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THE PROBLEM OF COOLING THE COLD IO TORUS

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Abstract. The transport of ions inward from Io's orbit is first modeled on the assumption that radial diffusion is the dominant transport mechanism and then modeled with a combination of diffusive and convective transport. Included in the model are thermal as well as number density transport, radiation, ionization and pickup of local neutrals, recombination, charge exchange, and Coulomb interactions. Pure diffusive transport is capable of accounting for the dramatic inward depletion of the torus only by invoking recombination or by postulating a massive increase in the production rate of torus ions sometime prior to Voyager encounter. It is shown that radical time dependence (it is necessary to increase the source strength by a factor of $\gtrsim$20 before the arrival of Voyager) cannot account simultaneously for the density and temperature observations. Similarly, recombination is found to be much too slow to be the cause of the observed density decrease inside of Io. The model combining convection and diffusion can reasonably match the data, but only with a diffusion coefficient 100 times less than that derived from Pioneer observations. It is shown that the Pioneer derived diffusion rate combined with Voyager temperature and density measurements imply a large non-radiative sink of energy in the inner torus.

Introduction

Voyager observations of the region around Io have revealed a plasma torus filled with heavy ions, predominantly sulphur and oxygen [Bridge et al., 1979; Broadfoot et al., 1979]. The densities of these ions decrease rapidly inside of Io, dropping by a factor of 50 in one Jovian radius (R_J), while outside of Io the density decreases much more gradually [Bagenal et al., 1980; Bagenal and Sullivan, 1981]. Ground-based observations of S II emissions from Io's torus indicate that it has existed since 1975, although possibly with somewhat lower densities than those observed by Voyager and with considerable time variability [Mekler and Eviatar, 1980; Trafton, 1980]. A recent reanalysis of in situ Pioneer 10 data indicates that some heavy ions were present in 1973 with a density profile similar in shape to that observed by Voyager in 1979 [Intriligator and Miller, 1981].

The ion temperature behaves similarly to the density, falling off rapidly inside of Io from a temperature of 30 eV at Io's orbit (L = 5.9) to less than 1 eV at L = 5 [Bagenal et al., 1980]. The electron temperature in the cold torus is about 5 eV from L = 6 to L = 5.5 and then falls to less than 1 eV by L = 4.9 [Scudder et al., 1980].

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A model based on the assumption that radial diffusion is the primary transport mechanism was used by Richardson et al. [1980] to fit the total ion density. It was known before this that in steady state solutions to the diffusion equation the density increases inward from Io and reaches a maximum inside of L = 2 [Siscoe, 1978]. Richardson [1980] allowed the possibility of a time dependent source and showed that in order for the diffusion model to fit the inward density decrease observed by Voyager, plasma injection must have increased substantially within 100 days prior to the arrival of the Voyager 1 spacecraft. The density decrease inside of Io is explained in this model by requiring the onset of ion injection to be too recent for diffusion to have populated fully the inner region. They also concluded that outward diffusion occurs much faster than inward diffusion, which they interpreted in terms of the action of centrifugally driven interchange diffusion outside of Io's orbit.

Because of the large decrease in density toward Jupiter, the explanation in terms of time dependence implied that prior to the postulated increase in the injection rate, the Io source strength was at least a factor of 20 less than the value at the time of the Voyager encounter. In addition, this reduced level must have been maintained for an interval of several diffusion time scales. Such a large change in injection rate is difficult to support in light of the relative stability of the neutral sodium cloud [Goldberg et al., 1980] and the relatively small changes in UV torus emission seen prior to and subsequent to Voyager encounter [Sandel et al., 1979]. Part of the motivation for this study was to investigate the possible role of recombination in contributing to inward density decrease.

The study of Richardson et al. [1980] also yielded a value for the Io source strength at the time of the Voyager encounter, namely $2\times10^{29\pm1}$ ions/s. Other determinations of the source strength have been made. Methods used included calculating the ion creation rate needed to maintain the radiation from the Io torus [Broadfoot et al., 1979] and from the Jovian aurora [Dessler, 1980; Eviatar and Siscoe, 1980; Sullivan and Siscoe, 1982] and to fix the radial distance at which corotation breaks down at its observed location [Hill, 1980], and to produce the degree of ionization of ion species in the hot torus [Shemansky, 1980]. These separate calculations define a range for the source strength of $\sim 10^{28\pm1}$ ions/s.

It has been proposed [Dessler et al., 1981; Hill et al., 1981] that an organized convection system exists in the torus region as a result of asymmetric mass loading of the torus. In the active sector of the magnetosphere where the magnetic field is below average the mass per unit magnetic flux is greater than it is in the non-active sector. This results in an outward flow in the active sector and a compensating inward flow in the nonactive sector. If the convection velocity V_c is primarily radial and is much less than the corotation speed, then $V_c \propto L^4$ [Hill et al., 1981], where $L = R/R_s$ is the McIlwain parameter. Voyager 1 was in the active sector when it passed through Io's torus, so the convection model predicts that observations made by Voyager are of an outward flowing plasma. This gives rise to another possible explanation for the density and temperature decreases inside of Io; the observations are of a steady state situation in which an inward diffusing front is held stationary by the outward flow.

