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Ion Bombardment of Europa

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1. Introduction

This abstract describes recent calculations of ion flux onto Europa's surface, the first such calculation since the Voyager era [1]. We describe the implications of that work and briefly describe ongoing and future work.

2. Ion Flux Calculations

The ion flux calculations are described in [2]. The technique used is similar to [3]. We used a numerical code that calculates ion trajectories. The code traces ion trajectories backwards in time, starting at Europa's surface. A given trajectory is specified by position on Europa's surface, incidence angle, and energy. If a given trajectory, traced backwards, makes it upstream of Europa without impacting the surface, then that ion and ions with similar initial conditions are considered to have access to Europa's surface.

The flux of those ions is calculated with the help of Liouville's theorem, which states that the phase space density along a dynamical trajectory is a constant. The flux at Europa's surface (per unit velocity interval) is given by

$$\rho(\vec{x},\vec{v})(\vec{v} \bullet \hat{n})$$

where $\rho(\vec{x},\vec{v})$ is the phase space density and $\hat{n}$ is the surface normal. $\rho(\vec{x},\vec{v})$ is unknown at Europa's surface, but it's known from spacecraft measurements in the vicinity of Europa, well away from Europa itself (e.g., [4]). The ion tracing program provides the link by calculating $(\vec{x}_u,\vec{v}_u)$ upstream of Europa. So our knowns are $(\vec{x},\vec{v})$ near Europa and $(\vec{x}_u,\vec{v}_u)$ and $\rho_u(\vec{x}_u,\vec{v}_u)$ upstream of Europa. The quantity we need for flux is unknown: $\rho(\vec{x},\vec{v})$. Liouville's theorem (e.g., [5]) tells us

$$\rho(\vec{x},\vec{v}) = \rho_u(\vec{x}_u,\vec{v}_u)$$

$\rho_u(\vec{x}_u,\vec{v}_u)$ is provided by [4] and other references.

In order to calculate ion trajectories we used guiding center drift theory, a simplified treatment that ignores the complex electric and magnetic fields near Europa. An alternative would be to use electric and magnetic field calculated by a plasma fluid simulation. Fluid simulations typically ignore high-energy ions, the very ones whose flux we are interested in calculating. We are pursuing this approach at Ganymede, whose internal dipole is impossible to ignore even at first order.

3. Results

Ion bombardment has a number of implications. One is for surface features, space weathering is visible in surface reflectance spectroscopy. Another is that ions 'sputter' or erode the surface and in the process produce O_2 and H_2, which form a tenuous atmosphere.

First we describe the ion bombardment pattern. Low energy ions, unsurprisingly, hit the 'trailing' hemisphere of Europa. Fig. 1, left, shows this bombardment pattern. For this example we used 100 eV S^{++} ions. Much higher energy ions hit the surface more uniformly. Surprisingly, they also tend to hit the poles preferentially (Fig. 1, right) [6].

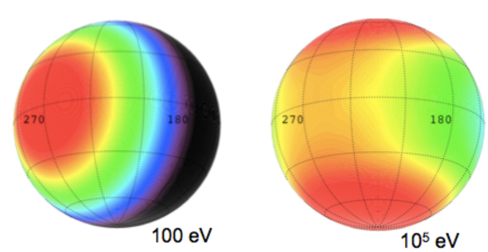

Figure 1: Bombardment patterns of S^{++} ions of indicated energies onto Europa. W. Longitude indicated on spheres, 270 is the apex of the trailing hemisphere.

This preferential polar bombardment is apparent in a map of the total sputtering rate (see the right-hand side of Fig. 2). Also apparent is a large contribution by low energy ions, as apparent in the "bullseye" centered on left-hand side of Fig. 2. The majority of sputtering is done by energetic ions (>20 keV), and mostly by sulfur ions.

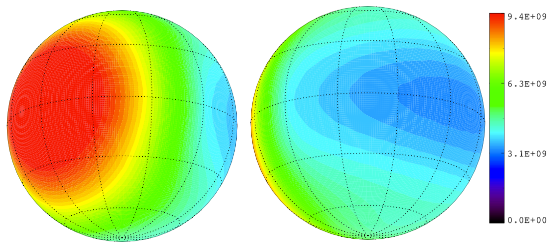

Figure 2: The calculated sputtering rate at Europa. The left-hand side shows the trailing hemisphere, the right-hand shows the leading hemisphere. There is a factor of ~3 difference in sputtering rates between the apexes of these two hemispheres.

The sputtered ejecta is mainly H_2O, but a fraction is O_2 and H_2. This O_2 fraction is primarily responsible for supplying Europa's atmosphere since, unlike H_2O, O_2 does not freeze to the surface. The H_2 quickly escapes Europa's gravity, forming a "neutral cloud" near Europa's orbit.

The O_2/H_2 portion of the yield is commonly assumed to be some constant fraction of the H_2O yield. But Teolis [3] showed that low energy ions are especially effective at producing O_2/H_2. So while most sputtering is done by high-energy ions, we found that most of the O_2/H_2 is produced by the low-energy ion population (~100 eV).

3. Discussion

Europa's atmosphere and extended cloud of neutrals is produced by magnetospheric ions bombarding its surface. Over the last three decades, models of this magnetosphere-moon interaction have taken one of two approaches. First, plasma-centric approaches that assume a static atmosphere; second, atmosphere-centric approaches that calculate ion fluxes while treating Europa as electromagnetically inert. We have used the second approach here.

Continuing this isolated approach will not suffice for Europa. The plasma bombardment produces the atmosphere, but the atmosphere also affects the plasma bombardment:

Magnetospheric ions produce Europa's atmosphere while magnetospheric electrons ionize it to produce an ionosphere. This ionosphere may divert plasma flow [7], limiting production of the atmosphere. Such flow diversion may be especially important for low-energy (thermal) ions, which we have shown are likely the primary producers of Europa's O_2 atmosphere.

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