OPTICAL OBSERVATIONS OF IO'S NEUTRAL CLOUDS AND PLASMA TORUS

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Abstract. A review of ground-based optical observations of Io's neutral clouds and plasma torus is provided. The physical processes determining the spatial distribution and intensity of torus emissions are described with reference to a model based on Voyager spacecraft data. The model is then compared to ground-based observations. Inconsistencies and variations in torus conditions over long timescales are emphasized. Periodicities in the torus evident in Voyager and ground-based are critically discussed.

Processes determining the spatial characteristics of the neutral clouds are discussed. Observations of the slow sodium cloud are compared to model calculations. Special attention is paid to recent observations of high velocity neutrals and species in the upper atmosphere of Io itself. The article concludes with suggestions for future observations and research.

1. Introduction

It is perhaps surprising that at a time when spacecraft are being sent to study the giant planets in our Solar System, ground-based optical observations are still valuable in the investigation of phenomena associated with these planets and their immediate environment. However, one should recall that past missions such as Pioneer and Voyager were fly-bys with the spacecraft in the vicinity of the planets for only a matter of hours and that future orbiter missions such as Galileo and Cassini will have capabilities limited by the restricted number of experiments onboard, the spacecraft lifetimes, their telemetry transmission rates, and their orbits. Ground-based observations provide a synoptic view of the system, cover phenomena not readily accessible to the spacecraft, allow the study of variability on timescales far longer than the lifetime of one spacecraft, and can provide more detailed study of specific emissions. They are therefore, in many senses, complementary to the dedicated missions. Even so, over the past 20 years, ground-based observers have had to use considerable skill and ingenuity to identify, quantify, monitor, and analyse specific emissions taking advantage of new technology whenever possible. This article summarizes the results obtained from optical (3500–9600 Å)[1] observations of Jupiter's magnetosphere and attempts to identify areas where future ground-based observations would provide significant input for the study of the Jovian system.

Two specific aspects of the Jovian system are discussed; the neutral clouds and

[1] 1 angstrom (Å) = 10^{-10} m.

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the Io plasma torus. The neutral clouds, discovered in 1972 (Brown, 1974), and the Io plasma torus, first detected by ground-based observation in 1975 (Kupo *et al.*, 1976), fill an enormous volume of the inner magnetosphere of Jupiter. They are composed of mainly sulphur and oxygen atoms and ions with traces of sodium and potassium species. These atoms and ions are supplied to the torus and clouds at a total rate of around 1 tonne s^{-1} by the volcanically active, innermost Galilean satellite, Io. Ground-based observations of optical emissions from the clouds and torus have been made on a fairly regular basis since their discovery. Together with results derived from the Voyager and International Ultraviolet Explorer (IUE) missions, these observations have provided some insight into the nature of the interaction between Jupiter's magnetosphere and Io. The considerable interest this has provoked has resulted in a vast quantity of literature on the subject, particularly since the Voyager fly-bys in 1979. Several relevant reviews have appeared during this time. The first notable review was by Brown and Yung (1976) which includes a description of the physics of sodium D-line emission and remains a standard reference on this topic (see also Chamberlain and Hunten (1987)). Post-Voyager reviews can be found in Pilcher and Strobel (1982) and Brown *et al.* (1983a) which provide a description of the morphology of Io's sodium cloud, a description of the main characteristics of torus emissions seen from ground-based, IUE, and Voyager observations, and physical interpretation of the emissions. A review of the *in situ* observations of the Voyager Plasma Science (PLS) experiment can be found in Belcher (1983). Io's atmosphere, the probable source for the material in the clouds and torus, has been discussed by Kumar and Hunten (1982), Fanale *et al.* (1982), and Johnson and Matson (1988). A necessarily brief review of all branches of research associated with Io has appeared in Nash *et al.* (1986) (see also Cheng *et al.*, 1986) while reviews of several aspects of the Io–Jupiter interaction have appeared in Belton *et al.* (1989). The chapter by Schneider *et al.* (1989a) describes the time scales involved in the physical processes which govern the morphology and brightness of the neutral clouds and attempts to relate these to the observations while Strobel (1989) discusses the variability of the plasma torus in both the optical and the UV. A recent general discussion of the magnetospheres of the giant planets has been presented by Bagenal (1992) and more detailed reviews of the interaction of Iogenic material with the magnetosphere of Jupiter have appeared in Cheng and Johnson (1988), Bagenal (1989), and Vasyliunas (1983).

This article begins by describing pre-Voyager ground-based observations (Section 2) and relevant Voyager results (Section 3). It will then provide an overview of the optical observations of the neutral clouds and plasma torus by describing the observable species, the physics associated with their emission, and the interpretation of the observations. The physical processes determining the geometry and brightness of the plasma torus appear in Sections 4 and 5 while Sections 9 to 12 cover the processes affecting the neutral clouds and neutral emissions from the

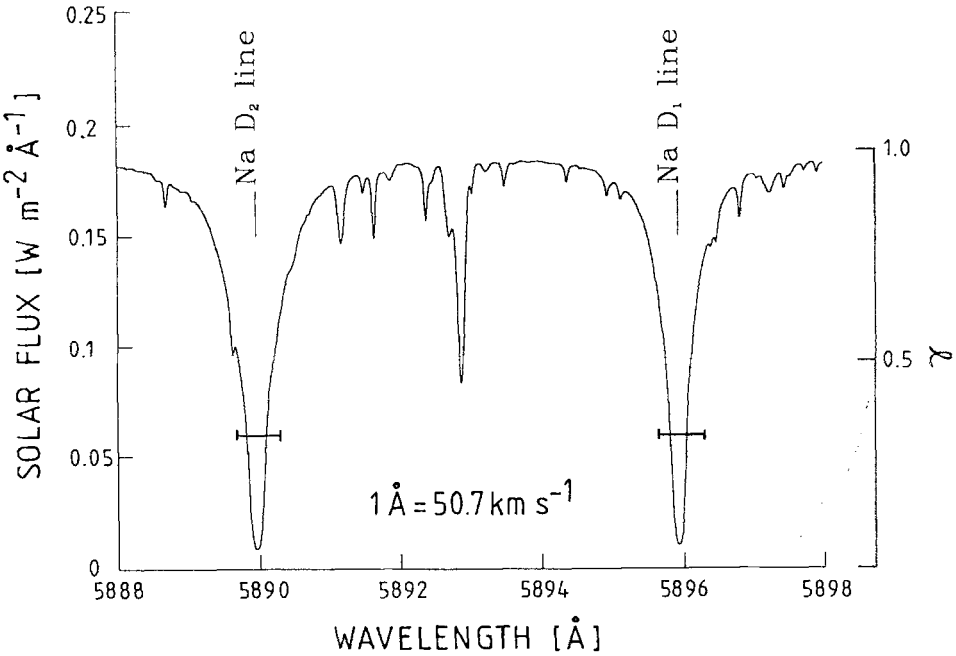


Fig. 1. The solar flux at 1 AU between 5888 and 5898 Å (Kurucz *et al.*, 1984). γ is the ratio of the flux in the solar absorption line to that of the nearby continuum. Sodium atoms resonantly scatter at wavelengths of 5890 Å and 5896 Å in their rest frames. The mean orbital speed of Io corresponds to ±0.34 Å (marked across the Fraunhofer lines with bars) which produces a variation in the flux of photons which can excite sodium in Io's environment of nearly an order of magnitude.

atmosphere of Io. A short overview of variable phenomena in the torus is provided in Section 7 and a brief discussion of the energy balance of the torus appears in Section 8. The article concludes with a summary of useful observations which could be performed in the future.

2. Pre-Voyager Observations

The observation of an extended cloud of neutral sodium atoms surrounding Io (Brown, 1974) provided the first evidence at optical wavelengths of a complex interaction between Io and Jupiter's magnetosphere. The observed D-line emission at 5889.95 Å and 5895.92 Å results from resonant scattering of sunlight (Bergstralh *et al.*, 1975; 1977). The angular velocity of Io about Jupiter (4.112×10^{-5} rad s^{-1}) corresponds to a mean orbital speed of 17.34 km s^{-1}. Hence, the apparent intensity of the Sun varies due to the combination of the Doppler shift and the solar Fraunhofer lines (Figure 1), leading to an observed brightness modulation of the cloud. The observations of Bergstralh *et al.* also showed that the cloud is about 25% brighter at eastern elongation than at western elongation (see Appendix).

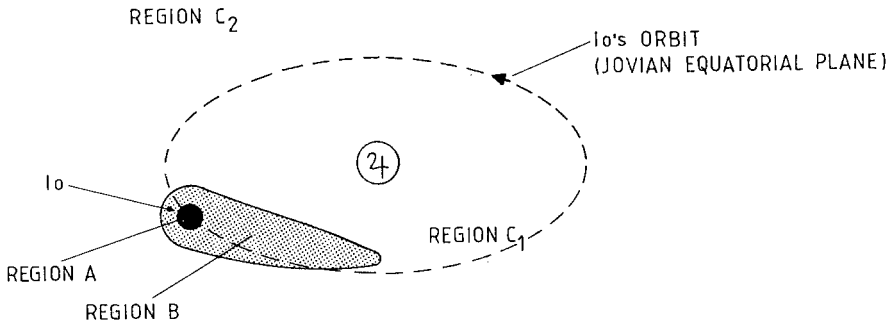


Fig. 2. Schematic diagram of the definition of "Regions" for the Io sodium cloud as defined by Brown *et al.* (1975) and Wehinger *et al.* (1976).

With the discovery of D-line emission several Jovian radii[2] (R_J) away from Io (Trafton *et al.*, 1974), Brown *et al.* (1975) suggested it would be appropriate to divide the cloud into several regions (Figure 2). Region A coincides with Io's visible disc (including atmospheric emissions) while Region B corresponds to the volume of space near Io where emission exceeds 1–2 k rayleigh (as re-defined by Pilcher and Strobel (1982)).[3] Region C was sub-divided into Regions C_1 and C_2 (Wehinger *et al.*, 1976), the former extending several R_J from Io in its orbital plane, the latter comprising the remainder of the Jovian magnetosphere.

Matson *et al.* (1974) suggested that the cloud might be produced by the ejection of Na from Io resulting from magnetospheric ions sputtering Io's surface. The *in situ* detection of magnetospheric ions (thought at the time to be low atomic weight ions) made by instruments on Pioneer 10 (Carlson and Judge (1974); Frank *et al.* (1976)) supported this. It was also recognized that the plasma provides the sink for neutral Na by electron impact ionization (Carlson *et al.*, 1975) thereby qualitatively explaining a time-dependent asymmetry in the cloud's spatial distribution correlated with Io's magnetic latitude (Trafton and Macy, 1975). The tilt of Jupiter's magnetic dipole with respect to the rotation axis was known to be $\approx 10°$ from Pioneer 10 magnetometer and ground-based radio measurements. Hill *et al.* (1974) pointed out that plasma sources within the magnetosphere would be subject to a centrifugal force so that plasma would be concentrated about a "centrifugal symmetry surface" (also known as the centrifugal equator) which would be inclined by $\approx 7°$ to the rotational equator (Section 4.2; Appendix). Hence, when Io is north of the centrifugal equator, the neutral Na lifetime against electron impact ionization is shorter to the south of Io than to the north and *vice versa*. The confinement of the plasma to a torus almost centred on the centrifugal equator was later confirmed by Pilcher (1980) and Trauger *et al.* (1980).

[2] $1\,R_J = 7.14\,10^7$ m.

[3] If the frequency-integrated intensity J, is in units of $[10^6\,\text{photon}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}]$, then $4\pi J$ is in [rayleigh] (Brown *et al.* 1983a; Chamberlain and Hunten, 1987).

