MULTI-FLUID MHD SIMULATIONS OF EUROPA'S PLASMA INTERACTION: EFFECTS OF VARIATION IN EUROPA'S ATMOSPHERE ON THERMAL PLASMA PRECIPITATION AND MAGNETIC FIELDS.

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Introduction: Various physical processes transfer mass and energy between Europa's atmosphere, surface, the ambient thermal plasma and energetic charged particles of Jupiter's inner magnetosphere, and the cold plasma of Europa's ionosphere. Europa's O_2-dominated atmosphere is generated primarily by sputtering interactions between magnetospheric particles and the icy surface [1]. Above the surface, neutral atmospheric O_2 is then ionized by solar photons and magnetospheric electrons, generating cold ionospheric plasma [2]. Ions recombine with electrons to form neutrals, and ionospheric ions undergo charge exchange with the atmosphere.

Though these individual physical processes are well understood, the complexity of the system, potential variability in different components, and limited *in situ* data make quantifying the coupling between Europa's plasma interaction and atmosphere challenging. Observations have constrained the column density of Europa's atmosphere to a range that nevertheless admits very different configurations. Furthermore, the density of Europa's atmosphere may vary due to the populations of magnetospheric ions and electrons that generate atmospheric O_2 through sputtering interactions with Europa's surface. The atmosphere comprises the source population for Europa's ionospheric plasma, and the ionosphere plays a critical role in shaping the electromagnetic fields resulting from Europa's plasma interaction. Therefore, in [3] we study the role of different configurations of Europa's atmosphere in the plasma interaction.

Methods: To better understand this coupling we conducted several simulations using the multi-fluid MHD model presented in [4] to span the parameter space of reasonable atmosphere variation for Europa.

The multi-fluid MHD model for Europa's plasma interaction is based on the BATS-R-US MHD code [4]. The model solves the multi-fluid MHD equations for three ion fluids representing thermal magnetospheric ions, ionospheric O^+, and ionospheric O_2^+, as well as the electron pressure equation for thermal electrons. Source terms in the mass, momentum, and pressure equations account for the effects of electron impact ionization, photoionization, recombination, and charge-exchange on each fluid [4].

Study parameters. Most parameters of the simulations were held constant. At the outer boundary of the simulation, we set the magnetospheric plasma speed relative to Europa to 100 km/s, the temperature of the magnetospheric ions to 129 eV, and the Jovian magnetic field to $B_J = -400$ nT. The properties of the electrons and the calculation of source and loss terms associated with ionization, recombination, and charge exchange, as well as other numerical details, are the same as described by [4].

The parameter study consists of 18 simulations covering the variation of the magnetospheric plasma density, and the atmospheric configuration. First, we varied the magnetospheric plasma density such that 9 simulations were conducted with a low density of 20 cm^{-3}, and 9 with 100 cm^{-3}. Within each of the two sets, we varied Europa's atmosphere. We set the scale height to be either 33 km, 100 km, or 330 km. For each scale height, we varied the surface density to be either 2.5×10^7 cm^{-3}, 5.0×10^7 cm^{-3}, or 7.5×10^7 cm^{-3}.

Results: Each simulation resulted in 3D solutions for the bulk plasma parameters and the magnetic fields.

Plasma density and magnetic fields. In the simulations with the largest scale-height atmospheres the region influenced by Europa's ionosphere extends far from Europa's surface and the plasma wake is loaded with high densities of ions. Where the atmosphere scale height is small, the ionosphere is confined close to Europa's surface.

The simulated magnetic field perturbations indicate that the magnetic field is compressed, or piled-up, on the upstream side of the interaction as the flow of magnetospheric magnetic field, which is frozen-in to the magnetospheric plasma, is forced to slow due to the interaction with Europa's ionosphere. The spatial extent of the upstream magnetic field pile-up, as well as the distance from Europa's surface at which streamlines start diverting from their ambient, straight paths, increases with the scale height of the atmosphere due to the increased extent of the ionosphere (Fig. 1).

Comparison of electron density with Galileo radio occultations. The simulated electron density is generally consistent with the densities derived from the *Galileo* radio occultation experiment [6]. While the highest density ionospheres are significantly denser than the *Galileo* electron densities, most of the simulations produced ionospheres similar to the data. Thus, we find that variations in Europa's atmosphere can cause the electron density to vary by multiple orders of magnitude at the same altitudes, in agreement with the observations.

