CHARACTERIZING ELECTRON BOMBARDMENT OF EUROPA'S SURFACE BY LOCATION AND DEPTH. G. Wesley Patterson, Chris Paranicas and Louise M. Prockter, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723, Wes.Patterson@jhuapl.edu.

Introduction: Europa is continuously bombarded by ions and electrons trapped in the Jovian magnetosphere. At higher energies, these particles pass through the satellite's tenuous and patchy atmosphere and penetrate the surface, weathering it physically and chemically [1,2]. The penetration depths of these particles depend on their type and energy, with particle doses at depths up to a few microns dominated by ions and at depths greater than 10 microns by electrons [1]. The influence of the latter varies spatially, as a function of energy, with electrons in the 10s of keV to ~25 MeV range affecting primarily the trailing hemisphere of the satellite [3]. We characterize the bombardment of energetic electrons onto Europa's surface, thereby isolating and quantifying a major contributor to exogenic processes that influence the surface albedo, chemistry, and astrobiological potential of the satellite.

Analysis: Charged particles moving in a magnetic field can be characterized by three principal motions: gyration about a field line, latitudinal motion along a field line, and longitudinal motion. For energetic electrons encountering a moon the size of Europa, we can generally ignore gyromotion because the radius of gyration is small compared to the satellite radius. The latitudinal motion of a charged particle along a field line in a dipole can be characterized by a mirror latitude, λ_m, corresponding to a bounce time, t_b. The longitudinal motion of a charged particle is the sum of the effects of the corotation electric field and drifts principally due to the effects of field line curvature and gradients in the magnetic field strength. In the Jovian system, the net longitudinal motion for electrons with energies below about 25 MeV is in the prograde direction with respect to Eurapa. In other words, above this energy, electrons have net longitudinal motion that is opposite to the moon's motion.

The longitudinal distance that an electron of a given energy and λ_m can travel in the equatorial plane of Europa can be represented, in fractions of a satellite radius, by the following particle-dependent equation,

$$d = \omega L\left(\frac{t_b}{2}\right)\left(\frac{R_J}{r_E}\right) \quad (1),$$

where ω is the net azimuthal rate at which the guiding center of the particle travels around Jupiter expressed in rad/s, L is the L-shell of Europa in the Jovian magnetosphere, t_b is the particle bounce time in seconds, R_J is the radius of Jupiter in kilometers, and r_E is the radius of Europa in kilometers.

To understand what this distance means in terms of the access electrons of a given E and λ_m have to Europa's surface, we can determine a projected distance in the equatorial plane of Europa, d_p, for any location $P(\theta, \phi)$ on the surface using,

$$d_p = \left[1 + \sin^2\theta\left(\cos^2\phi - \sin^2\phi\right) - 2\sin\theta\cos\phi\left(1 - \sin^2\theta\sin^2\phi\right)\right] \quad (2)$$

where θ is the polar angle or colatitude of the body and ϕ is the azimuthal angle measured clockwise from the direction into the flowing plasma. This quantity is expressed in fractions of a body radius and can be represented in the geographic coordinate frame of the body by a contour map.

Charged particles interacting with the surface of a body lose energy at a rate that depends on the ionization potential of the medium and varies as the number of electrons per cubic cm in the material [5]. Therefore, dense, high atomic number materials tend to be better at slowing electrons down. For Europa, we determine the approximate range electrons of energy, E, travel into the surface using values determined for water [6].

Results: To characterize the bombardment pattern of energetic electrons onto Europa's surface we utilize an energy spectrum fit from [7]. We assume a sinusoidal equatorial pitch angle distribution for trapped electrons. The pitch angle of a particle is the angle between the direction of its velocity vector and the local magnetic field vector and determines the particle's mirror latitude, λ_m. Previous work has assumed that bombarding electrons have a pitch angle distribution that is isotropic [7-9]. However, a sinusoidal distribution represents a more reasonable approximation to trapped distributions [10].

Using Eqn. 1, we have determined values of d for a representative sample of electrons having energies E in the range from 10 keV to 25 MeV and mirror latitudes λ_m in the range from 10° to 70.9°. Our results show that, independent of λ_m, the longitudinal distance d that an electron can travel in the equatorial plane of Europa decreases as E increases. This relationship is a result of the shorter bounce times and slower net longitudinal motions (in the prograde direction) of more energetic electrons.

Using contours determined from Eqn. 2, we can examine the bombardment pattern of electrons onto the surface of Europa in geographic coordinates (Fig. 1a). The resulting map clearly shows that the energies of electrons affecting the surface decrease toward the poles and that electrons having energies > 10s of keV do not strongly affect the leading hemisphere of the satellite. This is consistent with previous work describing Europa's radiation environment in broader terms [1,7,8].

