THE EUROPA CHARGING ENVIRONMENT

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ABSTRACT

The baseline design of the planned Europa Mission includes large solar arrays, which may experience surface charging. The spacecraft would encounter Europa ~40 times with some passes within ~25 km. This paper will describe the plasma environment expected near Europa during these encounters. Emphasis will be on the torus near Europa and on Europa's ionosphere. Whereas the spacecraft would encounter a cold, co-rotating torus plasma with a velocity of ~120 km/s near Europa, it may encounter Europa's ionosphere at a velocity as low as 5 km/s as Europa's orbital velocity is only ~14 km/s relative to Jupiter. The challenge is to estimate the rapid potential variations associated with these two disparate environments. The paper will present a review of models of the plasma torus and the ionosphere and their interactions with each other. Given the possibility of detecting plumes coming off Europa, the effects of these plasma environments take on additional significance as they may be critical in unraveling signs of life associated with Europa's ocean.

1. INTRODUCTION

A new mission to Jupiter and its moon Europa is being considered by NASA. The mission design currently calls for the spacecraft to make ~60 passes into 9-10 Rj. Of these ~40 would be flybys of Europa with some coming within ~25 km of Europa's surface. The proposed Europa mission design calls for large solar arrays which could be affected by spacecraft surface charging. In particular, the spacecraft would be exposed to the jovian plasma torus environment in which Europa is embedded and to Europa's ionosphere. These environments are characterized by dense electron, proton, and heavy ion (primarily O, S, and Na) plasmas in the energy range from a few eV to ~100 keV. Whereas the spacecraft would encounter a co-rotating cold dense torus plasma with a relative velocity of ~120 km/s with respects to Jupiter at the distance of Europa, it may encounter Europa's ionosphere at a velocity as low as 5 km/s (e.g., the difference between the spacecraft velocity and Europa's orbital velocity which is only 14 km/s). The challenge is to estimate the rapid potential variations associated with these two very disparate environments and develop mitigation methods so that Europa's large solar arrays and its plasma detectors would not be adversely affected.

This paper will review models of the plasma torus and the ionosphere and their interactions with each other. The first section will describe the jovian plasma torus temperatures and densities. Estimates of the cold plasma (E<5 keV) in terms of the electron and ion populations and the warm electron and proton environments (5 keV—100 keV) will be presented. The electron and proton Kappa distributions over the same range will be discussed. The latter distribution is included as it better represents the plasma environment over the energy range of interest to surface charging.

The second part of the paper will provide estimates of the neutral atmosphere and the ionosphere near Europa. While there are extensive in-situ measurements of the torus environment, little is currently known about either the Europa atmosphere or ionosphere. A few radio propagation/occultation measurements by Galileo, however, do provide estimates of its properties. In addition, some spectroscopic measurements of its atmosphere and of its thermal properties from Earth provide limits on models of the atmosphere. These will be reviewed and examples of a possible neutral atmosphere and ionosphere profiles described.

2. THE JOVIAN PLASMA TORUS

The plasma torus model to be presented here is based on the Divine and Garrett[1] family of jovian models developed in the 1980s. Garrett and colleagues have applied these models to the charging analyses of the Galileo, Juno, and Europa missions[2,3]. Since the original Pioneer and Voyager flybys on which the models were based, our understanding of those environments has been constantly improving. New measurements of that plasma environment from Galileo, Ulysses, Cassini, and Earth-based telescopes have become available (see McNutt, Sittler, Bagenal, and colleagues[4-10] and telescopic observations of the jovian aurora[11]). Recent work by the authors[12] incorporates these studies and new data into a revised, comprehensive environment model of the jovian plasma environment.

Any comprehensive plasma model of the jovian plasma must include the cold and warm electron and ion environments throughout the jovian magnetosphere. To model these environments, one needs to define the particle densities, temperatures, and, for the cold ion components, their composition, ionization state, and drift velocities. The particle distributions based on these parameters are usually defined in terms of either a Maxwell-Boltzmann distribution:

$$f_i(v) = \frac{N_i}{\pi^{3/2} v_0^3} \exp(-v^2 / v_0^2) \qquad (1)$$

where:

$v_0 = (2kT/m)^{1/2}$

v = particle velocity relative to observation point (km/s); convection velocity V_{cnvc} incorporated here

