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Energy Branching in the Io Plasma Torus: The Failure of Neutral Cloud Theory

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The energy branching of the hot Io plasma torus using model calculations which include all of the significant physical chemistry that affects the system has been examined in order to study energy source characteristics. Most theoretical discussions of the energetics of the torus assume that the system is maintained against radiative and other losses by the interaction of the plasma with neutral atomic clouds. The energy in this theory is derived from the kinetic energy acquired by ions created in the rotating planetary magnetic field. Coulomb collisions with the electron gas control the flow of energy to the ionizing and radiative processes. The energetics of this theoretical system is defined by fixing the electron density, the diffusive loss time, and the relative volumetric rates of injection of the major neutral constituents, oxygen and sulfur. On the basis of calculations of this kind in comparison with the characteristics of the observed system, the conclusion has been drawn that neutral cloud theory is qualitatively inadequate. At the measured electron densities in the plasma torus neutral cloud theory can only support a dominantly singly ionized system, whereas observation fixes the ratio [S II]/[S III] < 1.0. The theory also fails to predict observed plasma properties relative to variations in number density. A large fraction of the energy required by the observed system based on ion partitioning alone must be derived from some other interaction. Two possibilities for energy sources involving a particular interaction with an Io atmosphere and a heterogeneous source of energetic electrons are discussed.

INTRODUCTION

Most published discussion of the theory for Io plasma torus assumes that the system is maintained in mass and energy density by the ionization of neutral gas clouds originating from Io. The general description of the process is one in which cloud atoms interspersed with the plasma are ionized dominantly by reaction with electrons and subsequently accelerated to near corotation with the planetary magnetic field. The kinetic energy of the ions then heat the electron gas in a collisional-diffusive equilibrium in which most of the energy loss is through radiation. The energy for the system is therefore supplied in a direct way from the rotational energy of the planet. The basic mechanism of formation and acceleration of ions as the energy source for the plasma was first introduced as an idea during the Voyager spacecraft encounters and published as a suggestion by *Broadfoot et al.* [1979]. The viability of the process as the sole mechanism for supplying energy to the system has been questioned [*Thorne*, 1981; *Shemansky and Sandel*, 1982], but the issue has been clouded by uncertainty in the magnitude of the ion diffusive loss time. The problem of energy transfer and mass injection has been discussed in the earlier literature by *Sullivan and Siscoe* [1981], *Eviatar and Siscoe* [1980], *Richardson et al.* [1980], *Richardson and Siscoe* [1981], *Dessler* [1980], *Brown* [1981], *Shemansky* [1980], *Thorne* [1981]. More recent work on the subject may be found in *Brown et al.* [1983], *Smyth and Shemansky* [1983], *Barbosa et al.* [1983], *Richardson and Siscoe* [1983], *Eviatar and Barbosa* [1984], and *Smith and Strobel* [1985] (hereafter referred to as SMST). The proposed process by which the mass and energy is supplied through neutral clouds overlapping the plasma volume is described here as neutral cloud theory (hereafter described as NCT).

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The NCT as an explanation for the energetics of the Io torus is defined by three classes of source reactions:

(R1) $e + N_o \rightarrow N_i + 2e$

(R2) $N_i + N_o \rightarrow N_i + N_i + ne$

(R3) $N_i + N_o \rightarrow N_o + N_i$

where e, N_o, and N_i represent electrons, atoms, and ions. The equations are written in a general form in which the atoms and ions are not necessarily of the same species or charge. Another class of reactions included in the model calculations, ion-ion collisions, do not have a first order effect on the energetics of the system. Ionization by electrons (R1) and by ion-neutral collisions (R2) inject mass and kinetic energy into the plasma. Charge exchange reactions (R3) are basically different in their effect because net kinetic energy is injected into the system, but plasma number density remains unchanged. However, mass is lost from the system (but not from the plasma) in (R3) because the neutral product (N_o) is ejected from the plasma volume in a period of time too short to allow further significant reactions. The reaction (R3) is also essential to the stability of the torus in respect to interaction of the plasma with the Io atmosphere. The relationship between these three classes of reactions and the supply of neutral atoms uniquely define the condition of the equilibrated plasma in NCT. Given the premise that plasma wave instabilities do not play a significant role in the energy transfer process, the plasma in the NCT is stable and self regulating, as discussed below. In fact, there appears to be general agreement that Coulomb collisions are the dominant energy transfer process between electrons and ions [SMST; *Barbosa et al.*, 1985].

In this article the implications of NCT for the plasma torus are examined using model calculations which include all of the known reactions that have a controlling effect on the system (see the compilation by *Johnson and Strobel* [1982]). Given the rates for these reactions, the electron density, the relative oxygen/sulfur proportions and the ion diffusive loss time in the central volume, we can calculate the condition of the plasma. The introduction of any other constraints on the plasma such as in the partitioning of the ions, generally requires the imposition of sources or sinks to the electron energy, that violate the theory. We find in the development of the following discussion that NCT fails in a significant way to account for the observed condition of the plasma. Moreover, the theory predicts changes in the plasma parameters as a function of electron density that are not compatible with observation. The results indicate that some means of injecting further significant amounts of energy into the system, beyond the capability of the theory, must be devised in order to provide comparability with observation. This may be accomplished through some modification of the cloud theory such as the introduction of heterogeneous processes that alter the relationship between the (R1), (R2) and (R3) classes of reactions, or some other unrelated energy injection mechanism.

Energy and Species Partitioning

In the NCT the population of neutral gas in a given volume can be described by the equation

$$\frac{d[N_o]}{dt} = Y_o - [N_o].([e].k_z(T_e) + [N_i].k_{zc} + [N_i].k_x) \quad (1)$$

where Y_o is the volume injection rate of neutrals determined by some undefined process, $k_z\,(T_e)$ is the electron ionization rate coefficient, k_{zc} is the ionization rate coefficient defined by the class of reactions (R2), and k_x is the rate coefficient for charge exchange (reaction (R3)). The equations written here are in a general form and represent the entire range of species in the system. The rate coefficients are therefore effective, species dependent quantities that require detailed calculation of plasma parameters to determine their magnitude. The ion species populations can be described by equations of the form

$$\frac{d[N_i]}{dt} = Y_i - [N_i].(D_i + [e].\bar{a}(T_e) + [N_o].k_{zc} + [N_o].k_x) \quad (2)$$

where the volume source rate

$$Y_i = [N_o]([e].k_z(T_e) + [N_i].k_{zc} + [N_i].k_x) \quad (3)$$

D_i is the ion diffusive loss probability, and $\bar{a}(T_e)$ is the mean recombination rate coefficient. The terms involving k_x vanish from (2) when the calculation is made as a mean over all species, but must be retained for the detailed calculation which defines individual species populations. The terms in k_{zc} will in general be different in the source and loss term for a particular species. The detailed calculations defining the species populations follow the method described by *Brown et al.* [1983]. Solutions for two equations of the form of (1), and seven equations of the form of (2) are obtained under the constraint of charge neutrality. The assumptions involved in NCT constrain the reactions in (1) and (2) through control of the electron and ion temperatures, T_e and T_i, by the Coulomb collisional ion-electron energy transfer and radiative, diffusive, charge exchange, and recombination loss processes. The determination of the plasma parameters for the NCT therefore requires the solution of energy equations for the ions and electrons. Energy partitioning in the ions is described by the equation