Images of the Na cloud indicated that it was "banana-shaped" (Matson *et al.*, 1978; Murcray and Goody, 1978; Smyth and McElroy, 1978) extending up to 60° in front of Io in its orbit. Modelling suggested a mean ejection velocity of 2.6 km s^{-1} although high resolution spectra indicated that the outflow velocity may be variable and, in some cases, as high as 18 km s^{-1} (Trafton, 1975a). Other derived parameters relied to some extent on the electron density (n_e) near Io's orbit derived from Pioneer 10 data. However, ground-based observations were beginning to indicate inconsistencies. The discovery of a torus of singly-ionized sulphur (Kupo *et al.*, 1976), found by observation of the forbidden [SII] red doublet (6716.4 Å and 6730.8 Å), indicated $n_e = 1\text{–}3 \times 10^3\ \text{cm}^{-3}$ (Brown, 1976) and eventually led to the conclusion that the composition of the inner magnetosphere is dominated by heavy ions thereby contradicting the original interpretation of the Pioneer 10 data (e.g. Münch and Bergstralh, 1977). The detection of [OII] emission (Pilcher and Morgan, 1979) at 3726.0 Å and 3728.8 Å further supported this just prior to the Voyager fly-by in March 1979.

3. Voyager Observations

Voyager observations have contributed greatly to our knowledge of the Jupiter system and several measurements have had considerable influence on the study of the interaction between Io and the Jovian magnetosphere. The detection of active volcanism (Morabito *et al.*, 1979), following the prediction by Peale *et al.* (1979), stands out as the most remarkable result but many other measurements are relevant to this discussion.

- The Pioneer 10 radio occultation experiment had shown that Io possessed an ionosphere (Kliore *et al.*, 1974; 1975) and the detection of gaseous SO_2 by the Infrared Interferometer Spectrometer (IRIS) on Voyager 1 (Pearl *et al.*, 1979) at a column abundance of 5×10^{18} molecule cm^{-2} (a surface pressure of 10^{-7} bar) revealed one component of the associated atmosphere. The measurements have been interpreted in several different ways due to the possible influence of volcanic plumes (see Section 10) but the presence of SO_2 in gaseous form is undoubted.
- Several pre-Voyager studies of Io's spectral reflectance had concluded that elemental sulphur was likely to be a dominant constituent of Io's surface (e.g. Fanale *et al.* (1974); Wamsteker *et al.* (1974)). Multispectral images of the surface from Voyager confirmed the presence of sulphur but Soderblom *et al.* (1980) also showed that a better fit to the ultraviolet reflectance could be made by mixing S_8 with SO_2 frost. The presence of SO_2 frost supported ground-based spectroscopic measurements (Smythe *et al.*, 1979) and its physical state and spatial distribution were subsequently determined using IR measurements (Howell *et al.*, 1984). Further analysis of Voyager images has indicated that

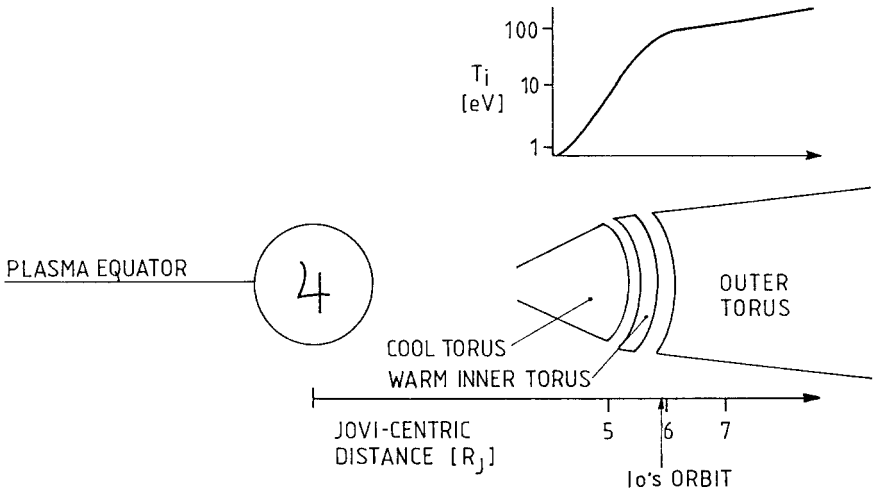


Fig. 3. Schematic diagram of the three regions in the torus showing the position of Io's orbit and the ion temperature (schematically) as a function of jovicentric distance in the torus.

between 30 and 50% of the surface may have been covered with SO_2 (McEwen *et al.*, 1988). Recently, comparisons between IR spectra of Io and laboratory samples have suggested that both H_2O and H_2S may be present in a mixture with SO_2 frost on Io's surface (Nash and Howell, 1989; Salama *et al.*, 1990). A tentative detection of CO_2 has also been made (Trafton *et al.*, 1991; Sandford *et al.*, 1991). This detection has, however, been questioned by De Bergh *et al.* (1991) (See also Lellouch *et al.*, 1992).

- The PLS (plasma sciences) experiment on Voyager 1 made detailed measurements of magnetospheric ions and their temperatures (Bagenal, 1985; Bagenal and Sullivan, 1981; Bagenal *et al.*, 1985). The plasma torus can be divided into three parts (Trauger, 1984a) (Figure 3). The cold torus generally refers to the region within 5.6 R_J of Jupiter. The ion temperature (T_i) in this region decreases sharply with decreasing radial distance from Jupiter (Figure 4). This suggests that plasma is slowly diffusing inward from the vicinity of Io's orbit as it loses energy due to collisional excitation and radiation in the UV and at optical wavelengths (Richardson *et al.*, 1980). The warm inner torus comprises the region between 5.6 R_J and Io's orbit at 5.91 R_J. Considerable numbers of hot ions are present in this region and the difference between the electron temperature (T_e) and T_i (compared in Figure 5) indicates that thermodynamic equilibrium has not been fully achieved. The warm outer torus covers the region outside Io's orbit. Plasma in this region is transported rapidly outward from Io's orbit. Peaks corresponding to individual ionic species are not resolved in PLS spectra obtained in this region (Bagenal, 1985). The derived composition is model dependent and relatively poorly defined. In Figure 6, the charge concen-

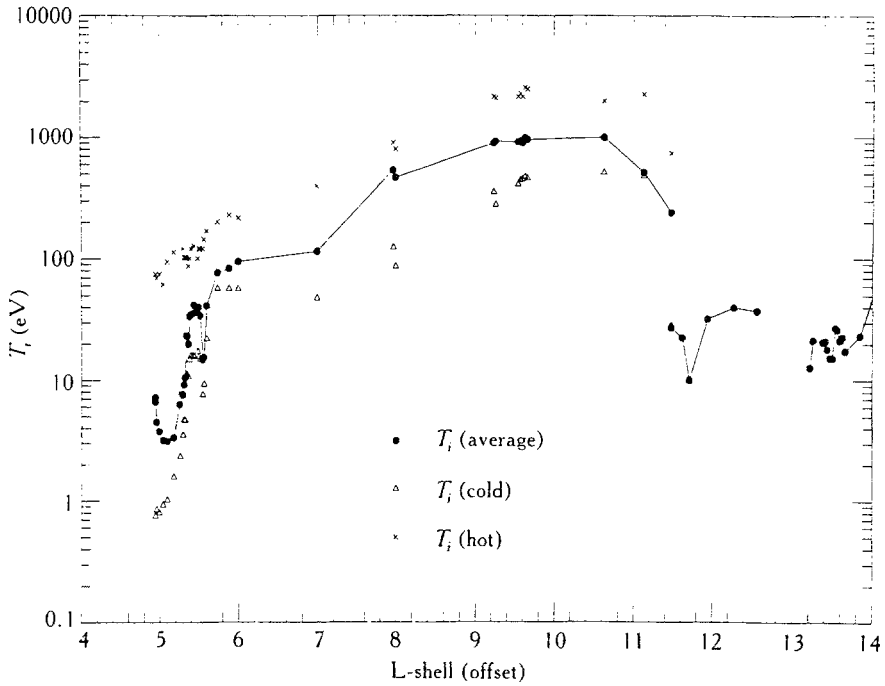


Fig. 4. on temperatures in the plasma torus derived from Voyager 1 PLS measurements (inbound) (from Bagenal, 1989).

tration measured along the Voyager 1 trajectory is shown. Electron concentrations derived from the Planetary Radio Astronomy (PRA) experiment observations are in good agreement with these results (Birmingham *et al.*, 1981). An estimate of the ion composition along the trajectory is also given.

- The equivalence of the mass to charge ratios of S^{2+} and O^{+}, two of the most abundant species in the torus, is unfortunate as the PLS experiment could not distinguish between the two. Data from the ultraviolet spectrometer (UVS) experiment have therefore been invaluable for the interpretation of the PLS data. T_e in the cold torus is too low to generate significant UV emission. However, Broadfoot *et al.* (1979) reported the detection of the warm torus in the UV centred at about 5.9 R_J. All lines in the UVS spectra are blended due to the comparatively low spectral resolution (30 Å) which makes determination of absolute intensities difficult. The spectra are characterized by five bright emission features (Shemansky, 1987) at 685 Å (corresponding to S^{2+}), 833 Å (O^{+} and O^{2+}), 1020 Å (S^{+} and S^{2+}), 1194 Å (S^{2+}), and 1256 Å (S^{+}). The superposition of the two oxygen ion emissions makes interpretation of the composition uncertain (Shemansky (1987); Strobel (1989)). However, modelling of the spectra has resulted in the compositions shown in Figure 7. It should be

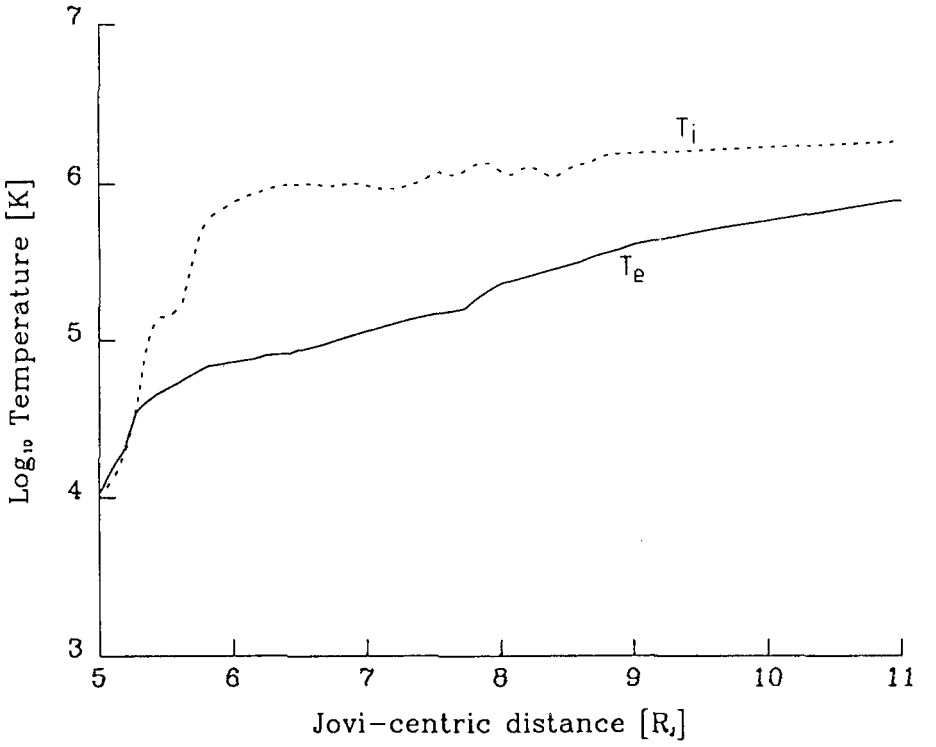


Fig. 5. The electron temperature in the plasma torus measured by Voyager 1 (after Sittler and Strobel, 1987) compared to the ion temperature (Bagenal *et al.*, 1985). Local thermal equilibrium was only strictly adherred to at Jovicentric distances less than 5.4 R_J.

noted that an alternative compositional model based, in part, on UVS results has been proposed by Moreno *et al.* (1985). However, it is not clear that this model provides an adequate fit to the observed UVS spectra (Shemansky, 1987). The data compare favourably with recent Earth-orbiting observations of the torus made by the Hopkins Ultraviolet Telescope (HUT) at high spectral resolution ($\approx$3 Å) reported by Moos *et al.* (1991) except for a relative excess of O^+ in the Voyager observations. Periodicities in the 685 Å emission are discussed in Sections 4.3 and 7.

