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The Injection of Energy Into the Io Plasma Torus

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Voyager EUV observations of the Io plasma torus showing a Jupiter local time asymmetry have been interpreted as a 10-hour periodicity in electron temperature in the corotating reference frame. The plasma shows two remarkable morphological characteristics. First, the intensity periodicity showed no tendency to change over the ≃0.5-year period of reduced data, indicating it to be a permanent feature of the torus. Second, deviations from the mean behavior, such as short-term magnetic longitude effects, all appear to be caused by electron temperature effects. Thus no local plasma mass variations have been detected during the observational period. These characteristics and the variability of the energy source required to drive the observed asymmetry lead to the conclusion that the dominant mechanism of energy transport to the plasma is electron-electron heating. If the parameters applied in coming to this conclusion are correct, the role played by mass loading from Io and planetary rotation in delivering energy to the plasma becomes much more obscure than the straightforward electron-ion transfer mechanism that has been considered to date.

INTRODUCTION

Averaged observations of the Io plasma torus via the use of the Voyager EUV spectrometers have shown an asymmetry in the distribution of intensity associated with local time in the Jupiter system [*Sandel and Broadfoot,* 1981]. The observation is of considerable importance since it indicates the presence of an intensity modulation in the corotating reference frame of significant magnitude on a 10-hour time scale. The phenomenon has a persistence that suggests it is a permanent feature, and the magnitude is such that a substantial amount of energy is injected into the torus at a 10-hour periodic rate. In this article we discuss the nature of the energy injection process as determined by the plasma parameters and the observed characteristics.

The argument that the energy required to maintain the Io torus and the auroral activity on Jupiter is most likely ultimately derived from the rotational energy of the planet is generally accepted [see *Eviatar and Siscoe,* 1980; *Dessler,* 1980]. The process by which the rotational energy is converted to the observed radiation is a matter that has not been settled and will no doubt require much further conjecture and discussion in the literature. The most straightforward mechanism proposed at the time of the discovery of the hot plasma torus [*Broadfoot et al.,* 1979] is one of ionization of neutrals that drift into the plasma from Io and subsequent acceleration of the ions in the corotating magnetic field. Effectively, all of the energy in this process goes into energy of the ion because the ion contains virtually all of the mass of the product fragments. The energy of the ions must then be delivered to the electrons for maintenance of the radiating system. This hypothesis for the supply of energy to the plasma encounters difficulty, as discussed below, for reasons involving the incompatibility of the ion relaxation time, the required mass loading rate of the torus, and the observed mean energy of the ions. The problem of energy transfer and mass injection has been discussed in the literature [*Sullivan and Siscoe,* 1981*b*; *Eviatar and Siscoe,* 1980; *Richardson et al.,* 1980; *Richardson and Siscoe,* 1981; *Dessler,* 1980; *Brown,* 1981*b*; *Shemansky,* 1980*a*; *Thorne,* 1981], but the issue is far from resolution.

The phenomenon discussed here, and earlier in a brief paper by *Shemansky and Sandel* [1980], requires a different mode of energy transfer, namely, electron-electron heating, as a substantial process maintaining the radiative output of the plasma. This requirement, dictated basically by the time scale of the intensity modulation, introduces a fundamental complication in our effort to understand the plasma torus, since it implies that the injection of mass from Io at least does not constitute a direct source of energy. If our understanding of this recently observed phenomenon is correct, the injection of mass into the torus is not necessarily directly connected to the maintenance of the radiating system and may only be a minor source of energy for the torus proper. We discuss below the factors that lead to this conclusion and suggest some possible sources for electron-electron heating.

THE OBSERVATIONS AND RESULTS

Details of the observational data reduction process are described by *Sandel and Broadfoot* [this issue]. Two main conclusions have been drawn on the basis of observations of the morphology of the strong S III 685-Å emission lines: (1) The emission on long-term average shows no measurable magnetic longitude dependence. The intensity modulation in System III (1965) longitude (λ_{III}) is estimated to be less than 10%. (2) The intensity of the 685-Å feature has a local time dependence with a peak near Jupiter's dusk meridian at 19:00 local time (LT). Figure 1 shows a brightness profile in 685-Å emission illustrating the asymmetry. The effect persists over the period in which data from the Voyager EUV instruments have been reduced for the study of morphological effects, from February 4 to June 8, 1979. Over this period of 125 days, no measurable variation in the average magnitude of the asymmetry was detected, implying that the feature is either permanent or present with a time constant larger than 1 year. The magnitude of the intensity modulation of a given volume of the torus is at least 40%.

The absence of measurable dependence on magnetic longitude implies uniform distribution, on average, of plasma mass around the circumference of the orbit—a fact that has been noted in the Voyager observational data, at times extending beyond the period discussed above [*Broadfoot et al.,* 1979, 1981; *Shemansky,* 1980*a*]. This absence of magnetic longitude dependence contrasts sharply with ground-based observations in S II 6700-Å radiation in which strong

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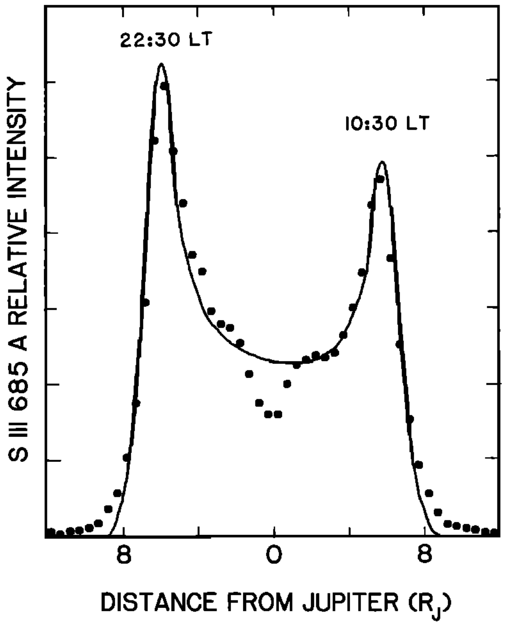

Fig. 1. System scans of Jupiter near the equatorial plane in S III 685-Å emission showing the intensity asymmetry described by *Sandel and Broadfoot* [this issue]. The data points are a summation of several scans obtained during the Voyager 1 postencounter period, days 74–95, 1979. The curve drawn through the points is a model calculation described in the text.

λ_{III} dependences have been observed [*Trafton*, 1980; *Pilcher and Morgan*, 1980; *Morgan and Pilcher*, 1982; *Trauger et al.*, 1980]. If geometric factors do not seriously confuse these results, the data must be interpreted as a λ_{III} dependence of mass loading of the torus, as opposed to a λ_{III} electron temperature dependence, say [*Shemansky and Smith*, 1981]. The reconciliation of these divergent results is not an easy matter. The torus is distinctly bimodal [*Sullivan and Siscoe*, 1981; *Shemansky*, 1980*a*; *Bridge et al.*, 1979] and the observed λ_{III} dependence in S II radiation may be associated mainly with the cold inner-torus region [*Shemansky and Smith*, 1981], which is too cool to be detected in the EUV [*Shemansky, 1980a*]. It should be noted at this point that longitudinally fixed intensity bulges have been detected in the hot-torus emission [*Sandel and Broadfoot*, this issue], with lifetimes of up to one Io orbit but not associated with any particular longitude, and attributed to enhanced electron temperatures rather than mass. We wish to raise two points in regard to these observations. First, although the ground-based observations of S II asymmetry are most likely associated with the cool inner-torus region, Io must ultimately be the source of mass for both modes of the torus; S II must be the immediate source for the S III observed in the hot torus [*Shemansky*, 1980*a*; *Shemansky and Smith*, 1981]. The production of S III in the torus by double ionization of S I is a very slow reaction for three reasons: The ionization threshold for double ionization of SI is 34 eV, as compared to 23 eV for single ionization of S II. Double ionization is an inefficent process in general, even given sufficient energy. The population of S I is bound to be an order of magnitude less than S II because of the efficient single ionization process. The difference in rates caused by threshold differences alone is an order of magnitude. Although we do not have a direct measure of S I → S III cross section, the process in general [*Massey and Burhop*, 1969] is at least an order of magnitude lower than the single ionization value. Thus the rate for the process S I → S III is expected to be of the order of 10^{-3} of the rate for the S II → S III reaction. The S II λ_{III} asymmetry must be interpreted as an asymmetry in plasma mass. It is therefore very difficult to reconcile the two sets of observations without introducing the assumption that Io itself has two distinctly different modes of mass injection. Second, a strong asymmetry in S II 6700-Å intensity distribution can be interpreted in only one way, given the range of plasma parameters in the torus [*Shemansky and Smith*, 1981], but asymmetries in the EUV can be interpreted as either mass or electron temperature effects. As discussed below, the EUV data, on average, shows no plasma mass asymmetry in any reference frame, and the observed local time variation is interpreted as a 10-hour cycle in electron temperature in the corotating reference frame. The relationship between the ground-based and EUV observations, in this regard, is certainly not straightforward and obvious. However, the EUV data are by far the most extensive [*Sandel and Broadfoot*, this issue], and we believe they define the characteristics of the hot torus. The fact that the local time asymmetry in the EUV data has not been observed in ground-based measurements is no surprise since excitation of emission from any of the torus subspecies in the visible or near-infrared region is insensitive to temperature variations of any reasonable magnitude [see *Shemansky*, 1980*a*, *b*].