N_i = number density (cm^{-3}) for e^-,H^+,O^+,O^{++},S^+,S^{++}, S^{+++},Na^+(i=0,1,2,..,7) or e^-(warm) and H^+(warm)

m = mass of species (g)

k = Boltzmann constant

T = temperature (°K) of species

or a Kappa distribution:

$$f_\kappa(E) = N_\kappa (m_\kappa / 2\pi E_0)^{3/2} \kappa^{-3/2} \frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)} \frac{1}{(1+E/\kappa E_0)^{\kappa+1}} \qquad (2)$$

where:

N_κ = Kappa number density (cm^{-3}) of species (e^- or H^+)

m_κ = Kappa mass (g) of species (e^- and H^+)

κ = Kappa value

E_0 = Kappa temperature (or characteristic energy)

E = Energy of particle (*1/2 mv*^{2})

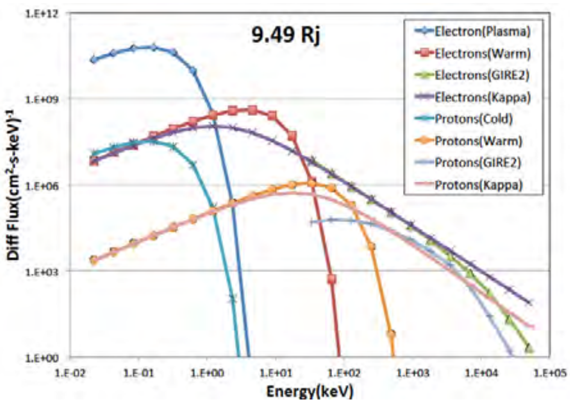


Figure 1. Cold ("Plasma") and warm ("Warm") Maxwell-Boltzmann plasma distributions for electrons and protons and estimates of the E>100 keV electrons and protons ("GIRE2") near Europa.

While the Maxwell-Boltzmann distribution with the convection velocity, V_{cnvc}, included is used to model the cold and warm plasmas, our studies have shown that between ~1 keV and ~50-100 keV, a Kappa distribution is usually much better for estimating spacecraft surface charging at Jupiter. Fig. 1 illustrates our torus model predictions for the cold (labeled "Plasma" in Fig. 1) and warm (labeled "Warm" in Fig. 1) electron and proton Maxwell-Boltzmann distributions near Europa (~9.49 Rj). Also shown are the high energy (labeled "GIRE2" in Fig. 1) electron and proton spectra at the same location. Superimposed on the warm and high energy spectra are the corresponding Kappa distributions. The latter were fit to the warm Maxwell-Boltzmann distributions and the corresponding high energy spectra to provide a continuous fit between 10 keV and ~500 keV.

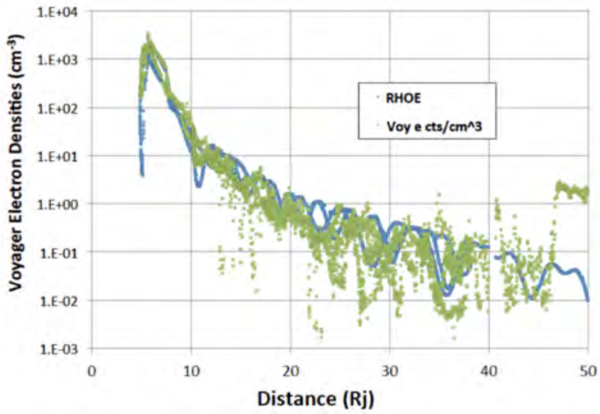


Fig. 2. Voyager PDS cold electron (A) data (green dots) and the JPL model (blue line) predictions versus distance from Jupiter[12].

Fig. 2 compares plots of the cold electron densities versus distance as measured by the Voyager spacecraft compared to the our updated model[12]—the sinusoidal variations correspond to the spacecraft moving in and out of the jovian magnetic equator and plasma sheet.

The charged particle densities, to first order, require that charge balance is maintained. That is, for a given ion mass, charge $z_k^* e$, and number density $N_k = g_k N$ (N is the cold electron concentration), charge neutrality is strictly maintained for the cold components (excluding the cold protons) by requiring:

$$\sum_{k=2}^{7} g_k z_k^* = g_0 = 1 \qquad (3)$$

where g_k is the fraction of the normalized charge density (assumed to equal the electron charge density "1"; i.e., the total ion charge density equals the total electron charge density). The specific composition assumptions for the ions considered in the Divine[1] models are H^+, O^+, O^{++}, S^+, S^{++}, S^{+++}, and Na^+. The original data sources are described in Ref. [1]. The "mean" composition mass (M), "mean" charge (Q), and the charge ratio (M/Q) as functions of distance along the equatorial plane for our model[12] are plotted in Fig. 3 along with the corresponding values from the recent Bagenal-Delamere plasma model[7]. The plasma temperatures in the model, which have been updated since Ref. [1], are compared with Voyager and Galileo data in Fig. 4 versus distance from Jupiter. As illustrated, the new model does a reasonable job of fitting the data.