- The orientation and geometry of Jupiter's magnetic field were fairly well known prior to the Voyager fly-bys from ground-based radio and Pioneer 10 *in situ* measurements. The Voyager magnetometer provided details of the field geometry but for our purposes (i.e. Jovicentric distances $\geqslant 5\ R_J$) the field can be approximated by an offset tilted dipole (OTD) model (see Appendix).

4. Distribution of Plasma in the Torus

In the next two Sections, the prediction by a semi-empirical model calculation of the brightness of plasma torus emission lines at the time of the Voyager encounter

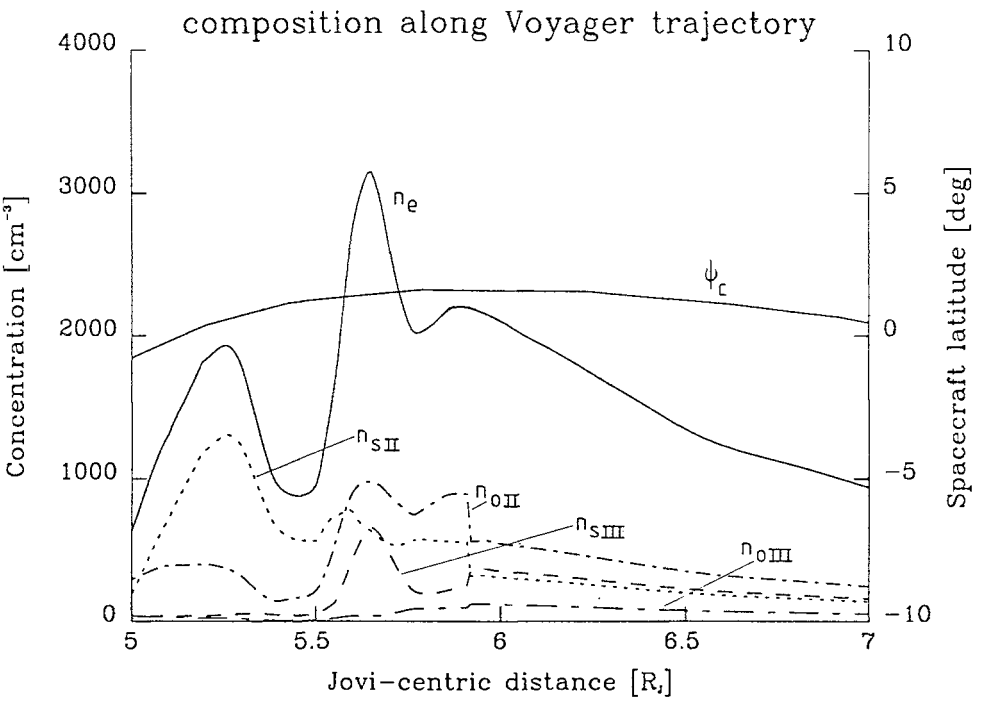


Fig. 6. Radial profile of the charge density derived from *in situ* measurements on Voyager 1 (Bagenal and Sullivan, 1981). The ion composition along the Voyager 1 trajectory derived from PLS measurements is also shown and compared to the spacecraft latitude with respect to the centrifugal equator. The composition beyond 5.9 R_J is model dependent and uncertain, particularly for the oxygen species. The graph indicates typical values for these species.

will be described. In later Sections, the model will be compared to ground-based observations to emphasize the spatial dependence and variability of the intensity of torus emissions.

4.1. Diffusive equilibrium

The mathematical description of a dipole field is straightforward and has been described by many authors (e.g. Roederer, 1970). Bagenal (1985) has given the equations required to determine the diffusive equilibrium distribution of a multi-species plasma along a magnetic field line in a dipole field. The equilibrium results from a balance between the thermal pressure gradient, the centrifugal forces arising from the corotation of the magnetic field, and an ambipolar electric field. Given the density of an ion species at a reference point, s_0, the density at a point s on the same field line can be computed from the equation (F. Bagenal, personal communication):

$$n_i(s) = n_i(s_0) \exp\left[\left(1 - \frac{T_\perp}{T_\parallel}\right) \log \frac{B(s)}{B(s_0)} + \frac{\frac{1}{2} m_i \Omega_J^2 (\rho^2(s) - \rho^2(s_0))}{kT_\parallel}\right.$$

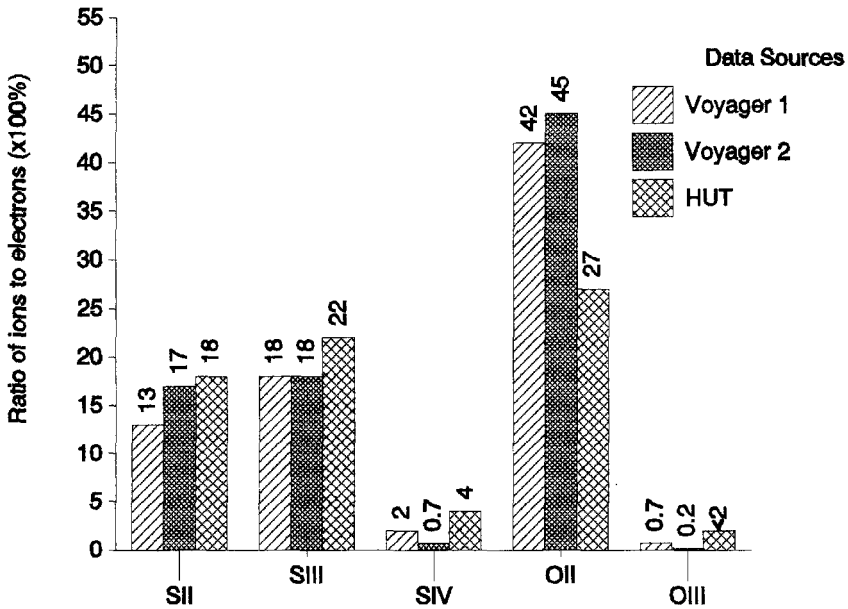


Fig. 7. The composition of the Io plasma torus derived from UVS results expressed as the ratio of the ion concentration to the electron density (Shemansky, 1987). Measurements centred at 5.9 R_J from Dec 1990 made using HUT on board the Astro-1 mission obtained at a spectral resolution of 3 Å (Moos *et al.*, 1991) are also shown for comparison.

$$- \frac{Z_i q(\phi(s) - \phi(s_0))}{kT_{\|}} \Bigg] \tag{1}$$

where n_i is the ion density, Z_i is the charge state, m_i is the ion mass, Ω_J is the angular velocity of the magnetosphere, ρ is the perpendicular distance from the rotational pole, B is the magnetic field magnitude (in [Tesla]), k is Boltzmann's constant and q is the elementary charge. The second term in this equation describes the centrifugal force, the third term describes the ambipolar electric force, while the first term includes the influence of the magnetic mirror force. The description given by Bagenal (1985) assumes that the ion temperature perpendicular to the field lines ($T_{i\perp}$) equals the ion temperature parallel to the field ($T_{i\|}$). Ground-based observation suggests that this condition is approximately adhered to near Io's orbit (see Section 5). Should the need arise, the ratio of the magnetic field magnitudes can be computed for a dipole field from:

$$\frac{B(s)}{B(s_0)} = \left\{\frac{1 + 3\sin^2 \psi_{m0}}{1 + 3\sin^2 \psi_m}\right\}^{1/2} \left\{\frac{\cos \psi_m}{\cos \psi_{m0}}\right\}^6 \tag{2}$$

where ψ_m is the latitude with respect to the magnetic equator (see Appendix). A coupled system of equations including all ion species can then be solved under the

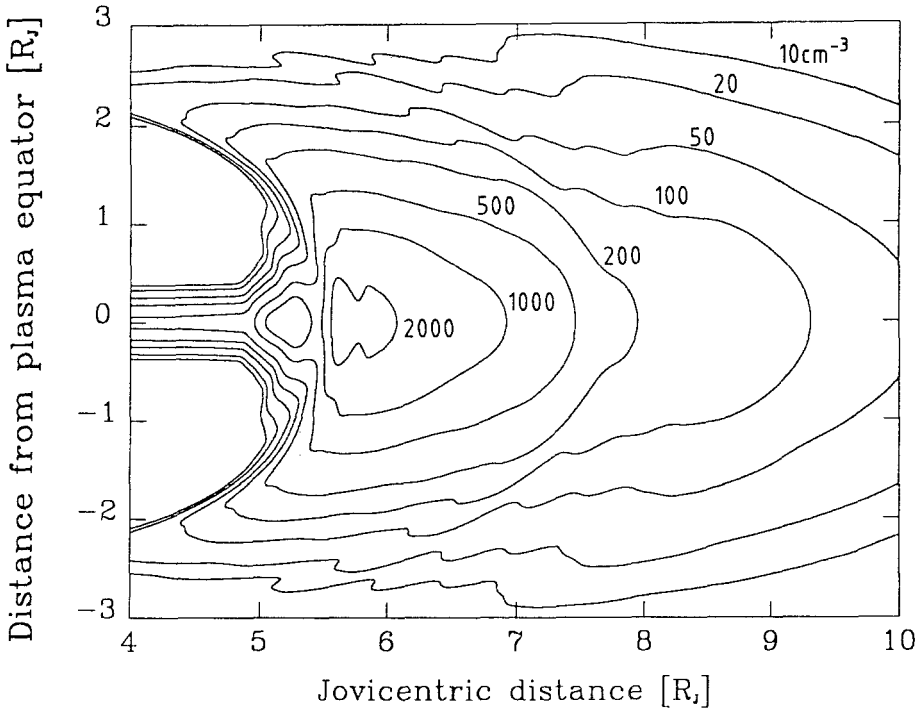


Fig. 8. The electron density distribution in the Io plasma torus at the time of Voyager 1 fly-by derived from Voyager PLS measurements of the ion distributions and temperatures at known latitudes and extrapolated to all points in the inner magnetosphere using the diffusive equilibrium equations given by Bagenal (1985).

assumption of local charge neutrality. It should be noted that the results are probably unreliable at high (>20°) latitudes.

The Voyager PLS measurements of the ion composition and temperature along the spacecraft trajectory can be used as input for this scheme to derive the electron and ion densities throughout the torus. In solving for the diffusive equilibrium distribution, one must take into account the latitude of the spacecraft relative to the plane defined by the maximum density of the plasma for all field lines during the observations. For the cold torus, this plane should be close to the centrifugal equator (see below). In Figure 8, the electron density distribution derived from Voyager observations assuming a tilt of 7° with respect to the rotational equator is shown.