Sandel and Broadfoot [1981] have described the local time asymmetry in S III 685-Å emission in system scans of the kind described in Figure 1. The observations are made essentially in the plane of the system, and line of sight integration mixes the various excitation conditions in the plasma radial cross section out to a radius of 5.7 R_J from planet center, where the brightness reaches a peak. The peak is caused by elongation of the line of sight path length

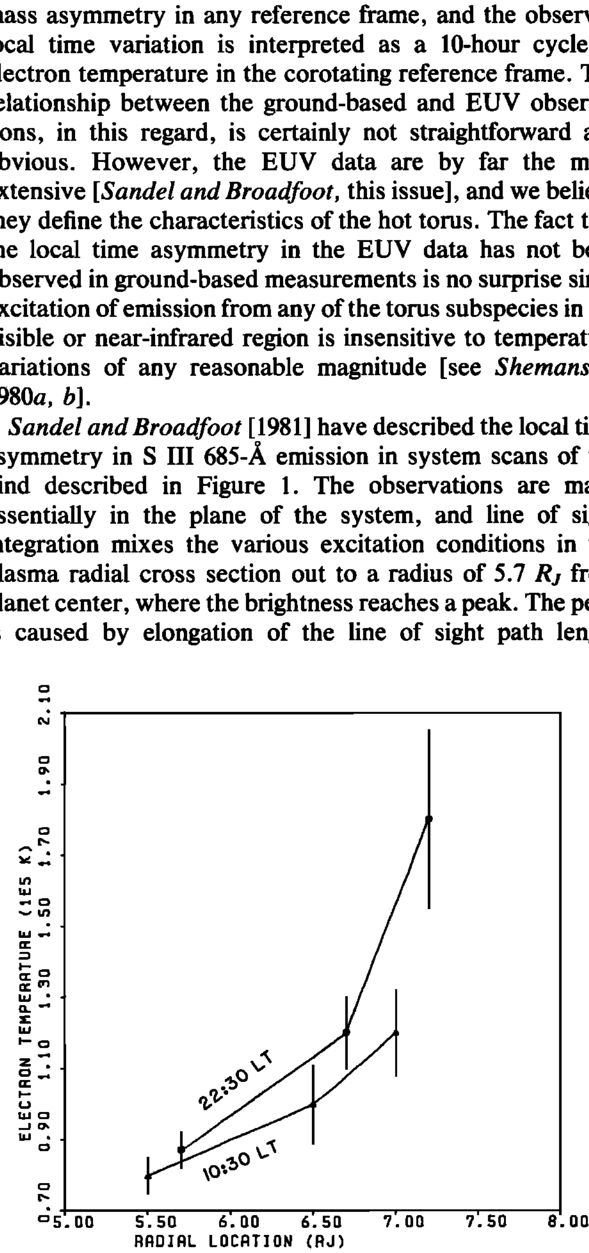

Fig. 2. Electron temperature as a function of line-of-sight radial position on the dusk and dawn sides of the planet, using EUV pre-Voyager 1 encounter data similar to those shown in Figure 1. The dusk/dawn temperature ratio increases with increasing radial position from 1.08 at 6.0 R_J to 1.3 at 7.2 R_J. The error bars shown are estimates of relative temperature uncertainty. The absolute uncertainty in temperature is judged to be similar in magnitude [see *Shemansky and Smith*, 1981].

through the plasma torus. The observed emission at $\leq 5.7\ R_J$ on either the eastern or western side of Jupiter generally shows little radial dependence in spectral content because the line of sight passes through a full radial cross section of the torus. However, beyond 5.7 R_J, where the line of sight does differentiate the torus radial cross section, the spectra show changes involving both electron temperature and ion partitioning [*Shemansky and Strobel*, 1980]. The EUV spectra yield estimates of electron temperature, and ion composition. The method of analysis used to produce the results given here is described by *Shemansky and Smith* [1981]. At 5.7 R_J the observed spectrum contains a mix of temperatures and densities. However, the spectrum is dominated by the central dense region of the torus and is analyzed in terms of a single effective electron temperature. As the radial location of the instrument line of sight is increased, the temperature inferred from the spectrum becomes more representative of the temperature at a particular radial location. Figure 2 shows temperature estimates made in this manner at the indicated radial locations on the dawn and dusk sides of Jupiter, using the data set indicated in Figure 1. The electron temperatures were estimated by using the relative intensities of S III and S IV lines in the spectrum. The error bars in Figure 2 represent the relative accuracy of the measurements. The absolute accuracy is judged to be comparable, according to the results obtained by *Shemansky and Smith* [1981]. The brighter dusk side spectra show systematically higher electron temperatures (T_e), with increasing differences at larger radial locations, as shown in Figure 2.

The analysis of the EUV spectrum produces a measure of a quantity we describe here as the abundance-density product (α). This product is defined by the equation

$$\alpha_n = \int [X_n]\,[N_e]\,d\rho \qquad \alpha_n = [\bar{X}_n]\,[\bar{N}_e]\,\bar{\rho} \tag{1}$$

where X_n is the density of ion species of charge $(n - 1)$, $[N_e]$ is the electron density, and ρ is distance along the instrument line of sight. We determine the electron density on the basis

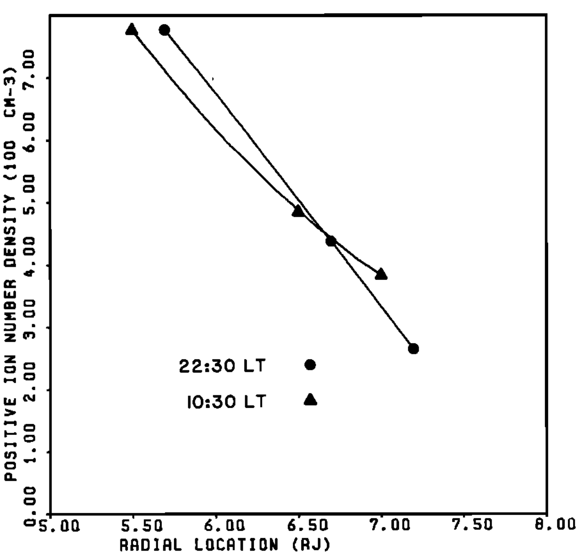

Fig. 3. Average plasma ion number density as a function of radial position estimated from analysis of the EUV data, applying the electron temperatures shown in Figure 2. The plasma ion density is the same on the dusk and dawn sides of the planet within measurement error.

of charge neutrality, with the assumption that the analysis of the EUV spectrum accounts for virtually all of the ions in the torus [*Shemansky*, 1980*a*; *Shemansky and Smith*, 1981]:

$$N_e = \Sigma(n - 1)\,[X_n] \tag{2}$$

thus

$$\bar{N}_e^2\,\rho = \Sigma(n - 1)\,\alpha_n \tag{3}$$

Through the application of (3) for each of the radial locations indicated in Figure 2, we then obtain measures of mean ion densities on the dusk and dawn sides of the planet. Figure 3 shows the estimated values, indicating that within experimental error, determined essentially by the estimated relative temperatures shown in Figure 2, the dusk and dawn sides of the torus have the same number density. We conclude that the intensity asymmetry shown in Figure 1 is caused by a 10-hour periodicity in electron temperature, with increasing proportional differences at larger radial distances.

