IO-ACCELERATED ELECTRONS AND IONS

STANLEY D. SHAWHAN, CHRISTOPH K. GOERTZ, RICHARD F. HUBBARD,
DONALD A. GURNETT, and GLENN JOYCE
Dept. of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242, U.S.A.

1. Introduction

Earth-based measurements of the Io-modulation effect on Jovian decametric radio noise emission (Bigg, 1964) and the recently announced observation of intense Sodium-D optical emissions from the vicinity of Io (Brown, 1974) as well as various results from the Pioneer 10 Jupiter flyby (see *Science*, 1974) indicate that the Jovian moon Io (and possibly Europa and Ganymede) play an active role in the Jovian magnetosphere.

We have been developing a model in which Io interacts with the Jovian magnetosphere through plasma sheaths in the vicinity of Io across which particles are accelerated to energies approaching the motional potential across Io in the corotating Jovian magnetosphere (several hundred kilovolts). This model was first suggested by Gurnett (1972) and has been developed in more detail by Shawhan *et al.* (1973a), Hubbard (1973), Shawhan *et al.* (1973b), and Hubbard *et al.* (1974).

In this paper several recent results available from Pioneer 10 are used to revise this Io sheath model. The revised model is then used to suggest an explanation for a number of Earth-based and Pioneer 10 observations and to suggest other phenomena which might be detectable with future experiments.

2. Revised Model Based on Pioneer 10 Results

Two experiments operating during the Pioneer 10 flyby of Jupiter suggest a revision of the Io sheath model and allow several parameters to be better determined. The magnetometer experiment (Smith *et al.*, 1972) has lead to the value of 4 G R_J^3 for the dipole magnetic moment of Jupiter. At Io (at 6 R_J) the magnetic field is approximately 0.02 G. Previously (see Hubbard *et al.*, 1974) the field was assumed in the model to be 0.035 G. This reduced field yields a maximum value of about 400 kV for the potential across Io due to its motion through the Jovian magnetic field. Occultation of the *S*-band signal by Io has shown a well defined Io ionosphere extending out beyond 750 km in altitude and having a peak density of 6×10^4 electrons cm^{-3} at about 100 km altitude (Kliore *et al.*, 1974a). From the presence of this ionosphere, the experimenters also infer the presence of an atmosphere with a surface density of 10^{10}–10^{12} cm^{-3}. The existence of the Io atmosphere-ionosphere system makes the Io sheath model more plausible because it provides a path of sufficiently high conductivity to close the current system in the vicinity of Io as required by the model. Without the presence of an Io ionosphere it was questionable whether the Io surface

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conductivity could be sufficient (see Hubbard *et al.*, 1974). Also preliminary results about the Jovian ionosphere and atmosphere (Kliore and Fjeldbo, 1974) indicate that the Jovian ionosphere has about the predicted electron number density and therefore probably has sufficient conductivity to close the current system in that region (see Hubbard *et al.*, 1974).

Figure 1 depicts the scheme of the revised Io sheath model (see Gurnett, 1972 and Hubbard *et al.*, 1974 for original model). Io moving at a velocity of 56 km s^{-1} relative to the Jovian magnetic field of 0.02 G develops a $\mathbf{v} \times \mathbf{B}$ electric field directed toward Jupiter. This electric field produces a potential difference of about 400 kV across Io. Plasma sheaths are assumed to form at the top of the Io ionosphere to make the transition from the plasma moving with Io to that corotating with Jupiter. At the top of the ionosphere on the face of Io toward Jupiter, the plasma potential is negative with respect to the Jovian plasma potential. The opposite face has a positive plasma potential. Therefore we call these transition regions negative and positive sheaths, respectively.

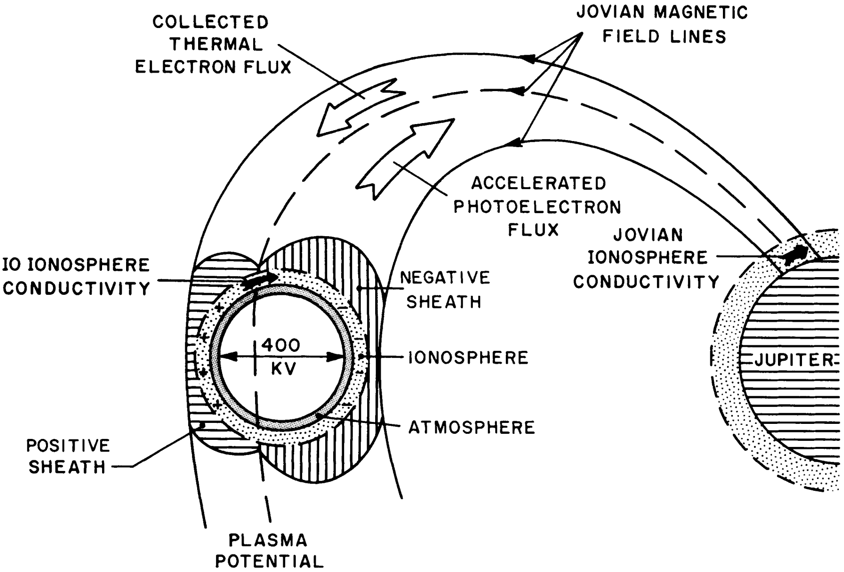

Fig. 1. Basic Io sheath configuration and electron flux path.

