

SHEATH ACCELERATION OF PHOTOELECTRONS

BY JUPITER'S SATELLITE IO

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Abstract. We are investigating a model of the influence of Jupiter's moon Io on Jovian decametric radiation due to plasma sheaths formed around Io's surface. With Io, we are dealing with a large, partially-conducting, and photoemitting body with a large $\mathbf{V} \times \mathbf{B}$ potential (~ 700000 Volts) across its diameter. A well-known model by Goldreich and Lyden-Bell (1969) assumes Jupiter's field lines are frozen to Io, while we are proposing instead that sheaths form around Io and electrons are accelerated across these sheaths.

Two types of sheaths are considered. A Debye sheath forms around regions of Io's surface which are negative with respect to the plasma potential while a photoelectron sheath forms where the surface potential is positive. The Debye sheath (of area A_p) accelerates emitted photoelectrons away from the surface (with current density J_p) while the photoelectron sheath (of area A_e) collects an ambient electron current ($J_e A_e$). The current balance is $J_p A_p = J_e A_e$. The boundary between the two regions has zero potential.

We estimate J_e and J_p to be $3 \times 10^{-7} \text{ A m}^{-2}$, but both may vary considerably. The emitted particle spectrum is critically dependent on the ratio J_e/J_p . Estimates of total power available in the accelerated photoelectrons are 10^{10} – 10^{13} W , well above the 10^7 W contained in a typical decametric burst. We have also studied the effect of Io's orbital position on our model since decametric bursts are strongly coupled to Io's position.

Although \mathbf{E} is probably radial through the sheath, we believe that the electron gyroradius is small compared with sheath dimensions so that the particles emerge almost parallel to Jupiter's field lines. Using an 'oblique' version of Child's Law, we estimate the typical sheath thickness as 10–50 km. High energy (up to several hundred keV) electrons thus travel along \mathbf{B} field lines and eventually produce the observed radio noise.

1. Introduction

Bigg (1964) demonstrated that the orbital position of Io, the innermost Galilean moon of Jupiter, was related to the modulation of the Jovian decametric wavelength radio bursts. Since that time a number of models to explain these Io related bursts have been published. Gledhill (1967) proposed that Io stimulates plasma waves from a plasma disc surrounding Jupiter. Piddington and Drake (1968), Goldreich and Lyden-Bell (1969), Dermott (1970), and Piddington (1972) suggested that the Io interaction for a sufficiently high electrical conductivity could be due to Io dragging its associated flux tube through the Jovian magnetosphere and ionosphere. Goldreich and Lyden-Bell suggested that the emission is due to Doppler-shifted coherent cyclotron radiation from energetic electrons streaming along the magnetic field lines. The radio emission is explained by Piddington as due to plasma oscillations from thin sheets with densities $\sim 10^7 \text{ cm}^{-3}$ in the lower ionosphere.

Duncan (1970) and Schatten and Ness (1971) consider the tilted dipole magnetic field geometry of Jupiter to explain the observed combinations of Io orbit position and longitude for which the noise storms occur. These storms occur as a result of emission from perturbed trapped electrons as Io moves through various magnetospher-

ic boundaries according to Duncan. Schatten and Ness suggest that a Moon-like (non-magnetic, non-conducting) body could scatter radiation belt particles to produce the bursts by synchrotron radiation. Mozer and Bogott (1972) propose that the photoelectric emission from Io in sunlight produces sufficient cold plasma locally to cause growing electrostatic waves which perturb the trapped energetic electrons. Gurnett (1972) concludes that a plasma sheath may form around Io allowing it to slip through the magnetospheric magnetic field. Bursts are emitted by photoelectrons accelerated to several hundred kilovolts by the motional emf of Io developing across this sheath.