Excitation-Relaxation

The emission of radiation from the torus is driven by electron excitation of existing ground state ions. Other processes generating radiation can be neglected, taking into account present uncertainties in the known plasma parameters [*Shemansky*, 1980*b*]. The generation of radiation depends entirely on the injection of energy into the electrons, even in plasma conditions in which the electron-ion system is in a state of substantial disequilibrium. Thus an explanation of the observed modulation depends on determining the means by which energy is delivered to the electrons in the plasma, since we have detected no measurable modulation of the plasma ion density.

The fact that the variation in electron temperature has a 10-hour period immediately eliminates electron-ion relaxation as a dominant process for delivering energy to the electrons on the basis of two disconnected arguments. First, we suggest the relaxation time for this mechanism is too slow to account for the phenomenon. This argument, based on the *Spitzer* [1962] equations for Coulomb collisional transfer, has been presented in recent papers [*Eviatar et al.*, 1979; *Shemansky and Sandel*, 1980; *Thorne*, 1981], but in less detail than the discussion below. Although the Spitzer equations are not strictly applicable to this case, the relaxation times estimated in this way are too slow by 2 orders of magnitude, and it is doubtful that the real rate can be that much faster. Second, the pool of energy resident in the ions is not sufficient to maintain the torus without significant mass loading effects on the time scale of a rotational period. There are several arguments against loading rates on this scale, as discussed below.

The ion-electron relaxation time and the rate of energy transfer depends on the energy difference between the electrons and the ions. Ion temperatures in the hot torus have been estimated from the in situ Voyager Plasma Science (PLS) experiment [*Bagenal and Sullivan*, 1981] at $T_i = 4\text{–}5 \times 10^5$ K on the assumption that the peak at a mass per charge of 16 in their data was dominated by S III. This is in reasonably good agreement with ground-based observations near the time of Voyager 1 encounter by *Trauger et al.* [1979], who obtained a value of 3×10^5 from the S III 9532-Å

TABLE 1. Electron-Ion Energy Transfer Properties

	τ_l, s†	τ_{eq}, s‡	T_i, K¶	N_i, cm^{-3}§	$N_i \frac{dE_i}{dt}$, ergs cm^{-3} s^{-1}‖	$N_i \frac{dE_i}{dt}$, eV cm^{-3} s^{-1}‖
S II	5.1 + 5*	4.3 + 6	5.4 + 6	44	−1.1 − 14	−6.8 − 3
S III	3.6 + 6	1.1 + 6	3.4 + 5	160	−8.0 − 15	−5.0 − 3
S IV	8.0 + 6	5.0 + 5	1.3 + 5	216	−4.5 − 15	−2.8 − 3
O II	4.2 + 6	2.2 + 6	5.7 + 5	49	−2.2 − 15	−1.4 − 3
O III	8.3 + 6	5.6 + 5	1.3 + 5	336	−6.4 − 15	−4.0 − 3
Total				805	−3.2 − 14	−2.0 − 2

*5.1 + 5 = 5.1×10^5

†Characteristic lifetime against diffusive loss ((13) and (15)) of the ions $D = 1.2 \times 10^{-7}$ s^{-1} (see text). Rate coefficients QX_i determined for $T_e = 8 \times 10^4$ K, from *Jacobs et al.* [1978, 1979].

‡Equipartition time (4).

¶Steady state ion temperature ((13) and (17)).

§Mean ion number density, from *Shemansky and Smith* [1981].

‖Ion-electron energy transfer rate (16). Formation energy of S II and O II is assumed to be 507 eV and 253 eV, respectively. If it is assumed that the ions lose all of their energy to the torus electrons, the deposition rate is 4.8×10^{-14} ergs cm^{-3} s^{-1}, determined by the value of D applied to the calculations. The radiative loss rate from the hot torus is estimated to be 4.8×10^{-13} ergs cm^{-3} s^{-1}.

line width. The electron temperature in the hot torus is $T_e = 8 \times 10^4$ K for the Voyager 1 encounter period according to *Shemansky and Smith* [1981]. This is in reasonable agreement with the interpolated results obtained from the in situ PLS data [*Scudder et al.*, 1981]. We make the assumption that the conditions $T_i = 3 \times 10^5$ K and $T_e = 8 \times 10^4$ K represent a steady state thermal disequilibrium of the hot plasma torus. *Brown* [1981*a*] reports recent measurements of the S II 6700-Å line shapes, which he has fitted with a mix of three Maxwellian distributions at temperatures of 3.1×10^4, 3.2×10^5, and 2.2×10^6 K, giving a mean effective temperature of 6.6×10^5 K. Although these measurements were obtained at a much later time, they appear to be compatible with the lower temperature applied here to the S III ions, since S III should relax at a higher rate, as discussed below. Discussions in the literature, based on early unpublished results of PLS measurements of electron energy distributions, refer to as much as 5% inclusions of 10^6–10^7 K electrons in the dense central hot torus [*Strobel and Davis*, 1980; *Brown*, 1981*b*; *Eviatar and Siscoe*, 1980]. It now appears, on the basis of a number of factors, that quantities of hot electrons, even as low as 1%, cannot be tolerated (*Scudder et al.* [1981], *Shemansky* [1980*a*], R. A. Brown and D. E. Shemansky, unpublished manuscript, 1981) and the direct estimates (0.025%) by *Scudder et al.* [1981] may well be correct. This appears to be a likely condition since the plasma EUV intensity and electron temperature appear to have been stable for the larger part of a year surrounding the time of Voyager 1 encounter. Although an understanding of how this state of steady thermal disequilibrium is established is not directly necessary for the calculation of equipartition time, it is a matter of importance to the loading of mass into the torus. *Bagenal and Sullivan* [1981] have discussed this issue in a general way in the context of assumptions necessary for the analysis of the PLS data. The observed temperature of the ions is an order of magnitude below the gyroenergy acquired from acceleration to full corotation at the point of ionization of the neutral atom. One explanation for this energy difference suggesed by *Richardson et al.* [1980] requires a high mass-loading rate in which ions are shielded from acquiring full corotational energy by strong interaction at Io. Although this possibility cannot be entirely discounted, it seems unlikely since measurable optical activity expected to be associated with such a process has not been observed [*Shemansky*, 1980*a*; *Moos and Clarke*, 1981]. An alternative process is one in which the diffusive loss time is long enough to allow the ions to relax to the observed energy. If this is the case, we expect the ions to have energy distributions that depend on both mass and charge.