The negative sheath accelerates Io ionospheric electrons down the Io magnetic flux tube toward the Jovian ionosphere. Thermal plasma electrons are accelerated through the positive sheath into the Io ionosphere. Because of the dynamic resistance of these sheaths, the motional potential is dropped across these two regions. Accelerated particles can then attain energies of several hundred keV. These two electron fluxes constitute a current system which can be closed at the ends of the Io flux tube within the Jovian and the Io ionosphere. The relative surface area on Io covered by the negative and the positive sheaths is determined by the requirement of continuity in the total current; the electron flux times the sheath area must be equal on the two faces of Io. The relative areas then determine the faction of the motional potential available for inward and outward acceleration of particles (see Hubbard, 1973; Hubbard *et al.*, 1974).

Several model parameters can be determined from assumptions based on the Pioneer 10 observations of the Io ionosphere. The dusk dayside ionosphere shows a peak density of 6×10^4 electrons cm^{-3} in the range of 50–150 km altitude and an extent of about 750 km with a scale height of ~220 km (Kliore *et al.*, 1974a). Preliminary results for the dawn nightside ionosphere show a peak of 9×10^3 electrons cm^{-3} at ~50 km and an extent of ~200 km (Kliore *et al.*, 1974b). These profiles are presented in Figure 2. The discontinuity in scale height of the dayside ionosphere at 750 km is consistent with a sheath at this altitude. Taking the density of 2.5×10^3 electrons cm^{-3} and a temperature for sodium ions of 400K (Kliore *et al.*, 1974b) at the lower side of the sheath with $\frac{1}{4}$ of the flux directed upward, the maximum topside electron current density would be 1×10^{-5} A m^{-2} emitted from Io at this point. This current density corresponds to an electron flux of 6×10^9 electrons cm^{-2} s^{-1}.

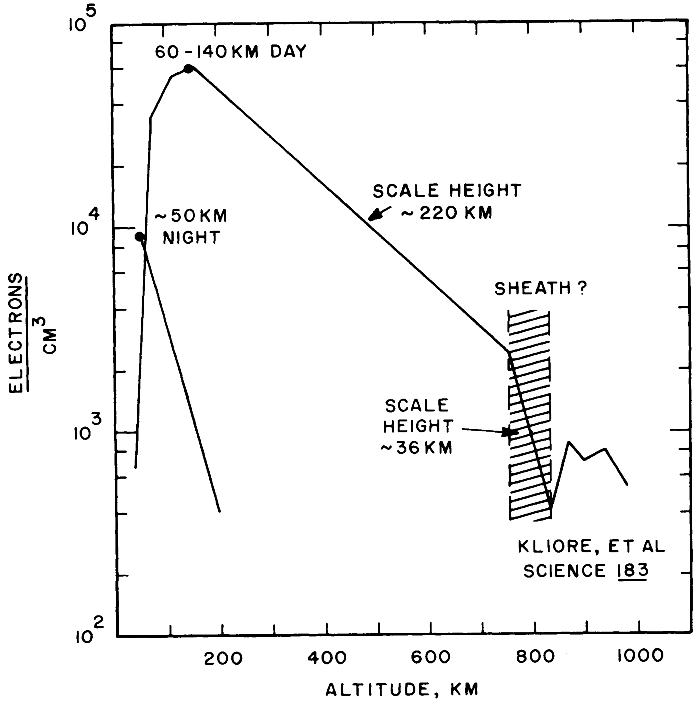

Fig. 2. Io dayside and nightside ionosphere (Kliore *et al.*, 1974a, b).

Measurements of the thermal plasma density and temperature were not made by Pioneer 10. An upper limit to the plasma density is available in the vicinity of Io from Figure 2. If it is assumed that the density above 850 km could be thermal magnetospheric plasma then an upper limit density would be $\sim 500\ \mathrm{cm}^{-3}$. The electron flux that can be accelerated into the Io ionosphere above the outward face is related to this density n_e and the electron temperature T_e by

$$F_e \sim n_e T_e^{1/2}.$$

Assuming $n_e = 200\ \mathrm{cm}^{-3}$ and $T_e = 10^5\ \mathrm{K}$ the flux would be 10^{10} electrons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ which is comparable to the outward accelerated flux.