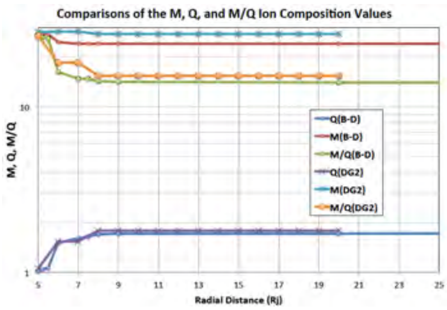


Figure 3. "Mean" composition mass (M), "mean" charge (Q), and charge ratio (M/Q) for the torus along the equatorial plane, Ref. [12] and the Bagenal-Delamere (B-D) model[7].

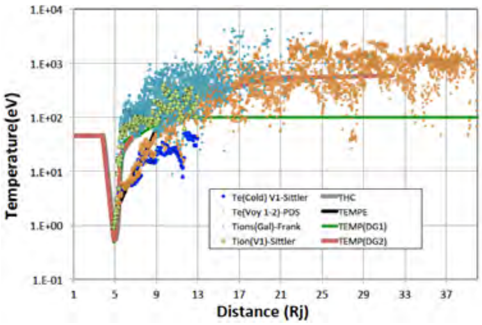


Figure 4. Voyager 1[6], PDS, and Galileo electron and ion temperatures for the torus versus distance from Jupiter compared with our model estimates[12].

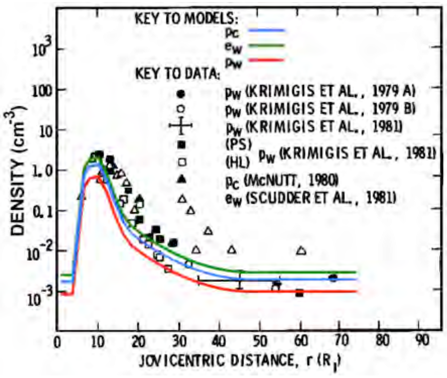
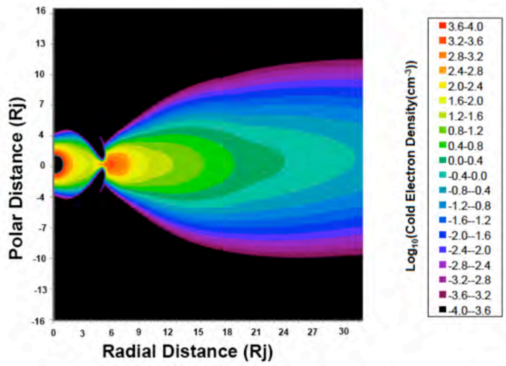


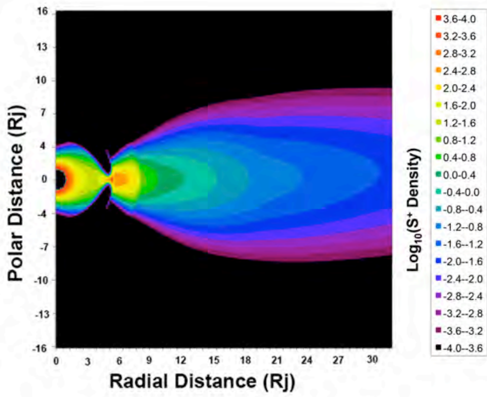
Figure 5. Cold proton, warm proton, and warm electron densities along the equator[12]. The figure is an update of Fig. 6 from Divine and Garrett[1].

Separate from the cold plasma torus components, the cold protons plus the warm protons are assumed to be approximately balanced by the warm electrons (where "warm" means between a few keV and 50-100 keV). Although the Galileo PLS instrument made measurements of the "warm plasmas", the warm electrons and protons and, in particular, the cold protons are still not well defined—the cold proton signal typically being "swamped" by the other heavy ions at very low energies and thus not resolved in most jovian plasma measurements. Fig. 5 is an updated plot of the cold proton and warm electron and proton densities for our best estimates of their densities. The variations of these three plasma parameters inside 10 Rj are still being adjusted, however, in our models and will likely change as more data become available (e.g., from Juno).