ION-ELECTRON RELAXATION

The equipartition time for Coulomb collisions (τ_{eq}) between two sets of particles can be written [*Spitzer*, 1962],

$$\tau_{eq} = 5.87 \frac{A_e A_i}{N_e Z_e^2 Z_i^2 \ln \Lambda} \left(\frac{T_e}{A_e} + \frac{T_i}{A_i} \right)^{3/2} \quad (s) \tag{4}$$

where A is the atomic number, Z is particle charge, and Λ is an impact parameter factor determined by the Debye shielding distance. For the range of temperatures considered here the magnitude of τ_{eq} is determined entirely by the electrons. It is therefore not important that the ions be in a Maxwellian distribution, and τ_{eq} can be regarded as an exponential decay constant. Equation (4) is applicable only to an isotropic plasma in which charge neutrality obtains beyond the Debye shielding distance. In the case of the plasma torus the plasma is formed in a magnetic field, and distributions are not necessarily isotropic and homogeneous. Thus some deviation from (4) may be expected. At the temperatures and densities considered here, (4) reduces to

$$\tau_{eq} = 1 \times 10^8 / Z_i^2 (23.2 - \ln Z_i) \qquad \text{sulfur} \tag{5}$$

and

$$\tau_{eq} = 5 \times 10^7 / Z_i^2 (23.2 - \ln Z_i) \qquad \text{oxygen} \tag{6}$$

using a mean electron density of $N_e = 1850$ cm^{-3} [*Shemansky and Smith*, 1981]. The equipartition times for sulfur and oxygen from (5) and (6) range from 50 days to 6 days, as shown in Table 1. A rough measure of departure from the Coulomb relaxation time estimated here may be obtained from the recent observations by *Brown* [1981*a*] of the S II energy distribution mentioned above. Brown obtains a three-temperature fit to the line shape, but this may simply be an artifact of the distribution, since one may not expect anything approaching a Maxwellian. The time history of the injection of neutrals alone may impart peculiar kinetic distributions. However, the mean energy of the S II ions in the *Brown* [1981*a*] observations is of interest since the value is approximately a factor of 8 below the predicted value in Table 1. The computation of the predicted mean ion energy is described in a following section. This result indicates that if the Brown measurement may be taken as typical the diffusive loss time in the calculation was too short (100 days) or that the equipartition time is too long. Many would argue reasonably that the Coulomb equipartition time is too long for S II ion in particular. This would reduce the equipartition time for S II from 50 days to 6 days. The relaxation time on this basis is still far too long for the required ≃2-hour response time. If the transfer rate were in fact this short (≃6 days), then most of the ion energy would be delivered by the singly ionized species. We note that *Brown* [1981*b*] reports a much higher temperature for the S III line at 6312 Å (≃10^6 K). We assume that this value is not typical of average conditions since, if it is, we have a serious problem of interpretation.

A further argument against the ion-electron transfer process involves the question of mass loading. If we take the *Brown* [1981*a*] mean S II energy as typical and the remaining data from Table 1, the pool of energy in the resident ions available for delivery to the electrons is ≃15 keV cm^{-3}. This quantity represents a capacity to sustain the torus at its normal emission rate for a period of 11 hours. Thus the pool of energy available to the electrons could sustain the torus for approximately one rotation period, if it could be delivered. This rather low capacity has two implications for a postulated ion-electron energy transfer system for sustaining the plasma torus. First, the low capacity requires that the energy be delivered to the ions with a local time periodicity rather than by some periodic catalysis of the transfer process. Second, the required rate of transfer introduces an

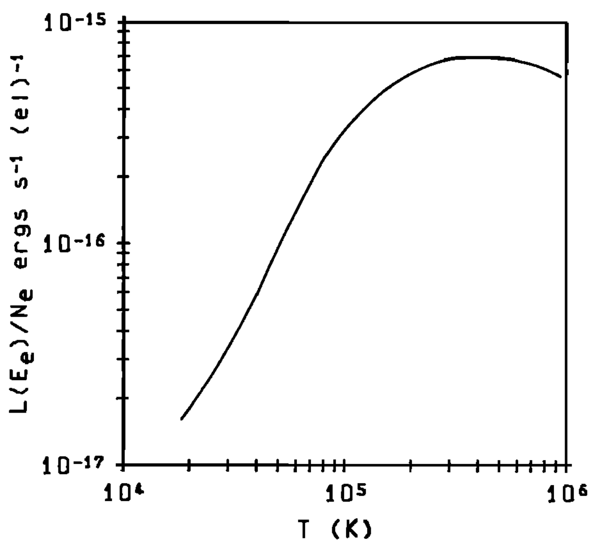

Fig. 4. Calculated total average radiative cooling rate per unit volume per electron for the torus composition shown in Table 1. The collision strengths used in the calculation are those given by *Shemansky and Smith* [1981].

unacceptable level of mass transfer to and from the torus. If the ions are postulated to be the energy transfer medium for the electrons, the energy for the system must enter through the creation of new ions. If, as the observations would dictate, most of the energy in the ions must be transferred during part of the 10-hour day, we require both a local time variation in mass loading and an unacceptably high rate. Several factors lead to this conclusion: (1) The EUV observations have never shown plasma mass variations, even in the observed occasions of short-term variability. (2) S III and S IV cannot be created in the time scale of a few hours, given our present knowledge of the plasma. The estimated lifetime of S II against ionization is ≃6 days (Table 1). (3) The injection of mass at the rate implied by the transfer mechanism requires a high influx of neutrals, whereas the only neutral emission detected in the torus is a weak O I 6300-Å line [*Brown*, 1981*b*]. The inferred amount of O I is about 2 orders of magnitude below the quantity required in this case. We conclude that the 10-hour modulation of torus emission cannot contain an ion-electron energy transfer component.

ELECTRON-ELECTRON RELAXATION AND ENERGY TRANSFER RATES

We have noted above that electron-ion relaxation times are at least an order of magnitude too long to account for a 10-hour modulation. Electron-electron relaxation on the other hand has rates which are 4 orders of magnitude faster than the ion-electron process. The relaxation time for particles interacting with themselves can be written [*Spitzer*, 1962]

$$\tau_e = \frac{11.4\, A^{1/2}\, T^{3/2}}{N\, Z^4 \ln \Lambda} \quad (s) \tag{7}$$

For electrons with $N_e = 1850$ cm^{-3}

$$\tau_e = 6.2 \times 10^{-6}\, (T)^{3/2} \quad (s) \tag{8}$$

A temperature of 8×10^4 K for the bulk of the electrons gives

$$\tau_e = 140 \quad (s)$$

Thus on the basis of relaxation times above, the observed modulation must be explained by some process involving electron-electron heating. We show below that the component of the torus energy input that varies with local time amounts to a substantial fraction of the energy required to maintain the torus and that, on the other hand, it is unlikely that any substantial uniform excitation component can be supplied by the ion-electron relaxation process.

The relaxation processes in the torus are rate limited by electron collisions, producing radiative loss from the torus. We are then in a system in which the ions relax toward the electron temperature, with the electrons acting as an energy sink. The rate at which energy is lost by radiation in the torus is estimated to be [see *Shemansky*, 1980*b*] 4.8×10^{-13} ergs cm^{-3} s^{-1} (0.30 eV cm^{-3} s^{-1}). This is a mean rate over the 1 R_J half-width of the torus, calculated by using the ion partitioning given by *Shemansky and Smith* [1981]. Figure 4 shows the radiative cooling efficiency as a function of electron temperature. This curve is specialized and must be used with caution because its derivation is based on a fixed

