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SHEATH EFFECTS AND RELATED CHARGED-PARTICLE ACCELERATION BY JUPITER'S SATELLITE IO

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ABSTRACT

Several current theories on the Jovian decametric radio emission, and its modulation by the satellite Io, assume that the plasma within the magnetic flux tube passing through Io is "frozen" to the motion of Io. This paper considers the effects of the plasma sheath around Io on the interaction of Io with the Jovian magnetosphere. It is found that under some conditions the plasma sheath around Io can effectively insulate the magnetospheric plasma from the motional electric field generated within Io, thus preventing the plasma from being frozen to the motion of Io. Under these conditions large potentials are developed across the plasma sheath and emitted photoelectrons can be accelerated to high energies. The sheath voltages which develop are controlled by the ionospheric conductivity at the base of the Io flux tube, as well as other plasma parameters at Io. A simplified model illustrating these basic effects is discussed.

I. INTRODUCTION

As has been known for several years (Bigg 1964), Jupiter's innermost Galilean satellite Io exercises a pronounced control of the Jovian decametric radio emission. It was suggested by Piddington and Drake (1968) that this control may be due to an electromagnetic disturbance produced by the motion of Io through the Jovian magnetosphere. To be effective, this mechanism requires that Io have a sufficiently large electrical conductivity to effectively "freeze" the plasma to the magnetic field lines intersecting Io, following traditional magnetohydrodynamics (MHD) concepts. Currents and disturbances associated with the motion of this flux tube through the Jovian magnetosphere and ionosphere were proposed to account for the observed radio-noise phenomena. Further investigation and calculations of the resulting currents and charged-particle acceleration have been performed by Goldreich and Lynden-Bell (1969) to explain many of the specific characteristics of the Io-controlled decametric radio-noise emissions. Schatten and Ness (1971) have shown that the main characteristics of the Io modulation can be explained if the radio noise is emitted near the intersection of the Io field line with the surface of Jupiter and in a direction perpendicular to the magnetic field. This radiation geometry could be explained by synchrotron radiation produced by electrons accelerated by Io.

In both the model of Piddington and Drake (1968) and that of Goldreich and Lynden-Bell (1969), it is assumed that the Jovian magnetosphere corotates with Jupiter. Because of the corotation of the magnetosphere, the magnetospheric plasma flows in an eastward direction past Io with a relative velocity of about 56 km s^{-1}. For a 10-gauss equatorial magnetic field strength at the surface of Jupiter the resulting motional electric field ($\boldsymbol{E}_{\mathrm{Io}} = -\boldsymbol{V}_{\mathrm{Io}} \times \boldsymbol{B}$) in Io, as viewed from a frame of reference moving with the plasma, is about 0.27 V m^{-1}. The corresponding potential difference across the diameter of Io is 9.1×10^5 V. Both Piddington and Drake (1968) and Goldreich and Lynden-Bell (1969) assume that this potential is transmitted essentially unattenuated along the magnetic field lines because of the assumed infinite conductivity of the plasma along the mag-

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netic field. It is the purpose of this paper to point out the importance of plasma sheath effects at the interface between the plasma and the surface of Io. Under some conditions, this sheath can serve to effectively limit the current to Io from the surrounding plasma and prevent the plasma from being frozen to the Io flux tube. Under these conditions, large voltages develop across the sheath and photoelectrons emitted from the surface can be accelerated to high energies. These sheath effects, which are described in more detail below, provide a substantially different new model of the interaction of Io with the Jovian magnetosphere.

II. SUMMARY OF PLASMA-SHEATH CHARACTERISTICS

It is well known that when an object is placed in a plasma, an inhomogeneous region called a plasma sheath forms around the object. This sheath is formed as a consequence of the current balance condition at the surface. Since the random electron velocity is usually many times greater than the ion velocity, the electrostatic potential at the surface of an object usually must be negative with respect to the plasma in order to maintain an equal electron and ion current to the surface. If the surface potential is negative, then the sheath is called a Debye sheath and the characteristic thickness of the sheath is the well-known Debye length λ_D (Langmuir and Mott-Smith 1924).