The ranges into the surface of Europa for the same representative sample of electron energies are also shown in Figure 1a and they are consistent with previous work examining the relationship between particle energy and penetration depth [8,9]. Spatial variations in the penetration depths of energetic particles bombarding Europa have been previously described in terms of how it affected surface radiation doses on the leading/trailing hemispheres and poles/equator [1]. Using our map of the bombardment pattern of electrons onto the surface of Europa, we can examine how penetration depths vary as a function of latitude/longitude (Fig. 1a).

The bombardment pattern of electrons for Europa can also be described in terms of the power per unit area delivered to the surface by energetic electrons [7,9]. This information can be useful when evaluating the radiation dose accumulated at the surface of the satellite [8] and has implications for astrobiology [11,12]. A map of the power per unit area as a function of latitude and longitude is shown in Figure 1b and was produced following the methodology of [9]. From this map, we can see that the flux of electrons into the surface is highest near the equatorial trailing hemisphere of Europa and decreases by more than an order of magnitude from the trailing to leading hemisphere and poleward of ~40 to 70° latitude in the trailing hemisphere (as a function of longitudinal distance from the trailing point). This translates to a globally averaged value for Europa of 9.5 x 10^6 $MeVcm^{-2}s^{-1}$. As in previous work [8,9], our results suggests a lens-type bombardment pattern along the trailing hemisphere of Europa but we find differences in the power per unit area exist as a result of the more realistic pitch angle distribution we use.

Conclusions: We have characterized the bombardment of energetic electrons onto Europa's surface by location and depth (Fig. 1a) and have provided a new estimate of the flux of energetic electrons onto Europa's surface (Fig. 1b). The pattern of bombardment clearly shows that the most deeply processed material can be found at low latitudes on the trailing hemisphere and that material unaffected by electron bombardment can be accessed at depths in the μm range for the leading hemisphere and higher latitude regions of the trailing hemisphere. We also find that the inclusion of a trapping pitch angle distribution for energetic electrons bombarding Europa results in a significantly lower integrated flux into the surface. The implication is that there will be less oxidized material available at the surface then had been previously indicated.

Our model of the bombardment of Europa's surface will be effected by incorporating the finite electron gyroradius and perturbations of the electromagnetic field near the body. However, we do not anticipate these factors will change our results in a significant manner.

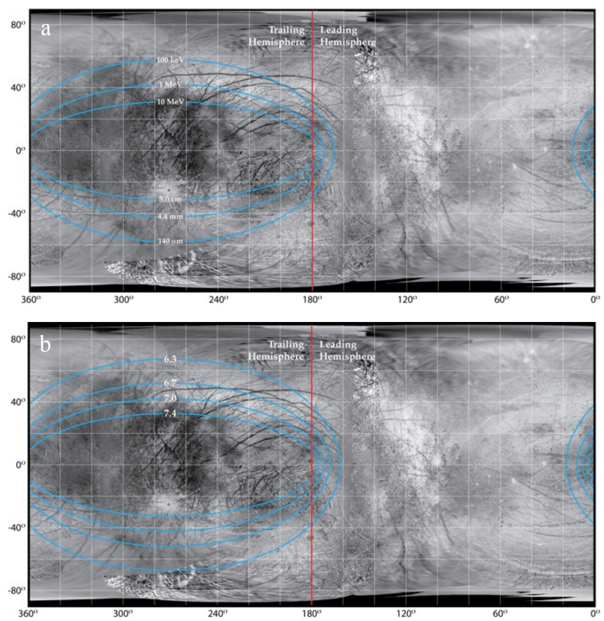

Fig. 1. Contour plots of electron bombardment of Europa for a λ_m of 45° overlain on a simple cylindrical mosaic of the surface indicating (a) energies and penetration depths for 100 keV, 1 MeV and 10 MeV electrons and (b) the integrate flux of electrons into the surface in the energy range from 10 keV to 25 MeV expressed in units of $\log_{10}$ MeV cm^{-2} s^{-1}. A λ_m of 45° was used because it encompasses 96% of the particles in a trapping pitch angle distribution at a given energy.

References: [1] Johnson et al., 2004. In *Jupiter*, Cambridge Univ. Press, 485-512. [2] Johnson et al., 2009. In *Europa*, Univ. of Arizona Press, 507-527. [3] Paranicas et al., 2002. *GRL*, 29, 2001GL014127. [4] Thomsen and van Allen, 1980. *JGR*, 85, 5831-5834. [5] Zombeck, 1982. Handbook of Space Astronomy and Astrophysics. Cambridge Univ. Press [6] Seltzer and Berger, 1982. *Int. J. Appl. Radiat. Isot*. 33, 1189-1218. [7] Paranicas et al., 2001. *GRL*, 28, 673-676. [8] Cooper et al., 2001. *Icarus*, 149, 133-159. [9] Paranicas et al., 2009. In *Europa*, Univ. of Arizona Press, 529-544. [10] Walt, 1994. Introduction to Geomegnetically Trapped Radiation, Cambridge Univ. Press. [11] Chyba and Phillips, 2001. *Proc. National Acad. Sciences*, 98, 801-803. [12] Hand et al., 2009. In *Europa*, Univ. of Arizona Press, 589-629.