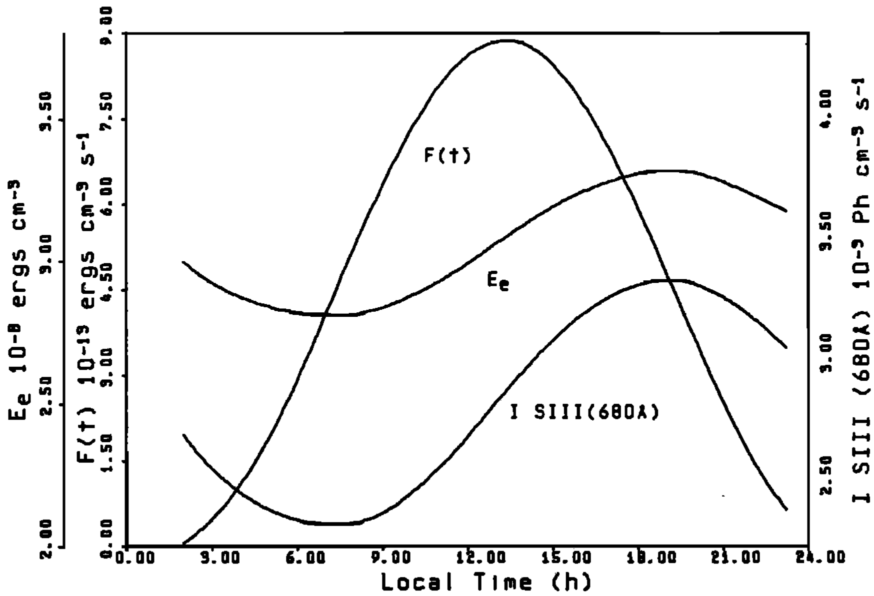

Fig. 5. Response of a given volume of the plasma torus to a sine wave electron energy source peaking at 13:30 LT. The electron energy loss function (Figure 4) has a characteristic time long compared to the 10-hour rotation rate. As a result, electron energy is pooled, and the energy density varies only 18%, as shown in the figure. The predicted S III 685-Å emission rate is also shown in the figure, and the electron energy density lags the source by a phase angle of ≈85°.

partitioning of ion species. The curve is therefore appropriate to short-term electron temperature variations, centered on $T_e = 8 \times 10^4$ K, relative to the ionization equilibration times, which range between several days and several months for the major torus ions. We note, however, that a curve based on equilibrated ion distributions would not be substantially different from Figure 4. The radiative-cooling curve depends on the assumption that the electron energy distribution in the central dense region of the torus is dominated by a single-temperature Maxwellian. As noted above, the *Scudder et al.* [1981] in situ measurements indicate that this is the case; the projected amounts of high temperature electrons have little effect on the calculated rate [*Shemansky and Smith*, 1981]. Deviations of the electron energy distribution from a Maxwellian caused by the radiative sink are estimated to be negligible, as indicated below. We thus expect the curve of Figure 4 to be a reasonably accurate estimate of the total radiative cooling efficiency.

The response of the torus to a time-varying electron-electron heating source can be estimated in the following manner. We make the assumption that longitudinal or radial diffusion of torus plasma in a 10-hour period is entirely negligible, so that a given volume of the central hot torus can be regarded as a closed system. The dependence of the electron energy density (E_e) of a given torus section on a source function $f(t)$ can be written

$$\frac{dE_e}{dt} + L(E_e) = f(t) \qquad (9)$$

It is important to note that (9), and the subsequent discussion, applies to the corotating frame of reference in which time relates to events in a given volume section of torus plasma. The exact nature of the observed intensity variation in local time around the torus cannot be determined [*Sandel and Broadfoot*, 1981] as a unique function, although the data do define an effective width for the source, and we simply assume for the purpose of illustration that $f(t)$ is a smoothly varying function of the form

$$f(t) = A\,(\sin \omega t + 1) \qquad (10)$$

where A is an amplitude and ω is the natural ($2\,\pi\nu$) frequency corresponding to the 10-hour period of the torus rotation. The energy loss function $L(E_e)$ determined from the curve of Figure 4 has a complex form that would require numerical integration of (9). However, the range of variation of E_e in this case is not large, and the loss function can be approximated by the equation

$$L(E_e) = Cv\,E_e \qquad \text{ergs cm}^{-3}\,\text{s}^{-1} \qquad (11)$$

where $Cv = 1.45 \times 10^{-5}\ (s)^{-1}$ is the loss probability determined at $T = 8\,E\,4$ K from the radiative cooling curve. The energy density as a function of time is then given by

$$E_e(t) = \left(\frac{A}{Cv}\right)\left[\left(\frac{\omega\, Cv}{Cv^2 + \omega^2}\right)\left(\frac{Cv}{\omega}\sin \omega t - \cos \omega t\right) + 1\right] \qquad (12)$$

for a steady state condition. The characteristic time of the electron energy density is roughly 20 hours, and $(Cv/\omega) = 8.3 \times 10^{-2}$. For this reason the energy density $E_e(t)$ shows a considerable phase shift in relation to the source function and a variation of only 18% over one period of rotation. The corresponding range of electron temperature is 7.3×10^4 K $< Te < 8.7 \times 10^4$ K. The corresponding variation in local volume emission rate of S III (685-Å) radiation is 43%, fractionally smaller than the 55% estimate from observation. On this basis, the 10-hour variational source could account for the total radiated energy of the torus. Figure 5 shows a plot in local time of the assumed source function, the electron energy density calculated according to (12), and the emission rate of the S III (685-Å) feature. If this emission rate distribution is inserted as a model in the torus, we obtain the fit to the observations shown in Figure 1. The agreement is much better than one might otherwise infer from the difference between the 43% variation of the model and the 55% value given by *Sandel and Broadfoot* [this issue] because the intensity distribution they assumed differs from that calculated here. It would be difficult to improve on the model fit shown in Figure 1. This does not mean that we advocate a sine wave source distribution. The data in fact indicate that at least some parts of the source variation must have a somewhat higher slope. The conclusion of importance here is that the data dictate the half width of the variational source, whatever the exact nature of the model variation may be. The half width of the source is the ultimate determinant of what fraction of the source must be variational in the corotating frame of reference. To this extent our conclusion does not depend on any particular model. The point is that model brightness profiles, calculated by using narrow impulse sources, fit the data very poorly—well beyond measurement error bars—and satisfactory results cannot be obtained as a function of viewing angle or within a given set of system scans as discussed by *Sandel and Broadfoot* [this issue]. The brightness profile measured across the torus is not well matched by such a model for any choice of the local time of the energy impulse. The dashed curve in Figure 6 shows a comparison of the best fit that can be obtained with a narrow impulse in energy with a measured brightness profile. Another model used by *Sandel and Broadfoot* [this issue] applies a source in which half of the energy is supplied by an azimuth-independent source, and the remainder is injected near 1300 local time. The brightness profile produced by this model is shown by the solid curve in Figure 6. A compromise between matching the east-west brightness ratio and matching the central profile has been reached in this curve, yet in neither case is the fit comparable to that produced by a source having a 4–5 hour half width in the variational component. The local time energy source must therefore extend over a range comparable to the source described in (10). It is of interest to note that the source function in the sine wave source peaks near noon local time in order to produce a peak emission rate near 19:00 LT, a phase difference of ≈85°.

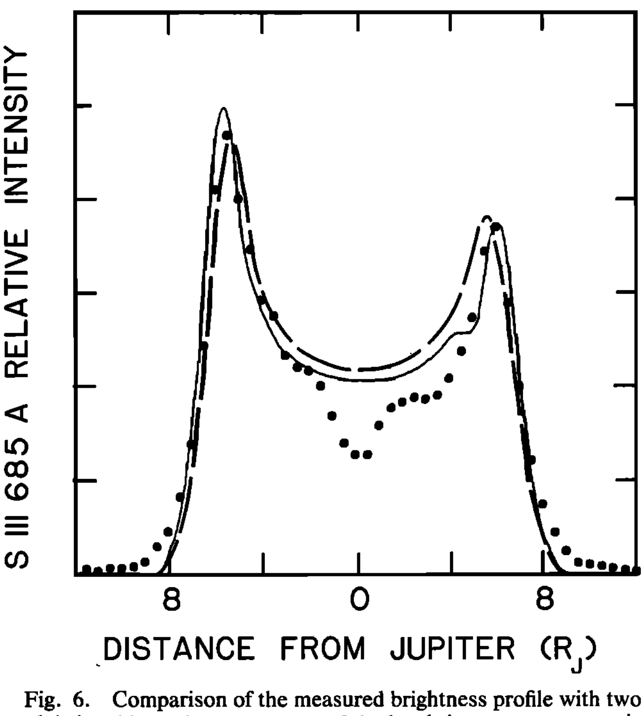

Fig. 6. Comparison of the measured brightness profile with two models in which azimuthal extent of the local-time energy source is infinitesimal. The dashed curve shows the brightness profile that would result if all the energy radiated by the torus were supplied in an infinitesimal range of local time chosen to yield the best fit of model and data. The solid curve corresponds to the best fit model of *Sandal and Broadfoot* [this issue] that included a step-function variation in brightness; in this model, half the energy is supplied in an infinitesimal range of azimuth, and half is distributed uniformly in azimuth. Both models are markedly inferior to those in which the local time source is distributed over a wide range of azimuth (Figure 1).