If the surface is emitting photoelectrons and if the photoelectron current exceeds the electron current which can be collected from the plasma, then the electrostatic potential at the surface must be positive to maintain the current balance (by decreasing the number of escaping photoelectrons). This type of sheath is called a photoelectron sheath. Photoelectron sheaths occur around objects exposed to solar ultraviolet radiation in a sufficiently dilute plasma (see, e.g., Singer and Walker 1962). The characteristic thickness of the photoelectron sheath λ_p is determined by the photoelectron energy spectrum and density at the surface. For a detailed discussion of photoelectron sheath characteristics, see Guernsey and Fu (1970) and Grard and Tunaley (1971).

If a bias current J is present at the surface of the object, then the surface potential Φ_s relative to the plasma can be determined if the energy spectrum of the plasma electrons and photoelectrons is known. (Throughout this discussion it is assumed that because of their much greater mass and smaller velocities the ion currents are negligible compared to the electron currents.) For a Maxwellian distribution of electron energies the current-voltage characteristics at the surface of the object are as shown in figure 1. The current densities J_e and J_p in figure 1 are the plasma-electron current and photoelectron current which would exist in the absence of sheath effects. The potentials U_e and U_p are the thermal potentials of the plasma electrons and photoelectrons. If the bias current is such that Φ_s is negative, a Debye sheath is formed; and if Φ_s is positive, a photoelectron sheath is formed. The transition between a Debye sheath and a photoelectron sheath occurs when $J = J_e - J_p$. For large negative potentials, $\Phi_s \ll -U_e$, the

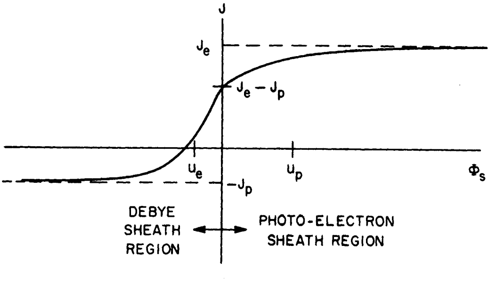

FIG. 1.—Current-voltage characteristic of a photoelectron-emitting surface. Ion currents have been neglected.

bias current to the surface is equal to the emitted photoelectron current $-J_p$, whereas for large positive potentials, $\Phi_s \gg U_p$, the bias current is equal to the electron current collected from the plasma. It is to be noted that for these large extremes of the surface potential the currents are nearly constant, independent of the potential, thereby limiting the current and producing a large dynamic resistance for currents passing through the sheath.

III. THE PLASMA SHEATH AROUND IO

As viewed from a frame of reference fixed to the plasma, the motion of Io through the Jovian magnetosphere produces an electric field $\boldsymbol{E}_{\mathrm{Io}} = -\boldsymbol{V}_{\mathrm{Io}} \times \boldsymbol{B}$ within Io as shown in figure 2. The direction of the Jovian dipole magnetic field shown in figure 2 has been determined from decametric emissions by Warwick (1963). The motional electric field $\boldsymbol{E}_{\mathrm{Io}}$ is associated with a corresponding variation in the electrostatic potential Φ_s at the surface of Io. The potential difference across the diameter of Io, from *a* to *e* in figure 2, is on the order of 9×10^5 V. As in Goldreich and Lynden-Bell's model, it is assumed that the electrical conductivity of Io is sufficiently large that the potential drop due to internal currents with Io is negligible.