The paper reports the progress on further calculations related to the plasma sheath model of Gurnett. In particular a range of values are estimated from a number of different models for the parameters assumed for the model: the photoelectron and thermal electron current densities, the Jovian ionospheric and Io surface conductivities. Numerically integrating an oblique version of Child's Law the plasma sheath dimensions are determined. Also, the particle gyroradius is shown to be small compared to the sheath dimension. Consequently the photoelectrons from Io are accelerated predominantly along the magnetic field line to several hundred kilovolts of energy. An estimate of the resulting particle maximum energy, current, and power as a function of Io's orbital position is given.

2. Review of Basic Model

The basic model to be discussed is that due to Gurnett (1972). An illustration of the model geometry with the important parameters indicated is shown in Figure 1.

Io's orbital velocity is different from the rotational velocity of Jupiter. Io, therefore, moves through the Jovian magnetic field producing a motional electric field. This field is directed toward Jupiter and results in a potential of up to ~ 700 kV across Io's diameter. Sheaths form around Io as a consequence of the current balance between photoelectrons emitted from the surface and thermal electrons collected from the magnetosphere. On the face of Io away from Jupiter, the surface potential is positive with respect to the plasma potential where a photoelectron sheath is formed. On the face toward Jupiter the surface potential is negative which creates a Debye sheath of thermal electrons.

Because of the large surface potentials compared to the potentials of the thermal or photoelectrons, the current I_p emitted in the Debye sheath region is predominantly from photoelectrons and the current I_e collected in the photoelectron sheath region is due to thermal electrons. The transition between the sheath regions (where $\Phi=0$) is determined by the current balance condition $I_e=I_p$ where $I=JA$; and J and A are the current density and the area of each region. The conductivity of Io σ_I is assumed sufficiently large that there is not a significant potential drop due to this current through Io.

These sheaths around Io can limit the current to Io and prevent the plasma from being frozen to the magnetic flux tube passing through Io. This frozen plasma is

assumed by the models of Piddington and Drake (1968), Goldreich and Lynden-Bell (1969) and Dermott (1970). The plasma is unfrozen from the motion of Io if the height integrated Pedersen Σ_p ionospheric conductivity is sufficiently high that currents flowing up and down the field lines are shorted across the field lines in the ionosphere.

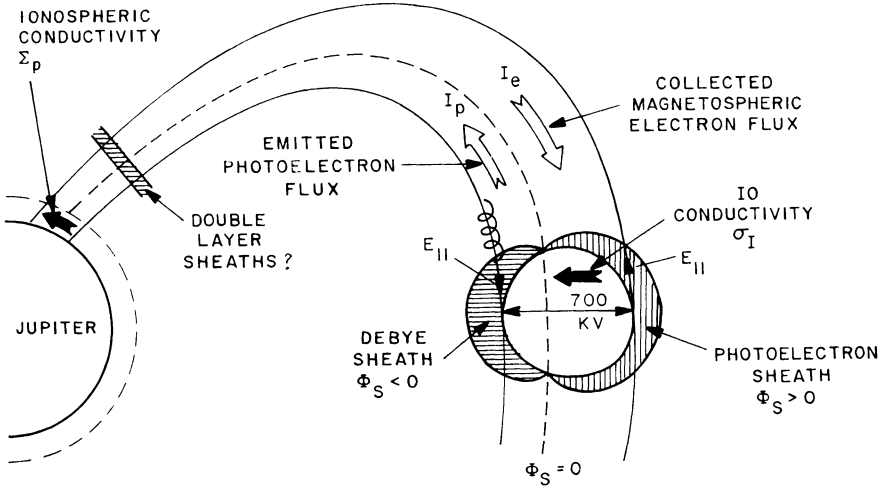


Fig. 1. A sketch of the basic Io sheath and current model with the important parameters indicated. Because of Io's motion through the Jovian magnetic field, a potential of ~ 700 kV is developed across Io. The position of the zero potential line ($\Phi_s = 0$) is determined by the current balance between the emitted photoelectrons and the collected magnetospheric electrons $I_e = I_p$. Where $\Phi_s < 0$ a Debye sheath forms and where $\Phi_s > 0$ a photoelectron sheath forms. If Σ_p the ionospheric height integrated Pedersen conductivity and the Io conductivity σ_I are sufficiently large, then the total potential drop will be across the sheaths. The emitted photoelectrons are accelerated through the Debye sheath along the magnetic field lines with energies of several hundred kilovolts.