4.2. The orientation of the centrifugal equator

Hill *et al.* (1974) showed that the equilibrium position of corotating plasma in a tilted dipole field is influenced by centrifugal force. For a given field line, the centrifugal force is at maximum at the point on the field line which is furthest

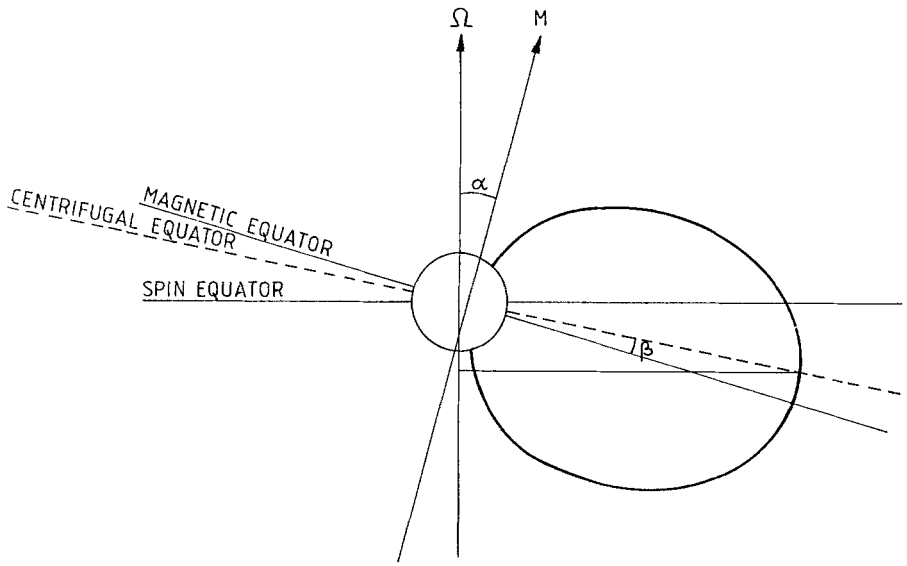


Fig. 9. The geometry of the offset tilted dipole field and the centrifugal equator (after Cummings *et al.*, 1980).

away from the rotation axis (Figure 9). The surface intersecting the points on all field lines satisfying this condition is referred to as the "centrifugal symmetry surface" or centrifugal equator. The angle between this surface and the magnetic equator is given (for small α) by (Hill *et al.*, 1974):

$$\tan \beta = \frac{(2/3) \tan \alpha}{1 + [1 + (8/9) \tan^2 \alpha]^{1/2}} \tag{3}$$

where α is the angle between the angular momentum vector (Ω) and the dipole moment (M). Thus, with $\alpha = 9.8(\pm 0.3)°$ (Dessler, 1983), the centrifugal equator is tilted by 6.6° to the rotational equator. The centrifugal symmetry surface is not strictly planar (Vasyliunas, 1983) but deviations from a plane are much smaller than the magnetic field's departure from a true OTD.

The equilibrium position of an ion in the tilted dipole field essentially depends on the ratio of the thermal to the corotational speed. If the ions are cold so that the pressure gradient (∇P) is much smaller than the centrifugal term $\rho \, d\mathbf{V}/dt$ (where ρ is mass density and $\mathbf{V}$ the velocity), then equilibrium is reached on the centrifugal equator. If the ions are hot, the magnetic equator forms the equilibrium position.

Cummings *et al.* (1980) show that the equilibrium latitude of a cold ion produced at Io and subsequently swept into corotation will actually be $\approx 1.5°$ from the centrifugal equator (or 8.1° from the rotational equator). If the ion is transported radially outwards with no increase in its cyclotron velocity then the centrifugal term becomes more dominant and the ion's equilibrium position will move closer

to the centrifugal equator. On moving inwards, the ion's equilibrium position moves nearer the magnetic equator. However, other energy source and loss terms affect this picture markedly. Inward moving ions are strongly cooled by collisional excitation and subsequent emission (Richardson *et al.* 1980) leading to a strong decrease in T_i with decreasing Jovicentric distance (Figure 4). Thus, for Jupiter's cold torus around 5.5 R_J, the plasma should be seen close to the centrifugal equator. The temperature gradient in this region is about 70 eV R_J^{-1} (c.f. the rise in the corotation energy of $\approx$145 eV R_J^{-1} for oxygen). Thus, the ratio of the thermal speed to the corotation speed rises sharply in the warm inner torus so that one might expect the equilibrium position to move towards the magnetic equator as the Jovicentric distance increases.

A further effect is the offset of the tilted dipole. For a given distance from the dipole centre the centrifugal force should vary with magnetic longitude perhaps leading to a variation in the equilibrium position. However, it is probable that effects of the deviation of Jupiter's magnetic field from a true dipole are likely to be more important.

Observations of the orientation of the plasma torus have been only rarely discussed since Trauger *et al.* (1980) reported a tilt of the plasma equator to the rotational equator of 7°. Pilcher *et al.* (1985) found a value of 7.7($\pm$0.5)° from studies of one ansa. Recently, the deduction of the orientation has been simplified by the use of focal reducers to increase the field of view at the telescope while still using charge-coupled device (CCD) detectors. Neutral density filters, which have a very small (<0.01%) transmission, have been used to cover Jupiter while imaging the torus on either side of the planet. Jockers *et al.* (1992) have reported that the plasma equator was tilted at 5.4 R_J by 7.8($\pm$0.6)° with respect to the rotational equator from observations of this type. The observations of Pilcher *et al.* (1985) and Jockers *et al.* (1992) are consistent with torus species having the energy of freshly picked up ions as determined by Cummings *et al.* (1980).

Trauger *et al.* (1991) have used imaging data to constrain models of the octupole moment of the Jovian magnetic field. A more detailed article on these results is currently in preparation (Schneider, personal communication).

4.3. The dawn–dusk asymmetry

Sandel and Broadfoot (1982a) showed that the approaching ansa of the plasma torus (as seen from Earth) at 685 Å (principally S^{2+}) was, on average, a factor of 1.35 brighter than the receding ansa. Comparison of Voyager in-bound and out-bound UVS data proved that this feature was stationary with respect to the Sun-planet line and did not corotate with the magnetosphere (a local time effect). Modelling indicated a maximum brightness above 19:00 local time and further studies by Shemansky and Sandel (1982) showed that a variation of T_e of $\pm$10% between dawn and dusk was sufficient to explain the observations.

The observations have been interpreted as indicating a dawn–dusk electric field

across Jupiter's inner magnetosphere (Ip and Goertz, 1983; Barbosa and Kivelson, 1983; Goertz and Ip, 1984) which is connected with plasma flow down the Jovian magnetotail. The electric field produces two effects on the torus which are observable from the ground. Firstly, the ions are shifted relative to the OTD coordinate system. Following Barbosa and Kivelson (1983) and Smyth and Combi (1988a), the displacement of the torus in relation to the OTD can be computed by the equation:

$$\tilde{L} = L(1 - \epsilon \sin[\Phi - (\eta_s - \pi)]) \tag{4}$$

where L is a dimensionless parameter describing the distance at which the field line crosses the magnetic equator in units of $[R_J]$ in the OTD frame, Φ is the departure of the plasma volume element from superior heliocentric conjunction (SHC), η_s specifies the direction of the field (180° for dawn to dusk) and ϵ is the "shift parameter" i.e. the ratio of the magnitudes of the dawn to dusk convection field to the corotation electric field. $\tilde{L}$ is the radial co-ordinate in the torus reference frame which includes the dawn-dusk electric field. Barbosa and Kivelson (1983) had suggested values of $\epsilon = 0.03$ and $\eta_s = 205°$ were sufficient to fit the UVS data from Voyager for which the shift of the torus would be 0.18 R_J at Io's orbit.

By observing both sides of the torus simultaneously and monitoring the positions of maximum brightness relative to the centre of Jupiter, the shift relative to the OTD can be determine more readily. Ground-based observations of the [SII] emission (6716 Å and 6731 Å) indicated $\epsilon = 0.024 \pm 0.009$ (Thomas *et al.*, 1992) in good agreement with estimates based on UVS data.

The second observable effect is the brightness asymmetry produced by the modified electron density and temperature. The generalized formulae for computing the variation in the electron density and temperature as a function of local time are:

$$\tilde{n}_e = (1 - 3\epsilon[1 + \sin(\Phi - (\eta_s - \pi))])n_e^w \tag{5}$$

$$\tilde{T}_e = (1 - 3\epsilon[1 + \sin(\Phi - (\eta_s - \pi))])T_e^w \tag{6}$$

where superscript w refers to the western side of the torus where Voyager measurements were made (Smyth and Combi, 1988a).

Morgan (1985a) determined $\epsilon = 0.04$ from the asymmetry of brightness of the torus at optical wavelengths (particularly the [SII] emissions at 6716 Å and 6731 Å) which corresponds to a field strength of $\approx 4.5\ \mathrm{mV\,m^{-1}}$ at Io's orbital distance. Smyth and Combi (1988a) modelled the east-west brightness asymmetry of the Na cloud (Bergstralh *et al.*, 1975; Section 2; Section 9.5) using $\epsilon = 0.025$ and $\eta_s = 180°$.

Finally, the data presented by Morgan (1985a) in his Figure 6 suggests that the magnitude of the shift parameter, ϵ, is dependent upon magnetic longitude. For

"plane of sky" longitudes (see Appendix) of 180° and 300°, the intensity difference between the receding and approaching ansae was around a factor of 2. However, for a plane of sky longitude of 240° no intensity asymmetry was observed. This is rather curious and has not been adequately explained.

5. Torus Brightness Calculations

In the previous Section, the distribution of plasma in the torus has been described so that a simple model of the torus temperature and density distribution can be constructed. The observable line emission from the plasma torus can now be modelled. The emission results from collisional excitation and subsequent de-excitation of low-lying energy levels. The method of calculation is straightforward and is described in Chapter 3 of Osterbrock (1989). The total collisional de-excitation rate per unit volume per unit time is:

$$n_e n_2 q_{21} = n_e n_2 \frac{8.629 \times 10^{-6}\,\Omega(1,2)}{T_e^{1/2}\,\omega_2} \tag{7}$$

where n_e is the electron concentration, n_2 is the ion concentration in the upper level, $\Omega(1,2)$ is the collision strength, ω_2 is the statistical weight of the upper level, and q_{21} is a rate co-efficient. The total collisional excitation rate is given by:

$$= n_e n_1 \frac{\omega_2}{\omega_1} q_{21}\, e^{-\chi/kT_e} \tag{8}$$

where χ is the energy threshold defined by $\chi = h\nu_{21}$ and sub-script 1 refers to the lower level for the transition.

Most ions of importance in the plasma torus have five low-lying levels. Four relevant examples are shown in Figure 10. Transitions can occur between any of these levels and a classical equilibrium calculation is required to determine the electron populations in each level (see Osterbrock p. 57) so that a solution to the system of equations described by:

$$\sum_{j \neq i} n_j n_e q_{ji} + \sum_{j>i} n_j A_{ji} = \sum_{j \neq i} n_i n_e q_{ij} + \sum_{j<i} n_i A_{ij} \tag{9}$$

where A_{ij} is the transition probability between the ith and the jth level in units of [s^{-1}] is needed. The emission from a volume element in [rayleigh cm^{-1}] is then computed from:

$$I = \frac{n_j n_e A_{ji}}{10^6} \tag{10}$$

if n_j and n_e are in [cm^{-3}]. Computation of the collision strengths and transition probabilities is far from trivial. There are many sources for these quantities in the literature and a compilation of atomic data for several ions has been given by