Because of the current limiting characteristics of the plasma sheath surrounding Io, we shall initially assume that the sheath effectively shields the magnetospheric plasma from the electric field within Io, thereby preventing the flux tube from being "frozen" to Io. The detailed conditions for this shielding to occur are discussed later. If no plasma motions are induced in the flux tube through Io, then the entire potential Φ_s must occur across the plasma sheath since $\boldsymbol{E} = 0$ in the plasma. The electrostatic potential at the various points, *a* through *e*, on the surface of Io in figure 2 is illustrated in figure 3 relative to the plasma potential ($\Phi_p = 0$). The overall potential of Io is determined by the condition that the net current to the satellite is zero. This condition establishes the

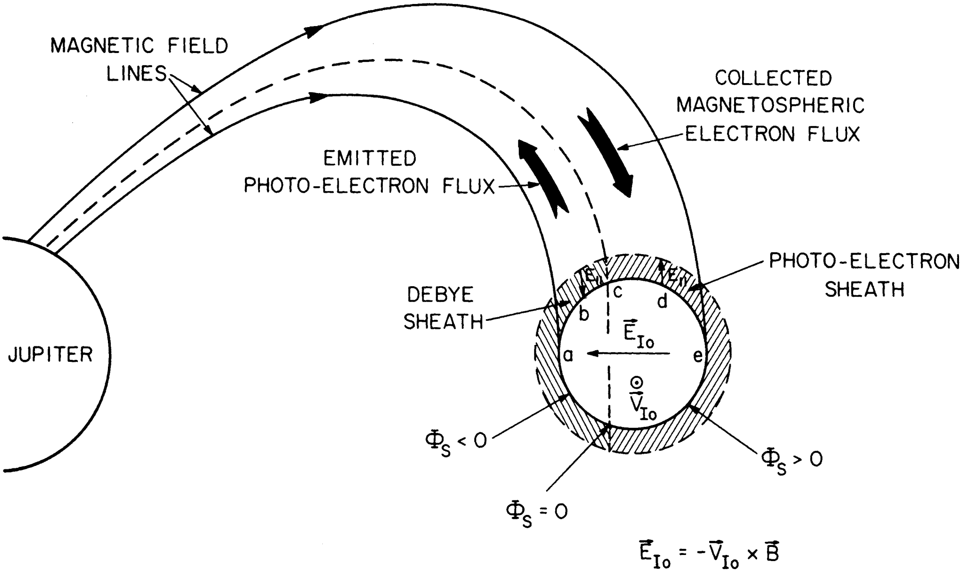

FIG. 2.—Sheath geometry around Io as viewed in a frame of reference fixed to the magnetospheric plasma, assuming that no flux tube motions are induced by Io. Photoelectrons emitted in the Debye-sheath region are accelerated toward Jupiter by the $E_\parallel$ electric field in the Debye sheath. Magnetospheric electrons are collected and accelerated toward Io (producing X-rays) in the photoelectron-sheath region.

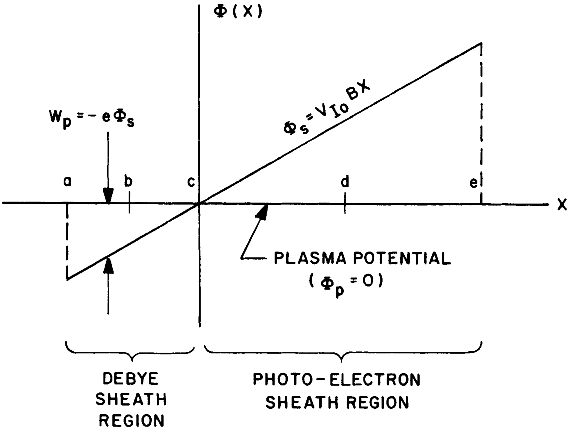

FIG. 3.—Comparison of the surface potential, Φ_s, at Io with the plasma potential, $\Phi_p = 0$, for various points on the surface of Io. The coordinate x is the distance outward from the rotational axis of Jupiter. Photoelectrons in the Debye-sheath region are accelerated to an energy $W_p = -e\Phi_s$.

point c at which the potential of the surface is zero with respect to the plasma. In the region from a to c the surface potential is negative and the sheath is a Debye sheath, whereas in the region from c to e the surface potential is positive and the sheath is a photoelectron sheath. The potential variations upward from the surface, along a magnetic field line, are illustrated in figure 4 for the various points a through e referred to in figures 2 and 3. These potential variations produce an electric field $E_\parallel$ parallel to the magnetic field which can accelerate charged particles. In the Debye-sheath region the direction of the electric field is such that photoelectrons emitted from the surface are accelerated along the magnetic field line, away from Io and toward Jupiter. In the photoelectron-sheath region the direction of the electric field is such that magnetospheric electrons which arrive at the sheath are accelerated into the surface. The principal observable effect of these electrons would be to produce X-rays when they strike the surface of Io.