Combining the measured Io ionosphere profile with the inferred atmosphere profile ($10^{12}\ \mathrm{cm}^{-3}$ surface density with 100 km scale height), the Io ionospheric conductivity can be calculated. Following the procedure of Webster *et al.* (1972) a value of 260 mhos is obtained for an equatorial belt region. This conductance is more than an order of magnitude larger than the conductance necessary to cause a significant potential drop at Io.

Since the Io ionosphere moves with Io and determines the Io 'surface' electrical properties, it seems reasonable to consider that the motional potential associated with Io is that developed across the Io ionosphere. For an ionosphere extending 750 km in altitude, the potential might be increased to ~ 580 kV.

A close-up view of the Io system is shown in Figure 3 roughly to scale. A significant atmosphere is inferred from the presence of an ionosphere with a maxima in the

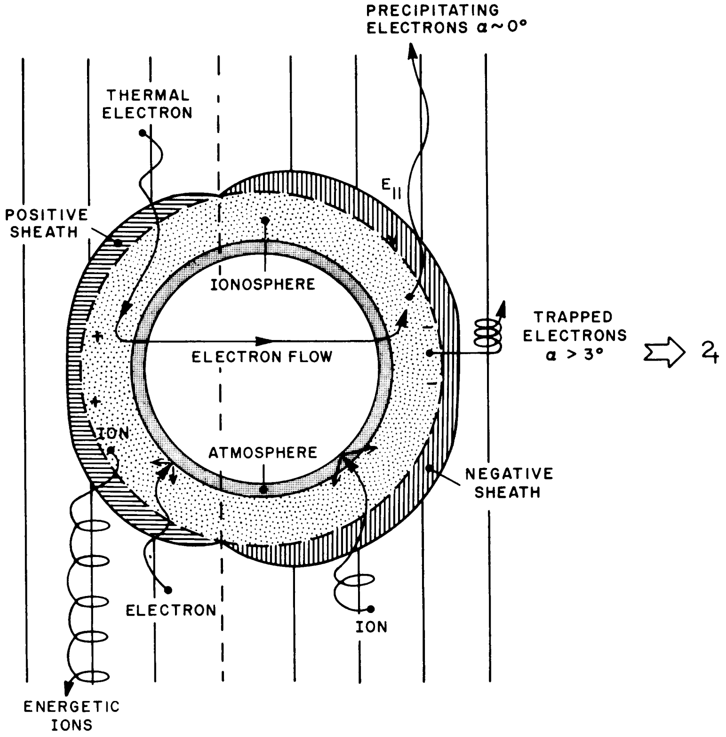

Fig. 3. Particle acceleration at Io.

density above the surface. We assume that the sheaths could be located at the top of the ionosphere. Characteristic sheath thicknesses have been estimated by Hubbard *et al.* (1974) to be in the range of 10 to 50 km. Since the sheaths separate two plasma regions with a strong current flowing between them, these sheaths are probably 'double layers' as described by Block (1972). From the work of Knorr and Goertz (1974) and of Goertz and Joyce (1975) a typical thickness for the double layer can be calculated. The relationship between the potential across a double layer and its thickness is given by

$$\frac{\phi}{L^2} \lesssim 0.14,$$

where ϕ is the potential in kT_e/e and L is the length in Debye lengths. For a number density of 2.5×10^3 cm^{-3}, a temperature of 400 K and a potential of 300 kV, the sheath thickness must be greater than $\frac{1}{4}$ km. For both thickness estimates the sheath size is larger than or comparable to a 300 keV electron gyroradius (~ 1 km) but comparable to or smaller than a 300 keV ion gyroradius (~ 50 km).

A qualitative picture of particle acceleration in the vicinity of Io is included in Figure 3. As mentioned earlier, the electrons carry the current in this dc circuit which is somewhat similar to the model of Goldreich and Lynden-Bell (1969). Although the ion currents are insignificant, the fluxes of accelerated ions may be significant and important to the Io related chemistry. The major features of particle acceleration are as follows:

2.1. FACE TOWARD JUPITER (NEGATIVE SHEATH)

2.1.1. *Electrons*

In the mid and high latitude regions of the Io face toward Jupiter a significant electric field component should exist in the magnetic field direction. Ionospheric electrons from this region can be accelerated to energies up to several-hundred keV. Because of the small random thermal energies, these electrons have pitch angles well within the Jovian atmospheric loss cone ($\alpha \lesssim 3°$) and are therefore beamed down the Io flux tube. This beam of $\sim 10^9$ electrons cm^{-2} s^{-1} from $\sim \frac{1}{2}$ of Io's area could constitute a current of 10^7 A which carries up to 10^{13} W of power.