$$\frac{d[N_i]E_i}{dt} = S_i - L_i \quad (4)$$

where S_i and L_i are source and loss terms,

$$S_i = [N_o]([e] \cdot K_{Ee}.k_z(T_e) + [N_i].k_x.(K_{Ex} - E_i) + [N_i].k_{zc}.K_{Ei}) \quad (4')$$

$$L_i = [N_i] \cdot (-[e].(E_e - E_i) \cdot k_{eq}(T_e,T_i) + E_i.D_i + [e].E_i.\bar{a}(T_e)) \quad (4'')$$

where E_i is the mean ion energy per ion, E_e is the mean electron energy per electron, k_{eq} (T_e,T_i) is the rate coefficient for Coulomb energy transfer between electrons and ions, K_{Ee} is the mean injection energy per ion produced by electron ionization, K_{Ex} is the mean injection energy per ion produced by reactions of class (R3), K_{Ei} is the mean injection energy per ion produced by reactions of class (R2). Ion-ion reactions do not appear explicitly in (4) because they simply represent a homogeneous redistribution of energy, only affecting the values of the relevant rate coefficients.

The energy budget for the electrons is described by

$$\frac{d[e]E_e}{dt} = S_e - L_e \quad (5)$$

where S_e and L_e are source and loss terms,

$$S_e = [e].[N_i].[E_i - E_e].k_{eq}(T_e,T_i) + J_e \quad (5')$$

$$L_e = [e]([N_i] \cdot \rho_i(T_e) + [N_o].\rho_o(T_e) + E_e.D_i + [N_i].E_e.\bar{a}(T_e)) \quad (5'')$$

where $\rho_i(T_e)$ and $\rho_o(T_e)$ are radiative cooling coefficients for ions and neutrals, and J_e is a heterogenous energy source term for the electrons required for one class of solutions to the plasma equations. The NCT is represented by these equations when $J_e = 0.0$.

The solutions of (1)-(5), which include the 25 reactions described by *Brown et al.* [1983] [see *Johnson and Strobel* 1982; SMST], require an iterative method because the system is coupled in a very nonlinear regime. The reactions included in the calculations are described in Appendix A. Equations (4) and (5) represent approximations to the plasma condition in the sense that the calculation is macroscopic, and does not describe the detail of the ion or electron energy distributions. This is not regarded as a serious deficiency in this case. Electron-electron relaxation times are very short compared to other processes in the plasma and we expect the electron energy distribution to be essentially Maxwellian, unless a heterogeneous source is introduced. The ion energy distribution is expected to deviate from a Maxwellian because relaxation rates are slower and they are the energy source particles in NCT with a step function in the distribution at the injection energy. The first terms

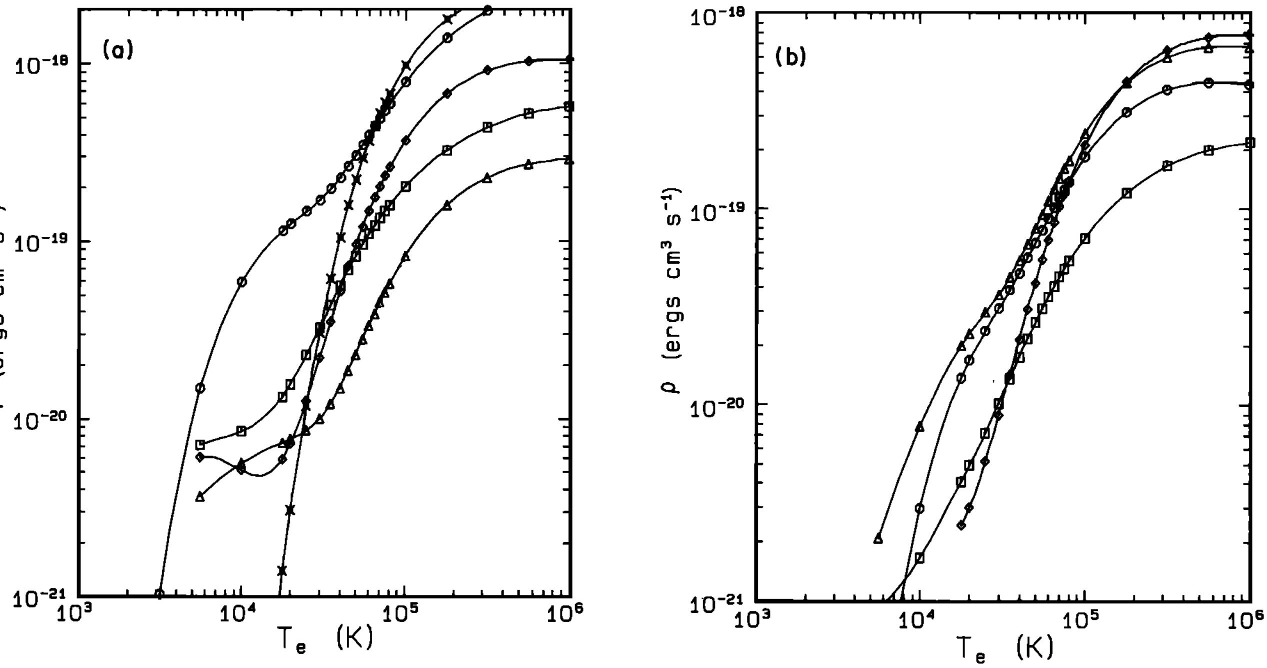

Fig. 1. Radiative cooling coefficients for sulfur and oxygen species calculated for collisional equilibrium at an electron density $[e] = 1000$ cm^{-3}. The calculations were based on the most recently available atomic and ionic data. Details of these calculations will be published at a later date. (*a*) Sulfur species: S I, square; S II, circle; S III x $\frac{1}{10}$, triangle; S IV x $\frac{1}{2}$, diamond; S V, cross. (*b*) Oxygen species: O I, square; O II, circle; O III, triangle; O IV, diamond.

of (4) and (5) are the same except for sign and define the electron-ion energy transfer rate by Coulomb collisions. The Coulomb energy transfer rate coefficient $keq\ (T_e, T_i)$ has a very weak dependence on the energy of the ions, and therefore the exact nature of the ion energy distribution is not a critical factor in the determination of the mean ion (E_i) or electron (E_e) energy in these calculations. Ion-ion reactions ((R24), (R25) of *Brown et al.* [1983]; Appendix A), have a strong dependence on energy over a certain range of values and care must be taken in these cases in the establishment of rates. The major sink for ion energy over most of the range of plasma parameters is Coulomb (term 1 RHS equation 4″) transfer to the electrons. Ion energy is also lost from the volume through charge exchange (term 2 RHS equation 4′), but these reactions end in a net gain of energy ($K_{ex} > E_i$) without adding net mass to the plasma. Other loss processes included in (4) are diffusion and recombination (terms 2, 3, RHS equation 4″). The diffusion and recombination processes ultimately result in the loss of both mass and kinetic energy. Kinetic energy and mass are injected through electron ionization and ion impact ionization (terms 1 and 3 RHS equation 4′). The major energy loss mechanism for electrons is radiative cooling (terms 1,2 RHS equation 5″). Additional loss processes in (5) are diffusion and recombination (terms 3,4), coupled directly to the corresponding terms in (4).