In this paper we extend the model of Richardson et al. [1980] to include information on individual ion species and charge states, and we add as dependent parameters the ion and electron temperatures. This involves incorporating in the model the process of thermal diffusion, radiation, recombination, ionization, charge exchange, and temperature equilibration through Coulomb interactions. The effects of convection are simulated by adding a convective term to the energy and ion transport equation. The density outside of Io has been determined to be consistant with a steady state model with a fairly rapid diffusion rate [Froidevaux, 1980; Siscoe et al., 1981]. We therefore restrict ourselves to looking at the region inside Io's orbit with the objective of accounting for the sharp density and temperature decreases observed there.

We will look at three different scenarios that could account for the observations. In the time dependent, purely diffusive case the source of ions turns on at some finite time before the arrival of Voyager. The plasma diffuses inwards and cools until it reaches the configuration observed at the time of Voyager. After the passage of Voyager the density profile evolves until it approaches the steady state profile predicted by Siscoe [1978] or until the source rate of ions changes again. The other two scenarios are steady state situations. In one the inward diffusing ions are lost via recombination, such that a steady state profile results. In the other convection is added, such that the outward convective flow of plasma balances the inward diffusion of plasma. We have ignored precipitation as a possible loss process; although the ions themselves are too cool to precipitate, they could be lost with the help of a field-aligned potential of ∿ 1 kV, and electrons can precipitate easily if a mechanism is available to scatter them in pitch angle.

The Model

Qualitatively, the process we are trying to model are as follows. At some time t = 0, Io begins injecting heavy ions into the torus. Whether the ions are injected directly or whether they originate in a neutral cloud that has itself been injected from Io is not important for the present calculation. The outward diffusion rate is significantly faster than the inward diffusion rate, so that the torus outside of Io's orbit reaches its steady state configuration, while inward diffusion is just beginning. Ions and electrons diffuse inwards from the outer torus, bringing energy with them. They are subject to ionization, recombination, charge exchange, and radiative cooling as they move inward. Electrons lose energy by exciting ions through collision. The ions then radiate away this energy, mostly in the UV, when returning to the ground state. The ion population can gain energy through the processes of charge exchange and electron impact ionization of neutrals. Both of these processes result in the creation of new ions that have an initial thermal energy equal to their corotation energy, on the order of several hundred eV. Electrons and ions can also exchange energy via Coulomb collisions.

The governing equation for radial transport is

$$V_c \frac{\partial N_i L^2}{\partial L} + \frac{\partial (N_i L^2)}{\partial t} = L^2 \frac{\partial}{\partial L} \frac{D_{LL}}{L^2} \frac{\partial}{\partial L} (N_i L^2) + S_i - R_i \quad (1)$$

[Falthammer, 1968; Siscoe, 1978], where N is the number of ions in a magnetic flux shell per unit L, D_{LL} is the diffusion coefficient, usually taken to be of the form $D_{LL} = KL^m$, where K and m are constants, $V_c = V_{Io} (\frac{L}{5.9})^4$ is the convection velocity, and S and R are the source and loss terms, respectively, for NL^2. We include in our model seven species of oxygen and sulphur that have been detected in the torus: S II, S III, S IV, S V, O II, O III, and O IV. The minor ions (K, Na) and protons are not included. For each species the source term in (1) is the sum of the ions that recombine from the next highest charge state and those that are ionized from the next lowest charge state, plus those that are created by ionizing neutrals and by charge exchange. Each species likewise suffers losses from ionization, recombination and charge exchange. Singly charged ions that recombine to form neutrals and neutrals that are formed in the charge exchange process are assumed to be lost from the system since they are no longer magnetically bound and they have velocities greater than the gravitational escape speed. Also, their transit time out of the torus is short in comparison with the ionization time.

The ionization terms are of the form $I = q(T_e) n_i n_e$ for the ionization of ions and $I = q(T_e) n_N n_e$ for the ionization of neutrals, where n_i, n_e, and n_N are the number densities of ions, electrons, and neutrals. The ionization rates $q(T_e)$ are taken from Jacobs et al. [1979] for sulphur, from Chandra [1976] for oxygen ions, and from Lotz [1967] for neutral atomic oxygen. Both dielectronic and radiative recombination are included and are of the form $R = \alpha(T_e) n_i n_e$. The recombination rates $\alpha(T_e)$ are given by Jacobs et al. [1979] for dielectronic recombination and by Spitzer [1956] for radiative recombination.

Charge exchange takes the form $CX = C(T_i) n_n n_i$. Charge exchange rates, which are a slowly varying function of T_i, are given by Brown et al. [1981] and Johnson and Strobel [1982]. Brown [1981] has detected the existence of a neutral oxygen cloud in the vicinity of Io's torus with a density of 30 cm^{-3}.