In the equatorial latitude range the electric field has a significant component directed transverse to the magnetic field lines and if the sheath region is thin enough, some electrons could gain a substantial amount of perpendicular energy which would trap them on field lines just inside Io's orbit. These electrons could diffuse inward toward Jupiter and contribute to the synchrotron emitting electrons in the hard trapping region (see Shawhan *et al.*, 1973b).

2.1.2. *Ions*

This same negative sheath can accelerate ions to several hundred keV energies into the Io atmosphere toward the Io surface. An estimate of the proton flux can be made by assuming the same parameters as for the magnetospheric electrons ($T_i = 10^5$ K, $n_i = 200$ cm^{-3}). The flux is then $\sim 2 \times 10^8$ protons cm^{-2} s^{-1}. These fluxes exceed energetic proton fluxes measured by Pioneer 10 (*Science*, 1974) and may be significant for ion-sputtering of the Io surface.

2.2. FACE AWAY FROM JUPITER (POSITIVE SHEATH)

2.2.1. *Electrons*

Thermal plasma electrons from the magnetosphere can be accelerated through the positive sheath region to several hundred keV energies. As indicated in Figure 3 these electrons are directed into the ionosphere and atmosphere of Io. The fluxes may be in the range of 10^9 to 10^{10} electrons cm^{-2} s^{-1} which is sufficient to cause optical emissions, impact ionization and heating. Primary and secondary electrons are conducted into the negative sheath region to complete the electron current circuit.

2.2.2. *Ions*

Ionospheric ions are accelerated through the sheath away from Io. Because of the small sheath size compared to a gyroradius most of these ions should gain perpendicular energy and be trapped on field lines just outside Io's orbit. If Sodium ions are assumed (Kliore and Fjeldbo, 1974) the flux could be as high as 3×10^7 ions cm^{-2} s^{-1} for energies up to several hundred keV.

TABLE I

Table of physical parameters

Parameter	Value
1. Maximum sheath potential (Maximum particle energies)	400 kV across Io 580 kV across Io ionosphere
2. Characteristic sheath thickness at $\sim$750 km altitude above Io ionosphere	$\frac{1}{4}$ to 50 km
3. Io ionospheric conductance (height integrated)	260 mhos
4. Maximum current density in Io flux tube near sheath;	1×10^{-5} A m^{-2}
Maximum electron flux in Io flux tube near sheath $<$580 keV	6×10^9 electrons cm^{-2} s^{-1}
5. Maximum proton flux available for sputtering $<$580 keV	2×10^8 ions cm^{-2} s^{-1}
6. Maximum electron flux precipitating into Io atmosphere for thermal plasma around Io of $\sim$200 cm^{-3} at 10^5 K	$\sim 10^{10}$ electrons cm^{-2} s^{-1}
7. Maximum outward flux of energetic Na$^+$-ions	3×10^7 ions cm^{-2} s^{-1}
8. Maximum power carried down Io flux tube	$\sim 10^{13}$ W

Important quantities deduced for this revised Io sheath model based on the Pioneer 10 measurements are summarized in Table I. These quantities are used later in the explanation of observed phenomena related to the Io-Jupiter interaction.

3. Related Pioneer 10 and Earth-Based Observations

A variety of observations from Earth-based and Pioneer 10 measurements seem to be associated with the Io-Jupiter interaction and related to the Io sheath model for this interaction. In Figure 4 the Pioneer 10 trajectory, the position of Io at the time Pioneer 10 crossed the Io orbital radius ($\sim 6\ R_J$), and a summary of observed phenomena are schematically depicted. The important characteristics of these phenomena are as follows:

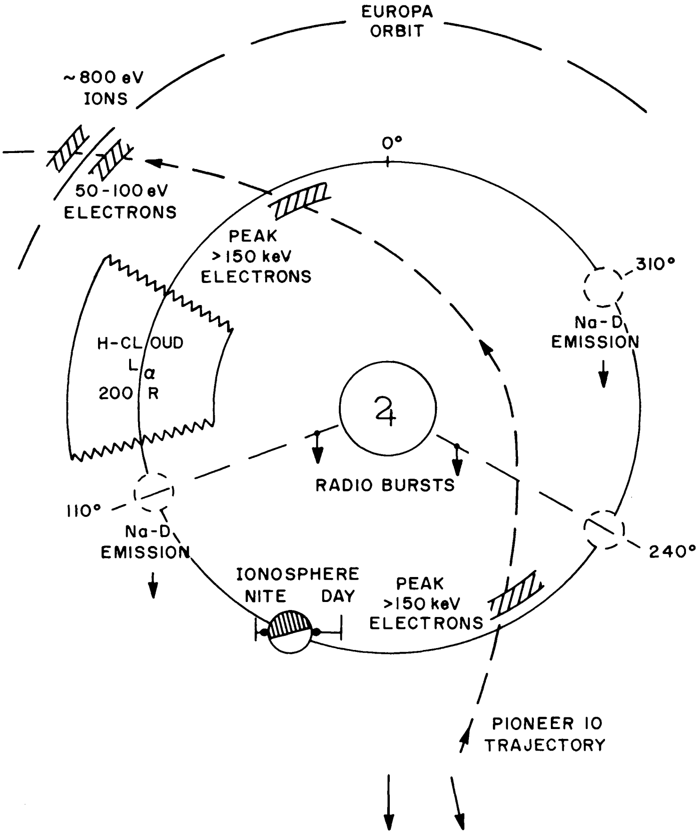

Fig. 4. Summary of related Pioneer 10 and Earth-based observations.

3.1. Peak in >150 keV electrons

From their experiment on Pioneer 10 McIlwain and Fillius (1974) observe a peak in the >150 keV electrons at $\sim 5.6\ R_J$ on the inbound and outbound pass which they attribute to injection by Io. The flux of these electrons above the background is about 2×10^7 cm^{-2} s^{-1} and the pitch angle distribution appears to be peaked in the perpendicular direction so that these electrons are trapped (Fillius, 1974).

3.2. NON-THERMAL ELECTRONS AND IONS

In crossing the orbit of Europa on the outbound pass of Pioneer 10, Frank and Ackerson (1974) have detected the presence of nonthermal electrons and ions using data from the plasma analyzer experiment (Wolfe *et al.*, 1974). These data show that electrons with a peak energy of 50 to 100 eV are present just inside the orbit of Europa and that ions with ~ 800 eV energy exist just outside the Europa orbit, A very preliminary estimate yields a number density of ~ 100 cm^{-3} for the ions. The possibility of non-thermal electron and ion populations with the same relative orbital positions at Io and Ganymede is also indicated by the data.

3.3. HYDROGEN Lα EMISSION

From a preliminary analysis of the Pioneer 10 ultraviolet photometer data Judge and Carlson (1974) suggested that Io might have a hydrogen Lα glow of 10 kR and that Jupiter is surrounded by a hydrogen torus with a mean diameter equal to the Io orbit and an uv intensity of several hundred rayleighs in Lα. Subsequent analysis (Judge, private communication, as quoted in McElroy and Yung, 1974) indicates that all the radiation comes from an extended cloud which precedes and follows Io in its orbit. The Lα intensity is 200 R and the cloud has dimensions of 120° in the Io orbital plane and less than one Jovian diameter perpendicular to the orbital plane. McElroy and Yung (1974) conclude that this emission is probably due to resonance scattering of sunlight although atmospheric air glow at Lα and emissions at Lβ and Balmer-α if detected could be due to corpuscular bombardment.

3.4. IO-ASSOCIATED SODIUM-D LINE EMISSION

The intense sodium-D line emission from the vicinity of Io announced by Brown (1974) have been further studied and interpreted by Brown and Chaffee (1974), Matson *et al.* (1974), Trafton *et al.* (1974), and McElroy and Yung (1974). Brown concluded that the sodium emissions were definitely associated with Io and deduced a column density of 2×10^{12} cm^{-2}. Peaks in the time varying emissions were observed to occur for Io at about 110° and 310° from superior geocentric conjunction as shown in Figure 4. Trafton *et al.* found that the sodium cloud extended to more than 10″ in radius from Io, and that the emission was stronger close to the orbital plane and especially on the face of Io toward Jupiter. Matson *et al.*, Trafton *et al.*, and McElroy and Yung agree that emission is probably due to resonant scattering of sunlight. Matson *et al.* and McElroy and Yung suggest that the sodium exists as an impurity in perhaps ammonia ice on the Io surface which is released by ion sputtering of the surface. The observed cloud requires a flux of $\sim 10^7$ atoms cm^{-2} s^{-1} from Io which could be provided by a flux of $\sim 10^8$ protons cm^{-2} s^{-1} or a lower flux of heavier ions which may include a cascade process (Matson *et al.*, 1974).

3.5. Io IONOSPHERE

A significant Io ionosphere has been reported by Kliore *et al.* (1974a, b) for both the illuminated side (solar zenith angle = 81°) and the dark side as shown in Figure 2. The illuminated side ionosphere has a scale height consistent with the presence of Na^+ ions (Kliore and Fjeldbo, 1974; McElroy and Yung, 1974). However, the dark side ionosphere has a significantly lower scale height and the peak density occurs at a lower altitude. McElroy and Yung consider six different models to explain the Io ionosphere. They conclude that dayside and nightside results can be made consistent if there are finite vertical drifts (upward during the day and downward at night ~ 1 km s^{-1}) which could be due to evaporation or condensation of gases on the surface or due to motional electric fields. Another plausible model requires incident corpuscular radiation such as 10 keV electrons or 10 MeV protons of $\sim 3 \times 10^7$ cm^{-2} s^{-1} on the dayside and about 1% of this flux on the nightside.