Based on the preceding, contour plots at 110° W longitude (SIII) have been generated that illustrate the basic structure of the plasma torus around Jupiter and at Europa. Fig. 6 is an example of the cold electron and ion (S^+) densities. For comparison, the warm electron Kappa components are plotted in Fig. 7.

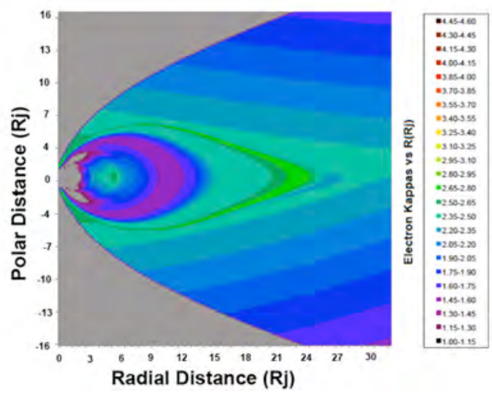


A.

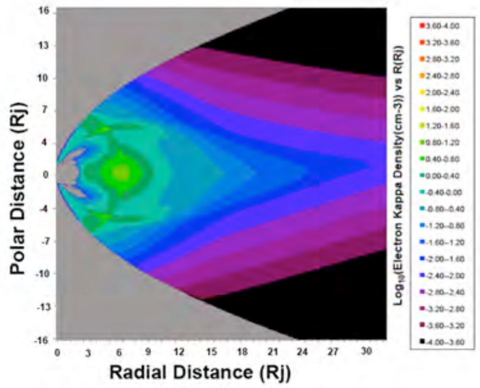


B.

Figure 6. Meridional contour plots at 110° W of; A) Log_{10}(Maxwell-Boltzmann cold electron density (cm^{-3})) vs R(Rj) at 110° W longitude. B) Log_{10}(cold Maxwell-Boltzmann S^+ density). All plots use jovian System III.



A.



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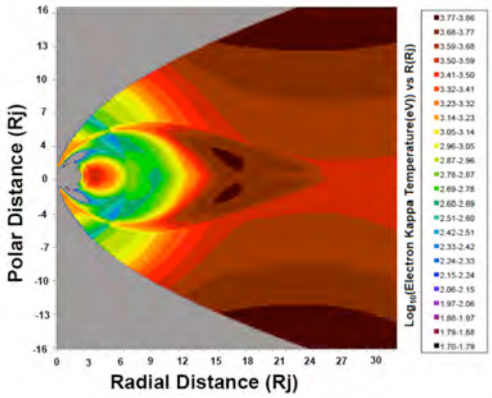

C.

Figure 7. Meridional plots of Kappa parameters (Kappa, density, and temperature) for Jupiter and Europa. Gray corresponds to regions where the program could not fit a Kappa distribution.

In addition to our models of the torus, Sittler, Bagenal, and colleagues[4-10] have developed models of the plasma torus near Europa. By way of summary, our values[12] are compared with Bagenal et al.[13] and Sittler et al.[14] in Tab. 1 at 100 km above the surface of Europa.

Table 1. Estimated torus composition at Europa above ~200 Km in plasma ram direction for different sources.

Torus Ion Densities (cm^{-3}) for 200 km, V_{cnvc} ~120 km/s								
Bagenal et al. [13]:	**O+**	**O++**	**S+**	**S++**	**S+++**			
	18.99	7.38	3.43	18.46	4.25			
Garrett et al. [12]:	**O+**	**O++**	**S+**	**S++**	**S+++**	**Na+**	**H+**	
	7.00	6.00	6.00	26.00	6.00	5.00	1.38	
Sittler et al. [14]:	**O+**	**O2+**	**SO2+**	**CO2+**	**OH+**	**NA+**	**H2+**	**H2O+**
	92.23	2.12	2.0E-3	4.3E-4	1.91	0.09	1.60	2.97

Finally, the energetic neutral atom (ENA) imaging technique used by the Magnetospheric Imaging Instrument on NASA's Cassini spacecraft observed a possible enhanced torus associated with Europa as Cassini flew past Jupiter in early 2001[15]. The ENA detected a hydrogen enhancement consisting of a torus of plasma and neutral gases associated with the extended atmosphere of Europa. We have not yet included these observations in our model but they will need to be considered in any future models of the jovian torus near Europa.