Neutrals have been included in our model with the density of neutral oxygen falling linearly from 18 cm^{-3} at L = 5.9 to 2 cm^{-3} at L = 5.1, and set equal to 1 cm^{-3} inside of L = 5.1 [D. E. Shemansky, private communication, 1982]. Since the ionization rate of S I is about an order of magnitude higher than for O I and SO_2 from Io is a likely source of neutrals, the S I density has been set equal to 1/4 the density of O I. The amount of energy gained by the ions as a result of these processes is equal to the number of new ions formed by charge exchange and ionization of neutrals multiplied by the temperature (which is equal to the corotation energy) of each newly formed ion.

The equation for thermal transport is (see appendix)

$$V_c \frac{\partial(NL^4 T_{i,e} T_i^{1/3})}{\partial L} + \frac{\partial(NL^4 T_{i,e} T_i^{1/3})}{\partial t} = L^2 \frac{\partial}{\partial L} \frac{D_{LL}}{L^2} \frac{\partial}{\partial L} (NL^4 T_{i,e}{}^{1/3}) + S_{i,e} - R_{i,e} \quad (2)$$

where $T_{i,e}$ is the ion (electron) temperature. We assume that Coulomb collisions are sufficiently fast that all ion species have the same temperature, and that the thermal velocity distribution is isotropic. The electron energy loss is equal to the rate of radiation emitted from the torus, $R_e = \rho(T_e)n_i n_e$, where $\rho(T_e)$ is the radiation rate for which values are given by Shemansky [1980]. The exchange of energy between ions and electrons is governed by the equation

$$\frac{dT}{dt} = \frac{8(2\pi)^{1/2} \nu^* \ell n \Lambda (T_i - T_e) n_i n_e}{3 m_i m_e K^{3/2} (T_e/m_e + T_i/m_i)^{3/2}} = C(T_i, T_e) n_i n_e \quad (3)$$

[Spitzer, 1956] where ν^* is the charge state of the ion, Λ is the Coulomb logarithm, k is Boltzman's constant, and m_i and m_e are the ion and electron masses.

All of the source and loss terms are of the form S, $R = C(T_e, T_i) n_i n_e$, where a Maxwellian temperature distribution is assumed. The number density n can be related to N, the density per unit L, by the equation

$$N = 2\pi L R_J^2 \int_{-\infty}^{\infty} n_i(z) dz = 2\pi^{3/2} L R_J^2 n_o H \quad (4)$$

where $n_i(z) = n_o \exp(-z^2/H^2)$ [Hill and Michel, 1976], n_o is the number density at the equator, and H is the scale height of the plasma above the equator. For simplicity of calculation we assumed the plasma is well mixed with average mass m^* and charge ν^*, then

$$\frac{1}{H^2} = \frac{3\Omega^2 m^*}{2KT_i} \Big/ \left(1 + \frac{\nu^*}{\nu^* + T_i/T_e}\right) \quad (5)$$

where Ω is the angular velocity of Jupiter. We are aware that the plasma will actually be stratified with the heavier components lying closer to the centrifugal equator [Bagenal and Sullivan, 1981]. Combining (3)-(5) gives an expression for $n_i(z)$ in terms of N.

We now have a set of 9 coupled second order differential equations, seven for the different ion species, and two for the ion and electron temperatures, which we solve numerically. For boundary conditions we assume that all the ions are absorbed at the outer edge of Jupiter's ring at L=1.8.

At Io's orbit we set $N_{S\ II} = N_{O\ III} = 2 \times 10^{38}$ and $N_{S\ III} = 5 \times 10^{33}$, and let the ion and electron temperature equal 4×10^5 °K and 5×10^4 °K respectively [Bagenal and Sullivan, 1981].

The value of the diffusion coefficient, $D_{LL} = KL^m$, to be used in (1) and (2) is uncertain. Values derived from Pioneer 10 data are in the range $2 \times 10^{-9\pm1} L^{2.5\pm.5}$ [Goertz and Thomsen, 1979]. We use m = 3 in our model and vary the value of K.

Results

Time Dependence Scenario

The original objective of this study was to vary the value of the diffusion coefficient to achieve a simultaneous matching of the temperature and density profiles. In this way it was expected that our model would provide a unique value for the diffusion coefficient and the turn on time of the source. It was found, however, to be impossible to fit both the temperature and density profiles. As shown by Richardson et al. [1980], the density profile can be fit for any value of K by choosing the proper turn on time for the source as long as the diffusion rate is fast enough that recombination is not important (see next section). Some time dependent fits to the density data are shown in Figure 1. The diffusion coefficient K and the time τ at which the best fit to the data is achieved are related by $\tau(s) = 6 \times 10^{-4}/K\ (R_s^2/s)$ where τ is measured from the onset of injection. Ion temperatures are shown in Figure 2 for $K = 10^{-12}$ and 2×10^{-12}. These profiles are plotted at the time for which the best fit for the density profile is achieved, namely 6×10^8 s and 3×10^8 s for $K = 10^{-12}$ and 2×10^{-12}, respectively. For both of these cases, the temperature reaches a minimum at L ∿ 5.5 and increases inside of this, in contrast to the measured temperatures that continued to fall as Voyager moved inward to L = 4.9. For $K = 2 \times 10^{-12}$, the model profile roughly matches the observed profile from L = 5.5-5.9. For $K = 1 \times 10^{-12}$ the model temperature falls off more sharply than observed between L = 5.9 and 5.5.

