TIME DEPENDENT PLASMA INJECTION BY IO

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Abstract. A two parameter model of time-dependent, flux-tube interchange diffusion is fit to the Voyager 1 plasma data obtained in the Io plasma disk. The interpretation of the parameters required to achieve the fit is that plasma injection increased suddenly and substantially (by more than an order of magnitude) at some time prior to the arrival of Voyager 1 (between 1 and 100 days prior). The injection rate was about $2 \times 10^{29\pm1}$ ion/sec. At this rate, the centrifugally driven interchange instability dominated outward diffusion, causing the outward diffusion rate to be about a factor of 50 greater than the inward diffusion rate. The material diffusing inward had time to cool by radiation, possibly accounting for the observed temperature drop inside the orbit of Io.

Introduction

The passage of Voyager 1 through the Io plasma disk revealed a multicomponent heavy ion plasma with large spatial gradients in the *in situ*-measured density (Bridge et al., 1979; Warwick et al., 1979). In particular, the density exhibited two maxima, one virtually coinciding with the orbit of Io. The other, somewhat smaller, occurred inside Io's orbit, at a planetocentric distance of about 5.3 R_J. The density decreased rapidly Jupiterward of the second maximum. The region of the second maximum and subsequent density decrease was characterized also by a precipitous decline of the temperature (Bridge et al., 1979; Bagenal et al., 1980).

The location of the main maximum at Io's orbit and composition indicative of dissociation products of sulfur oxides identifies Io as the source of the plasma. We address in this note the question of the radial transport of the plasma inward and outward from Io's orbit. Because of arguments that have been reviewed elsewhere (Siscoe, 1979), the main mechanism of radial transport is believed to be by cross-L diffusion by the process of magnetic flux tube interchange (which at the low energies of the Io-derived plasma is the same as cross-L diffusion by violation of the third adiabatic invariant). Our purpose here is to determine how well this mechanism can account for the Voyager observations, and, given that an adequate fit to the data can be found, interpret the model parameters required for the fit in terms of the underlying physical processes.

Prior solutions of the radial transport problem assumed steady state with a source at Io's orbit and sinks at Jupiter's atmosphere and at some outer boundary located around 40 R_J, where a radially outflowing wind is presumed to dominate the transport process. These solutions exhibited a single maximum in density at about 1.4 R_J, i.e. well inside the maximum observed by Voyager (Siscoe, 1978; Goertz and Thomsen, 1979). Even should the newly discovered ring be used as the sink to the inward flux, the maximum would be located around L = 2. Thus, the time independent, loss-free solutions can not account for the Voyager observations, in which the density is maximum near the orbit of Io, L = 6.

Time-Dependent Solution to Io Plasma Data

The equation governing time dependent radial diffusion of plasma by the flux tube interchange process is

$$\frac{\partial NL^2}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial NL^2}{\partial L}\right) + L^2(S-R) \qquad (1)$$

(Fälthammar, 1978; Siscoe, 1978) where N is the total number of ions of all species in a flux shell per unit L, D_{LL} is the diffusion coefficient, and S and R are the source and loss strengths in a flux shell per unit L. We take S to be constant between 5.8 and 6.2 R_J (corresponding to two step-intervals in the numerical integration).

The loss, R, of N, which is a measure of the total number of ions in a flux shell, can only occur by recombination or by precipitation along magnetic field lines into Jupiter's atmosphere. Losses to Io merely reduce the value of S and do not enter into determining R. The life-time against recombination of S^+ in the Io torus is calculated to be of the order of 100 years (Shemansky, 1980; Jacobs et al., 1979). This is much longer than estimated diffusion times. The life-time of electronically similar O^+ will also be long compared to diffusion times. The loss by precipitation along field lines can be neglected, because the centrifugal potential holding the ions in the neighborhood of the centrifugal equator is of the order of 600 ev (Michel and Sturrock, 1974), whereas the thermal energy of the ions is less than about 30 eV.

Although a number of different processes can drive flux-tube interchange diffusion, all that have been considered theoretically lead to a diffusion coefficient with the algebraic form

$$D_{LL} = kL^m \qquad (2)$$

For the purpose of obtaining explicit solutions to (1) we take m = 3, for which there is both theoretical and observational support (e.g. Goertz et al., 1979). At the time of Voyager encounter,

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mass loading appears to have been sufficiently large that, as will be shown, the mechanism driving the diffusion is different inside and outside of the orbit of Io. The justification for using m = 3 is weak in this case, especially outside of Io's orbit. However, in the absence of compelling alternatives, the value m = 3 at least allows the qualitative behavior of the solutions to be explored. Froidevaux (1980) shows that the slope of the ion density outside of L = 6 is consistent with m = 4 or 5 for steady state diffusion. However, the solution that we find is time dependent, and as such the slope of the ion density determines the onset time of the injection event rather than the value of m, which must be assumed.