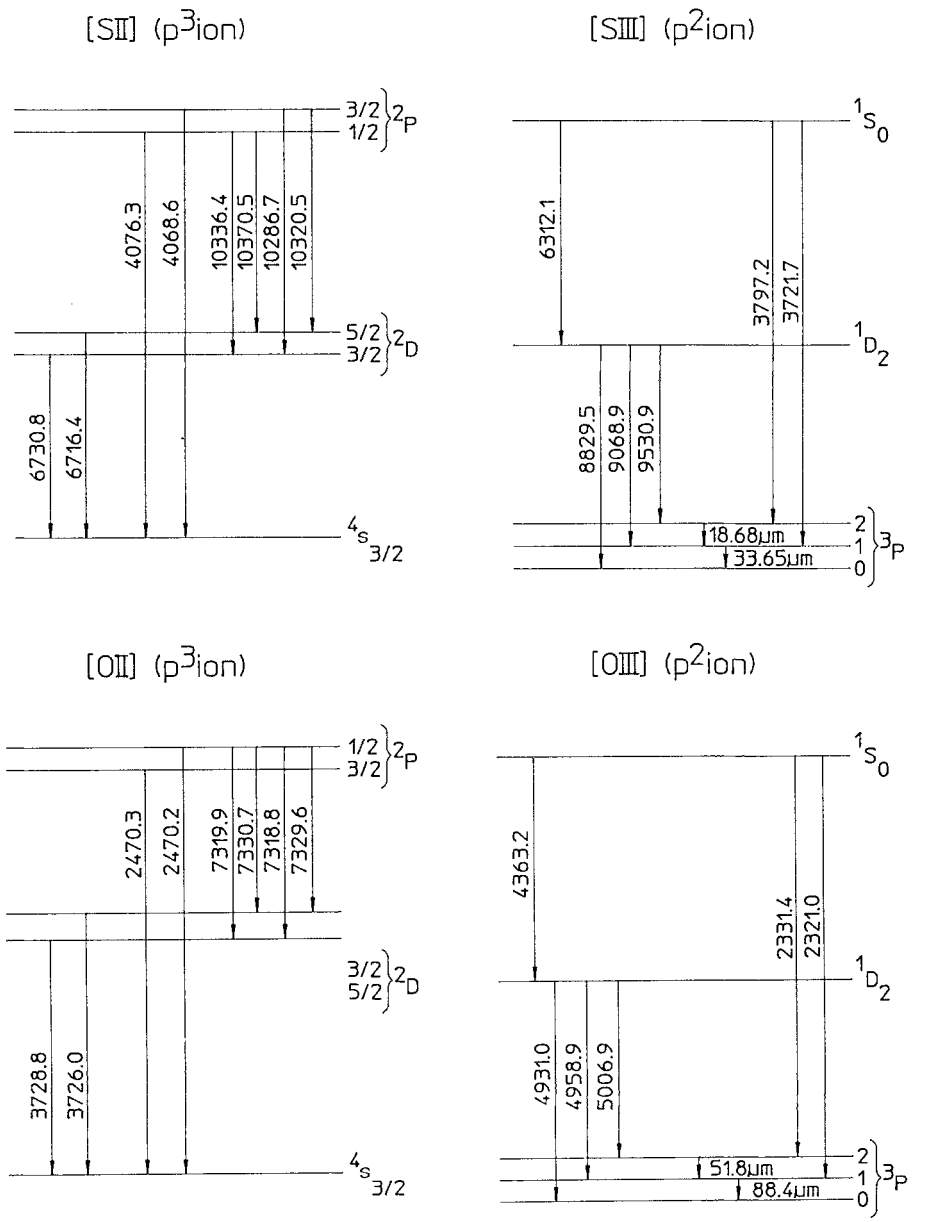


Fig. 10. Energy level diagrams for the lowest transitions of the O^+, O^{2+}, S^+, and S^{2+} ions.

Mendoza (1983). In Table I, atomic data sources for several optically emitting species in the Io system are provided.

Transitions from two different levels with nearly the same excitation energy can provide measurements of n_e in a plasma. The SII ^{2}D level is a good example (see Figure 10). If collisional de-excitation is unimportant ($n_e \rightarrow 0$), then every colli-

TABLE I
Sources of atomic data for atoms and ions important in Io torus studies

Ion	Sources of collision strength data	Sources of transition probability data
SII	Tayal *et al.* (1987) Pradhan (1976; 1978) Mendoza (1983)	Mendoza and Zeippen (1982a)
OII	Pradhan (1976)	Zeippen (1982)
SIII	Mendoza (1982)	Mendoza and Zeippen (1982b)
OIII	Aggarwal (1983; 1985)	Aggarwal (1983) Nussbaumer and Storey (1981)
OI	Berrington and Burke (1981)	Mendoza (1983)
SI		Mendoza and Zeippen (1983)

sional excitation is followed by emission of a photon so that the emission rate will be proportional to the statistical weights of the two levels. If collisional de-excitation is important, then the line strength becomes proportional to both the statistical weight and the transition probability.

Transitions from two levels with widely different excitation energies can provide measurements of T_e. The [SIII] transitions are a particularly good example here (see Figure 10) because the principle transitions (the ^1S–^1D transition and the ^1D–^3P transitions) give emission at visible wavelengths. Clearly, the higher the temperature, the greater the electron population in the ^1S level. Contour plots of the line ratios for the [SII] transitions at 4069 Å, 6716 Å, and 6731 Å using the collision strengths given by Tayal *et al.* (1987) are provided in Figure 11. The 6716/6731 line ratio varies with n_e in the range 10^2–10^4 cm^{-3} while the 4069/6731 ratio is strongly dependent upon T_e over a similar range. The 3729/3726 and 2470/3726 line ratios are the [OII] analogues.

Once the brightness of a volume element has been computed, a line of sight integration taking into account the orientation of the torus can be performed to provide a simulated image of the torus in [rayleigh]. The OTD, the dawn–dusk asymmetry, and the position of the observer relative to the Jovian equatorial plane are fairly simple to include in this computation. Simulated images based on Voyager data are shown in Figure 12. The diagram shows several distinct features. There are two maxima in the brightness distribution, one at 5.4 R_J, the other at 5.9 R_J. The latter corresponds to the feature described as "the ribbon" by Trauger (1984a) which is frequently observed from the ground in images of [SII]. This feature, usually seen just inside the orbit of Io, is in the warm inner torus. The secondary maximum corresponds to the cold inner torus. The effect of increasing ion temperature with increasing radial distance can be seen in the extension of the emission above and below the plasma equator. The colder the ions, the more the ions are confined to the plasma equator. When the torus is seen edge on,

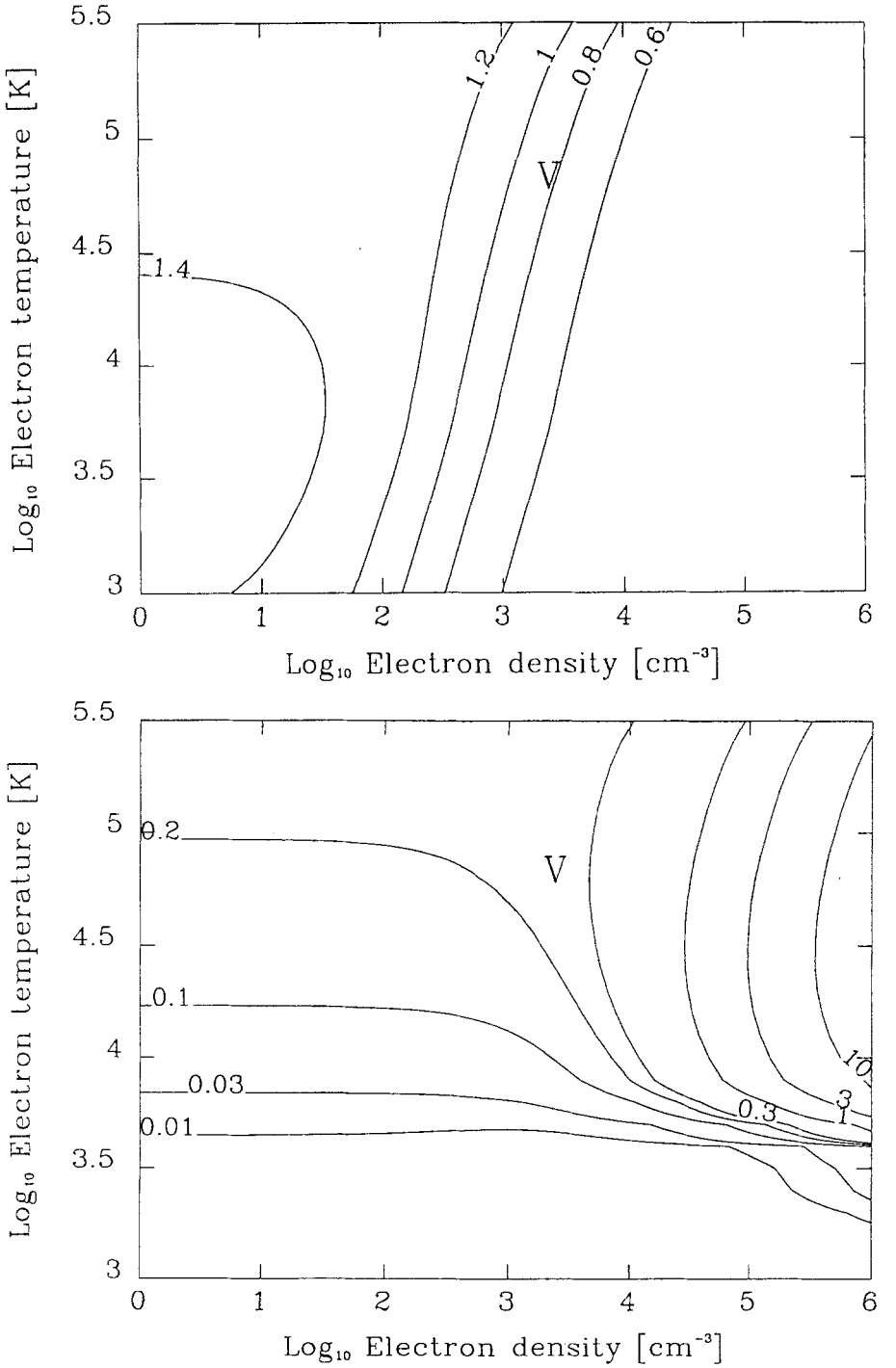


Fig. 11. Dependence of [SII] line ratios on n_e and T_e. The 6716/6731 line ratio (top) indicates the electron density in the plasma while the 4069/6731 ratio (bottom) varies strongly with T_e for $n_e < 10\,000\ \mathrm{cm}^{-3}$. Voyager 1 observations at 5.4 R_J are marked with a "V".

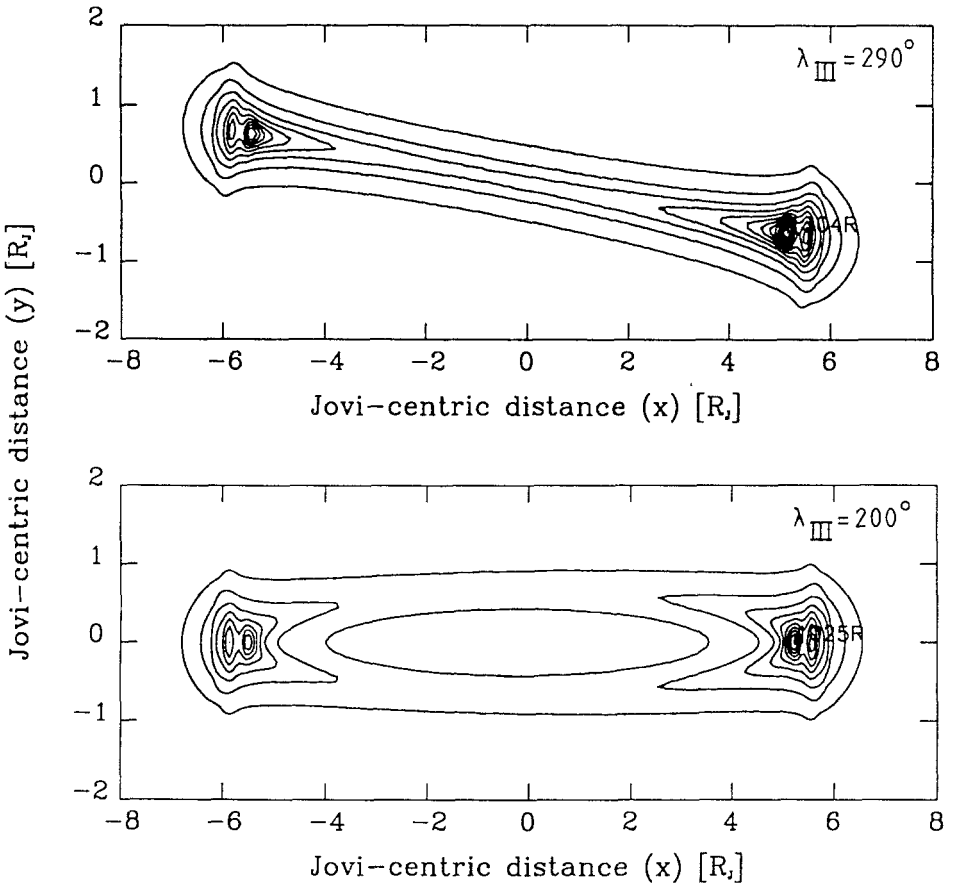


Fig. 12. Model calculations of the [SII] emission at 6730.8 Å from the Io plasma torus using Voyager data for the ion and electron densities and temperatures. The calculation method was as described in Sections 4 and 5. The observer is in the Jovian equatorial plane for these calculations and north is up. As Jupiter rotates the torus opens and closes. The torus to the west (right) is brighter than to the east due to the dawn-dusk electric field. The torus morphology is described in the text. Note that the vertical scale is extended. Contours are marked every 100 Rayleigh.