3. THE ATMOSPHERE OF EUROPA

Europa's ionospheric composition is ultimately tied to its background neutral atmosphere. To define a model of the ionosphere, we first need to develop a vertical profile of the atmosphere. Over the last decade, several such models have been developed. Although a growing body of data from HST, Galileo, Cassini, and various ground-based sources have improved our understanding of it, Europa's atmosphere is still not well defined (see Refs. [16,17] for reviews of recent data and models). Here, after a careful analysis of the various models described in Refs. [16-20], two atmospheric profiles were selected as representative of the current thinking with regards to the atmosphere at Europa.

The first profile is based on a "1-dimensional" direct simulation Monte Carlo (DSMC) model. This model assumes sublimation and sputtering sources for H_2O and radiolytically produced O_2 (these are disassociated into O, HO, etc. by high energy electron, solar UV-photon, and photoelectron impacts). The model was developed by Ref. [19]. A key assumption (given that Earth-based observations place the surface temperature of Europa at ~110 °K) is that the all species except O_2 either gravitationally escape or recondense on the surface. The O_2 does not adhere at the surface temperatures on Europa but rather is reemitted after being thermally accommodated on the surface forming an atmosphere in hydrostatic equilibrium (up to ~200 km). Several different versions of the model were developed by varying the oxygen to water ratio and other variables. Here model D was selected[19]. All the species but O_2 are roughly constant with altitude with O_2 approaching a constant above 200 km. This model gives an atomic oxygen density of ~7.4×10^4 cm^{-3} and an O_2 density of ~2.77×10^6 cm^{-3} at 100 km. The neutral temperature is assumed to vary from ~100 °K at the surface to ~1000 °K at a 1000 km.

The second model[20] is a so-called "2-dimensional" DSMC and is the average of the day and night profiles (a potential issue for these models, however, is that the atmosphere at Europa is likely highly variable over the moon's surface). While the O_2 profile[20] was very similar to the 1-D case, the 2-D O profile falls off somewhat faster with altitude varying from about a factor of 0.3 at 100 km to ~10 less at 600 km. The two sets of profiles[19,20] for O_2, O, H_2O, H_2, and OH were averaged together and the resulting fits presented in Fig. 8. These "average" atmospheric profiles will be used in the next section to provide a starting point for estimating the ionic composition of Europa's ionosphere. Note that the main component of this average model changes from O_2 to H_2 above 100-150 km.

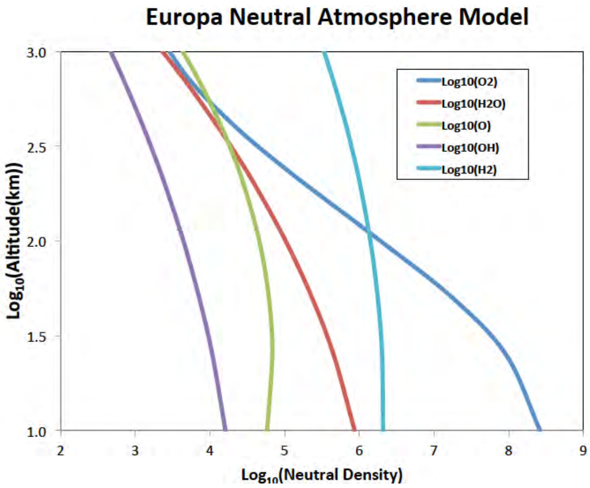

Figure 8. Atmospheric profiles for Europa based on [19,20] for their 1-D and 2-D DSMC atmospheric simulations. Units are N#/cm^3.