The critical ionospheric conductivity for the plasma freezing is given by

$$\Sigma'_c = \frac{J_p l_p}{E_{Io}} (2 \cos \theta_{\text{colat}})^{-1}, \quad (1)$$

where l_p is the linear dimension in the ionosphere corresponding to the Debye sheath dimension at Io, J_p the photoelectron current density, E_{Io} the motional electric field across Io, and the $2 \cos \theta_{\text{colat}}$ accounts for the field line convergence. If $\Sigma_p > \Sigma'_c$ then the motional emf is developed across the sheath at Io. Photoelectrons emitted from the surface in the Debye sheath region are accelerated to hundreds of keV. These energetic particles may cause the observed decametric radio bursts related to Io.

3. Estimation of Model Parameters

In order to further assess the plausibility of this sheath model, working values for the key parameters have been re-evaluated based on a combination of calculations

TABLE I
Range and working value of assumed parameters

Parameter	Gurnett (1972)	Range	Working value
Photoelectron current density, J_p ($A m^{-2}$)	4.5×10^{-6}	1×10^{-7} – 3×10^{-6}	3×10^{-7}
Thermal electron current density, J_e ($A m^{-2}$)	4.0×10^{-7}	1×10^{-7} – 1×10^{-6}	3×10^{-7}
Critical ionospheric conductivity, Σ'_c (mhos)	4.8	0.2–3.2	0.6
Expected ionospheric conductivity, Σ_p (mhos)		0.33–20.	> 0.6
Critical Io conductivity, σ_c ($\Omega^{-1} cm^{-1}$)	2×10^{-8}	5×10^{-11} – 2×10^{-8}	5×10^{-11}
Expected Io conductivity, σ_I ($\Omega^{-1} cm^{-1}$)		10^{-31} – 10^{-1}	≈ 0 darkside $\approx \infty$ lightside

and available literature. These parameters as indicated on Figure 1 and listed in Table I are the photoelectron current density, the thermal electron current density, the Jovian ionospheric conductivity and the conductivity of Io.

3.1. PHOTOELECTRON CURRENT DENSITY

A realistic estimate of the photoelectron current density from Io must await more detailed knowledge of the state and composition of the surface material. An empirical determination of the photoelectron current density has been made, however, by scaling results from the Charged Particle Lunar Environment Experiment of Apollo 14. Typical measurements of photoelectron fluxes between 40 and 200 eV have been fit by curves which extrapolate the fluxes to lower energy (Reasoner and Burke, 1971, Figure 7 for $V=0.1$). We have integrated this curve to cutoff energies of 3 eV and 0.01 eV and scaled the value by 1/27 to account for the decrease in solar photon flux at Io. The resulting photoelectron current densities range between 1×10^{-7} and $3 \times 10^{-6} A m^{-2}$. We find that cutting off the spectrum near 3 eV is consistent with the photoelectron energy density value of $7.4 eV cm^{-3}$ which is 1/27 of $200 eV cm^{-3}$ determined for the Moon by Criswell (1971). We, therefore, choose a working value of $J_p \sim 3 \times 10^{-7} A m^{-2}$. Gurnett (1972) had used $4.5 \times 10^{-6} A m^{-2}$, as indicated in Table I, but considered that this value might be an order of magnitude high.