imaging provides an estimate of the ion temperature parallel to the magnetic field. The ion density along the field line can be approximated by the equation:

$$n_i \approx n_0 e^{-z^2/H_i^2} \tag{11}$$

where n_0 is the ion density at the plasma equator, $z = \mathrm{L} \sin \psi_p$ and H_i is the centrifugal scale height in $\mathrm{R_J}$ for ion species i given by (Hill and Michel, 1976):

$$H_i = \left(\frac{2kT_{i\|}}{3M_i^* \Omega_J^2 \mathrm{R}_J^2} \right)^{1/2} \tag{12}$$

where M_i^* is the effective ion mass (Bagenal and Sullivan, 1981) which for a single ion plasma becomes:

$$M_i^* \approx \frac{M_i}{1 + Z_i \dfrac{T_e}{T_i}}. \tag{13}$$

It can be seen from Equation (8) that the intensity of the observed emission in the low density limit for a single species is proportional to n_e^2. Hence, the brightness distribution along the field line becomes (Oliversen *et al.*, 1991):

$$I_i \approx I_0 \, e^{-2z^2/H_i^2} \tag{14}$$

However, one should be aware that significant errors are possible when applying this equation to the [SII] 6716 Å, 6731 Å and the [OII] 3726 Å, 3729 Å doublets because the plasma torus near 5.9 R_J is neither single species nor close to the low density limit where collisional de-excitation is unimportant.

By observing the torus edge-on (e.g. Figure 12, top), Woodward *et al.* (1991) determined the ion temperature[4] of S^+ at 5.5 R_J by application of Equation (14) and found $T_{i\|}$ to be 37.0 eV. This is somewhat higher than the Voyager PLS observations would suggest so close to Jupiter. The model can be used to evaluate whether projection effects could be responsible. By fitting Gaussians to the modelled brightness distribution for an edge-on Voyager type torus seen in [SII] 6731 Å, $T_{i\|}$ can be calculated assuming that $T_i \gg T_e$ (as assumed by Woodward *et al.*, 1991). Perhaps surprisingly, the resulting temperature is $\approx$40 eV almost independent of distance between 5 and 6 R_J. A local maximum is apparent at 5.5 R_J where the modelled temperature is $\approx$50 eV. Thus, the ion temperature derived by Woodward *et al.* (1991) is, in fact, consistent with Voyager PLS measurements. (Note that poor "seeing" would tend to smear the maxima in the torus. This could also lead to an over-estimate of $T_{i\|}$.)

Woodward *et al.* (1991) also used spectra of the [SII] red doublet to derive $T_{i\perp}$ and found a value of 36.5 eV in good agreement with the measurement of $T_{i\|}$. Hence, the diffusive equilibrium equations given by Bagenal (1985) should adequately describe the plasma distribution along the field lines for the cold torus close to the plasma equator at least. Previous measurements of $T_{i\|}$ and $T_{i\perp}$ were made by Roesler *et al.* (1982) using a Fabry-Perot imaging spectrometer. They found $T_{i\|}(S^{2+}) = 19$–56 eV at 5.8 R_J, $T_{i\perp}(S^{2+}) = 121 \pm 52$ eV at 6.5 R_J and $T_{i\|}(S^+) = 5.0 \pm 0.7$ eV at 5.8 R_J for observations obtained in March 1980.

The model and the observable brightness distribution described above is not completely self-consistent in that the ion partitioning in the torus is assumed rather than computed from the physical characteristics of the ions and their spatial and temperature distributions. Several charge-exchange reactions in the torus are dependent upon the plasma temperature and can markedly affect the partitioning of ions between lower and higher ionization states. To be self-consistent, a mass

[4] 1 eV is equivalent to a temperature of $1.16048\ 10^4$ K.

and energy balance is required (Section 8; Shemansky, 1988a,b). However, there are several free parameters (diffusion time scale, neutral partitioning, energy input rate) which allow considerable scope for fitting the observations of the major species. Conversely, the Voyager 1 PLS observations of O^{2+} in the cold torus and the apparent presence of either SO_2^+ or S_2^+ at 5.3 R_J are hard to reconcile with any ion partitioning calculations and Voyager UVS observations (cf. Figure 7). Further observations of [OIII] may help clarify this situation.

6. Emissions in Jupiter's Magnetosphere

6.1. Known species and composition

Table II provides a list of reported and expected emission lines at optical wavelengths from the plasma torus, their strength in [rayleigh], and their predicted strength according to Voyager observations. The table also includes values for neutral emissions and some selected UV lines.

It is apparent from Table II that many lines have been observed occasionally but that efforts have concentrated on the study of the [SII] red doublet in order to derive n_e. Few publications have appeared since 1985. Observers were most active in the period between the discovery of the torus and about 1983. One or two groups have remained active since but the number of formal publications has been limited.

Near-simultaneous observations from different sites, although rare, have occasionally been made. An example is a set of observations made by Brown and Shemansky (1982), Oliversen *et al.* (1991), and Morgan (1985a) which took place within a week or so of each other in 1981. The results are not particularly satisfying in that observed intensities do not agree and derived conclusions concerning periodicities actually contradict each other (Section 7.3). This reflects several difficulties in evaluating the data for the [SII] red doublet shown in Table II.

Before imaging became a common method of studying the torus, long-slit spectrographs were used. Although observers were aware of the orientation of the plasma equator, prior to the Voyager fly-by it was not clear at which Jovicentric distance the greatest intensity could be found so that observations were frequently made well inside 5.0 R_J. Trafton (1980)'s data set provides a good example here. Low intensities (<250 R) were found in 26 spectra between January 1976 and March 1978. But whenever an observation was made around 5.5 R_J (where one would expect the highest intensities given a Voyager type model), the plasma latitude at which the observation was made was high. Thus it would be incorrect to draw the conclusion that [SII] emission was depressed during this time without further evaluation (see Section 7.4). From Sections 4 and 5, it is also apparent that errors in pointing or small drifts during guiding could affect strongly the observed intensities. Similarly, the methods used to determine the brightnesses

TABLE II
Strengths of emission lines from Jupiter's magnetosphere for known species

Species	Wavelength of emission line[3] [Å]	Predicted strength[1] [rayleigh]	Observed strength[2] [rayleigh]	Date of observation	Author	Comment
SII	4068.6	235	62 ± 32	Jan–Mar 1979	Morgan and Pilcher (1982)	Long slit spectrograph No guiding leading to 2–3″ drifts
			10–80	Feb–May 1981	Morgan (1985a)	As Morgan and Pilcher (1982)
SII	4076.4	70	≈40	Jan–Mar 1979	Morgan and Pilcher (1982)	Long slit spectrograph No guiding leading to 2–3″ drifts
SII	6716.4	1060	0–100	Oct 1976	Trauger *et al.* (1980)	1.5 R_J diameter aperture spectrograph
			20–170	Jan 1976–Mar 1978	Trafton (1980)	29 × 0.3″ slit parallel or perpendicular to Jupiter's spin axis. Data averaged over slit.
			50–800	Jan–Jun 1979	Trafton (1980)	See above
			131 ± 32	Jan–Mar 1979	Morgan and Pilcher (1982)	Long slit spectrograph No guiding leading to 2–3″ drifts
			≈300	Feb–Apr 1981	Brown and Shemansky (1982)	See corresponding note at 6731 Å
			≈220	Feb 1981	Oliversen *et al.* (1991)	Imaging data for a range of magnetic longitudes
			130–260	Feb–May 1981	Morgan (1985a)	As Morgan and Pilcher (1982)
			≈650	May 1983	Trauger (1984)	Imaging data
			390 ± 50	Dec 1989	Jockers *et al.* (1991)	Imaging with torus seen open
SII	6730.8	1280	0–70	Oct 1976	Trauger *et al.* (1980)	1.5 R_J diameter aperture spectrograph
			60–300	Sep–Oct 1975	Brown (1976)	Derived from Kipo *et al.* (1976)
			215 ± 28	Jan–Mar 1979	Morgan and Pilcher (1982)	Long slit spectrograph No guiding leading to 2–3″ drifts
			425 ± 230	Feb–Apr 1981	Brown and Shemansky (1982)	6.7 × 0.5″ slit. Feb data with long axis perpendicular to Jovian rotation axis offset by 5.9 R_J from Jupiter *in the satellite plane*. April data with long axis parallel to Jovian rotation axis offset by 5.9 R_J along centrifugal equator
			≈570	Feb 1981	Oliversen *et al.* (1991)	Imaging data for a range of magnetic longitudes
			200–400	Feb–May 1981	Morgan (1985a)	As Morgan and Pilcher (1982)
			≈850	May 1983	Trauger (1984a)	Imaging

TABLE II (continued)

Species	Wavelength of emission line[3] [Å]	Predicted strength[1] [rayleigh]	Observed strength[2] [rayleigh]	Date of observation	Author	Comment
			410 ± 50	Dec 1989	Jockers *et al.* (1991)	Imaging with torus open
			40–240	Jan 1976–Mar 1978	Trafton (1980)	29 × 0.3″ slit parallel or perpendicular to Jupiter's spin axis. Data averaged over slit.
			50–1600	Jan–Jun 1979	Trafton (1980)	See above
			2400	Unspecified	Trafton (1980)	See above
OII	3726.0	275	36 ± 7	Jan–Mar 1979	Morgan and Pilcher (1982)	Long slit spectrograph No guiding leading to 2–3″ drifts
			30–50	Feb–Mar 1981	Morgan (1985a)	As Morgan and Pilcher (1982)
OII	3728.8	225	27 ± 10	Jan–Mar 1979	Morgan and Pilcher (1982)	Long slit spectrograph No guiding leading to 2–3″ drifts
			20–35	Feb–May 1981	Morgan (1985a)	As Morgan and Pilcher (1982)
OII	7319.9					Undetected
SIII	3721.7	32	17 ± 8	Jan–Mar 1979	Morgan and Pilcher (1982)	Long slit spectrograph No guiding leading to 2–3″ drifts
			≈14	Feb–May 1981	Morgan (1985a)	As Morgan and Pilcher (1982)
SIII	3797.2					Undetected
SIII	6312.1	70	48 ± 5	Mar 1980	Brown (1981a)	0.32 × 0.05 R_J effective aperture centred at 5.9 R_J
			58 ± 40	Feb 1981	Brown *et al.* (1983)	
			≈260	May 1983	Trauger (1984a)	
SIII	9068.9	190				Roesler *et al.* (1984) observed this line but no results have been reported.
SIII	9530.9	480	≈500	Feb 1981	Oliversen *et al.* (1991)	Imaging data for many magnetic longitudes
			200–700	Apr 1982	Roesler *et al.* (1984)	
			≈2000	May 1983	Trauger (1984a)	Imaging
OIII	4363.2	7				
OIII	4958.9	19				
OIII	5006.9	53	<7 (west ansa) <3 (east ansa)	May 1981	Brown *et al.* (1983b)	0.05 × 0.3 R_J slit centred at 5.9 R_J on centrifugal equator
			11 ± 5	Dec 1990	Moos *et al.* (1991)	Derived from detection of the [OIII] 1661 Å, 1665 Å lines by the HUT using a 0.43 × 5.52 R_J slit.