The rate coefficient for Coulomb energy transfer is calculated according to

$$k_{eq}(T_e, T_i) = \frac{1}{\sum_i [N_i]} \cdot \sum_i \left[\frac{[N_i] Z_i^2 \ln(\Lambda_i)}{(5.87 A_e A_i)} \left(\frac{T_e}{A_e} + \frac{T_i}{A_i} \right)^{-3/2} \right] \qquad (6)$$

where in this case N_i refers to individual ion species, Z_i is ion charge, A_e, A_i are atomic weights of electrons and ions, and Λ_i is the electron shielding parameter [see *Spitzer*, 1962]. The parameter Λ_i is given by

$$\Lambda_i = \frac{3}{2 Z_i e^3} \left(\frac{k^3 T_e^3}{\pi [e]} \right)^{1/2} \qquad (7)$$

where e is the ESU electron charge. The diffusive loss probability (D_i), assumed to be species independent in these calculations, is one of the free parameters in the modeling process described below.

The physical chemistry quantities required for the solution of (1)-(5), are as given by *Brown et al.* [1983] and *Shemansky* [1987] (Appendix A). The radiative cooling coefficients in the present calculations differ from earlier published values *Shemansky*, 1980; *Shemansky and Sandel*, 1982; *Brown et al.*, 1983] because of advances in atomic physics in the interim. In some cases, especially for S II, the new radiative coefficients are substantially larger. The coefficients differ with those of the recent SMST values mainly because of the inclusion of additional states in the calculations, rather than significantly different values of collision strengths for particular transitions (see Appendix B). As discussed below, the species to species relationships in the radiative quantities, play a strong role in determining the equilibrated condition of the plasma in NCT. The radiative cooling coefficients for sulfur and oxygen are given in Figure 1 as a function of electron temperature.

These results are based on the latest available collision strength and electronic structure data. Details on the calculation of the coefficients will be given in later publications. The effect of the present coefficients is to increase the esti-

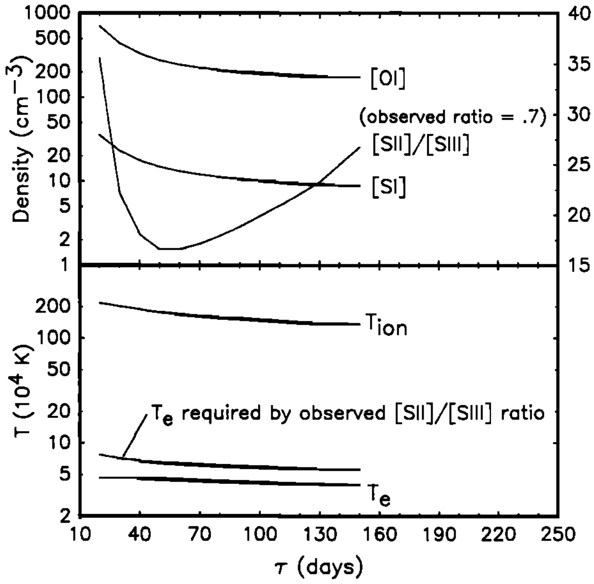

Fig. 2. Calculations of collisional diffusive equilibrium as a function of ion diffusive loss time in the IO torus according to neutral cloud theory. The calculation is for a plasma volume positioned at 5.75 R_J with electron density $[e]$ = 2000 cm^{-3}, and neutral source rate ratio $Y_0(O)/Y_0(S) = 8.0$. Curves showing O I and S I densities, [S II]/S III] partitioning, electron temperature T_e, and ion temperature T_i are indicated on the figure.

mated energy lost in radiation over previous values for the measured torus plasma at any given electron temperature.

Results

The calculations of collisional equilibrium in the plasma torus are restricted to the region of the hot torus near the maximum density at a planetocentric radius of 5.75 R_J. No attempt has been made to model the spatial detail of the plasma torus physical condition. The purpose of the present work is to point out a fundamental difficulty in explaining the energetics of the plasma with NCT. Calculations have been made using a number of limiting factors. If the term J_e in (5) is fixed to zero, then the calculated equilibrium in the plasma depends entirely on the continuous creation of fresh ions to maintain the plasma in both mass and energy density. If the source is neutral atoms in a cloud occupying the same volume as the plasma, then as discussed above, the calculation corresponds to the NCT for the torus. Each new ion acquires the kinetic energy in gyromotion, corresponding to the tangential velocity of the rotating magnetic field with respect to the cloud atom. The energy source for the system is confined to the delivery of the ion kinetic energy to the plasma electrons. The calculation of collisional equilibrium in this system then requires only the definition of electron density, relative source rates of neutral atom species feeding the volume, and the ion diffusive loss time. The introduction of any other additional physical limiting factor, such as a measured partitioning of ions, then requires the inclusion of a finite heterogeneous energy source or sink for the plasma electrons. Calculations of both kinds ($J_e = 0.0$, $J_e > 0.0$) are undertaken in this article in order to illustrate the nature of the problem. Another variable introduced here is plasma number density. Recent significant results obtained in ground based observations [*Pilcher and Morgan*, 1985] have shown that plasma densities in the hot torus can on some occasions be as high as [e] $\approx 10^4$ cm^{-3}, compared to the values $[e] \approx 2{,}000$ cm^{-3} measured at Voyager 1 encounter. The behavior of ion partitioning under these conditions of different plasma densities has important implications for torus plasma theory. Calculations are shown below for both the high and low plasma densities quoted above, indicating the requirements in energy injection rates to the electrons for maintenance of the observed ion partitioning.

Figure 2 shows the calculated plasma partitioning for some of the species required by NCT ($J_e = 0.0$) for plasma density $[e] = 2{,}000$ cm^{-3} and oxygen/sulfur source rate ratio $Y_0(O)/Y_0(S) = 8.0$ as a function of diffusive loss time, $\tau_i = 1/D_i$. The source parameter $Y_0(O)/Y_0(S)$ provides roughly equal proportions of oxygen and sulfur ions in the plasma, which according to *Brown* et al. [1983] and *Shemansky* [1987] is close to the observed partitioning. The source rate ratio $Y_0(O)/Y_0(S)$ required to provide a given partitioning of oxygen relative to sulfur ions is a variable with a dependence on plasma electron temperature. If the temperature of the plasma is raised by some means, the relative injection rate of oxygen must be reduced (see Table 1) in the model to maintain a particular mix of oxygen and sulfur ions. This raises a significant point in regard to observed variations in the torus discussed below. The parameter chosen as a reference to observation in Figure 2 is the number density ratio, [S II]/[S III]. Observations of the plasma torus using ground-based, Earth satellite, and spacecraft instruments have uniformly indicated [S II]/[S III] < 1. The present calculations based on the NCT obtain values in the range [S II]/[S III] = 10-20 for a reasonable range of values of τ_i, encompassing observational constraints [*Shemansky*, 1987; *Smyth and Shemansky*, 1983; *Brown et al.* 1983], and most other published estimates (see Figure 2). Electron temperatures in the range T_e = 4.6 - 4.0 x 10^4 K are obtained for ion diffusive loss times in the range τ_i = 30-150 days. Evidently there is no condition of the plasma equilibrium with a neutral cloud source that can satisfy the observed dominance of S III among the sulfur ions. The large ratio [S II]/[S III] is simply indicative of a low electron temperature, and a comparison of predicted and observed species distributions for the Voyager encounter epoch shows the general inadequacy of the theory. The theoretical calculation for τ_i = 80 days is compared to the observed partitioning in Table 1. An increase in plasma density in this regime causes a reduction in the electron temperature of the equilibrated system. Calculations using an electron density $[e] = 10^4$ cm^{-3} end in a ratio [S II]/[S III] = 26, and electron temperature T_e = 3.6x10^4 K for the same values of τ_i and $\Sigma O_i/\Sigma S_i$ given in Table 1. This result reflects a basic characteristic of NCT; increased mass injection rates and higher plasma densities lead to lower temperatures in the equilibrated plasma.