3.2. THERMAL ELECTRON CURRENT DENSITY

The thermal electron current density depends on the ambient electron number density and temperature. A magnetospheric model by Ioannidis and Brice (1971, Figure 11) gives values of ~ 3 electrons cm^{-3} and 10^5 K in the vicinity of Io. This value of number density is consistent with the upper limit < 10 electrons cm^{-3} placed on the magnetospheric number density from Faraday rotation measurements by Warwick and Dulk

(1964). Using these numbers we obtain a value for the thermal electron current density of $J_e = 3 \times 10^{-7} \text{ A m}^{-2}$. This value is consistent with Gurnett (1972). We consider that the value could easily range between 1×10^{-7} and $1 \times 10^{-6} \text{ A m}^{-2}$ as indicated in Table I due to Io's orbital inclination to the 'donut' of plasma density in the magnetic equatorial plane.

3.3. IONOSPHERIC CONDUCTIVITY

In order for the plasma to be unfrozen from the flux tube passing through Io at any instant, the ionospheric (height integrated Pedersen) conductivity must exceed a certain value. From Gurnett (1972) this value is given by Equation (1). Using the range of possible values for the photoelectron and thermal electron current densities we find the critical conductivity can range between 0.22 and 3.2. Using the working values for J_p and J_e , $\Sigma'_c = 0.6$ mhos. This value is lower than the 4.8 mhos of Gurnett primarily because of the lower photoelectron current density value.

Goldreich and Lynden-Bell (1969) calculate a height integrated Pedersen conductivity of 0.57 mhos but suggest that this value could be low by more than a factor of five. Brice and Ioannidis have estimated the conductivity to be 2–20 mhos. Using the Gross and Rasool (1964) and the Prasad and Capone (1971) Jovian upper atmosphere models, we obtain values of the conductivity ranging from 0.3 to 1.0 mhos. As pointed out by Gurnett (1972) these calculated values are valid only for the undisturbed ionosphere. Since our model predicts precipitated particles of up to a few hundred kilovolts energy, a significant amount of impact ionization would be expected which would increase the conductivity. Therefore it seems from a number of estimates that Io may be effectively decoupled from its field lines.

3.4. IO CONDUCTIVITY

In our model the conductivity of Io is important as it relates to the voltage drop across the Moon for the total current passing through it. Goldreich and Lynden-Bell (1969) estimate a critical conductivity for Io of $\sigma_c \approx 2 \times 10^{-8} \Omega^{-1} \text{ cm}^{-1}$. Dermott (1970) using a different model for the temperature dependent conductivity, obtains $\sigma_c \approx 5 \times 10^{-11} \Omega^{-1} \text{ cm}^{-1}$ at 100K. This conductivity corresponds to a resistance through Io of 0.2Ω . For $3 \times 10^{-7} \text{ A m}^{-2}$ collected over 25% of Io's area this resistance would drop the motional emf to approximately two thirds its value. We, therefore, take $\sigma_c \approx 5 \times 10^{-11} \Omega^{-1} \text{ cm}^{-1}$ as being the critical Io conductivity.

Possible values for Io's conductivity cover a very large range. Goldreich and Lynden-Bell (1969) guess the conductivity might be like the Earth's upper mantle and use $\sigma_1 \sim 10^{-5} \Omega^{-1} \text{ cm}^{-1}$. If Io is composed of olivines, in particular fayalite, then Dermott (1970) finds its conductivity would be $\sigma_1 \ll 10^{-10} \Omega^{-1} \text{ cm}^{-1}$ and perhaps as low as $10^{-31} \Omega^{-1} \text{ cm}^{-1}$ at 100K. An outer layer of (water) ice on Io would give a conductivity at 100K of $\sigma_1 \approx 10^{-25} \Omega^{-1} \text{ cm}^{-1}$. Lewis (1971) discusses a steady state thermal model for icy satellites including Io. He estimates that the inner Galilean satellites may have a surface coating of aqueous NH_3 solution with a conductivity as high as $10^{-1} \Omega^{-1} \text{ cm}^{-1}$, but cautions that this value may not apply directly to Io.

In order to present the least complicated model, we assume at present that $\sigma_1 \sim \infty$ on the dayside and $\sigma_1 \sim 0$ on the nightside compared to $5 \times 10^{-11} \Omega^{-1} \text{ cm}^{-1}$.