4. THE IONOSPHERE OF EUROPA

Kliore et al.[21] analyzed 6 sets of observations of Galileo radio occultations by the ionosphere of Europa. In five of the six occultations they detected the presence of a tenuous ionosphere on Europa with an average maximum electron density of ~10^4 cm^{-3} near the surface. Fig. 9 is a plot of the average electron density profile they found. This average profile has a plasma scale height of 240±40 km below 300 km and 440±60 km above 300 km [27]. We have fit the electron profile in Fig. 9 with an equation of the form:

$$N_e = 2.36939E\text{-}08x^4 - 6.86235E\text{-}05x^3 + 7.41943E\text{-}02x^2 - 3.77475E{+}01x + 9.03055E{+}03 \quad (4)$$

where:

x = altitude above Europa (km)

N_e = electron density (cm^{-3})

Europa's ionosphere is presumably produced by photoionization and by charged particle impacts on the neutral atmosphere. This profile can be explained by a neutral surface density of about 10^8 cm^{-3}. If composed primarily of O_2, then the ionosphere is primarily O_2^+ and the neutral atmosphere temperature implied by the 240 km scale height is about 600 °K. If it is composed of H_2O, it is primarily H_3O^+ and the neutral temperature is about 340 °K. These temperature estimates are much higher than those observed on Europa's surface (~110 °K) implying an external heating source from the jovian magnetosphere may be required. The increase in scale height above 300 km may also be due to a change in the neutral atmospheric composition.

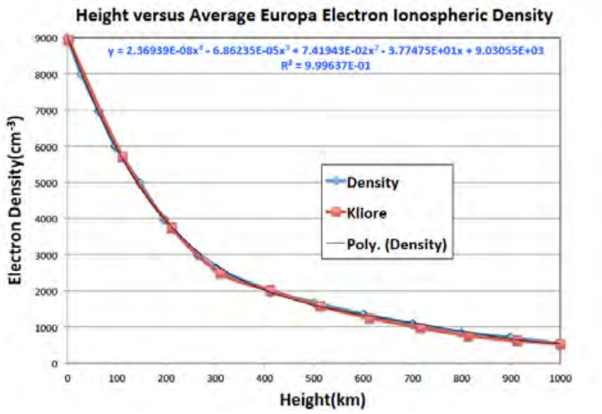

Figure 9. Average electron ionospheric profile for Europa estimated from occultation measurements by Galileo [21].

A very simple model of the ionospheric composition can be derived by assuming that at a given altitude the ionosphere has the same constituents in roughly the same proportions as the ambient atmosphere. That is, given the neutral composition (Fig. 8) and the electron charge density (Fig. 9) variations with height, the altitude variation in ionospheric composition can be determined by multiplying the electron density by the percentage of that component relative to the other neutral species at that altitude. An ionospheric model based on this concept is plotted Fig. 10.

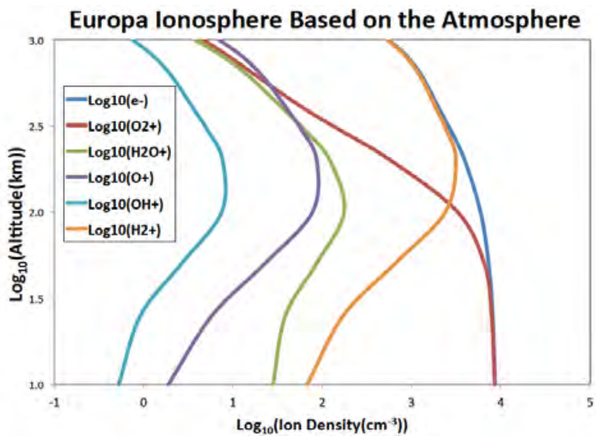

Figure 10. Europa ionosphere based on the neutral atmosphere in Fig. 8 and the electron profile in Fig. 9.

The ionosphere as represented by Fig. 10 extends to 1000 km or higher. In reality, however, the high velocity torus plasma interacts with the ionosphere ramming into it. Depending on the assumptions made, the torus can push the ionosphere on the ram side of Europa down to Europa's surface while leaving it relatively unaffected on the wake side (e.g., the direction Europa is moving). Fig. 11 from Ref. [14] is an example of a detailed simulation illustrating the ionosphere below the ionopause (the height, here at ~39 km, below which the ionosphere dominates) and the torus dominated region at higher altitudes.

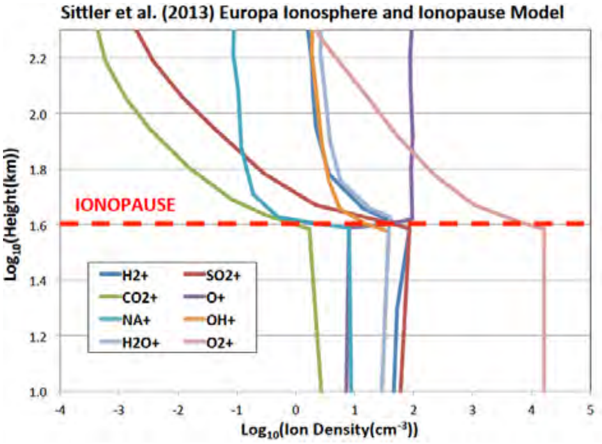

Figure 11. A model of the interaction of Europa's ionosphere and torus [14].