The physical explanation for this odd behavior of the model temperature is as follows. Ions diffusing in from the hot outer torus start out with a temperature of 4×10^5 °K. Those newly formed via charge exchange or ionization of a neutral start with a temperature of 3×10^6 (O) or t x 10^6 (S) °K, and in our model are assumed to equilibrate in temperature rapidly with the cooler ions. The only way for the ions to lose energy is via Coulomb interactions with the cold electrons. As shown in (3), the cooling rate is proportional to the number density of both ions and electrons, or to the total density squared. Soon after the source of ions is turned on, the density inside Io is small and cooling is negligible, so temperatures actually increase with decreasing L as the addition of energy from newly created ions is greater than the amount lost to electrons. As inward diffusion continues and density increases, this situation changes and

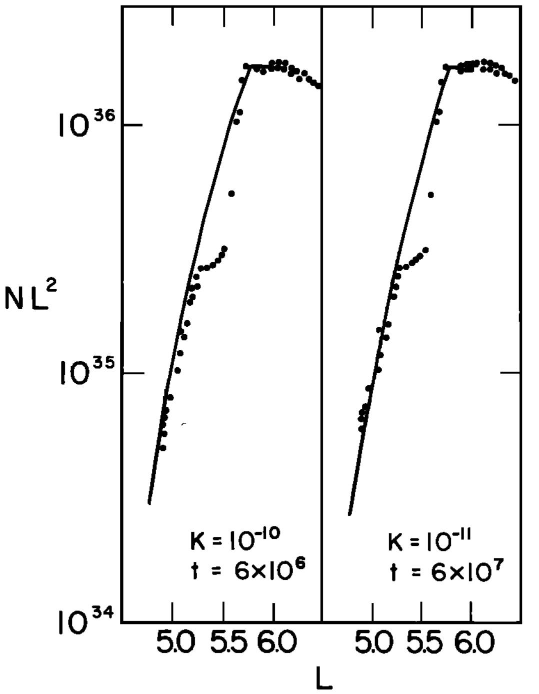

Fig. 1. Model density profiles for $K = 10^{-10}$ and $K = 10^{-11}$ (solid lines) compared with observations (data points). The diffusion coefficient K and the onset time of injection τ are related by T (s) = 6 x 10^{-4}/K (R_J^2/s).

cooling dominates in the higher density region just inside of Io. The temperature profiles of Figure 2 result from a situation where the densities from L = 5.5 - 5.9 is high enough for cooling to occur efficiently, whereas inside L = 5.5 the density is too small for substantial cooling to have occurred. Note that model temperatures are already too small from L = 5.5 to 5.9 to match the observations - decreasing the diffusion coefficient further to improve the fit to the data inside of 5.5 will only worsen the fit outside of 5.5. Also note that since the scale height H is proportional to $(T_I)^{1/2}$, once cooling starts it is spurred by a positive feedback mechanism; a lower T_I means a smaller scale height and therefore a greater number density causing faster cooling.

Recombination

Within the framework of purely diffusive transport, there are only two apparent ways to create the density fall off inside of Io, namely, recombination, in which the ions form neutrals that then leave the system, and, as already discussed, time dependence. Figure 1 shows that the best fits to the density profile for K = 10^{-10} and 10^{-11} R_J^2/s. For K = 10^{-10}, recombination has no effect on the density profile, and the best fit is reached at a time 6 x 10^6 s after diffusion starts. For K = 10^{-11} a slight deviation from a pure diffusive profile is seen owing to recombination. For K ≥ 10^{-11} (when recombination time scales are slow in comparison with diffusive time scales) the diffusion paramter K and the time τ at which the best fit to the data is achieved are related by τ = 6 x 10^{-4}/K, where τ is measured from the onset of injection. For K = 10^{-12} recombination is fast enough to duplicate the density drop without having to resort to time dependence. Thus, the solution given in Figure 3a for K = 10^{-12} is a steady state solution. However, approximately 30 years are needed to reach the steady state with such a small diffusion coefficient. This is unreasonably long in view of the substantial variation of the torus over lesser time scales. In addition such a slow rate of diffusion would not bring energetic electrons towards Jupiter fast enough to supply the power for the observed synchrotron radiation [Birmingham et al., 1974].

As well as the long time scales required for a diffusion-recombination steady state, the temperature profile poses another problem for this model. Figure 3b shows the ion and electron profiles corresponding to the steady state situation shown in Figure 3a with K = 10^{-12}. This model ion temperature clearly falls much more rapidly than observed profile inside of Io. As this result is insensitive to the variation of model parameters, it seems that recombination also can be ruled out as a cause for the density and temperature dropoff.