TABLE II (continued)

Species	Wavelength of emission line[3] [Å]	Predicted strength[1] [rayleigh]	Observed strength[2] [rayleigh]	Date of observation	Author	Comment
			1200–32 000 (Io)	Feb 1990	Scherb and Schultz (1991)	5.2 × 5.2″ aperature. Emission intensity dependent on filling factor.
			<8000 (Io)	Autumn 1987	Schneider *et al.* (1989b)	Spectrograph plus CCD
OI	6363.8	≈3				Undetected
NaI[4]	5889.95 5895.92		≈10–30 000	Nov 1976–Jan 1977	Murcray and Goody (1978)	Image intensifer tube plus camera. Many other measurements have been made. Too numerous to list here.
KI	7664.91 7698.97		1000	Sep–Dec 1975	Trafton (1977)	
OI	1304		3.6 ± 2.0 (torus)	May 1981	Durrance *et al.* (1983)	Slit averaged emission (15″ × 110″)
			95 ± 12 (Io)	Jul 1986	Ballester *et al.* (1987)	≈6″ FWHM point spread function resolution at Io
SI	1429		2.5 ± 1.2 (torus)	May 1981	Durrance *et al.* (1983)	Slit averaged emission (15″ × 110″)
	1814		107 ± 12 (Io)	Jul 1986	Ballester *et al.* (1987)	≈6″ FWHM point spread function resolution at Io
SIV	1406		18 ± 7	Mar 1979–1984	Moos *et al.* (1985)	

[1] Predicted maximum intensity from the Voyager-type torus model for the western ansa with the torus seen edge-on.
[2] Peak intensities are quoted for imaging data. Ranges apply to multi-image sets of data.
3 With the exception of the UV transitions, wavelengths have been taken from Osterbrock (1989) and references therein.
[4] Wavelengths after Morton (1991).

depended on the detector, the calibration technique adopted (comparison with Jupiter following Woodman *et al.* (1979) or stellar calibration), and the evaluation procedure. Hence, different observers' results are not easy to compare.

Within several data sets, there is evidence for exceptionally high intensities (e.g. Trafton, 1980). Morgan (1985a) also reports occasional low values (≈ 0.3) of the [SII] 6716/6731 line ratio which would imply a very high n_e (Figure 11). One explanation offered for this phenomenon is "clumping" of plasma in the magnetosphere (Section 7.6). Electron density measurements (Table III) have in general shown values in the range 1000–3000 cm^{-3} with occasional measurements reflecting the inferred clumping. It is not entirely clear whether the different values of n_e seen in Table III are real variations, consequences of sampling at different Jovicentric distances, or merely reflect the inadequacy of the measurements.

[SIII] observations are broadly in agreement with the estimates based on the Voyager data. Data presented by Trauger (1984a) are an exception but there appears to be a corresponding decrease of the [SII] intensity in this data set which may reflect a slightly higher ion temperature and hence a different ion partitioning. The emission was nearly 2.5 times greater than the [SII] 6731 Å line in the warm inner torus. The model of the Voyager data would predict a 9531/6731 ratio of about 0.4. From statistical equilibrium calculations (Shemansky, 1988a), this would be adequately explained if T_e in the warm inner torus were a factor of two higher during the May 1983 observations of Trauger than during the Voyager fly-by. Short-term variability in S^{2+} data (Roesler *et al.*, 1984) is discussed in Section 7.3.

[OII] emission seems generally weaker than predicted although the observations of Morgan (1985a) may have been made at an unusual epoch. The same could well apply to the [OIII] emission at 5007 Å. The absence of this particular line in the search conducted by Brown *et al.* (1983b) has been used to question the interpretation of the Voyager PLS data but this may not be justified as the conditions in the torus appear to have been substantially different in 1981 (when Brown *et al.*, 1983b, acquired their data) than during the Voyager epoch (Section 7.4). Similarly, only one measurement of the 6300 Å [OI] emission in the torus has been published. Other neutral emissions will be discussed in Section 9.

Controversy has recently arisen over the detection of the [OI] 6300 Å in Io's atmosphere itself. The 2-σ detection by Schneider *et al.* (1989b) has been followed by a further detection by Scherb and Schultz (1991) with basically similar equipment (spectrograph with $\lambda/\Delta\lambda \approx 120\,000$). There is, however, a discrepancy between the derived intensities of more than a factor of 4 (Section 8). No observation of the collisionally excited [SI] lines in the visible have been made although UV detections have been made in both the torus and in Io's atmosphere itself (Durrance *et al.* (1983); Ballester *et al.*, 1987).

6.2. Limits on other species

In recent years, ground-based observers have tended to concentrate on known emissions in order to determine the morphology and variability of the plasma

TABLE III
Io plasma torus electron density measurements

Species	Source	Electron density [cm^{-3}]	Radial distance [R_J]	Date	Author
[SII]	Ground-based	2000		26, 27 Sep 1975, 15–19 Oct 1975	Brown (1976)
[SII]	Ground-based	3000	3–5	25, 26 Mar 1978	Brown (1978)
[SII]	Ground-based	1000–25 000	Wide range	Many years	Trafton (1980)
[SII]	Ground-based	1000–2000	5	7–11 Oct 1976	Trauger *et al.* (1980)
[SII]	Ground-based	5000	Averaged over detected part of slit	Jan–Mar 1979	Morgan and Pilcher (1982)
[SII]	Ground- based	1500 (cold torus)	5.5	May 1983	Trauger (1984a)
[SII]	Ground-based	4000 (ribbon)	5.9	May 1983	Trauger (1984a)
[SII]	Ground-based	4000	5.9	Feb–Apr 1981	Brown and Shemansky (1982)
[SII]	Ground-based	3000–>10 000	Clumping	Feb–May 1981	Morgan (1985a)
[SII]	Ground-based	2000	5.4	Dec 1989	Jockers *et al.* (1991)
[OII]	Ground-based	2000		Jan–Mar 1979	Morgan and Pilcher (1982)
	Voyager I UVS	>2100		Mar 1979	Broadfoot *et al.* (1979)
	Voyager I PLS	2000		Mar 1979	Bagenal *et al.* (1980)
	Voyager I PRA	2000		Mar 1979	Warwick *et al.* (1979)

TABLE IV
Concentrations of species required to generate an intensity of 10 R in a Voyager type torus by collisional excitation

Species	Wavelength[3] [Å]	Required n_i/n_e to generate 10 R
CIII	5517.7	0.004
CIII	5537.7	0.005
NII	6383.4	0.006
NII	5754.6	0.05
OI	6300.3	0.03
CI[2]	4621.6	2.47
CI[2]	8727.1	0.04
CI[2]	9850.3	0.008
NI	3466.50	0.03
NI	3466.55	0.03
NI	5200.2	0.24
NI	5197.9	0.93

[1] Neutrals are assumed to have the same density distribution as ions for this calculation. This is, of course, not valid but gives a crude indication of the densities required to detect the appropriate line.
[2] Collision strength data for transitions between the ^3p levels of CI were not available. The calculation is based on estimates. Note also that collision strength for this atom very strongly dependent on T_e.
[3] Wavelengths are from Mendoza (1983) converted into air wavelengths using the formula given by Morton (1991) (see notes to Table VI). The error in the given wavelength may be up to ±1 Å.

torus and neutral clouds. Some effort has been made to determine upper limits for emissions from Io's torus and atmosphere expected on theoretical grounds (e.g. Brown *et al.* (1983b) for O^{2+} in the torus) but little attention has been paid to providing upper limits for other elements. The one exception is chlorine (Brown *et al.*, 1983b). In view of the possible detection of CO_2 in Io's atmosphere (Sandford *et al.*, 1991) and the inferred presence of silicon-bearing compounds on the surface (Clow and Carr, 1980; Johnson *et al.*, 1988), one should perhaps ask if carbon species could be present in the torus and what limits can be placed on other elements. Table IV shows a small number of estimates of the concentrations in the torus required to provide an intensity of 10 R by collisional excitation. The estimates were derived from the five-level equilibrium computation discussed in Section 4.1. It has been assumed that the neutrals have a similar spatial distribution to ions in the torus which is not particularly satisfactory but it illustrates the sort of concentrations one might require. O^0 has been included in the table although detected to illustrate the accuracy of the calculation for the neutrals. Detected at 8 R, Brown (1981a) estimated an O^0 concentration in the torus of around 40 cm^{-3}, hence our estimate is within a factor of 2.

TABLE V
Upper limits for other emission lines in the vicinity of Io (from Trafton (1976))

Wavelength range	Detection limit [kR]
Red	0.4–0.6
Blue/Green	0.6–1.6
Violet	5

It is clear N^0 will be almost undetectable since the concentrations required are very high compared to O^0. The [NII] emission at 6583 Å however may be a candidate in that the concentration required in the torus to generate 10 R is well under 1% although recent observations of the 1085 Å NII line at 3 Å resolution may provide a firmer constraint (Moos *et al.*, 1991). Detection of the [CI] emission at 9850 Å may also be possible if CO_2 and/or its dissociation products can escape from Io in sufficient quantities.

Few hard upper limits exist for neutral species near Io. Pre-Voyager results are of little significance (one possible exception here being the limit on Mg^0 emission at 4571 Å of 170 R from Macy and Trafton (1975)) with limits no lower than 400 R throughout the visible spectrum (Table V). Published upper limits in the post-Voyager era are rare but the results of unpublished surveys by R. A. Brown (personal communication) suggest that upper limits are actually in the range 25–100 R.

Table VI gives a list of emission lines produced by resonant scattering together with their respective oscillator strengths. The column densities required to produce an emission of 10 R are also shown (see Section 9.4). Na and K are included for comparison. Ca^0 would be very bright if the calcium abundance with respect to Na in Io's neutral cloud were anywhere near Solar System abundance. An erroneous "detection" of the Ca^0 line was made in the mid-1970's but it now appears that an upper limit of about 400 R can be placed on this line. Lithium would be considerably fainter but perhaps still detectable. Although magnesium has a higher Solar System abundance than Na, the oscillator strength of the 4571 Å line is very low and its absence in measurements by Macy and Trafton (1975) is not surprising.

Obviously, Table IV and Table VI do not provide an exhaustive list but given the possible existence of other compounds on Io and the low detection thresholds now achievable, a search for other emissions (including emission from alkali metals due to resonant scattering) may prove fruitful.

7. Variations in the Plasma Torus

The Voyager data provided a snapshot of plasma torus conditions. However, both remote sensing data from the spacecraft and ground-based observations have

TABLE VI
Column densities of species required to generate an intensity of 10 R at Jupiter by resonant scattering

Species	Wavelength[1] [Å]	Oscillator strength	Column density per 10 R [10^7 atom cm^{-2}]
CaI	4226.73	1.753	2.60
CaII	3968.47	0.3145	22.22
CaII	3933.66	0.6346	11.76
MgI	4571.10	$2.05\ 10^{-6}$	$1.61\ 10^{6}$
LiI	6707.91	0.247	5.52
LiI	6707.76	0.495	2.75
AlI	3961.52	0.113	62.89
AlI	3944.01	0.113	65.79
NaI	5895.92	0.318	5.32
NaI	5889.95	0.631	2.68
KI	7698.97	0.305	3.28
KI	7664.91	0.611	1.64

[1] Wavelengths are from Morton (1991) converted from vacuum to air using the IAU standard definition:

$$\frac{\lambda_{\text{vac}} - \lambda_{\text{air}}}{\lambda_{\text{air}}} = 6.4228 \times 10^{-5} + \frac{2.94981 \times 10^{-2}}{146\sigma^2} + \frac{2.5540 \times 10^{-4}}{41\sigma^2}$$

where $\sigma = 10^4/\lambda$ and λ is in [Å].

indicated that the plasma properties of the torus are variable, perhaps highly so. Several periodicities in the torus have been recognized although detailed models of the systematic variations are in most cases unavailable. The simplest variability is one with magnetic longitude.