The observational requirement that [S II]/[S III] < 1.0 forces the introduction of a heterogeneous energy source for the electrons in the model calculation ($J_e > 0.0$, equation (5), for any value of the ion diffusive loss probability. Figure 3 shows calculations for $[e]$ = 2000 cm^{-3} in which a ratio [S II]/[S III] = 0.7 is imposed as a condition for the equilibrated plasma. The additional heat source required for the electrons in order to maintain the [S II]/[S III] ratio is positive over the whole range of τ_i and is larger than the energy

TABLE 1. Calculated and Observed Plasma Partitioning

	Analysis of Voyager 1 EUV Spectrum †	Neutral Cloud Theory	Modified Theory ‡
[O I]$^{cm^{-3}}$	21.	211.	29.
[O II]	880.	977.	832.
[O III]		2.4	30.
[O IV]		0.69-4	0.66-1
[S I]		11.2	3.7
[S II]	283.	916.	255.
[S III]	359.	51.	364.
[S IV]	123.	0.11	41.5
[S V]		0.90-5	0.116
[e]	2250.	2000.	2000.
$Te(10^4K)$	6.5	4.27	6.00
$T_i(10^6K)$		1.56	0.80
$\bar{z}$		1.03	1.31
τ_i(days)		80	80
$\Sigma[Oi]\ \Sigma[Si]$	1.15	1.21	1.31
$Y_0(O)/Y_0(S)$		8.0	3.5
$Y_0(O)$ (cm^{-3}s^{-1})		0.270-2	0.441-3
$Y_0(S)$/(cm^{-3}s^{-1})		0.338-3	0.126-3
$E_T(10^{-12}$ergs cm^{-3}s^{-1})		1.58	0.74
(eV cm^{-3}s^{-1})		0.99	0.47
E_{rad} (10^{-12}ergs cm^{-3}s^{-1})		0.59	0.63
(eV cm^{-3}s^{-1})		0.37	0.39
$N_i \cdot E_i(10^{-12}$ergs cm^{-3}s^{-1})		1.58	0.32
(eV cm^{-3}s^{-1})		0.99	0.20

*0.69-4 ≡ 0.69 x 10^{-4}

†Obtained from *Brown et al.* [1983] scaled to total electron density of $[e] = 2250$ cm^{-3}, 5.75 R_J.

‡Heterogenous heating of electrons to meet the additional constraint [S II]/[S III] = 0.7

input rate from the ions in the range $\tau_i \geq 50$ days (Figure 3). The electron temperature in this calculation is in the range of values estimated from Voyager data [*Smyth and Shemansky*, 1983; *Sittler and Strobel*, 1987]. Figure 4 shows calculations for $[e] = 10^4$ cm^{-3}, constrained by a ratio [S II]/[S III] = 0.64, corresponding approximately to observations by *Pilcher and Morgan* [1985]. The additional energy required by the electrons is as much as a factor of 5 larger than the energy supplied from Coulomb collisions with the ion population. The additional heating rate required for the electrons is remarkably independent of the ion diffusive loss probability, with a value near 1.x10^{-11} ergs cm^{-3} s^{-1}, and close to the total radiated energy rate, while the contribution from electron–ion collisions varies in the range 4 - 1.5x10^{-12} ergs cm^{-3} s^{-1} for τ_i = 40–150 days (Figure 4). The total energy required for the system varies from 1.5 - 1.0x10^{-11} ergs cm^{-3} s^{-1} over the same range in τ_i.

DISCUSSION

Comparison With Other Work

The results in the present work differ significantly from two earlier publications examining the energetics of the torus. *Barbosa et al.* [1983], and SMST examine the properties of the plasma torus with the assumption that energy is derived according to the NCT as defined above. *Barbosa et al.* [1983] concluded that the NCT is adequate as an explanation. However, the latter calculations were limited by two factors that altered the result in a fundamental way. First, the radiative cooling efficiency was obtained from a calculation by *Shemansky and Sandel* [1982] which is fixed to observed ion species partitioning. The calculation therefore does not account for the dependence of the cooling rate on the partitioning of the ions. Second, *Barbosa et al.* [1983] introduced a peculiarity in the energy partitioning of the ions in order to increase ion-electron energy transfer rates, in effect causing an internal inconsistency in the calculation [see SMST]. The most detailed and comprehensive calculation to date is that of SMST, in which Fokker-Planck operators for the collisional processes are applied to define the energy distribution of the ions. As we have noted above, the energy transfer rate coefficients (*keq*) are basically independent of the ion energy distribution; the term containing T_i in (6) is negligible relative to the term containing Te. However, the *keq* coefficient does depend on ion population partitioning. An iterative adjustment of $k_{eq}(T_e, T_i)$ is therefore generally unnecessary at the end of a computational loop in which the mean energy of the ions is defined. For this reason, SMST (R.A. Smith, private communication, 1985) used mean ion energy rather than detailed distributions in the final stages of their calculation. In effect this places the present method and the SMST work at an equivalent level in the accuracy of the results (Appendix B). In fact, it has been found in a comparison of the present method using the SMST parameters for their case II, that the results are equivalent within computational accuracy (Appendix B). The basic difference between the present results and those of SMST lies with the physical parameters used in the calculations. The radiative cooling coefficients in the SMST work, for the principal radiators in the plasma, S II and S III, are factors of ≈ 5 and ≈ 2 smaller than the present values (Figure 1). Other differences, involving ionization rates of O I, S I, and S II, and the inclusion of ion-ion and other reac-