Diffusion plus Convection

Since the observations have not been explained by using a purely diffusive transport mechanism, we now look at the result of adding convection to

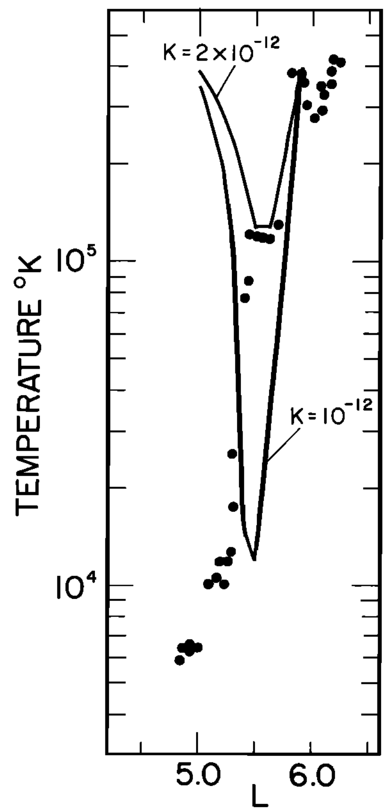

Fig. 2. Model ion temperatures for $K = 10^{-12}$ and 2 x 10^{-12} (solid lines) compared with observations (data points). Temperature profiles are shown for times when the observed density profile is best matched by our model.

the model. The steady state density gradient inside is determined solely by the ratio of the convective velocity $V_c = V_{Io}(L/5.9)^4$ to the diffusion coefficient ($D_{LL} = KL^3$). The density profiles resulting from using V_{Io} = 2, 3, and 4 times D_{LL} at L = 5.9 are shown in Figure 4. While none of the profiles reproduces the detailed structure of the observed profile, it is clear tht $V_{Io} = 3\ D_{LL}$ best fits the data. A somewhat better fit to the data is obtained by letting the source extend inward to L = 5.8, but the ledge centered at 5.35 cannot be reproduced by using this simple model.

Now that the required ratio of V_c to D_{LL} has been determined we use this result to find the value of the diffusion coefficient required to fit the temperature observations. Figure 5 shows the steady state ion temperature resulting from using three different values of K. The best fit to the temperature profile is obtained by using $K = 3 \times 10^{-12}\ R_J^2/s$, with the result being fairly sensitive to small changes in K. This value of K can be used to calculate a value for V_c; $V_{Io} = 3\ D_{LL} = 1.8 \times 10^{-9}\ R_J/s$ = 13 cm/s. so V_c = 13 cm/s $(L/5.9)^4$. A lower limit for the source rate of 1.2×10^{26} ion/s can be determined by assuming outward transport occurs by a combination of outward convection and diffusion. This is a lower limit because we expect another transport mechanism will dominate outside of Io - centrifugally driven interchange diffusion [Richardson et al., 1980; Siscoe and Summers, 1981].

The model-derived electron temperature for

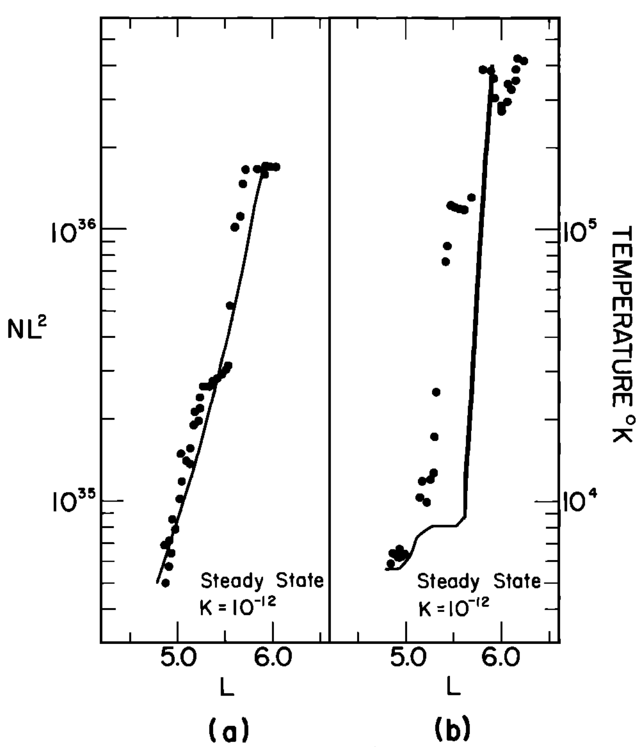

Fig. 3(a). Steady state model result (solid line) in which inward diffusion is balanced by recombination. Data points are observations. (b). Ion temperature profile resulting from steady state situation shown in Figure 3a (solid line) compared with observations (data points).

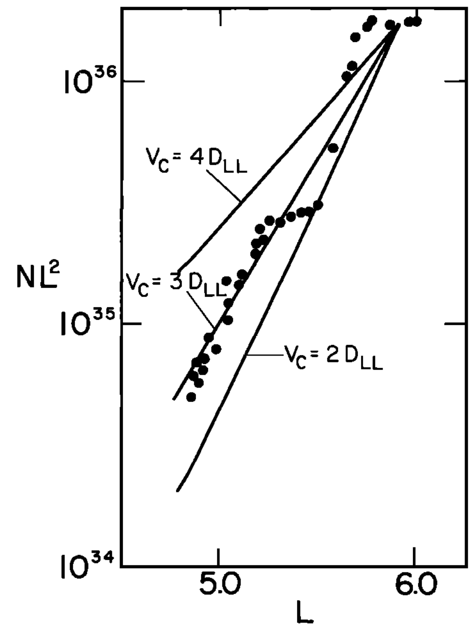

Fig. 4. Steady state density profiles resulting from using V_c at Io equal to 2,3, and 4 times D_{LL} are compared with observed density profile (data points).