An estimate of the ion-electron energy transfer rates in the hot torus depends to some degree on how the ions are assumed to enter the torus. However, the rates we estimate here depend essentially on the observations indicating S III temperatures in the vicinity of $T_i = 3 \times 10^5$ K. The mean energy of the ions depends on the time history of the species in the torus. The production and loss of a species $[X_i]$ in a given radial cross section of the torus can be approximately described by the equation

$$\frac{d[X_i]}{d\tau} = \gamma_i - [X_i]\,[[N_e]\,QX_i + D] \qquad (13)$$

where QX_i is the ionization rate coefficient, N_e is electron density, D is the diffusive loss probability, and γ_i is the source function. Recombination is neglected as a source in this calculation since it is not significant in the hot torus [*Shemansky*, 1980*a*; *Strobel and Davis*, 1980]. Thus γ_i is determined by

$$\gamma_i = [X_{i-1}]\,[N_e]\,QX_{i-1} \qquad (14)$$

the characteristic time of an ion species in the torus is then determined by a system of coupled equations in the form of (13). The number density of neutral particles (X_1) in a given volume of the torus most likely has a strong modulation at 13.0 hours, the period of Io's orbit relative to λ_{III}. This is especially true of S I, which has a lifetime of ≈10 hours against ionization at $T_e = 8 \times 10^4$ K, and we expect an asymmetric distribution concentrated around the position of Io (W. H. Smyth and D. E. Shemansky, unpublished manuscript, 1981; *Smyth* [1979]). The production of S II and O II in the torus volume will then have a 13.0-h modulation (14). However, the lifetime of S II and O II against ionization and diffusive loss is 6 days or longer (Table 1), and we do not expect to obtain a measureable 13.0-hour variation in source particles because of the resultant background of resident X_2 ions as an average condition of the torus (see Appendix). We therefore assume that γ_2 is constant. The characteristic loss time (τ_i) of the X_2 ions in the torus is then given by

$$\tau_i = 1/[N_e QX_i + D] \qquad (15)$$

and τ_2 may be taken as an estimate of the residence time of the S II and O II ions in the torus.

The characteristic residence time for the more highly ionized atoms is, in principal, more complex, since γ_i, $i > 2$, is a time-dependent quantity. However, the values of τ for each higher stage of ionization differ by factors large enough that the values of τ_i for $i > 2$ are also a satisfactory approximation to residence time (Appendix).

The energy transfer rate per particle can be written [*Spitzer*, 1962]

$$\frac{d\,E_i}{d\,t} = (E_e - E_i)/\tau_{eq} \tag{16}$$

where E_i is the mean energy per ion, E_e is the mean energy per electron, and τ_{eq} is given by (4). The mean ion energy as a function of time is then given by

$$E_i(t) = E_e + (E_i(0) - E_e) \exp(-t/\tau_{eq}) \tag{17}$$

An estimate of the mean energy of the ions can then be obtained by setting $t = \tau_i$. If we assume the S II and O II ions obtain full corotational energy, we require a 100-day diffusive loss time to reduce the temperature of the S III ions to the observed value of $\simeq 3 \times 10^5$ K. The characteristic times, ion temperatures, and energy transfer rates for the observed species calculated on this basis are given in Table 1. The total electron-ion energy transfer rate is $\simeq 3 \times 10^{-14}$ ergs cm^{-3} s^{-1} (2×10^{-2} eV cm^{-3} s^{-1}) compared to the 4.4×10^{-13} ergs cm^{-3} s^{-1} (0.3 eV cm^{-3} s^{-1}) required to maintain the radiative system. We note that *Brown* [1981*b*], in a similar calculation, obtains a considerably larger value for the transfer rate from S III ions ($\simeq$0.09 eV cm^{-3} s^{-1}). The differences in these estimates are due to a number of factors. The Brown results were obtained at a later date, with indications of increased mass. The Brown calculation applies an S III density 3 times greater than the value used here, with a commensurate implied increase in electron number density and total radiated energy. In addition the Brown work includes a lower electron temperature and the higher S III ion temperature (10^6 K) mentioned above. As we have indicated, we regard the very high S III temperature obtained by Brown as atypical.

DISCUSSION

An attempt to understand the results presented here inevitably becomes entangled in more than one way with the mass loading and diffusive loss rates in the hot plasma torus. The observed 10-hour modulation in EUV emissions, given the electron energy loss rates applied here, indicates that effectively all of the radiated power in the torus is supplied by a periodic energy source. That is, if a constant source relative to a 10-hour time scale were postulated as being mixed with the time-varying source, it would be very difficult to reproduce the observed average magnitude of the local time asymmetry. If this conclusion holds, we have a result of high significance since the energy must be transferred to the torus plasma by an electron-electron heating process on the grounds that electron-ion rates cannot relax in the required time and that the creation of new ions as a mechanism to supply the energy is basically incompatible with the observations. The result certainly complicates our understanding of torus energetics because up to this point we have almost exclusively discussed processes in terms of direct energy transport from ions accelerated in the rotating magnetic field. The ultimate source process now becomes much more obscure. For this reason it is important that the quantities entering the analysis be examined in detail to determine the degree of confidence that can be placed on the conclusions. The required study goes beyond the scope of this article, but we propose to discuss the uncertainties in a general way. The assumption in calculating the electron energy loss rate was that it was controlled by radiative excitation of the ambient ions (Figure 4). If our conclusion about the nature of the energy source were to change substantially, we would require some conditions not considered in the present calculation to substantially alter the energy loss rate of the electrons. An electron energy loss component that has been ignored in this calculation is the energy required to ionize the mass injected into the torus. An estimate of this loss rate depends on a quantity that has not been established; estimates of mass loading rates by various methods have ranged through orders of magnitude from $\simeq 10^{27}$ s^{-1} to $\simeq 10^{30}$ s^{-1}. The favored value in more recent work [*Dessler*, 1981; *Eviatar and Siscoe*, 1980; *Hill*, 1980] seems to be in the range of the 3×10^{28} s^{-1} rate originally estimated by *Broadfoot et al.* [1979]. This loss rate corresponds to a 9-day diffusive loss time [*Shemansky*, 1980*a*]. Assuming that equal numbers of oxygen and sulfur ions enter the torus, and a mean energy loss of 12 eV per ion produced, the electron energy loss rate through ionization would be 1.4×10^{-14} ergs cm^{-3} s^{-1} (8.7×10^{-3} eV cm^{-3} s^{-1})—negligible compared to the radiative loss rate. Subsequent ionization processes are slower (Table 1). The suggestion by *Cheng* [1980] that there are on the order of 1000 cm^{-3} SO_2 molecules in the torus is completely at variance with these results. As we have noted above, the pool of energy resident in the torus ions is low enough that substantial mass variation in local time would be required to explain the observations of intensity modulation, whereas we have concluded the variation is not one of mass. A diffusive loss time shorter than 9 days, in our judgement, is highly unlikely, based on optical observations and other grounds [*Smyth and Shemansky*, 1981; *Shemansky*, 1980*a*]. However, it should be kept in mind that a high diffusive loss rate of $\simeq 10^{30}$ s^{-1} would measurably increase the electron energy loss rate. The energy required for the ionization process at these rates would exceed the radiative loss. Other electron energy loss processes not considered here are plasma wave interactions that give rise to radio emissions. The calculated energy loss curve of Figure 4 does not have a high sensitivity to reasonable deviations of the applied partitioning of ion species. Earlier calculations by *Shemansky* [1980*b*], using a somewhat different partition function, produced very nearly the same total radiative loss rate used in the present calculation.