Equation 1 shows that the quantity that diffuses in this formalism is the product NL^2. Figure 1 displays the radial variation of NL^2 inferred from the in situ plasma observations during the inbound passage through the Io plasma disk (Bagenal et al., 1980). The data points exhibit a single maximum located between 5.8 and 6 R_J, i.e. virtually coincident with the orbit of Io. In diffusive transport, every maximum of the diffusing quantity corresponds to a source. We see that the assumption of flux-tube-interchange diffusion identifies a diffusant, NL^2, that bears the correct relationship to the source. By contrast, if the transport were diffusion of single particles by scattering off of waves or other particles, the diffusant would be pure number density, which exhibits a double maximum, and thus would require two sources.

The basic character of the profile of the data points for NL^2 shown in the figure is readily simulated in a diffusion solution by a step-function source. The source is assumed to change instantaneously from a strength of zero (or negligibly small) to a finite value, and then to remain at that value indefinitely. The solution begins with zero density everywhere and increases initially with steep gradients leading to a maximum at the source. After many diffusion times, defined as the reciprocal of the diffusion coefficient evaluated at the source, the solution broadens and approaches a nearly constant value except near the boundaries, where it falls to zero. In terms of this sequence, Figure 1 corresponds to a solution that has evolved for less than one diffusion time.

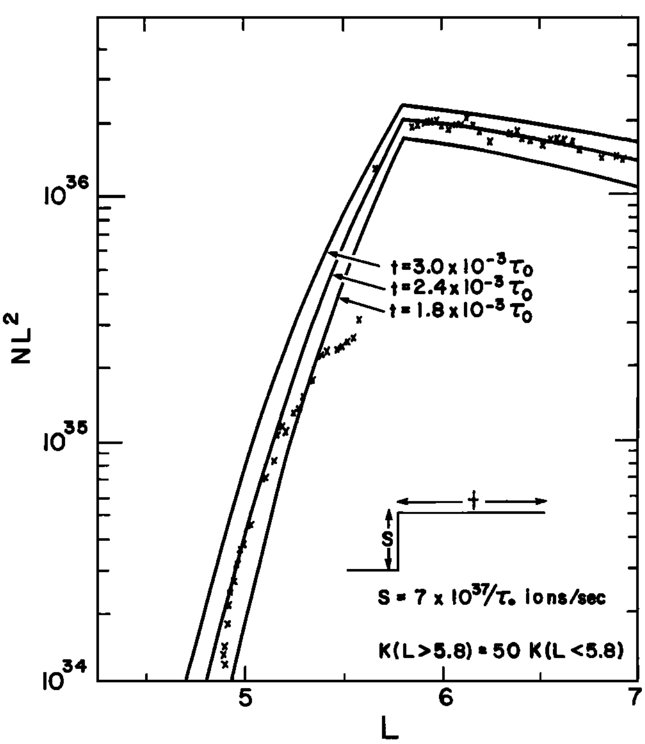

Fig. 1. Values of NL^2 inferred from the Voyager 1 plasma data are indicated by x's. Three solutions of the time-dependent diffusion equation are shown. The middle solution gave the best fit of all parameter combinations tried.

Solutions based on the use of equation (2) to represent D_{LL} for all values of L show nearly equal inward and outward gradients of NL^2 during initial phases of the evolution of the profile. Differences in the inward and outward gradients as large as that observed are never realized in such solutions. To simulate this feature of the observations it is necessary to change the diffusion coefficient discontinuously at the source, such that $D_{LL}(L > 5.8) > D_{LL}(L < 5.8)$. In our numerical solutions, we retain the form of equation (2) with m = 3 in both regions, and make $k(L > 5.8) > k(L < 5.8)$, although a change in the value of m could also occur (Froidevaux, 1980).

The model parameters that were adjusted to fit the observed profile of NL^2 are the ratio of outward region to inward region values of k and the time between the onset of the source and the arrival of Voyager. The time is given in units of the reciprocal of the inward region value of k (i.e. solution time is proportional to diffusion time in the inward region). In the figure $1/k(L < 5.8)$ is denoted by τ_o.

The figure shows the curve obtained by adjusting the two model parameters to obtain the best fit to the values of NL^2 derived from the observations. The best fit parameters are

$$t = 2.4 \times 10^{-3}\ \tau_o \text{ sec} \qquad (3)$$

$$\frac{k(L > 5.8)}{k(L < 5.8)} = 50 \qquad (4)$$

In terms of goodness of fit, the uncertainties in these numbers is less than a factor of 2. For comparison, the figure shows two different times, slightly before and after the one chosen. For the shorter time the outward gradient is too steep, as can be seen by shifting and overlaying the theoretical and observed profiles. For the longer time the inward gradient is too shallow. Similarly, diffusion coefficient ratios of 25 and 100 give a clearly poorer simulation of the data-inferred NL^2 profile.