$K = 3 \times 10^{-12}$ is shown in Figure 6. It falls rapidly inside Io to about 5000°, then levels off. In the equation for transport of electron energy, the diffusive and convective terms are negligible in comparison with the source and loss terms arising from Coulomb interactions and radiation. Thus this equation reduces to a balance between these two terms, with a total of about 10^{11} W emitted inside of L = 5.8. These results are fairly insensitive to changes in the values given for T_i and T_e at L = 5.9.

Scudder et al. [1981] have reported electron temperatures of 5 eV between L = 5.5 and 5.9. These are much larger than those determined by our model (Figure 6). However, the electron temperature is not a well determined quantity due to spacecraft changing, and could be much lower than 5 eV throughout the region inside of Io [Scudder et al., 1981].

The composition of the torus plasma changes as a function of L due to the effects of charge exchange. Figure 7 shows the rate N_s/N_o as a function of L. At L = 5.9 we start with equal parts of S and O. The solid lines show the neutral density used in our model and the resulting ratio of N_s/N_o. This ratio increases rapidly inside of Io's orbit, and levels off at about 30 inside of L = 4.5. The reason for this, as pointed out by Brown et al. [1982], can be seen by looking at the charge exchange coefficients and ionization rates of Brown et al. [1982]. The reaction S I + O II → S II + O I proceeds 100 times faster than O I + S II → O II + S I, so oxygen ions are replaced by sulphur ions as the plasma diffuses inward. Coupled with the fact that ionization rates for sulpher are much faster than those for oxygen, this leads to large N_s/N_o ratios shown in Figure 7. These ratios are larger than those observed by Voyager. Composition measurements inside of Io [Bagenal and Sullivan, 1981] indi-

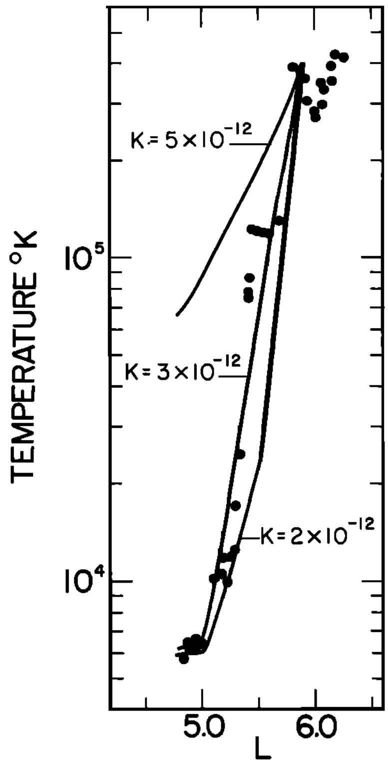

Fig. 5. Steady state ion temperatures resulting from a model combining inward diffusion and outward convection are shown for three values of K (solid lines) and are compared with observations (data points).

cate that a typical value for N_s/N_o is about 3. However, this ratio is sensitive to the neutral density used in our model. If we cut the number of neutrals in half, then the diffusion coefficient that best fits the data is $D_{LL} = 5 \times 10^{-12} L^3$, and the ratio of N_s/N_o is much smaller, equalling 4 at L = 5.3 as shown by the dotted lines in Figure 7. Factor of 2 adjustments are well within the limits of uncertainty in the O I density, so the composition data do not pose a real problem in our model.

The very low value for the diffusion coefficient needed to fit the ion temperature does pose a problem. As mentioned earlier, such long time scales make it hard to understand the rapid (∿ days) temporal variation of S II emission [Morgan and Pilcher, 1981] and do not bring in enough energetic electrons to provide the observed synchroton emission [Birmingham et al., 1974]. They also conflict with Pioneer derived estimates of the diffusion coefficient, which give a range for D_{LL} of $1 \times 10^{-9\pm1}$ $L^3 R_J^2/s$.

Discussion

We have ruled out time dependence as a possible scenario because it is impossible simultaneously to fit the temperature and density profiles. Recombination is too inefficient to provide a loss mechanism for ions without encountering problems with time scales and ion temperatures. A steady state mixture of convective and diffusive transport provides a reasonable match to the ion temperature and density profiles, but runs into problems with the derived electron temperature and with diffusion coefficients derived from Pioneer data. Although the conflict with the electron temperature may be reconcilable, the conflict with the diffusion coefficient probably is not. Several different methods have been used to derive diffusion coefficients from Pioneer data [see Mogro-Campero, 1976] and they independently lead to similar values for $D_{LL} \approx 2 \times 10^{-9\pm1} L^3 R_J^2/s$. Although these values were derived for energetic ($\gtrsim$ 1 MeV) ions, they should be the same for the torus ions and the 1 MeV ions as the drift frequencies for both are very close to the corotation frequency.