The electron-ion energy transfer rate calculated for the partitioned species depends on the assumed mode of entry of the ions into the torus and on an estimate of the diffusive loss time. The energy transfer rates calculated here depend on the assumption that the ions acquire the full corotational energy imparted by the magnetic field. The Spitzer equations for equipartition time and the observations indicating $T_i \simeq 3 \times 10^5$ K for S III then fix an estimated diffusive loss time of $\simeq$100 days and total energy transfer rate of 3×10^{-14} ergs cm^{-3} s^{-1}, as given in Table 1. If we assume a common speed model [*Bagenal and Sullivan*, 1981], we obtain approximately the same rate, although the relative rates of the partitioned species are quite different in the two cases. It then appears that ambient ions in the torus can supply only a minor fraction of the energy required by the torus, whether the calculation is based on a common speed model or on the assumptions applied in the present work. Thus the estimate for ambient ions shows a certain independence of calculated ionization and diffusive loss rates and depends essentially on the observed temperature of the S III ions. The assumption of a common thermal speed for the ions places a rather strong constraint on the physical processes in the torus since it would require that the diffusive loss time be shorter than 6 days to avoid substantial cooling of O III and S IV ions. Consequently, a hot electron component greater than 5% [see *Scudder et al.*, 1981; *Shemansky*, 1980*a*; *Strobel and Davis*, 1980] would be required to generate measurable numbers of the higher ions in the first place. As we have noted above, the possibility of either of these conditions is unlikely. There is a question about the accuracy of applying the Spitzer equation for equipartion time (τ_{eq}, (4)), especially to the cooling of S II and O II because of the anisotropy of the velocity distribution. However, a shorter equipartition time for the singly ionized species would have to be accompanied by comparably larger ionization rates in order to significantly increase the rate of energy transfer from the electron-ion process. The recent observations by *Brown* [1981*a*] suggest that S II relaxation is faster than the coulomb rate by approximately an order of magnitude, but the inferred interaction rate is still too slow to contribute to the observed modulation.

If the conclusions drawn here are correct, the nature of the energy source becomes more difficult to understand since we must discount the direct process of electron-ion energy transfer. The fact that the observed asymmetry is a local time effect and that the peak in the source function occurs near Jupiter's noon meridian certainly suggests that solar input is a controlling factor. The presence of a measurable hot electron component in the torus, and in the magnetosphere outside the torus [*Scudder et al.*, 1981], may be an indicator of a magnetospheric source of energetic electrons capable of transferring energy to the plasma. Electrons and protons backscattered from the aurora on Jupiter [*Thorne*, 1981] may make some contribution, but it is not clear why a local time effect should appear. Photoelectrons are produced near the exobase in the higher latitudes of Jupiter and would tend to generate an asymmetry, but we require a detailed examination of the feasibility of providing energy from photoelectrons and protons accelerated up the field lines through the torus.

The radial distribution of temperature at the eastern and western elongations (Figure 2) indicates that the energy input to the electrons is distributed over the width of the torus. In fact the ratio of dusk to dawn temperatures increases with increasing radial distance to at least 7.5 R_J. It is of interest to note that the relative numbers of hot electrons observed by *Scudder et al.* [1981] in the torus show the same trend. In view of the very short relaxation times for electrons it is very likely that the hot electron component has a magnetospheric source and is not confined to the torus volume. The energy density of hot electrons at 8.9 R_J is 5.6 KeV cm^{-3}, using the *Scudder et al.* [1981] data, compared to 20 keV cm^{-3} for the electrons in the central hot torus. It is conceivable that the much lower densities of hot electrons in the central torus relative to those at 8.9 R_J may be caused by a transfer of energy by a magnetospheric electron flux accompanied by protons to the denser ambient electron field.

The results we obtain here do not necessarily make a statement limiting the energy delivered to the magnetospheric system by mass loading from Io. In fact, differences between the ground-based and EUV morphology may be best explained by a mass loading process that on occasions delivers large amounts of mass to the magnetosphere, but only very inefficiently to the hot plasma torus [*Brown et al.*, 1981]. However, the analysis does indicate that, on the average, processes such as electron-ion collisions that have relaxation times longer than 5 hours do not contribute more than ~10% of the energy required to maintain the plasma emission. This clearly places some ill-defined limit on mass loading of the hot torus in particular since increased mass loading and ion production rates increase the electron-ion energy transfer rate. The mass loading limit for the hot torus cannot be defined on this basis until better estimates of relaxation times can be obtained and until we obtain an understanding in greater detail of how particles from Io are converted to torus ions. If we make the assumption that the ions are produced with full corotational energy, the diffusive loss time will be at least 50 days, based on an upper limit of 20% for a constant source over the torus rotational period and assuming that all of the ion energy is supplied to the torus plasma.

CONCLUSIONS

The asymmetric distribution observed in the hot plasma torus emission in the EUV [*Sandel and Broadfoot*, this issue] is interpreted as a 10-hour local time modulation in electron temperature in the corotating reference frame. The magnitudes of the modulation and the estimated electron energy loss rate per electron are such that essentially all of the power requirement for the maintenance of the torus must be supplied by a 10-hour variational source. If this source is assumed to be a smooth function varying between some maximum value and zero, the peak of the energy input must occur near noon local time in order to produce the observed intensity maximum at 19:00 LT. The energy supply for the torus has been discussed in the literature in terms of direct ion-electron energy transfer from ions accelerated by the rotating magnetic field. We conclude that the time constants for such a process are too slow to account for the present source requirements, and most of the energy must be supplied by some source producing electron-electron heating in the torus. Although these results tend to disconnect the mass loading rate of the hot torus as a direct source of energy, an ill-defined limit on the loading rate is fixed by the fraction of the energy source that can be tolerated as an approximately constant function over a 10-hour period. We place a generous upper limit of 20% on such a source. If the ions injected into the torus acquire full corotational energy, this limits the diffusive loss time to at least 50 days.

We recommend that the conclusions drawn here be investigated in further detail since they represent an important statement on how energy enters the plasma torus. There are distinct morphological differences between the ground-based observations of S II and the EUV measurements of the torus that are difficult to understand. It is essential to do further observational work with careful differentiation in radial location in order to relate the S II emissions to the more highly ionized species so that source processes can be more easily understood. Ion temperature measurements of the various stages of S and O ionization are also essential for the determination of source and relaxation processes. It is remarkable that the Voyager EUV observations of variability have revealed no effects that can be attributed to mass loading variations, whereas the ground-based observations of S II show strong effects, apparently indicating ion density asymmetries in magnetic longitude. Unfortunately, local time effects in electron temperature probably cannot be investigated satisfactorily from the ground. Possible source processes driving the local time electron-electron heating of the torus must be investigated.