4. Energy Gain Across Sheath

A comparison of estimated conductivity values to critical values allows the possibility that the large potentials develop across the sheaths surrounding Io. Gurnett (1972) has implicitly assumed that the emitted photoelectrons will gain energy along the magnetic field lines equivalent to this potential. We have investigated this assumption in more detail using an oblique version of Child's law.

In Figure 2 is shown in geometry and coordinate system for a particle emitted from Io in the Debye sheath region. Two extreme possibilities exist for the emitted particle. If the gyroradius for the particle is larger than the sheath dimension or if the v_D is much larger than the velocity along the magnetic field v_{\parallel} , the particle would follow the path ab and would be recollected on the surface. At least it would not gain a significant amount of parallel energy. Path ac could be the case for $v_D \ll v_{\parallel}$ and for the gyroradius small compared to the sheath dimension.

Taking z along the magnetic field direction and x perpendicular to the magnetic field and the electric field \vec{E} initially radial, Poisson's equation can be written

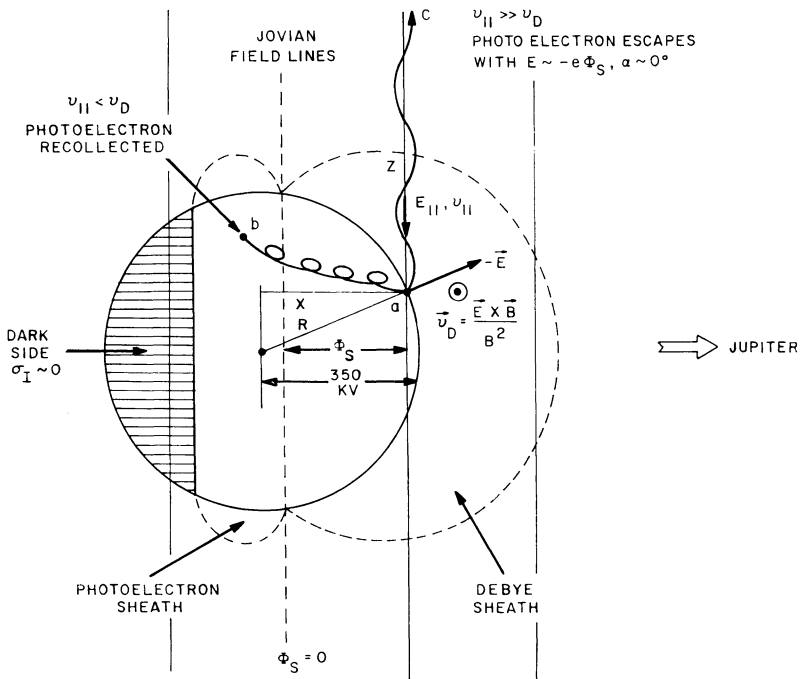


Fig. 2. Geometry for evaluating Child's Law where \vec{E} is not parallel to the magnetic field direction. For the electron gyro-radius large compared to the sheath dimension or $v_D \gg v_{\parallel}$ an emitted photoelectron would follow path ab . However, the sheath dimension is tens of kilometers and $v_{\parallel} > 10 v_D$. Photoelectrons gain nearly the surface potential at the emission point along the path ac .

$$\frac{d^2\Phi}{dz^2} = \frac{J}{\epsilon_0} \left(\frac{m}{2e}\right)^{1/2} \Phi^{-1/2} \left(\frac{z^2}{x^2 + z^2}\right), \quad (2)$$

where Φ is the potential and J the current density. We have solved this equation numerically for a photoelectron emitted at 45° latitude. The resulting sheath thickness is approximately 40 km ($=L_D$). For a 300 keV electron at Io the gyroradius would be approximately 200 m which is significantly less than the sheath thickness. Over the sheath region the ratio of drift to parallel velocity ranges from 10^{-1} to 10^{-2} . Consequently the assumption that photoelectrons follow path ac is well justified. Emitted photoelectrons therefore gain the large sheath potential in energy and these leave the sheath region with pitch angles peaked about 0° . A significant fraction of these particles can penetrate to the atmosphere of Jupiter.