Fig. 12 illustrates our (qualitative) approximation to the shape of an ionopause in the equatorial plane relative to Jupiter. The elliptical shape in this figure is given by:

$$R(\theta) = \frac{1.5}{(1-0.25\cdot\cos(\theta))} \quad (5)$$

where:

R = distance of ionopause from the center of Europa in Europa radii (Re)

θ = Angle relative to Jupiter; 90° toward Jupiter

Re = Europa radius (1560.8 km)

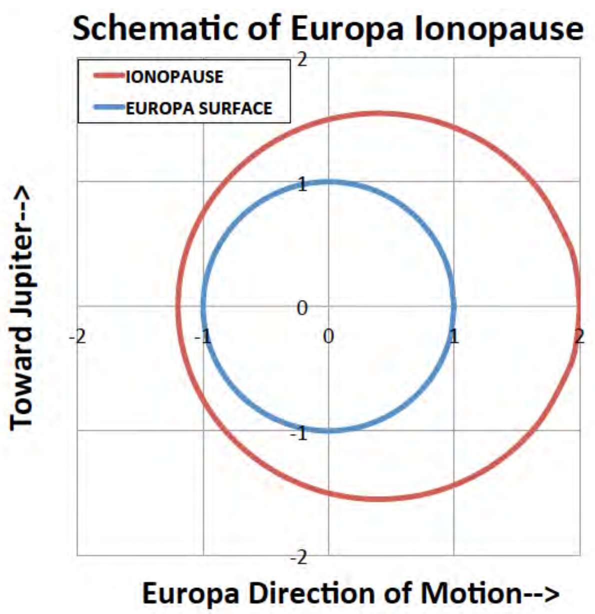

Figure 12. Schematic of a possible ionopause boundary resulting from the interaction of Europa's ionosphere and Jupiter's plasma torus. Units are Re.

The predictions of the simple ionosphere model below the ionopause presented here are compared in tabular form to the more complex model of Ref. [14] model in Tab. 2.

5. CONCLUSION

The panned Europa Mission would rapidly pass from the jovian torus into Europa's ionosphere and back out ~40 times. These two regions represent very different compositions and velocity regimes. For example the spacecraft would be moving (dependent on its vector velocity) at ~14 km/s relative to Europa's ionosphere. Unfortunately, little currently is known about the composition and structure of this ionosphere. Europa is also immersed in the relatively dense jovian plasma torus. In contrast, this plasma is moving at ~120 km/s relative to Europa and, depending on the spacecraft's direction vector, roughly a similar velocity relative to the Europa spacecraft. These rapid changes in composition and relative plasma velocities as the spacecraft moves from the torus to the ionosphere and out again will have potentially significant changes on how the spacecraft interacts with the plasma. To better estimate the ramifications of these changes, this paper has summarized some of the key aspects of these two environments and provided estimates of their properties that can be used in surface charging calculations. These calculations are important in estimating effects on the solar arrays and on plasma measurements. Ultimately, the latter may be critical in interpreting any possible plume encounters at Europa and hence the detection of life.

Table 2. Comparison of the ionospheric populations in the lower ionosphere (e.g., below the ionopause) for our model (HBG) which based on a percentage of the neutral atmosphere and that of the Ref. [25] model.

Europa Ionosphere* Densities (cm^{-3})									
Sittler et al. [25]:	O+	O2+	SO2+	CO2+	OH+	NA+	H2+	H2O+	Total e-
0 Km	6.00	1.62E4	33	6.00	18	10	30	18	1.63E4
38 Km	7.98	1.62E4	84.8	1.69	3.77	7.98	84.8	37.7	1.65E4
%Atms (HBG):	O+	O2+			OH+		H2+	H2O+	Total e-
10 Km	1.90	8.56E3			0.527		68	28.2	8.66E3
25 Km	5.84	7.91E3			0.922		173	38.8	8.13E3
50 Km	22.7	6.56E3			2.65		652	86.1	7.32E3

*V_{europa} ~13.85 Km/s

6. ACKNOWLEDGEMENTS

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