Europan ionosphere was detected by the Galileo spacecraft (Kliore et al., 2002). A radar sounder signal propagating through a charged and magnetized environment, such as a planetary ionosphere, can suffer distortion and attenuation that can alter the performance and detection capabilities of the instrument (Witasse et al., 2001; Safaeinili et al., 2003). This paper investigates the possible impacts of Europa's ionosphere on the performance of planned or potential radar observations. In Section 2 we provide a physical description of a planetary ionosphere and define its constitutive parameters. In Section 3, we review the known characteristics of the ionosphere of Europa and its space environment. Finally, we present the various ionospheric effects on radio wave propagation at Europa (Section 4) and discuss their impacts on potential future radar sounders (Section 5).

2. Fundamental background

A planetary ionosphere is an electrically neutral plasma populated by an equal number of positive and negative charges. Free-moving electrons and ions contribute nearly equally to the plasma charge population in an environment that is also occupied by various species of neutral particles. Interactions between electromagnetic waves and charged particles can be a significant and highly dispersive effect. This effect is a function of constitutive relationships describing the particles' displacement and their contribution to the notional electric polarization of a uniform plasma. In response to this perturbation, electrons and ions oscillate; creating charge gradients in space and this fundamental motion (i.e. the plasma oscillation) is characterized by the plasma frequency (f_p), and is solely dependent on the particle density number (N_i) (Budden, 1985):

$$f_p = \frac{q_i}{2\pi\sqrt{\epsilon_0 m_i}}\sqrt{N_i} \tag{1}$$

where $\varepsilon_0 = 8.85418781762 \times 10^{-12}$ F m^{-1} is the vacuum permittivity, while q_i and m_i are the particle charge and mass, respectively. Charged particles moving through an external magnetic field of strength B travel in a gyro-motion around the magnetic field lines characterized by the cyclotron or gyro- frequency (Budden, 1985):

$$f_g = \frac{Bq_i}{2\pi m_i} \tag{2}$$

Because ions are 10^3–10^4 times heavier than electrons, while in similar density and charge, they have an insignificant contribution to the plasma oscillations and gyro-frequency. For that reason, the electrons are commonly used as the only effective species determining the global properties for the plasma so that the plasma frequency and gyro-frequency can be calculated from $f_p = 8.98\sqrt{N_e}$ and $f_g = 2.8 \times 10^{10}$ B after reduction of (1) and (2) with the charge ($q_e = 1.602176565 \times 10^{-19}$ C) and mass ($m_e = 9.10938291 \times 10^{-31}$ kg) of an electron. When the plasma environment is also populated by neutrals the plasma oscillations are damped by $2/\nu$, where ν is the average collision frequency between neutrals and electrons that can be given by (Melnik and Parrot, 1999):

$$\nu = 2.12 \times 10^{-16} N_n \sqrt{T_e} \tag{3}$$

where N_n is the density number for the neutrals and T_e the average electron temperature in Kelvin (1 eV = 11,605 K). The various ionospheric effects on radio wave propagation are dominantly determined by the frequencies described above and therefore depend on the plasma physical constituents (e.g. electrons and neutrals) along the propagation path, electron temperature, and superimposed magnetic field strength. These parameters at Europa are discussed in the following section.

3. Europa plasma environment

The two main processes for ionosphere production are photoionization and particle-impact ionization of a neutral atmosphere. At Europa, both processes have a peak production in specific

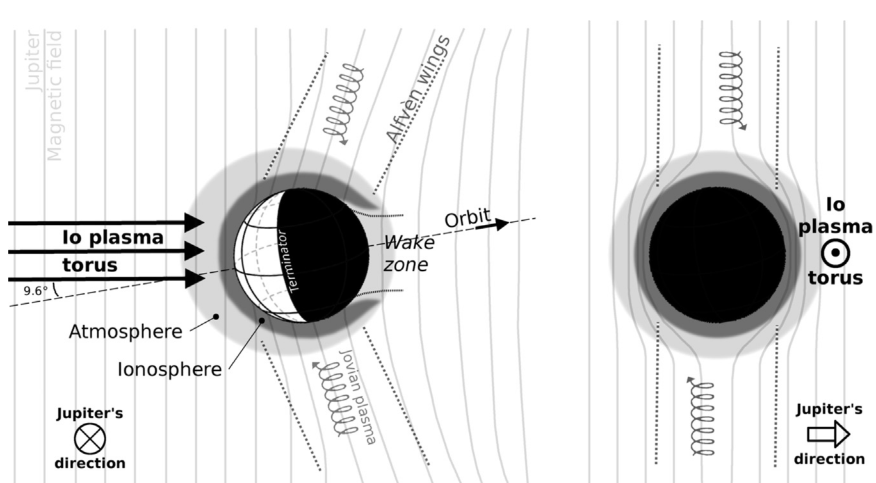

Fig. 1. Low-order schematic views of the geometry and main contributors to Europa space environment as described in Section 3. The reader is facing the antijovian side (Left) and the trailing side (right). The terminator circle (day/night boundary) is not static and rotates with Europa's revolution around Jupiter. The higher-order radial shrinkage of the Alfvèn Wings is not illustrated. The relative position between the day side and the trailing side (facing the Io plasma torus) drives the balance between impact- and photo- ionization. It might be responsible for most of the temporal variabilities in ionosphere production at Europa. Adapted and upgraded from Kivelson et al. (2009).