The problem that the previously established range of the diffusion coefficient poses for our model results can be stated as a problem of how to get rid of the excess energy from the inner torus. An estimate of the power entering the region inside Io is given by the first term of the energy transport equation, $L^2 (\partial/\partial L) (D_{LL}/L^2) (\partial/\partial L) NL^4 T_i^{4/3}$ that must equal the loss term in a steady state situation. Using smoothed temperature and density profiles and letting $D_{LL} = 10^{-9} L^3$ (near the midpoint of the range of values derived from Pioneer data) we find that there are 1.8×10^{12} W entering the inner torus. This does not include the energy added by the creation of new ions, which is negligible in comparison, namely about 3.2×10^{10} W.

Some of this energy is radiated away, most of it in the S II 6720 Å doublet which is the most efficient emitter at these temperatures. Morgan and Pilcher [1981] observe an average emission of 350 Rayleighs from this doublet. A generous estimate of the total power emitted from the entire region is 5×10^{10} W; this means 97% of the

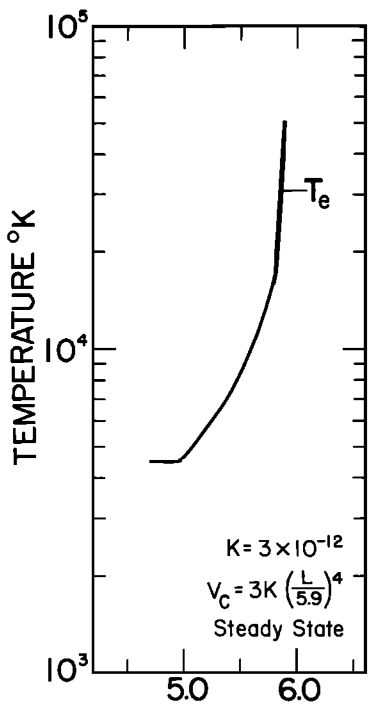

Fig. 6. Model derived electron temperature for combined convection - diffusion scenario with $K = 3 \times 10^{-12} R_J^2/s$.

power entering the inner torus must be lost by some other method. If we take the lower limit for D_{LL} obtained from Pioneer $2 \times 10^{-10} L^3$, 8.5×10^{11} W diffuse inwards, which is still much larger than the energy radiated by S II.

Precipitation is an obvious loss mechanism which we have not previously considered. As mentioned earlier, a field-aligned potential of ~ 1 Kv would allow ions to be drawn from the torus into the ionosphere. However, to lose 8×10^{11} W requires a loss of ~ 10^{29} ions/s with a temperature of 4×10^5 °K. This is an unreasonably large loss rate, larger than most estimates of the total source strength.

Some energy will be transferred to electrons, but Coulomb collisions can account for only about 1/10 of the necessary energy loss. If another mechanism can be found to transfer energy from ions to electrons (wave-particle interactions, for example), we still have to find a loss mechanism for this energy since not more than about 5% can be radiated without violating observational constraints. This would imply a lifetime for 5×10^4 °K electrons of $(NKT/8.5 \times 10^{11}) = 2.5 \times 10^4$ s, about 7 hours. This minimum lifetime for loss under strong diffusion for these electrons is about 5 days, so it does not seem possible to remove electrons fast enough to deplete the necessary energy.

This leaves us with a dilemma. If the diffusion coefficient is less than ~ $2 \times 10^{-10} L^3$, not enough energetic electrons diffuse inwards to provide the observed synchroton emission [Birmingahm et al., 1974; Stansberry and White, 1974]. The drop out of energetic particles across the orbits of Io and Amalthea [Mogro-Camero, 1976, and references therein] also indicate $D_{LL} \gtrsim 2 \times 10^{-10} L^3$. However, these values of D_{LL} combined with Voyager plasma observations imply an inflow of energy 20 times greater than the observed emitted radiation. It seems impossible to remove this energy by precipitation.

It is possible that time dependent processes can account for this apparent discrepancy. Morgan and Pilcher [1982] report observations over a three-day period consistant with an electron density $n_e \gtrsim 3 \times 10^4$ cm/^{3} and $T_e \lesssim 10^4$ °K. Such a high density of low-temperature electrons could quickly remove energy from the ions via Coulomb interactions. When the electron density returns to normal we might have a situation as observed by Voyager where the ion density and temperature having sharp inward gradients which are in the process of flattening out, as the amount of energy diffusion inward exceeds the local losses. Since S II emission cannot be detected by the UVS experiment inside Io's orbit, fluctuations in S II output will not conflict with the observations of fairly constant emissions from the hot torus for 100 days prior to Voyager's closest approach. Fluctuations in intensity and shape of the torus with a time scale on the order of a day are commonly seen in the S II emissions [Pilcher, 1980; Pilcher and Morgan, 1980; Morgan and Pilcher, 1981].