3.6. Io-MODULATED DECAMETRIC RADIO EMISSION

The earliest evidence for Io's interaction with the Jovian magnetosphere comes from the Io modulation of the Jovian decametric radio bursts (Bigg, 1964). Bursts of up to 10^8 W and less than 40 MHz in frequency are observed for Io at orbital positions of $\sim 90°$ and 240° from superior geocentric conjunction and for several ranges of Jovian central meridian longitude. These bursts are thought to be due to beamed radiation from a very small source region near the Jovian ionosphere at the foot of the Io magnetic flux tube (see Warwick, 1967; Carr and Gulkis, 1969). Recently Europa-modulation of bursts at ~ 1 MHz has been reported (Carr, 1974).

4. Io Sheath Model Explanation of Observations

The particle acceleration mechanism which we propose for the vicinity of Io seems to explain, at least qualitatively, the experimental results enumerated in the previous section. These explanations are summarized schematically in Figure 5.

4.1. ELECTRONS > 150 keV

Energetic electrons with energies < 580 keV fluxes $< 6 \times 10^9$ cm^{-2} s^{-1} and small pitch angles are predicted to exist within the Io flux tube inside the Io position (see Gurnett, 1972; Shawhan *et al.*, 1973a, b). It is felt that a significant fraction of these electrons could gain energy perpendicular to the magnetic field and be trapped so that they would be observed at Io's orbit. As suggested earlier, the mechanism for perpendicular energy gain could be acceleration through a sheath thinner than a gyroradius perpendicular to the Jovian magnetic field. Also electrons could be backscattered at some point in the Io flux tube due to an instability (Goertz, 1973a) and consequently trapped. Consideration has not been given to distortion of the magnetic field in the vicinity of Io due to the current system (Goertz, 1973b). This distortion may be important for creating a trapped electron population. To calculate the possible equilibrium flux of trapped electron requires an experimental estimate of the energetic electron diffusion coefficient which is not yet available.

4.2. NON-THERMAL ELECTRONS AND IONS

The separation of non-thermal particle populations with ions just outside and electrons just inside the moon's orbit follows from the polarity of the sheath acceleration. For all of the moons the electric field would be directed toward Jupiter. The particle energies observed at Europa by Frank and Ackerson (1974) suggest a sheath system with a total potential of several kilovolts. From the motion of Europa in the Jovian magnetic field a maximum potential of ~200 kV might be expected (~40% Io, see Dermott, 1970). The lower observed potential can be explained if Europa has little or no ionosphere and a low surface conductivity. A similar situation may exist at Ganymede.

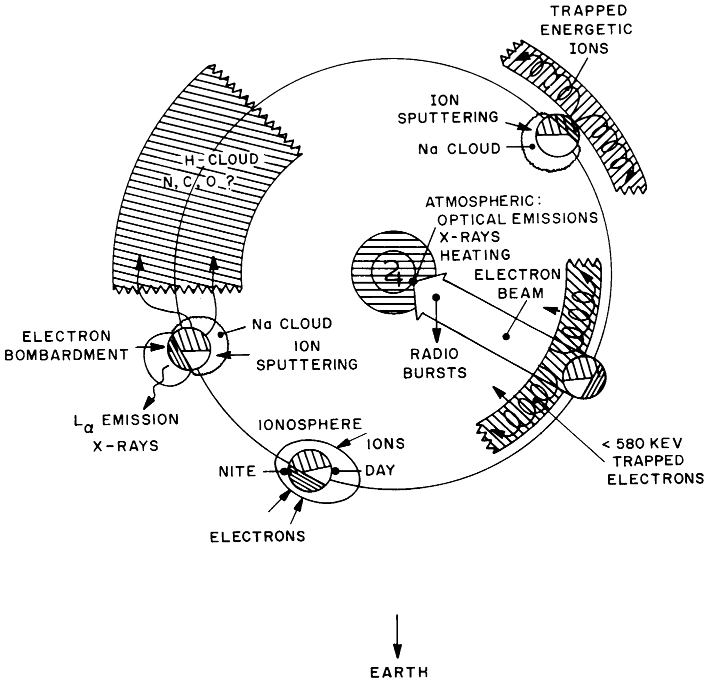

Fig. 5. Consequences of Io-accelerated particles.