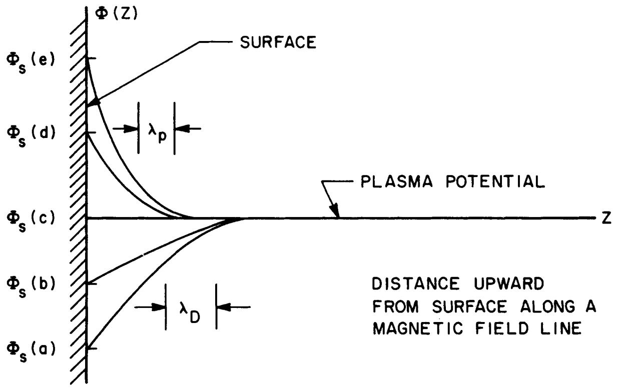

FIG. 4.—Schematic illustration of the electrostatic potential upward from the surface along a magnetic field at the various points shown in figs. 2 and 3. The distances λ_p and λ_D are the characteristic length scales of the Debye sheath and photoelectron sheath, respectively.

The energy gained by the emitted photoelectrons is $W_p = -e\Phi_s$ as they pass through the Debye-sheath region. The maximum energy of the emitted photoelectrons is determined by the position of the line of zero surface potential (c in figs. 2 and 3) which in turn is controlled by the current balance condition. Clearly the maximum energy of the emitted photoelectrons can be considerable (>100 keV) because of the large potential difference available across the diameter of Io.

Since the surface potentials involved are generally much larger than the thermal potential of either the plasma or the photoelectrons, the current density at the surface of Io is almost completely due to the emitted photoelectrons ($-J_p$) in the Debye-sheath region and due to the collected magnetospheric electrons (J_e) in the photoelectron-sheath region (see fig. 1). As a rough approximation, ignoring the variations in the photoelectron flux due to the geometry of the solar ultraviolet illumination, the current balance condition can be written

$$J_e A_e + (-J_p) A_p = 0 ,$$

where A_p and A_e are the surface areas of the Debye-sheath and photoelectron-sheath regions. Using a photon-to-photoelectron conversion efficiency of 2×10^{-5}, as used by Goldreich and Lynden-Bell, we estimate the photoelectron current density at the surface of Io to be

$$J_p = 4.5 \times 10^{-6} \text{ amperes m}^{-2} .$$

From the magnetospheric model of Ioannidis and Brice (1971), the electron density and temperature at Io are estimated to be $n_e = 3.0$ electrons cm^{-3} and $T_e = 10^5$ ° K, respectively, giving an electron current density of

$$J_e = 4.0 \times 10^{-7} \text{ amperes m}^{-2} .$$

For these parameters the ratio of the Debye-sheath area to the photoelectron-sheath area, A_p/A_e, is approximately 0.1 and the width of the Debye-sheath region (from a to c in fig. 3) is approximately 30 percent of the radius of Io. The maximum photoelectron energy in this case is $W_p(\max) = (0.3) \times (1/2) \times (9.0 \times 10^5) = 135$ keV. The total current of the emitted photoelectrons is approximately 3.6×10^6 amperes, and the total power input into the emitted photoelectrons is 2.4×10^{11} watts, about a factor of 10^4 greater than the power in the Io-controlled decametric radio noise. Since most of the energy is gained in accelerating the electrons along the magnetic field line, it is expected that a substantial fraction of the emitted electrons are precipitated into the Jovian atmosphere.

In the photoelectron-sheath region, magnetospheric electrons accelerated into Io are expected to produce an intense flux of X-rays ($\sim 2 \times 10^{25}$ photons s^{-1}) with energies of several hundred keV. Although this X-ray flux is currently not detectable at the Earth, it would be of great interest to look for such X-ray fluxes from Io with spacecraft instrumentation flying by Jupiter.