Another possibility is that these very slow diffusion rates occur only in the region of the steep density and temperature gradients inside of Io. In this region atmospherically driven diffusion would be inhibited by the density gradient. This gradient has a stabilizing effect

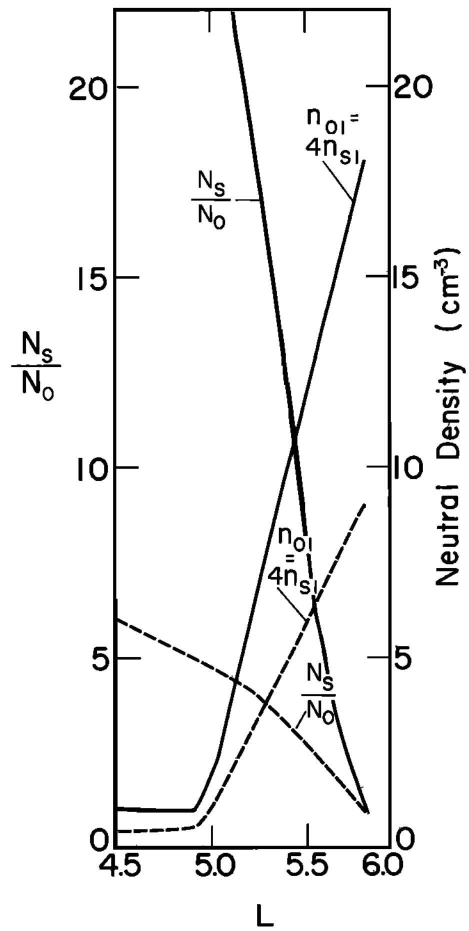

Fig. 7. Ratio of N_S to N_O as a function of L for convection - diffusion scenario.

on interchange motion. In any interchange of flux tubes more energy is required to compress the plasma in the inward moving, higher density flux tube than is released by expansion of the plasma in the outward moving, lower density flux tube. Thus in the region of the steep density gradient the diffusion rate may be reduced to the values required by the calculation presented earlier, $K = 3 \times 10^{-12} L^3$. The stabilizing influence of the adverse density gradient does not operate inside of this region, and thus atmospherically driven diffusion proceeds at its normal uninhibited rate.

A long residence time for ions in the cold Io torus was also inferred by Shemansky [1982], who modeled the ion partitioning in this region and found that diffusion times on the order of 30 years are required to create the observed partitioning. However, the problem of bringing in the energetic electrons fast enough to provide the synchroton emissions still exists in this model, in which slow transport is restricted to a thin shell. Although the region of slow diffusion extends only over the region of the steep density gradient, about 0.5 R_S in radius, it takes the plasma at least 15 years to cross this region, whereas the electrons providing the synchroton radiation must be replenished on a time scale of about 1 year.

Conclusion

We have investigated several different mechanisms in an attempt to explain the sharp density and temperature fall-offs inside of Io. Radical time dependence, in which the source rate of ions is increased by a factor of at least twenty at some time prior to Voyager's arrival, cannot account for the observed temperature profile. Neither can a steady state situation in which recombination balances inward diffusion. A model in which outward convection balances inward diffusion can match the data, but only if we choose a diffusion coefficient 100 times smaller than the generally accepted number. One possible explanation is that short term temporal variations of electron temperature and density cause the inner torus to assume various nonequilibrium configurations, one of which was encountered by Voyager.

Appendix

The general form of the equation that describes transport by flux tube interchange diffusion is

$$\frac{\partial Y}{\partial t} = L^2 \frac{\partial}{\partial L} \frac{D_{LL}}{L^2} \frac{\partial Y}{\partial L} + S_Y - R_Y \qquad \text{(A1)}$$

where Y is any quantity contained in a flux tube as it moves under the interchange motion. S_Y and R_Y are the local rates of creation and destruction of Y. For a given physical quantity, one identifies the appropriate Y to represent it by finding an expression involving it which is preserved under interchange motion in the absence of sources and sinks. For example, in the case of number density n, the quantity that is preserved is the total number of particles in a flux tube, i.e.,

$$Y_n = \frac{\sqrt{\pi}}{B_J} L^3 H n_o \qquad \text{(A2)}$$

$$= \left(\frac{1}{2\pi R_J^2 B_J}\right) L^2 N \qquad \text{(A3)}$$

in which Y_n is the number of particles per weber (i.e., in a flux tube of unit magnetic flux), B_J, is the equatorial field strength at the 'surface' of Jupiter, and the other quantities are as defined in (4) and (5). The coefficient of n_o in (A2) is the equivalent volume of the plasma-containing portion of a unit magnetic flux tube. By substituting (A3) into (A1) and dividing through by the constant coefficient, one recovers the diffusion equation as given in the text (equation (1)).

In the case of internal energy of the plasma, in the absence of sources and sinks, the plasma responds adiabatically to the change in the volume of a flux tube as it undergoes a radial displacement under interchange motion. The preserved quantity is

$$Y_u = \frac{3}{2} n_o k T \left(\frac{\sqrt{\pi}}{B_J} L^3 H\right)^{5/3} \qquad \text{(A4)}$$

where we assume that the pressure is isotropic. By combining equations (4), (5), and (A4) and substituting into (A1) one arrives at the diffusion equation for temperature. In the form for it given by (2), we have dropped the term involving T_i/T_e from (5), which makes only a minor contribution.

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