The solutions also give the magnitude of the source required to produce the observed values of NL^2. For the two chosen values of the model parameters specified above, the source strength is

$$\text{Io source strength} = 7 \times 10^{37}/\tau_o \text{ ions/sec} \qquad (5)$$

The major new conclusions of the analysis, namely that the source of plasma turned on suddenly some time prior to Voyager encounter and that the diffusion coefficient was discontinuous at the orbit of Io, are very insensitive to assumptions about model parameters. No reasonable alternative inner and outer boundary conditions alters those characteristics of the solutions upon which the conclusions are based. A sensitivity analysis was performed of the effect of varying the power, m, to which L is raised in the expression for the diffusion coefficient (equation 2). The range $0 \leq m \leq 5$ was considered. Larger values of m could not reproduce the observed outer slope of the NL^2 profile. Discontinuities in m at L = 6 with m (L > 6) > m (L < 6) were also treated. The observed NL^2 profile could not be even approximately simulated with the allowed freedom in choosing m without including both time dependence and a discontinuity in k at Io's orbit, as we have illustrated for the case m = 3. The numerical coefficients in relations 3, 4 and 5 do not change dramatically by obtaining good fits with different values of m. Thus, the main uncertainty in the numerical values lies in the parameter k.

Discussion and Interpretation

While the fit to the data points is reasonably good considering the simplicity of the model, there is a significant departure, which approaches a factor of three, immediately inward from the source point. This feature may result from more complicated time dependence of the source than a simple step function. In fact, the observed profile can be simulated very closely by use of a two-pulse time structure to represent the plasma injection rate.

The assumption of axial symmetry may be violated to some degree and thereby cause the finer-scale structure in the NL^2 profile. We are aware of the ground-based observations by Mekler et al. (1977) and Trauger et al. (1979) indicating longitudinal asymmetry of the [SII] nebula. However, the electron densities inferred from the planetary radio astronomy experiment onboard Voyager 1 exhibited a reasonably symmetrical distribution on the inbound and outbound portions of the penetration of the disk (Warwick et al., 1979). (On the outbound portion, the plasma instrument was not favorably oriented to view the corotating plasma, thus precluding direct verification of axial symmetry for the ions.)

We interpret the discontinuity in the diffusion coefficient at Io's orbit to be the onset of centrifugally driven interchange diffusion at that radial distance. Centrifugally driven interchange diffusion can only act outward from the source. If it acted inward, centrifugal potential would increase rather than decrease. Chen (1977) showed that if the source strength of heavy ions at Io exceeds about $10^{37}/\tau_o\ sec^{-1}$, the diffusion coefficient is dominated by the centrifugally driven interchange instability, rather than by atmospheric winds in Jupiter's upper atmosphere, which would otherwise dominate. The time-dependent diffusion fit indicates that the threshold for enhanced, centrifugally driven, outward diffusion was exceeded at the time of the Voyager encounter. Froidevaux (1980) observes that this conclusion is consistent with the observed slope of the ion density outside of L = 6.

The diffusion time scale of the solution was fixed by the value of the inward diffusion coefficient, which according to this interpretation, is the same as the atmospheric wind driven diffusion for which a number of determinations have been made. The values of $k(= 1/\tau_o)$ in the literature have the range $2 \times 10^{-(9\pm1)} sec^{-1}$, with a recent preference stressed for the value $3 \times 10^{-9}\ sec^{-1}$ (Goertz et al., 1979).

Keeping the order of magnitude uncertainity in k in mind, we can summarize our findings as follows: The Voyager plasma data are consistent in the main with a model in which plasma injection at the rate of $2 \times 10^{29\pm1}$ ions/sec began at a time between 1 and 100 days prior to Voyager encounter. With the preferred k, the time is 10 days. The injection so mass-loaded the region around Io, that centrifugally driven interchange diffusion rapidly diffused ions outward, while the slower atmospherically driven diffusion transported a smaller number inward. The inward diffusing ions remained virtually stationary subsequent to their injection, diffusing a distance of only about 1 R_J. In the hot portion of the torus, the plasma radiates in excess of 10^{12} watts in the UV part of the spectrum (Shemansky, 1980), and in excess of 10^{10} watts in the red lines of S^+ in the cool portion (Brown, 1978). The energy for the radiation is supplied by the thermal energy of the plasma, which is thereby reduced in the process. This perhaps is the reason that the slowly diffusing plasma is observed to be cold. The fast outward diffusing plasma leaves the high-density, radiating portion of the torus before it has cooled appreciably through radiation.

In interchange diffusion in the absence of ion losses, the relative abundance of ion species should be independent of distance and time, if the source maintains fixed relative abundance ratios. This fact could help resolve ambiguities in determining the relative of the S^{++} and O^+ charge states, which have identical signatures in the plasma spectra.

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