4.3. HYDROGEN $L\alpha$ EMISSION

According to McElroy and Yung (1974) the presence of hydrogen in the partial torus associated with Io can be explained by a thermal escape flux of 10^{11} atoms cm^{-2} s^{-1} which could be maintained by photolysis of atmospheric NH_3. We suggest that the inward accelerated ion flux which impacts the Io surface facing Jupiter may be important for the liberation of NH_3 into the atmosphere by sputtering. Clouds of other components such as C, N and O might also be expected. The limited extent of the hydrogen cloud requires a rapid loss process. McElroy and Yung (1974) suggest that hydrogen can be lost by charge exchange with $\sim 10^9$ cm^{-2} s^{-1} fluxes of low energy protons. Io could be producing fluxes of $\sim 10^8$ protons cm^{-2} s^{-1} with energies up to several hundred keV from the face away from Jupiter which may contribute to the loss process.

Io accelerated electrons and ions impinging on the ionosphere and atmosphere should produce other observable optical emissions.

4.4. Io-ASSOCIATED SODIUM-D OPTICAL EMISSIONS

Ion sputtering of the Io surface seems to be the most plausible explanation for the release of sodium into the vicinity of Io (Matson *et al.*, 1974; McElroy and Yung, 1974). Our model accelerates ions into the face of Io toward Jupiter. This is the face for which Trafton *et al.* (1974) observed the more intense sodium emissions. A flux of sodium atoms of 2×10^7 atoms cm^{-2} s^{-1} is necessary to maintain the observed sodium cloud (McElroy and Yung, 1974) which requires an incident energetic proton flux of 10^8 cm^{-2} s^{-1}, a lower flux of heavier energetic ions or a cascade process (Matson *et al.*, 1974). According to our calculations the proton flux accelerated by Io would be 10^8 cm^{-2} s^{-1} and 3×10^7 cm^{-2} s^{-1} if sodium ions. As pointed out by Matson *et al.*, the sheath thickness is less than an ion gyroradius so that it could be that liberated sodium ions are energized and could reimpact the surface to liberate more sodium atoms and ions in a cascade process. The primary energetic ion fluxes as observed with Pioneer 10 (*Science*, 1974) are insufficient to provide the necessary sodium flux.

Matson *et al.* (1974) and Trafton *et al.* (1974) suggest that the sodium emission is excited by resonant scattering of sunlight. McElroy and Yung (1974) favor a combination of sunlight scattering and of collisional excitation in the atmosphere with light scattering in the extended could. From our model energetic electrons are accelerated into the Io atmosphere on the face away from Jupiter. The sporadic nature of the enhanced sodium emissions (Brown, 1974) may be explained by requiring a significant production of Na by ion sputtering and sufficient excitation by electron impact as viewed from the Earth. These conditions vary with Io's orbital position and with its latitude with respect to the magnetic equatorial plane.

4.5. Io IONOSPHERE

McElroy and Yung (1974) show that the two observations of Io's ionosphere at ~ 0700 and ~ 1900 local Io time cannot be compatible unless strongly time dependent particle influxes or bulk motions of the ionosphere are invoked. It is not obvious that such variations are related to the difference between the illuminated and the dark sides of Io. We propose a different explanation in the context of the Io sheath model for which the ionosphere formation may be related to the particular face of Io – toward or away from Jupiter. On the face toward Jupiter ('illuminated' side when observed by Pioneer 10), ions are injected which tends to inflate the ionosphere. On the face away from Jupiter ions are lost so the ionosphere tends to be deflated. Also it could be assumed that the ionosphere is maintained by photoionization (or impact ionization) of ion sputtered sodium. On the face toward Jupiter the accelerated ions provide a directed flux of 10^8 cm^{-2} s^{-1} for sputtering so that a significant ionosphere would be expected. On the face away from Io primary protons from the radiation environment are decelerated so that only ions with energies greater than several hundred keV could impact the surface. The flux of these ions is $\lesssim 10^7$ cm^{-2} s^{-1} as measured by various experiments on Pioneer 10 (*Science*, 1974). Consequently a less significant ionosphere would be expected.

4.6. IO-MODULATED DECAMETRIC RADIO EMISSION

As yet a detailed model of Io-modulated decametric radio emission has not been developed in the context of the Io sheath model. Energetic electrons with energies up to several hundred keV energies constitute a current of $\sim 10^7$ A in the Io flux tube and transport 10^{13} W toward the Jovian ionosphere. The emission mechanism needs to be only 10^{-4} to 10^{-5} efficient to explain the power in the decametric bursts. One suggestion is that the bursts may be related to instabilities or to the formation of double layers along the Io flux tube which produce coherent emission from a small source region (Shawhan *et al.*, 1973a). Radio emission associated with Europa may be explicable by a similar mechanism.