5. Variation with Io's Orbital Position

From the proposed sheath model of Io's interaction with Jupiter, the main characteristics we can predict are those related to the accelerated particles which may be the cause of the observed decametric radio bursts. It is, therefore, of interest to see how the particle characteristics change with Io's orbital position. Our present model assumes that no photoelectrons are emitted and no magnetospheric electrons are collected on the dark side. The particles gain the surface potential in energy from the point that they are emitted. As Io moves around Jupiter, it is the position of the $\Phi_s=0$ V line and the photoelectron emitting area that changes. We have taken $J_p=J_e=3 \times 10^{-7}$ A m $^{-2}$ so that the current balance condition is reduced to equating the photoelectron emitting and magnetospheric electron collecting areas $A_p=A_e$.

TABLE II
Range of model dependent quantities with Io's orbit

Quantity	Range	Io angle at maximum
Particle maximum energy	156–396 keV	120°, 240°
Particle current	8.4×10^5 A	
Particle power	4.4×10^{11} –0 (occultation) W	90°, 270°
X-ray flux	5×10^{24} photons s $^{-1}$	

In Figure 3 the maximum potential obtainable by a photoelectron is plotted as a function of the Io orbital position. Toward the Earth (and Sun) is defined as the 180° position. At 0° , 90° and 240° the illumination and $\Phi_s=0$ line are illustrated. This maximum potential is seen to vary from 156 to 396 kV with peaks at 120 and 240° . Maximum power is imparted to the particles at 90° and 270° . This power is approximately 10^4 times that in a typical Jovian decametric burst. Other quantities of interest are recorded in Table II.

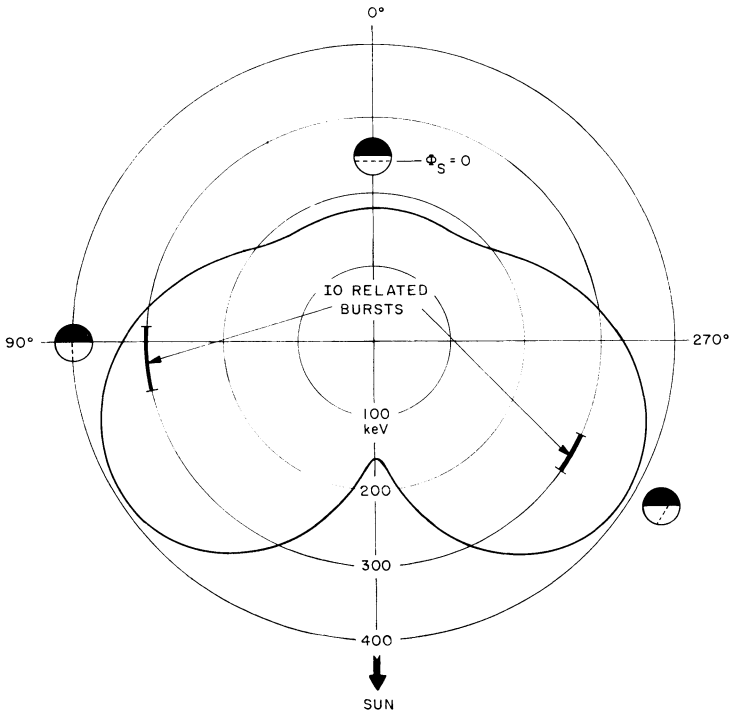


Fig. 3. The maximum energy gained by photoelectrons as a function of the Io orbit position. 180° is toward the Earth and Sun. The regions of Io related bursts are also indicated.