IV. FACTORS DETERMINING THE MOTION OF THE IO FLUX TUBE

In the discussions of the previous section it was assumed that the plasma in the flux tube through Io remains stationary with respect to the corotating magnetosphere of Jupiter, completely "unfrozen" from the motion of Io. Since substantial currents do exist through the sheath and into the Jovian magnetosphere, it remains to be determined under what conditions this model would be valid. The conductivity of the Jovian ionosphere plays an important role in determining the motion of the plasma in the flux tube through Io. If the ionospheric conductivity is very large, then the currents produced by Io are "shorted" across the magnetic field lines within the ionosphere and cause only a very small potential drop across the magnetic field lines. The transverse electric field is therefore small and the $\boldsymbol{E} \times \boldsymbol{B}$ motion of the plasma in the Io flux tube is negligible. If instead the ionospheric conductivity is made very small, then a large potential drop occurs across the magnetic field lines within the ionosphere and the plasma potential increases until the potential across the sheath is reduced to zero, effectively "freezing" the flux tube motion to that of Io.

To quantitatively estimate the ionospheric conductivity at which the magnetic field lines become "frozen" to the motion of Io, we consider the simplified two-dimensional model illustrated in figure 5. In this model we represent Io by a conductor moving with a velocity V_{Io} directed out of the page. The magnetic field lines are vertical (along the z-axis). A sheath is presumed to form around the conductor with corresponding current densities (along the z-axis) of $-J_e$ and J_p in the photoelectron- and Debye-sheath regions, respectively. These currents close through the conducting ionosphere as shown in figure 5. The ionospheric conductivity Σ_p is the height-integrated (Pederson) conductivity (Fejer 1965).

Following the usual MHD model, we assumed that the electric-field component parallel to the magnetic field is zero every place except in the sheath region. The magnetic field lines are therefore equipotentials (except in the sheath), and an electric field

$$E_c = I_x/\Sigma_p \tag{1}$$

is produced by the (height-integrated) horizontal current I_x flowing through the base of the ionosphere. This electric field is mapped upward with a constant value along the magnetic field lines, producing a convection velocity

$$\boldsymbol{U} = \boldsymbol{E}_c \times \boldsymbol{B}/B^2 \tag{2}$$

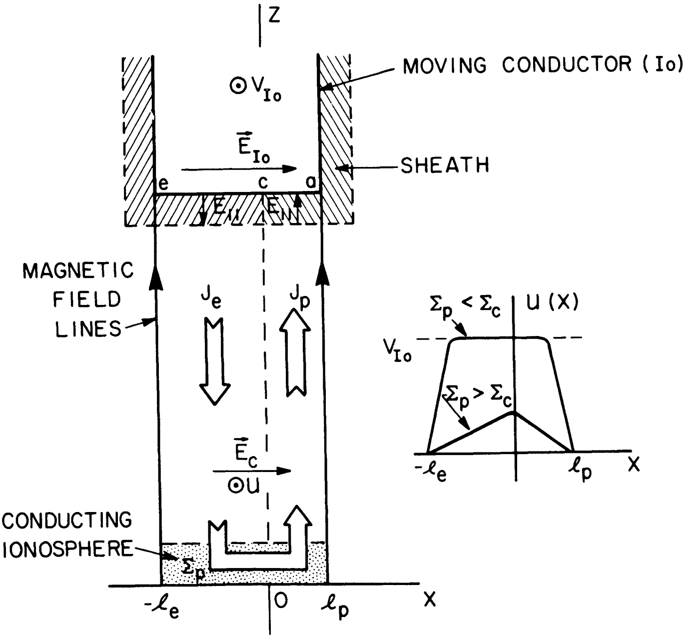

FIG. 5.—Simplified two-dimensional model with straight magnetic field lines to illustrate the effect of ionospheric conductivity on the flux tube motion. The conductor is moving out of the paper. The current through the ionosphere produces an electric field $\boldsymbol{E}_c$ due to the Ohm's law voltage drop within the ionosphere. This electric field produces a plasma motion with velocity $\boldsymbol{U} = \boldsymbol{E} \times \boldsymbol{B}/B^2$ out of the paper.