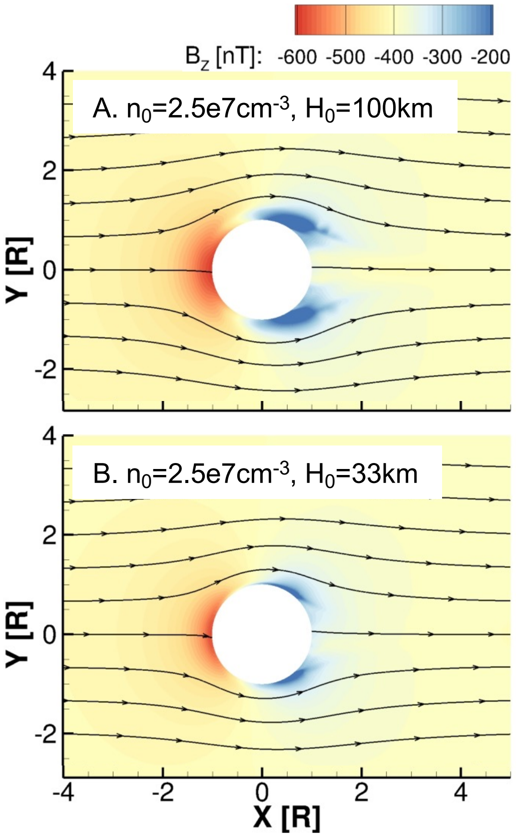

Figure 1. B_Z and streamlines of the charge-averaged plasma velocity in the XY plane for two simulations.

Discussion: We integrated the downward number flux of the magnetospheric plasma over Europa's surface to calculate the total precipitation rate for each simulation. In [4], the rate ranged from $(5.6–26)\times10^{24}$ ions/s: while in this study, the rate ranges from $(1.5–3.3)\times10^{24}$ ions/s for the simulations with low magnetospheric plasma density and $(5.2–15)\times10^{24}$ ions/s for the simulations with high plasma density. [4] showed that the precipitation rate increased linearly with the density of the magnetospheric plasma. Consistent with that result, we find that for all atmosphere cases the precipitation rate increases with the magnetospheric plasma density. For both the high- and low-density simulations, the precipitation rate drops quickly as the atmosphere column density increases to 0.5×10^{15} cm^{-2}, and for simulations with higher atmosphere column densities the precipitation rate is approximately constant, leveling off at 2×10^{24} ions/s for simulations with low magneto- spheric plasma density and 6.4×10^{24} ions/s for simulations with high magnetospheric plasma density.

Conclusions: To better understand how variations in Europa's atmosphere affect the bulk plasma properties and magnetic fields near Europa, we conducted a parameter study that explores a reasonable parameter space for Europa's O_2 atmosphere.

The leveling-off of the precipitation rate with increasing column density, combined with the effect observed by [4], where the magnetospheric plasma precipitation rate increased approximately linearly with the magnetospheric plasma density, creates a more complete picture of how these two effects can alter the precipitation of magnetospheric plasma onto Europa's surface, and control the thermal plasma contribution to sputtering. Based on the results of [4], the thermally sputtered contribution of atmospheric O_2 may increase when Europa is near the center of Jupiter's plasma sheet, and decrease as the plasma sheet moves away and Europa is subjected to less dense magnetospheric plasma due to Jupiter's rotation. If the atmosphere becomes sufficiently dense, the results of this study suggest that the thermally sputtered contribution to the atmosphere will decrease. This coupling would tend to have a self-limiting effect on increases in the density of the ionosphere: high ionosphere density would increase the pile-up of magnetic field, reducing the sputtering yields from magnetospheric plasma and energetic particles [7], leading to decreased sputtering contributions to the density of the atmosphere, and therefore reducing the amount of neutral O_2 available to be ionized to form Europa's ionosphere. If the sources of mass for the ionospheric plasma are suppressed relative to the losses caused by recombination and the transport of plasma downstream, the ionosphere density would then decrease. Thus, the coupling between Europa’s atmosphere and plasma interaction causes stabilizing feedback in the system.

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