6. Discussion

By considering a number of points in detail, we feel that the sheath model proposed for Io and the acceleration of charged particles is plausible. Further development of the model should include detailed calculations of the particle energy and pitch angle distributions so that various emission mechanisms for radio noise can be tested. The effect of the tilted and possibly offset Jovian magnet dipole must be included. For instance, because of the 'donut' density distribution of thermal plasma, the thermal current density will change significantly with Io's orbital position. Also consideration should be given to the possibility of other sheaths detached from Io where particles might be accelerated or turbulent regions where anomalous resistivity could limit the current and modify the proposed model. Block (1972) discusses the possibility of double layer sheaths forming at density minima from field aligned currents flowing in the Earth's ionosphere. Several of these layers could be formed (indicated on Figure 1). In the laboratory these layers have been observed to appear and disappear at a 10–100 kHz rate. Such a time scale is suggestive of the Jovian S-burst duration.

Acknowledgements

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References

- Bigg, E. K.: 1964, *Nature* **203**, 1008.
 Block, Lars P.: 1972, submitted to *Cosmic Electrodyn.* **3**.
 Criswell, David R.: 1971, *EOS* **52**, 855.
 Dermott, S. F.: 1970, *Monthly Notices Roy. Astron. Soc.* **149**, 35.
 Duncan, R. A.: 1970, *Planetary Space Sci.* **18**, 217.
 Gledhill, J. A.: 1967, *Nature* **214**, 155.
 Goldreich, P. and Lynden-Bell, D.: 1969, *Astrophys. J.* **156**, 56.
 Gross, R. H. and Rasool, S. I.: 1964, *Icarus* **3**, 311.
 Gurnett, Donald A.: 1972, *Astrophys. J.* **175**, 525.
 Ioannidis, G. and Brice, N.: 1971, *Icarus* **14**, 360.
 Lewis, John S.: 1971, *Icarus* **15**, 174.
 Mozer, F. S. and Bogott, F. H.: 1972, *Astrophys. J.* **174**, 153.
 Piddington, J. H. and Drake, J. F.: 1968, *Nature* **217**, 935.
 Piddington, J. H.: 1972, *Cosmic Electrodyn.* **3**, 240.
 Prasad, S. S. and Capone, L. A.: 1971, *Icarus* **15**, 45.
 Reasoner, David L. and Burke, William J.: 1971, 'Direct Observation of the Lunar Photoelectron Layer', preprint Dept. of Space Science, Rice University.
 Schatten, K. H. and Ness, N. F.: 1971, *Astrophys. J.* **165**, 621.
 Warwick, J. W. and Dulk, G. A.: 1964, *Science* **145**, 380.

DISCUSSION

Thomas: The decametric radiation has a well-known frequency versus time structure. Do you attribute this structure to variations at the source or to changes in group-travel times of the various frequency components as they travel through Jupiter's ionosphere, as is done for example by Wu and co-workers (Univ. of Md.)?

Shawhan: I feel that the frequency time characteristics are due both to the emission mechanism and the propagation characteristics of the emitted radio waves.

Srnka: Your values of electron current densities mean that the drift velocities of the electrons are much larger than the ion sound speed, and nearly equals the electron thermal speed. This means the current-carrying plasma should be turbulent, and exhibit an anomalous plasma resistivity. Have you considered this?

Shawhan: We have considered anomalous plasma conductivity, but we have not yet made detailed calculations. At the moment, we cannot say whether a highly resistive plasma path for the current would be important in the problem.

Fredricks: Brice's model of the distribution of thermal plasma around Io's orbit, as I remember, is a pancake-like distribution confined quite closely to the equatorial plane. If this model is correct, then the strong field-aligned currents due to your runaway electrons would not lead to plasma turbulence and anomalous resistivity along field lines at higher latitudes. Thus, the absence of plasma along the field lines away from the equator means no background necessary to carry the plasma instability due to beam-plasma or streaming interactions, and thus it may be that a very high conductivity exists over most of the field line. Then, the important plasma wave stimulation would mainly occur when your runaway electron currents enter the low altitude Jovian ionosphere at the base of the field line.