4.7. JUPITER-ASSOCIATED X-RAYS

Remote measurements have been made to detect Jovian X-rays using the Uhuru (Hurley, 1975) and Copernicus (Vesecky *et al.*, 1975) satellites. Upper limits to the X-ray flux at the Earth in the energy range of 2–6 keV are 5×10^{-4} cm^{-2} s^{-1} and in the range 0.6 to 1.9 keV 8×10^{-3} cm^{-2} s^{-1} respectively. An order of magnitude estimate can be made from the Io sheath model for the X-ray flux from the Jovian atmosphere at the root of the Io flux tube and from the Io atmosphere. For both cases an electron flux $\sim 10^9$ electrons cm^{-2} s^{-1} is associated with an area of $\sim 10^{17}$ cm^2. Assuming a constant energy spectrum to 300 keV (Hubbard *et al.*, 1974) the specific source intensity is approximately 3×10^{23} electrons s^{-1} keV^{-1}. For a photon efficiency of $\sim 10^{-2}$ the photon intensity is approximately 10^{22} photons s^{-1} keV^{-1}. The corresponding flux at the Earth would be 10^{-5} photons cm^{-2} s^{-1} keV^{-1} which is more than an order of magnitude below the detection limit of either experiment. To detect these X-rays it seems that a Jupiter orbiter experiment located outside of the hard trapping region is necessary.

5. Further Consequences of the Sheath Model

If the precipitating electron beam, associated with the Io flux tube, exists and reaches the Jovian atmosphere, then ionization, optical emissions and atmospheric heating should result as the beam is dissipated in the atmosphere. Estimates of these effects are made to see if they are significant and to suggest further experimental observations.

5.1. BEAM DISSIPATION AND ATMOSPHERIC IONIZATION

A model calculation has been carried out to determine the penetration depth of the Io-related precipitating particle beam and the resulting impact ionization. The initial electron spectrum at the top of the Jovian atmosphere is assumed to have a flux of 10^9 electrons cm^{-2} s^{-1} keV^{-1} up to 300 keV where account has been taken for the field line convergence. A model atmosphere due to McElroy (1973) was used. Energy loss was assumed to be by impact ionization only (30 eV for each collision) with a cross section varying as $E^{-1} \ln E$ and having a value of 2×10^{-19} cm^2 at 100 keV.

The beam was completely dissipated at about 0 km altitude (the Jovian cloud tops) so that the associated effects would occur above this altitude. In the ionospheric region (100–400 km), the impact ionization rates are several orders of magnitude below the photoionization rates. The maximum contribution to the electron density is 10^4 electrons cm^{-3} at 200 km (for a radiative recombination coefficient of 6.6×10^{-12} cm^3 s^{-1}) which is 10% of the photoionized density.

5.2. OPTICAL EMISSIONS

Optical emissions associated with the probable atmospheric constituents (H, H_2, He, CH_4 and NH_3) are expected due to energetic electron excitation. These electrons could be those precipitating due to Io or those precipitating from the radiation belts.

For the Io-related electrons a power flux of 10^{13} W spread over 10^5 km^2 (10^{-5} of the disk area) yields a maximum energy flux of 10^5 erg cm^{-2} s^{-1}. Rees (1973) has carried out model calculations that indicate an upper limit Hα (6563 Å) intensity of about 10^3 kR for this input energy flux. Dulk and Eddy (1966) searched for Hα emission from Io-related electrons. With a threshold of 1.2 kR no aurora were observed. Although their entrance slit aperture is not specified it would have to cover only 10^{-3} of the disk area to be able to observe the predicted optical intensity.

Based on Rees' calculations and the 10^5 erg cm^{-2} s^{-1} energy flux, the most intense radiations with 10^4 kR could occur for the Lyman series from H_2, for the Werner series from H_2 and for some singlet line emissions from He especially at 10830 Å.

5.3. ATMOSPHERIC HEATING

Energy not lost from the Io electron beam by radio emissions, by ionization or by optical emissions goes into heating the Jovian atmosphere. Assuming that the other losses are insignificant, the 10^5 erg cm^{-2} s^{-1} energy flux, at least locally, probably exceeds other energy sources. Consequently, a hot spot or warm strip may exist associated with the foot of the Io field line. Such a feature would have a linear dimension of $R_J/500$ so that it would be observable with the Pioneer 10 and 11 IR radiometer (resolution of $R_J/100$, Chase *et al.*, 1974). This localized heat source might be important in understanding the atmosphere dynamics.

6. Summary

By using Pioneer 10 results concerning the Jovian magnetic field and the Io ionosphere we have quantitatively revised the Io sheath model for the interaction of Io with the Jovian magnetosphere by accelerated particles. This model has then been invoked to explain qualitatively and somewhat quantitatively a number of experimental results derived from Earth-base and the Pioneer 10 flyby observations. The agreement between the model and the experimental observations suggests that this Io sheath model is plausible and that it can be used to make quantitative predictions to test against further experimental results.

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