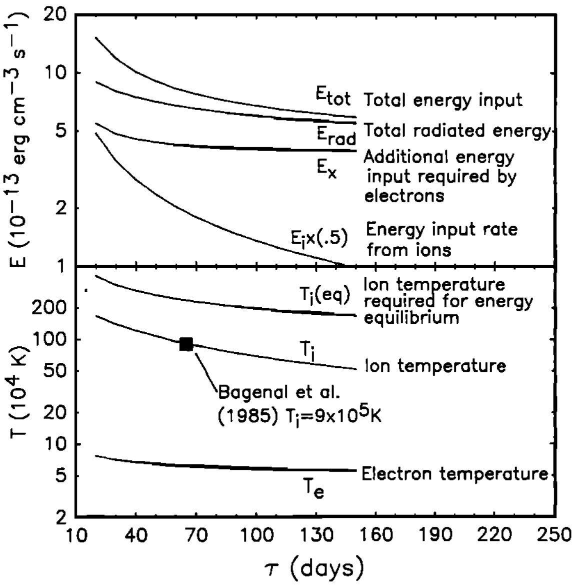

Fig. 3. Calculations of collisional diffusive equilibrium, as in Figure 2, but with additional energy deposited in the electrons as required to maintain the partitioning ratio [S II]/[S III] = 0.7, conforming with EUV observation of the plasma torus. Electron and ion mean temperatures T_e, T_i are indicated on the figure along with the mean ion temperature ($T_i(eq)$) required if all of the energy is supplied by the ions. The volumetric total energy input (E_T), radiated rates (E_{rad}), ion input rates (E_i) based on neutral cloud theory, and additional input rate required by the electrons (E_x) are indicated on the figure.

tions in the present calculations, that are not in the SMST model (Appendix A) are relatively minor. The fact that S II and S III are the dominant radiators in the plasma forces a different conclusion relating to the role of neutral clouds as a source of kinetic energy for the plasma electrons. SMST concluded that the Voyager 1 epoch torus luminosity must be revised downward to $\approx$ 0.15 eV cm^{-3} s^{-1}, on the assumption that the NCT was valid for the hot plasma torus. The conclusion in this work in this regard is that the observed partitioning of the torus, especially [S II]/[S III], requires that the radiation loss be 0.43 eV cm^{-3} s^{-1} (Figure 3), and that the NCT can supply only $\approx$ 1/3 of the total $\approx$ 0.47 eV cm^{-3} s^{-1}(τ_i = 80 days) required to maintain the torus.

Characteristics of a Plasma Torus Controlled by a Neutral Cloud Source

The most important characteristic of NCT for the plasma torus is the dependence of electron temperature on plasma number density. In this case the plasma number density can only be increased by an increase in the mean density of the neutral cloud. In equilibrium the density of the neutral cloud is defined by (1) and (2),

$$[N_o] = \left[\frac{1}{\bar{z}}\right] \frac{D_i + [e].\bar{\alpha}(T_e)}{[k_z(T_e) + (1/z).k_{zc}]} \quad (8)$$

The recombination term in (8) is small, and the diffusive loss probability (D_i) has only a weak dependence on plasma density in the range of values considered here. An increase in the neutral number density can therefore only occur if the ionisation rate coefficient is reduced through a reduction in electron temperature. Although the structure of the relationship of neutral density to electron temperature is described by (8), the physical processes are obscured. The truly independent variable in this process is the source rate of neutral gas (Y_0, equation (1)). The system reacts to changes in Y_0 to balance (8). An increase in Y_0 increases the plasma density. The energy loss processes in the plasma have a quadratic dependence on [e], while the energy injection rate is essentially first order in [e]. An increase in plasma density therefore forces a decrease in electron temperature as a natural compensation for the initial excess in radiated energy. The cooling process in the plasma is dominated by the S II and S III species. The oxygen species are generally less efficient (Figure 1). The large radiative cooling coefficient of SII has a tendency to restrict the plasma to a population of singly ionized species (Table 1). This is is the basic difficulty in explaining the plasma torus through the NCT, because torus observations in both the near infrared and EUV indicate that S III is a dominant plasma ion. A possibly more important statement on the role of neutral clouds in providing energy for the system is the fact that *Pilcher and Morgan* [1985] have observed high-density plasma ([e] $\approx$ 10^{4}cm^{-3}), with an estimated [S II]/[S III] $\approx$ 0.6. The NCT cannot explain a plasma at this high density with electron temperature sufficient to maintain significant numbers of doubly ionised species. The predicted ratio [S II]/[S III] $\approx$ 26, in this case with $T_e \approx$ 3.6x10^{4}K, clearly represents the total failure of the theory to explain observation.

The proportion of oxygen relative to sulfur in the torus is a matter of considerable interest in relation to source processes [see *Ballester et al.*, 1987*b*; *M. E. Summers et al.*, The structure of Io's atomic corona and implications for at-

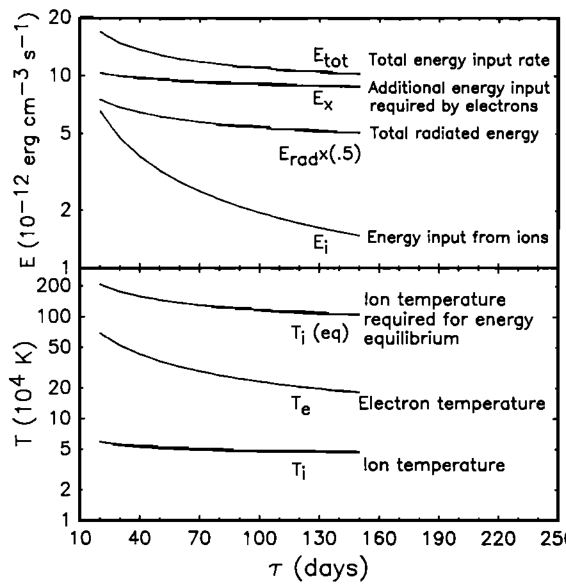

Fig. 4. As in Figure 3, except [e] = 10^4 cm^{-3}, and [S II]/[S III] = 0.64 corresponding approximately to observations by *Pilcher and Morgan* [1985].

mospheric escape, submitted to *Astrophysics Journal*, 1986; *Shemansky*, 1987]. The relative rates at which oxygen and sulfur ions are produced from a given assumed source in the NCT depend essentially on electron temperature. A variation in plasma electron temperature with a given independent source of neutral atoms therefore should cause a variation in the oxygen/sulfur ion partitioning in the torus. Variation in electron temperature has in fact been observed [*Shemansky*, 1987]. The response of the plasma ion partitioning to the change in temperature should then provide a clue to the behavior of the atomic neutral source process. As I have indicated above, the model calculations have been constrained to produce the approximate proportions of oxygen and sulfur ions determined from Voyager EUV data. The relative neutral atom injection rate $Y_0(O)/Y_0(S)$varies nonlinearly in response to this constraint as a function of plasma electron temperature (Table 1). In reality of course, the relative injection rate of neutrals into the plasma is likely to be an essentially independent quantity. The observed well-defined variation in electron temperature described by *Shemansky* [1987], therefore should show a corresponding change in ΣO_i; ΣS_i, if NCT is to be regarded as a controlling factor for the plasma. However, the oxygen/sulfur partitioning in the torus appears invariant in spite of significant change in T_e and number density [*Shemansky*, 1987] occurring between Voyager 1 and 2 encounters. This suggests that the diffusive lifetimes of plasma ions may be long enough that relaxation is significantly longer than 100 days. Otherwise, it would be necessary to introduce the possiblility that ionization of neutral cloud atoms is not the main mechanism for the introduction of mass to the plasma. The magnitude of the neutral injection rate ratio $Y_0(O)/Y_0(S)$ in NCT affects the terminal temperature of the plasma. Two opposing effects are involved, in that the introduction of more oxygen allows a higher temperature because of less efficient radiative cooling, but ion production and energy injection rates are slower because of higher thresholds and lower mass per nucleus. Thus in order to produce significantly higher plasma temperatures in NCT, the ratio $Y_0(O)/Y_0(S)$ must be raised to the order of 100, giving an order of magnitude more oxygen ions in the plasma relative to sulfur. There are no observational data supporting quantities of this magnitude.