parallel to the direction of motion of the conductor. To determine this convection velocity the horizontal current I_x must be related to the field aligned (z-component) current J_z into the ionosphere. The appropriate continuity equation is

$$\partial I_x/\partial x = -J_z\,. \tag{3}$$

If the plasma slips relative to the conductor, so that large voltages occur across the sheath, then the field-aligned current density is $J_z = -J_e$ for $x < 0$ and $J_z = J_p$ for $x > 0$. Solving equation (1) subject to the boundary condition that $I_x = 0$ at $x = -l_e$ and $x = l_p$, one obtains solutions

$$I_x = J_e(l_e + x) \text{ for } x < 0\,, \quad \text{and} \quad I_x = J_p(l_p - x) \text{ for } x > 0\,.$$

Note that the current balance condition for the conductor, $J_e l_e = J_p l_p$, assures that I_x is continuous at $x = 0$. From equations (1) and (2), the convection velocity of the plasma can be determined:

$$U(x) = \frac{J_e}{\Sigma_p B}(l_e + x) \text{ for } x < 0\,, \quad \text{and} \quad U(x) = \frac{J_e}{\Sigma_p B}(l_p - x) \text{ for } x > 0\,.$$

The maximum convection velocity occurs at $x = 0$ and is given by

$$U_{\max} = \frac{J_e l_e}{\Sigma_p B} = \frac{J_p l_p}{\Sigma_p B}\,. \tag{4}$$

If the ionosphere conductivity is decreased until $U_{\max}$ becomes comparable to V_{Io}, then the potential across the sheath decreases until a portion of the flux tube (first at $x = 0$) begins to move with the conductor. This "freezing" of the plasma to the motion of the conductor is indicated by the flat top portion of $U(x)$ shown in figure 5 for $\Sigma_p < \Sigma_c$. The critical conductivity, Σ_c, at which this "freezing" of the flux tube to the motion of the conductor first occurs is determined from equation (4) by letting $U_{\max} = V_{\text{Io}}$,

$$\Sigma_c = \frac{J_p l_p}{V_{\text{Io}} B} = \frac{J_e l_e}{V_{\text{Io}} B}\,. \tag{5}$$

In summary, (1) if $\Sigma_p > \Sigma_c$, then substantial slippage of the flux tube relative to the conductor occurs and large sheath voltages develop, with attendant large energies imparted to the emitted photoelectrons; and (2) if $\Sigma_p < \Sigma_c$, then a portion of the flux tube is "frozen" to the conductor, with the width of the "frozen" region increasing, and the sheath voltages decreasing, as the ionospheric conductivity is reduced. As the ionospheric conductivity goes to zero, the sheath voltages become comparable to the thermal potentials of the plasma, the currents go to zero, and the entire flux tube is frozen to the motion of the conductor.

Using the previously quoted values of $J_p = 4.5 \times 10^{-6}$ amperes m^{-2}, $l_p = 0.3\ R_{\text{Io}}$, $V_{\text{Io}} = 56$ km s^{-1}, and $B = 0.048$ gauss at Io, one obtains the critical value of the ionospheric conductivity for this simplified two-dimensional model, $\Sigma_c = 8.9$ mhos. To relate this conductivity to the corresponding critical conductivity of the Jovian ionosphere, the convergence of the magnetic field lines from Io down to the ionosphere must be considered. Assuming that the electrostatic potential and field-aligned current are conserved along a flux tube, the transformation necessary to convert the ionospheric conductivity of the straight-line magnetic field model in figure 5 to the corresponding conductivity of the Jovian ionosphere (primed) is given by

$$\Sigma'_p = \Sigma_p(2\cos\theta)^{-1}\,, \tag{6}$$

where θ is the polar angle (colatitude) at which the magnetic field line of Io intersects the base of the ionosphere. Since $\theta = 24\overset{\circ}{.}3$ for Io, the corresponding critical conductivity for Jupiter's ionosphere is

$$\Sigma'_c = 4.75 \text{ mhos} .$$

This value for the critical conductivity must of course be considered only an order-of-magnitude estimate because of the simplified assumptions used in its derivation and the great uncertainty in the various parameters involved. It does, however, provide a rough criterion with which to determine the possibility of large sheath voltages around Io.