APPENDIX

Production of Ions

Limits to the variability in plasma ion mass of a given torus volume can be estimated by assuming a step function distribution of neutrals in the orbit of Io. Thus

$$X_1(t) = A\left[\sum_{n=0}^{\infty} (\mu(t - n\phi) - \mu(t - n\phi - \tau))\right] \qquad \text{(A1)}$$

$$n = 0, 1, \ldots$$

describes the time variability of the neutral population of the torus volume, where A is an amplitude, $\mu(t)$ is the unit step function, ϕ is the period (13.0 hours), and τ is the time width of the neutral atoms. Insertion of (A1) in (13) and (14), then, gives the variability of the singly ionized species

$$X_2\,(n\phi + \delta) = \frac{A[1]}{[2]}\left[\frac{(e^{[2]\tau} - 1)}{(e^{[2]\phi} - 1)} \cdot e^{-[2]\delta} + 1 - e^{-[2]\delta}\right] \qquad \text{(A2)}$$

$$\delta \le \tau$$

$$X_2\,(n\phi + \delta + \tau) = \frac{A[1]}{[2]}\left[\frac{(e^{[2]\tau} - 1)}{(e^{[2]\phi} - 1)} \cdot e^{-[2](\tau+\delta)} + e^{-[2]\delta}(1 - e^{-[2]\tau})\right] \qquad \delta \le (\phi - \tau) \qquad \text{(A3)}$$

for $n \rightarrow \infty$, where $[1] = [N_e]\,QX_1$ and $[2] = [N_e]\,QX_2 + D$. Substitution of the appropriate ionization rates (Table 1), and setting $\tau = (0.1)\phi$, produces a variability of singly ionized species of $\simeq$4%. If the diffusive loss time is reduced to 10 days, we obtain a variation of 14%. It is doubtful that a 14% variation would be detectable in ground-based observations. In fact, no Io-associated effects have been observed. It appears that only strong transient events or direct injection of ions from Io would be observable. However, such events would appear as magnetic longitude effects with apparent 10-hour periodicity for observations at elongation.

The time-dependent production of the higher ions can then be calculated, assuming a constant source term for the singly ionized species. The population of doubly ionized species can then be written

$$[X_3](t) = \frac{\gamma_2 N_e Q X_2}{[2][3]}\left[1 - \left(\frac{[2]}{[2, 3]}\exp(-[3]t)\right) \cdot \left(1 - \frac{[3]}{[2]}\exp(-[2, 3]t)\right)\right]$$

where $[2, 3] = [2] - [3]$, and $\gamma_2 = [X_1][N_e]QX_1$, with X_1 assumed to be constant in time. If $[2] \gg [3]$ the characteristic time tends to be controlled by the loss probability [3]. A similar argument applies to X_4 ions.

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REFERENCES

Bagenal, F., and J. D. Sullivan, Direct plasma measurements in the Io torus and inner magnetosphere of Jupiter, *J. Geophys. Res.*, *86*, 8447, 1981.

Bridge, H. S., et al., Plasma observations near Jupiter: Initial results from Voyager 1, *Science*, *204*, 987, 1979.

Broadfoot, A. L., et al., Extreme ultraviolet observations from Voyager 1 encounter with Jupiter, *Science*, *204*, 987, 1979.

Broadfoot, A. L., et al., Overview of the Voyager Ultraviolet Spectrometry results through Jupiter encounter, *J. Geophys. Res.*, *86*, 8259, 1981.

Brown, R. A., The probability distribution of S^+ gyrospeeds in the Io torus, *J. Geophys. Res.*, in press, 1981*a*.

Brown, R. A., The Jupiter hot plasma torus: Observed electron temperature and energy flows, *Astrophys. J.*, *244*, 1072, 1981*b*.

Brown, R. A., C. B. Pilcher, and D. F. Strobel, Photometric study of the Io torus, in *Physics of the Jovian Magnetosphere*, edited by A. J. Dessler, Cambridge University Press, New York, 1981.

Cheng, A. F., Effects of Io's volcanos on the plasma torus and Jupiter's magnetosphere, *Astrophys. J.*, *242*, 812, 1980.

Dessler, A. J., Mass-injection rate from Io into the Io plasma torus, *Icarus*, *44*, 291, 1980.

Eviatar, A., and G. L. Siscoe, Limit on rotational energy available to excite Jovian aurora, *Geophys. Res. Lett.*, *7*, 1085, 1980.

Eviatar, A., G. L. Siscoe, and Yu. Mekler, Temperature anisotropy of the Jovian sulfur nebula, *Icarus*, *39*, 450, 1979.

Hill, T. W., Corotation lag in Jupiter's magnetosphere: A comparison of observation and theory, *Science*, 207, 301, 1980.

Jacobs, V. L., J. Davis, J. E. Rogerson, and M. Blaha, Ionization equilibrium and radiative energy loss rates for C, N, and O ions in low-density plasmas, *J. Quant. Spectrosc. Radiat. Transfer*, *19*, 591, 1978.

Jacobs, V. L., J. Davis, J. E. Rogerson, and M. Blaha, Dielectronic recombination rates, ionization equilibrium, and radiative energy loss rates for neon, magnesium, and sulfur ions in low-density plasmas, *Astrophys. J.*, *230*, 627, 1979.

Massey, H. S. W., and E. H. S. Burhop, *Electronic and Ionic Impact Phenomena*, p. 125, Oxford University Press, New York, 1969.

Moos, H. W., and J. T. Clarke, Ultraviolet observations of the Io torus from earth orbit using the IUE observatory, *Astrophys. J.*, *247*, 354, 1981.

Morgan, J. S., and C. B. Pilcher, Plasma characteristics of the Io torus, *Astrophys. J.*, *248*, 1981.

Pilcher, C. B., and J. S. Morgan, The distribution of S II emission around Jupiter, *Astrophys. J.*, *238*, 375, 1980.

Richardson, J. D., and G. L. Siscoe, Factors governing the ratio of inward to outward diffusing flux of satellite ions, *J. Geophys. Res.*, *86*, 8485, 1981.

Richardson, J. D., G. L. Siscoe, F. Bagenal, and J. D. Sullivan, Time-dependent plasma injection by Io, *Geophys. Res. Lett.*, *7*, 37, 1980.

Sandel, B. R., and A. L. Broadfoot, Io's hot plasma torus—A synoptic view from Voyager, this issue.

Scudder, J. D., E. C. Sittler, and H. S. Bridge, A survey of the plasma electron environment of Jupiter: A view from Voyager, submitted to *J. Geophys. Res.*, 1981.

Shemansky, D. E., Mass loading and the diffusion loss rate of the Io plasma torus, *Astrophys. J.*, 242, 1266, 1980*a*.

Shemansky, D. E., Radiative cooling efficiencies and predicted spectra of species of the Io plasma torus, *Astrophys. J.*, *236*, 1043, 1980*b*.

Shemansky, D. E., and B. R. Sandel, Radial dependence of the Io plasma torus spectrum in the EUV, *Bull. Am. Astron. Soc.*, *12*, 674, 1980.

Shemansky, D. E., and G. R. Smith, The Voyager 1 EUV spectrum of the Io plasma torus, *J. Geophys. Res.*, *86*, 9179, 1981.

Shemansky, D. E., and D. F. Strobel, Ion composition of the Io plasma torus, paper presented at IAU Colloquium, Honolulu, Hawaii, May 1980.

Smyth, W. H., Io's sodium cloud: Explanation of the east-west asymmetries, *Astrophys. J.*, *234*, 1148, 1979.

Spitzer, L., *Physics of Fully Ionized Gases*, Interscience, New York, 1962.

Strobel, D. F., and J. Davis, Properties of the Io plasma torus inferred from Voyager EUV data, *Astrophys. J. (Lett.)*, *238*, L49, 1980.

Sullivan, J. D., and G. L. Siscoe, In situ observations of Io torus plasma, in *Satellites of Jupiter*, edited by D. Morrison, University of Arizona Press, Tucson, 1981.

Thorne, R. M., Jovian auroral secondary electrons and their influence on the Io plasma torus, *Geophys. Res. Lett.*, *8*, 509, 1981.

Trafton, L., the Jovian S II torus: Its longitudinal asymmetry, *Icarus*, *42*, 111, 1980.

Trauger, J. T., G. Munch, and F. L. Roesler, Ground-based observations of [S II] and [S III] in the Jovian magnetosphere near the time of the Voyager 1 encounter (paper P74A), paper presented at AGU Spring Meeting, Washington, D. C., 1979.

Trauger, J. T., G. Munch, and F. L. Roesler, A study of the Jovian S II nebula at high spectral resolution, *Astrophys. J.*, *236*, 1035, 1980.

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