OTHER ENERGY INJECTION MECHANISMS

The consideration of mechanisms for providing the required energy to maintain the plasma torus must be constrained by the apparent ability of the system to maintain a constant or possibly slightly higher electron temperature against significantly increased mean plasma density, as demonstrated in the *Trauger* [1984] and *Pilcher and Morgan* [1985] results. The longitudinal asymmetry described by these observations must have survived long enough to allow the production of substantial quantities of S III, so that the region of increased density must have been subjected to proportionately larger sustained volumetric energy injection rates to the electrons, in quadratic relation to plasma density. The NCT clearly does not have this characteristic, according to the above discussion.

The local time asymmetry in the spatial structure of the emission [*Shemansky and Sandel*, 1982] must certainly play a role in the explanation. However, the involvement of both EUV and near infrared emissions in the phenomenon [*Morgan*, 1985*a*, *b*] introduces a complexity in this aspect of torus energetics, that is beyond the scope of the present work. If electric fields are involved in the explanation [*Barbosa and Kivelson*, 1983; *Ip and Goertz*, 1983], then the local time phenomenon is partially adiabatic. The required increase in volumetric energy deposition rate on a change in density from $[e] = 2000$ cm^{-3} to $[e] = 10^4$cm^{-3} is approximately a factor of 15 if ion partitioning is to remain approximately constant, as the observations indicate. This factor is more than double the capability of the NCT. In other words the increased energy input rate from the ions in the NCT is approximately proportional to the plasma number density, whereas observation indicates a requirement for a higher order relationship, in order to maintain the apparent electron temperature stability. This limitation of the NCT is a fundamental one because the process of injecting fresh ions and hence kinetic energy in reactions R1 and R2 also injects net mass into the system. An increase in volumetric rates for R1 and R2 then simply tends to cool the plasma, as discussed above. Relatively higher ion temperatures could be achieved if the proportionality of reactions R3 could be increased relative to R1 and R2, because R3 does not alter the net mass of the plasma. A change in the proportionality of these reactions can be accomplished only by introducing a heterogeneous process, such as a particular physical interaction with Io. A scenario of this kind would require that Io have an atmosphere with an exobase above the level of the solid surface. The lack of an observed EUV emission from Io [*Shemansky*, 1980] suggests that plasma electrons interacting with the Io environment must be cooled in a relatively dense ionosphere. *Ballester et al.* [1987*a*] have reported recent FUV observations of emission from atmospheric O I and S I, that *Summers and Strobel* [1987] have interpreted in terms of cold electron ($\approx$ 1.5 eV) excitation. *Ballester et al.* [1987*b*] prefer an alternative suggestion that the neutral emissions are produced in the collisionally thick region of the atmosphere in an auroral-like dissociative excitation of SO_2 by electrons. *M. E. Summers et al.* (1987) and *McGrath and Johnson* [1987] present preliminary analysis of possible torus plasma atmospheric interaction and suggest that a strong interaction would result in an excessively large neutral flux. *Smyth and Combi* [1984] on the other hand have suggested that it may be possible to obtain a relatively large charge exchange rate from interaction with an extended atmosphere. *Ip* [1982] using an electrodynamic model of the interaction system, suggests that charge exchange ion products could have initial energies as high as $\approx$ 2 keV per ion as a result of local convection effects, and neutral momentum transfer products could be produced at velocities as high as 100 km s^{-1}. *Schneider et al.* [1987] report observations of an extended distribution of atmospheric sodium showing characteristic kinetic temperature unrelated to the surface temperature. The most plausible explanation for the energetic sodium outflow appears to be charge exchange reactions [*Smyth and Combi*, 1984; *Schneider et al.*, 1987; *Ip*, 1982]. The dominance of reactions of the R3 class at Io could plausibly supply sufficient additional energy to the torus ions without increasing net plasma mass. The attraction of this possible source is that it provides a ready explanation for the apparent ability of the system to

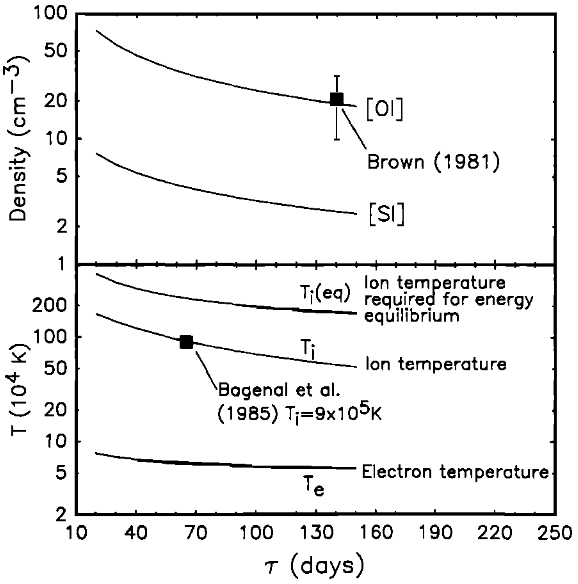

Fig. 5. As in Figure 3, showing O I and S I densities, T_e, T_i and T_i (*eq*). The plotted points are derived from *Bagenal et al.* [1985] (T_i) and *Brown* [1981] ([O I]).