Estimates of the height-integrated Pederson conductivity for the Jovian ionosphere have been given by Brice and Ioannidis (1970) and Goldreich and Lynden-Bell (1969). For a 10-gauss equatorial surface field (which was used in our estimates) Brice and Ioannidis, using the Gross and Rasool (1964) model ionosphere, estimate that Σ'_p is about 20 mhos. Goldreich and Lynden-Bell in their calculations use a value for Σ'_p of 0.57 mhos, although they consider that this value could be low by a factor of 5 or more. Since these estimated ionospheric conductivities are more or less comparable to the critical conductivity estimated in this paper, it is concluded that substantial slippage of the flux tube by Io probably does occur and that large sheath voltages will develop if Io has a sufficiently low internal resistance. In comparing these values with the estimated critical conductivity, it should also be pointed out that the quoted values for the ionospheric conductivity are for undisturbed conditions and that the electrons precipitated into the atmosphere from the Io flux tube will very likely increase the ionospheric conductivity considerably, thereby increasing the tendency for slippage and large sheath voltages. Also, recent measurements of photoelectron conversion efficiencies for material from the lunar surface (Feuerbacher and Fitton 1971) suggest that the photoelectron current density at the surface of Io may be a factor of 10 or more smaller than the value used by Goldreich and Lynden-Bell, thereby decreasing the critical conductivity of the ionosphere and further contributing to the tendency for slippage and large sheath voltages.

As in Goldreich and Lynden-Bell's model, there is also a critical conductivity σ_c for Io below which the voltage drop due to the currents within Io is important. Since the voltages and currents obtained in this plasma sheath model are similar to those obtained by Goldreich and Lynden-Bell, the corresponding critical conductivity of Io is about the same, $\sigma_c \simeq 2 \times 10^{-8}$ ohm^{-1} cm^{-1}. However, even if the conductivity of Io is a factor of 10^{-2} smaller than this value, very significant voltage drops (~keV) are still developed across the plasma sheaths, although the total power output is greatly reduced.

V. DISCUSSION

The purpose of this paper was to demonstrate that sheath effects at the surface of Io may play an important role in determining the interaction of Io with the Jovian magnetosphere and in accelerating the charged particles responsible for the decametric radio noise emissions associated with Io. The model considered involves a combination of concepts largely based on the MHD frozen-field model of plasma motion together with more or less traditional ideas regarding sheath formation at the boundaries of the plasma. To keep the model simple and to illustrate the essential features, we have omitted certain complicating effects such as the variations of the photoelectron emission over the surface, the absence of photoelectron emission on dark side of Io, ion currents, and the effect of secondary electron emission. These effects can certainly be included, but it is doubtful that any significant change in the overall picture will result from these effects. There are, however, more fundamental aspects of this model which are not yet clearly resolved. If both Io and the base of the ionosphere are sufficiently good conductors, then it is clear that a potential drop must occur somewhere along the magnetic field line between Io and the base of the ionosphere. In this model we assume that the potential drop occurs across the plasma sheath at Io. Since a plasma sheath is almost certain to form around Io, it is considered a reasonable assumption that the potential drop occurs in the sheath and not somewhere else. This viewpoint is also consistent with laboratory measurements which show that when a large negative potential is applied to a probe in a plasma, the sheath structure is confined to the immediate vicinity of the probe (Langmuir and Mott-Smith 1924). However, it has not been conclusively established that the main potential drop could not occur in a sheathlike structure somewhere else along the magnetic field line, possibly in a space-charge region of the type suggested by Carlqvist and Bostrom (1970). The occurrence of such space-charge regions within the Io flux tube is a possibility which requires further investigation.

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