provide the increased volumetric energy input rate to maintain a near constant electron temperature, in response to a local substantial increase in plasma density. However, the energy requirements are rather stringent, and there are other factors that raise questions on the viability of the process. The flux of ions in the Voyager 1 epoch torus at the location of Io is $\approx 10^{10}$ cm^{-2} s^{-1}. The translational kinetic energy of the plasma ions then provide an energy flux of $\approx$ 6 ergs cm^{-2} s^{-1}. On the basis of the data in Table 1, we require a mean energy of 1. x 10^{-13} ergs cm^{-3} s^{-1}, or 1. x 10^{19} ergs s^{-1} total, from a source in excess of that provided by the NCT. On the basis of a simple energy flux consideration, this requires a minimum interaction area at Io of $\approx$ 2 x 10^{18} cm^2, corresponding to 4 Io radii. These considerations are first order in nature, and examination of the electrodynamics of the system is required to provide more realistic quantities [see *Ip*, 1982]. The question of the nature of the plasma torus interaction with an Io atmosphere is clearly complex with a number of unknown parameters [see *M. E. Summers et al.*, 1987; *McGrath and Johnson*, 1987]. The physical quantities (above) required for energy injection through an interaction dominated by reaction (R3) appear to be obtainable, but relationships between momentum transfer, charge exchange and electron cooling must be examined in detail to determine the viability of the process. In this scenario, the direct plasma torus interaction with the Io atmosphere would provide the additional ion energy, but a negligible amount of the net mass required to account for the observed torus. The mass required to maintain the torus must then be derived from the tenuous neutral cloud. Neutral momentum transfer products from the interaction at Io would presumably have lower densities because of high mean velocities. The question then is how a system of this kind would respond to an increase in plasma density of the order of that measured by *Pilcher and Morgan* [1985]. Presumably, the increased plasma density would be in response to an event on Io. The observations require that subsequent interactions maintain a plasma temperature high enough to obtain the relatively small [S II]/[S III] ratio. The volumetric energy input rate on the basis of the data in Figures 3 and 4 must rise in proportion to $\approx [e]^{1.7}$. If the longitudinal asymmetry observed by *Pilcher and Morgan* [1985] is assumed to be near equilibrium, then the production rates of ions would simply be proportional to $[e]$, in both neutral cloud and Io atmosphere interactions; it would be necessary for Io to eject low-energy neutral atoms periodically to maintain the longitudinal asymmetry. This may be accomplished in a natural way if the higher density region of the plasma produces proportionally more neutral outflux through interaction with the Io atmosphere, along with a larger volumetric charge exchange rate. The stability of the torus in this feedback system depends on the relationship of the cool and hot components of the neutral gas delivered into the system. However, relaxation times are shorter in a plasma of greater density, so that as Figure 4 indicates, the mean ion "temperature" is reduced by a factor of order 2. This has the effect of increasing the energy per ion delivered to the plasma so that the volumetric energy input rate develops a proportionality to $[e]^n$ with $n > 1$. If the longitudinal asymmetry must be regarded as a transient event, the same argument applies except that if the observations were made during the phase of declining neutral cloud density, the factor n would tend to be larger. Thus there appears to be some possibility that an interaction of the kind described here with an Io atmosphere in combination with an extended atomic cloud could describe the basic properties of the observed hot plasma torus.

The plasma torus is known to contain a non-Maxwellian electron energy distribution [*Scudder et al.*, 1981; *Sittler and Strobel*, 1987]. The electron gas can be roughly described as a two-temperature distribution. The high-temperature component ($T_{eh} \approx 10^7$ K) has a very small mixing ratio near the region of maximum plasma density [*Scudder et al.*, 1981; *Sittler and Strobel*, 1987] and can only account for 1-2% of the total radiated energy. At larger radial positions in the torus the mixing ratio of high-temperature electrons rises, and the role of this component becomes more important, and at $\approx 8R_J$ beyond the bulk of the torus, may play a dominant role in plasma energetics. There is some quantitative uncertainty in the role of the hot electron component because the measurements do not cover the full range of pitch angles, and energy [*Scudder et al.*, 1981; *Sittler and Strobel*, 1987] and the source has not been defined. However, the spectroscopic evidence places a limit on the integrated hot electron contribution. The contribution of the high temperature electrons to the energetics of the plasma therefore cannot be discounted as unimportant. The mean energy of the ions in the plasma is a crucial point in this consideration. Figure 5 shows an equilibrium calculation for $[e] = 2000$ cm^{-3} confined to the observed [S II]/[S III] ratio, assuming that electron- electron heating supplies the required additional energy. Two measured data points are shown in Figure 5; the measured ion "temperature" [*Bagenal et al.*, 1985], and the neutral atomic oxygen density based on measurements by *Brown* [1981]. The ion temperature measurement is plotted on the curve showing the mean ion temperature defined by the rate at which ions must be supplied from a neutral cloud. The plotted point corresponds to a diffusive loss time of $\tau_i \approx 70$ days. This agrees within measurement uncertainty with the value $\tau_i =$ 140 days defined by the *Brown* [1981] neutral oxygen observation (Figure 5). If all of the energy were supplied from the ions, the *Bagenal et al.* [1985] data point would lie at a much larger diffusive loss time. However, there appears to be enough uncertainty in both measurements, and in the fact that they relate to different epochs, that a conclusion cannot be obtained. *Morgan* [1985*a*] reports observations of the hot torus region in which plasma densities were a factor of ≈ 2 larger than values at Voyager 1 encounter. The estimated ion temperature in this case [*Morgan*, 1985*a*] was $\approx 1/2$ the value reported by *Bagenal et al.* [1985] for Voyager 1 encounter. If most of the energy for the torus is to be supplied by the plasma ions, the model calculations presented here (Figure 3, 4) indicate that the mean ion temperature must show a variation less than a factor of 2 for a factor of 5 change in plasma density. The *Morgan* [1985*a*] results, if they are consistent with the usual behavior of the plasma, seem to indicate on this basis that electron heating is controlled by some other mechanism. However, ion temperature measurements obtained spectroscopically are rather difficult [*Brown*, 1982] if the ions are not thermally equilibrated and we require further measurements before a conclusion can be drawn.

CONCLUSIONS

An examination of the energetics of the hot plasma torus relative to the commonly accepted NCT indicates that the theory is inadequate to explain basic observed torus properties. Calculations corresponding to the location of the density maximum in the torus show that the equilibrated plasma relaxes to an essentially singly ionised state. The calculations include all of the known significant reactions in the plasma [*Brown et al.*, 1983; *Johnson and Strobel*, 1982; SMST]. The present work differs with the *Barbosa et al.* [1983] conclusions because of the restricted dimensionality of the radiative cooling coefficients used in the latter work. The results in the present work also differ with those of SMST, but mainly because the radiative cooling coefficients in their calculations do not reflect the total emission efficiencies of the sulfur species.

The observations of high density regions in the plasma [*Pilcher and Morgan*, 1985] according to the calculations shown here require the volumetric input of energy to vary according to $E_T \approx [e]^n$, where $n \approx 2$. This dependence violates the basic mechanics of NCT and an alternative energy source is required to supply most of the energy for the maintenance of the system. The observed plasma torus shows an electron temperature stability relative to changes in plasma density that neutral cloud theory cannot provide. A mechanism favored here for producing the observed properties is an interaction of the torus plasma with an Io atmosphere in which charge exchange reactions dominate over ionisation processes. A nonlinear relationship $E_T \approx [e]^n, n > l$ can develop in this case through variation in the relaxation rate of ion energy, and variation in the number of neutral atoms available for charge exchange in the Io atmosphere in proportion to the plasma density. In this scenario, mass for the maintenance of the system is derived from extended neutral clouds, and most of the energy for the plasma is produced through charge exchange reactions of the Io atmosphere. The atmospheric reactions could produce of order 6 ergs cm^{-2} s^{-1} a large fraction of which may be available for deposition below the exobase in the form of energetic neutral atoms. This process would provide an energy source for the establishment of an atmospheric blowoff [*Hunten*, 1985], giving one explanation as to why the Io torus is not totally dominated by oxygen ions. Another source of energy for the torus plasma is the hot electron population observed to be present in the hot plasma region [*Scudder et al.*, 1981; *Sittler and Strobel*, 1987]. However, the population density appears to be insufficient to provide the required energy, and it is not clear how this source could provide the observed electron temperature stability against changes in plasma density. It is important in this context that accurate measurement of ion temperatures be obtained over a range of plasma torus densities in order to define the role of the ions in plasma energetics. These energy sources clearly require further serious investigation with the realization that NCT is demonstrably inadequate.

APPENDIX A: REACTIONS INCLUDED IN THE PRESENT PLASMA MODEL CALCULATIONS

The reactions given below in Table A1 correspond to those listed in Table 5 of *Brown et al.* [1983]. The rate quantities applied to the calculation are also the same as those applied by *Brown et al.* [1983] with the exception of reaction (19) [*Shemansky*, 1987]. The reactions (1)-(9) include both flow directions; electron ionization and the sum of dielectronic and radiative recombination. An examination of Table 1 of SMST shows that they did not include (Table A1) reactions (11), (15), (17), (18), (24) and (25) in their calculations, contributing to some differences in the results. The present model does not include the reaction

$$S^+ + S^{2+} \rightarrow S^{2+} + S^+$$

which affects kinetic energy relaxation rates between S^+ and S^{2+} but not relative population rates (see SMST).

APPENDIX B: COMPARISON OF PRESENT NCT MODEL WITH THAT OF SMITH AND STROBEL [1985]

Although the present calculations differ with those of SMST in several respects, the major effect separating the two results is the magnitude and temperature dependencies of the radiative cooling coefficients of S II and S III. The SMST radiative cooling coefficients are established using simple approximations based on the major EUV transitions, but do not include a comprehensive set of known electronic states. As a result the SMST coefficients tend to be underestimates of the total cooling rates. The present calculations are based on exact calculations of collisional equilibrium which include a comprehensive set of electronic states for each of the atomic systems. The present calculations include nonlinear dependencies on electron density. The present and SMST values for the S II system in particular, differ by very large and variable factors apparently because a number of significant transitions were not included in the SMST calculation (D. F. Strobel, private communication, 1987). The S II radiative cooling function is the principal parameter causing gross differences between the present and SMST results. We compare the present model

TABLE A1. Plasma Reactions

Number	Reaction	k, 10^{-9} cm^3 s^{-1}
1.....	$O + e \rightarrow O^+ + 2e$	a
2.....	$O^+ + e \rightarrow O^{2+} + 2e$	a
3.....	$O^{2+} + e \rightarrow O^{3+} + 2e$	a
4.....	$O^3 + e \rightarrow O^{4+} + 2e$	a
5.....	$S + e \rightarrow S^+ + 2e$	a
6.....	$S^+ + e \rightarrow S^{2+} + 2e$	a
7.....	$S^{2+} + e \rightarrow S^{3+} + 2e$	a
8.....	$S^{3+} + e \rightarrow S^{4+} + 2e$	a
9.....	$S^{4+} + e \rightarrow S^{5+} + 2e$	a
10.....	$O + O^+ \rightarrow O^+ + O$	12.0
11.....	$O + S^+ \rightarrow O^+ + S$	0.06
12.....	$S + O^+ \rightarrow S^+ + O$	8.0
13.....	$S + S^+ \rightarrow S^+ + S$	16.0
14.....	$O^{2+} + S \rightarrow S^+ + O^+$	11.0
15.....	$O^{2+} + S \rightarrow S^{2+} + O^+ + e$	3.0
16.....	$S^{2+} + O \rightarrow S^+ + O^+$	6.0
17.....	$O^{2+} + O \rightarrow 2O^+$	0.2
18.....	$S^{2+} + S \rightarrow 2S^+$	0.6
19.....	$S^{3+} + O \rightarrow S^{2+} + O^+$	4.4
20.....	$S^{3+} + O \rightarrow S^+ + O^{2+}$	5.6
21.....	$O^{2+} + O \rightarrow O + O^{2+}$	5.0
22.....	$S^{2+} + S \rightarrow S + S^{2+}$	7.0
23.....	$S^{3+} + S \rightarrow S^{2+} + S^+$	20.0
24.....	$O^{2+} + S^+ \rightarrow O^+ + S^{2+}$	5.9[b]
25.....	$O^{2+} + S^{2+} \rightarrow O^+ + S^{3+}$	2.8[b]

[a] Rates show a strong electron temperature dependence. See *Brown et al.* [1983] for particular values.

[b] Values given at the high temperature limit. See *Shemansky* [1987].

with the SMST calculations in an approximate way in Table B1, by substituting the erroneous SMST values for S II and S III cooling coefficients into the computer code. This substitution does not bring all physical parameters used in the two calculations into agreement, but it does account for most of the divergence in the results. The two calculations also differ in the inclusion or exclusion of some reactions (Appendix A), but these differences are minor relative to

TABLE B1. Comparison of Present Model With That of Smith and Strobel for a Particular Case

	Present Model[a]	*Smith and Strobel* [1985][b]	Present Model Modified[c]
[O I](cm^{-3})	333.	31.2	41.5
[O II]	520.	660.	698.
[O III]	0.28	42.5	13.
[O IV]	0.17-5*	...	0.10-1
[S I]	36.	6.	8.2
[S II]	1422.	355.	476.
[S III]	28.5	432.	377.
[S IV]	0.74-2	11.8	15.5
[S V]	0.17-6	...	0.20-1
[e]	2000.	2000.	2000.
$Te(10^4K)$	3.935	5.51	5.616
$T_i(10^6K)$	2.01	1.28	1.09
τ_i(days)	58.	58.	58.
$\Sigma[Oi]\ \Sigma[Si]$	0.36	0.88	0.82
$Y_0(O)/Y_0(S)$	2.00	2.2	2.00
$Y_0(O)$ (cm^{-3}s^{-1})	2.34-3	4.2-4	5.40-4
$Y_0(S)$/(cm^{-3}s^{-1})	1.17-3	1.9-4	2.70-4
E_T(10^{-12}ergs cm^{-3}s-1	2.18	—	0.505
Erad (10^{-12}ergs cm^{-3}s^{-1})	0.72	0.24	0.31

* 0.17-5 ≡ 0.17 x 10^{-5}.

[a] Present model based on the NCT for conditions similar to those forming case II of SMST.

[b] The NCT calculation of SMST; case II.

[c] Present model as in footnote *a* with the substitution of radiative cooling coefficients for S II and S III as given by SMST.

those mentioned above. Differences in ionisation rates for S II and S III occur for unknown reasons because both calculations use the same literature data base. The present radiative cooling function for O II is also significantly larger than that of SMST.

The first data column of Table B1 shows the present model calculations for specific parameters chosen to correspond to the SMST case II, for the purpose of comparison. The larger radiative cooling coefficients in the present model force a much larger flow of mass through the system through charge exchange with a much larger population of neutrals; the electron density is forced to be 2000 cm^{-3}. The large charge exchange rate reduces the proportion of oxygen ions in the plasma. The second data column is from the SMST case II calculation. The energy radiated in the SMST calculation is a factor of 3 less than that shown in the first data column in spite of a higher electron temperature, a symptom of lower radiative cooling coefficients. Much more energy flows through the system in the present model (first data column) because of the large density of neutrals required to maintain the system. The terminal electron temperature is too low to produce sulfur ion partitioning dominated by S III using the present parameters; the neutral populations and sulfur ion partitioning are both in gross disagreement with observation. The third data column is the present model modified to contain the same radiative cooling functions for S II and S III as the SMST calculation, as indicated above. There is obvious basic agreement with the SMST results in all of the critcal parameters, with relatively minor differences that can be partly explained by differences in the remaining input parameters as discussed above. We conclude that the present and Smith and Strobel models are basically equivalent, given the same input parameters.

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