7.1. Periodic variations with magnetic longitude

Jupiter's surface magnetic field deviates appreciably from an OTD. Such deviations are referred to as "magnetic anomalies" (Hill *et al.*, 1983). A magnetic anomaly can affect the distribution of plasma within the magnetosphere thereby creating a longitudinal asymmetry (Dessler and Hill, 1975). An anomaly where the surface field is lower than predicted by a best fit OTD also provides a mechanism by which plasma flow from Jupiter's ionosphere to the equatorial plane can be enhanced. The magnetic anomaly region near $\lambda_{\text{III}} = 260°$ has been referred to as the "active sector" of Jupiter's magnetic field and several articles in the early 1980's sought to relate observed variations in the brightness of torus emissions to this feature. Pilcher and Morgan (1980) suggested that the [SII] intensity was enhanced over 180° in magnetic longitude centred at $\lambda_{\text{III}} = 250°$. This study suffered from a rather limited data set. Trauger *et al.* (1980) also argued for a longitudinal variation in the [SII] brightness. Their data showed a maximum at $\lambda_{\text{III}} = 180°$ and a minimum

at 270–280° with a variation of about a factor of 2. However, as Morgan (1985b) points out, variations of about 50% are a natural consequence of the geometry of the OTD with maxima at around $\lambda_{III} = 200°$ and 20° and minima at $\lambda_{III} = 290°$ and 110°. Furthermore, the log of Trauger *et al.* (1980)'s observations indicates that during one night (11 October 1976) when a series of spectra were obtained between about $\lambda_{III} = 180°$ and $\lambda_{III} = 270°$, ψ_c (the latitude with respect to the centrifugal equator, see Appendix) for the observations gradually increased. This may also explain the decrease in the observed brightness and is not particularly convincing evidence for a systematic variation in the torus. The data from Trafton (1980) show a strong maximum between $\lambda_{III} = 230°$ and 290° and would appear to support the concept of an active sector in this longitude range. The amplitude of the variation in this case is a factor of 5. Imaging data (Pilcher *et al.*, 1985) from March and April 1981 shows a minimum at about $\lambda_{III} = 60°$ rising sharply by almost a factor of 6 to a maximum at $\lambda_{III} = 170°$ appearing to contradict Trafton's results. Morgan (1985b) also reports a maximum at 170°, after taking into account the geometry of the torus, with a distinct minimum at 270°. Qualitative support for this phenomenon has been supplied by Oliversen *et al.* (1991). They also report that in [SIII] a factor of 2 increase in brightness is seen at longitudes where [SII] brightness is at a minimum which suggest that the ion partitioning varies longitudinally possibly due to variations in T_i. Morgan (1985b) also states that no longitudinal enhancement in [OII] (3726 Å, 3729 Å) was evident in his data set. It is difficult to envisage a clear and simple explanation for these observations and resolution of this problem must await data with improved spatial and temporal resolution.

Brown and Shemansky (1982) reported no longitudinal dependence of the [SII] intensity upon System III. Some of their data were acquired within a few days of Morgan's and yet the intensities were a factor of 4 higher (Morgan, 1985a) and showed sharp variations (> a factor of 4 in intensity over $\frac{1}{2}$h). Near-simultaneous observations by Oliversen (1983) tend to support Morgan's stellar calibration over the method employed by Brown and Shemansky which assumes a brightness ($\approx$5.5 MR Å^{-1}) for the centre of Jupiter's disc (after Woodman *et al.*, 1979), although the effects of the positioning and of the slit width of the spectrographs employed by the observers have not been quantitatively taken into account.

Cheng *et al.* (1984) report the existence of a longitudinal asymmetry in the torus from analysis of data from the Voyager 1 low energy charged particle (LECP) experiment. They found an adequate fit to their measurements by assuming a translation of the torus by 0.25 R_J towards 1320 local time and thus nearly orthogonal to the dawn-dusk electric field (Section 4.3). Alternatively, the authors suggest that, rather than being fixed in local time, the disturbance may be due to a corotating convection field linked to the magnetic anomaly near $\lambda_{III} = 200°$. However, the magnitude of the field when combined with the proposed dawn–dusk asymmetry should provide occasional extreme shifts of the torus relative to

the OTD when observed from the ground. No such effect has been reported. On the other hand, results from the Voyager 1 radio signals (Campbell and Synnott, 1985), when compared to an axisymmetric model of the torus based on planetary radio astronomy (PRA) data (Birmingham *et al.*, 1981) indicate that the torus above the nightside of Jupiter was translated to larger distances from the planet (opposite to that suggested by Cheng *et al.*, 1984). As with PLS, the PRA results were based on measurements made during the inbound section of the fly-by. This inconsistency has not been resolved.

From the foregoing discussion, there is some evidence for a variation with magnetic longitude. However, the reported longitudinal variations suggest a more complex relationship and further observations are needed to study these effects.

7.2. Periodic variations with Io's orbital position

Sandel and Broadfoot (1982b), using data acquired with the Voyager UVS experiment, found a 25% modulation in the SIII brightness at 685 Å which was dependent upon Io's orbital phase. The approaching ansa was found to be brightest when Io was 40° before eastern elongation (equivalent to $\theta_{Io} = 50°$ when viewed from the ground) and the receding ansa was brightest when Io was at a similar angle before western elongation (equivalent to $\theta_{Io} = 230°$). It was concluded that the brightness increase resulted from an Io-related energy source which was responsible for about 20% of the energy radiated by the torus.

At optical wavelengths, no evidence for or against a variation of this type has been presented. Given that Io provides almost 1 tonne s^{-1} to the torus, a variation resulting from Io's orbital phase may not be surprising. However, the mass input into the torus at Io will only increase the S^+ column density in the torus immediately downstream of Io by around 1–5%. The effect reported by Sandel and Broadfoot (1982b) is an order of magnitude larger. Alternatively, the increased brightness may be due to variations in electron temperature. However, why the enhanced intensity should be 40° in orbital phase downstream of Io is unclear. This topic clearly warrants some ground-based investigations.

7.3. "System IV"

The Voyager UVS experiment has also been used to study a systematic variation in the torus now widely referred to as "System IV". Roesler *et al.* (1984) made a series of observations of the [SIII] 9531 Å emission line. They plotted their data against System III magnetic longitude and found no correlation. However, on plotting the data against a period ≈16.5 minutes longer than the System III period, clear trends became apparent. A similar variation had been noted in narrow band kilometric (nKOM) emission from Jupiter near Voyager 1 closest approach (Kaiser and Desch, 1980) and Sandel and Dessler (1989) also replotted [SII] data at 6731 Å from Brown and Shemansky (1982) against the longer period, suggesting that the data showed less scatter. On re-analysis of the Voyager UVS data (Sandel and

Dessler, 1988), strong periodicities were found at Io's orbital frequency (see Section 7.2), the System III frequency, and a third frequency at a period of System III plus 3%. The latter has been termed "System IV" and has been given the definition (Sandel and Dessler, 1989):

$$\lambda_{\mathrm{III}} = \lambda_{\mathrm{IV}} + 338 - 25.486t \tag{15}$$

where t is measured in days from 00:00 UT on January 1, 1979. It is not clear, however, that System IV is a fixed, persistent frequency in the Jovian system. The modulation could be a spurious period resulting from a combination of other related frequencies (see e.g. Barrow, 1989; and Dessler and Sandel, 1989). Possible spurious periodicities in ground-based measurements can be computed from the equation (Douglas and Bozyan, 1970):

$$\frac{1}{P} = \frac{k}{P_J} + \frac{l}{P_{\mathrm{Io}}} + \frac{m}{P_E} + \frac{n}{P_{sy}} \qquad k, l, m, n = 0, \pm 1, \pm 2, \ldots \tag{16}$$

where P_J, P_{Io}, P_E, and P_{sy} are Jupiter's rotation period, Io's orbital period, the Earth's rotation period, and Jupiter's synodic period, respectively. There are several solutions for this equation giving a modulation of around 10.22 hours, the simplest being $k = -3$, $l = 17$ and $m = n = 0$ which gives $P = 10.21$ h. A 14.1 day modulation was also present in the UVS data. By setting $k = 4$, $l = -17$, $m = n = 0$ then $P = 14.4$ days is obtained. (Solutions given by Dessler and Sandel (1989) are in error). Thus this period could result from a spurious period between Io's orbital period (as has already been mentioned UVS data indicates a strong variation in the torus with Io's period) and Jupiter's System III period although Yang *et al.* (1991) claim to have excluded this suggestion.

A further problem is that the observed modulation may not be a fixed frequency. Kaiser and Desch (1980), for example, report a deviation of 3.3% from System III for Voyager 1 nKOM observations and a deviation of 5.5% during Voyager 2. Analysis of nKOM observations (Daigne and Leblanc, 1986) suggests that the source regions are best studied using System III and that periodicities in nKOM vary between System III and a period 2–3% greater. Significant System IV modulation is also absent in ground-based data obtained by Woodward *et al.* (1991) in November and December 1988. Their periodogram analysis of [SII] 6731 Å observations shows a persistent period of 10.14 ± 0.06 hours over the entire observing run, significantly different from both Systems III and IV (R. C. Woodward, personal communication).

The source locations for nKOM emission are probably on the outer flanks of the torus (Kaiser and Desch, 1980). It is possible that the longer period results from a corotation lag of plasma in the torus (Hill, 1979; 1980). The electron density in the torus may have been up to 50% higher during the Voyager 2 fly-by (Shemansky, 1987) and hence the increased deviation from System III in nKOM

observations during the Voyager 2 fly-by may have resulted from increased mass loading of the torus causing a more significant corotation lag. Both ground-based observations and Voyager PLS data have provided evidence for corotation lag. Brown (1983), using spectral observations of [SII] emission, concluded that at 5.9 R_J the torus deviated from corotation by $6 \pm 4\%$. PLS data suggests a radial dependence. Corotation was adherred to around 5.0 R_J from Jupiter but a distinct lag of 1–3% was evident at 5.6 R_J (Bagenal, 1985). Since S^{2+} is found predominantly in the warm outer torus while relative concentrations of S^+ are higher inside Io's orbit, increasing lag with radial distance qualitatively explains why the periodicity is apparently longer in ground-based [SIII] 9531 Å data than at 6731 Å. If corotation lag is responsible for the observed periodicities, then Dessler and Sandel (1989)'s concern with regard to the persistence of "System IV" is almost certainly justified. It is apparent that a long term monitoring program is required to provide further data on this topic.

The lack of a persistent periodicity greater than System III has led Horton and Smith (1988) to suggest that large scale convective motions or "vortices" arise in the torus which can persist for many jovian rotations. This would be in closer agreement with the magnetic field data from Pioneer 10 and Voyager which show no major differences in the field in the regions ($L = 6$–10) where corotation lag would be expected (Connerney and Acuña, 1982). Kropotkin and Mozzhukhina (1990) estimate, on the other hand, that the characteristic scale length of vortices in the torus is only about 300 km, considerably smaller than Horton and Smith (1988) suggest and too small to provide the observed fluctuations. This remains unresolved.

7.4. Variations over long timescales

Evidence for long term variability in the torus has been accumulating since the Pioneer 10 fly-by in December 1973. After the discovery of the torus, ground-based observers sought to quantify n_e in the torus by studying the ratio of the intensities of the [SII] red doublet (Section 5). Although handicapped by a lack of accurate atomic data, results suggested that n_e could vary by up to a factor of 5 (Table III) and enormous variations in the maximum observed intensity of the [SII] red lines were evident (Table II). Inter-comparison of these measurements is, however, complicated because of the different apertures selected, the positioning of the aperture relative to Jupiter and the plasma equator, the accuracy with which this position could be determined, and the quality of the absolute calibration. As is evident from Section 4, changing the position by just 5 arcsec (1 arcsec corresponds to roughly 2 Io radii (r_{Io})[5]) with a long-slit spectrograph can make the difference between observing the ribbon or the cold torus. Frequently,

[5] $1 r_{Io} = 1805$ km; $1 R_J = 39.5 r_{Io}$.

the values quoted were averages over the length of the slit or the section of the slit where there was observable signal.

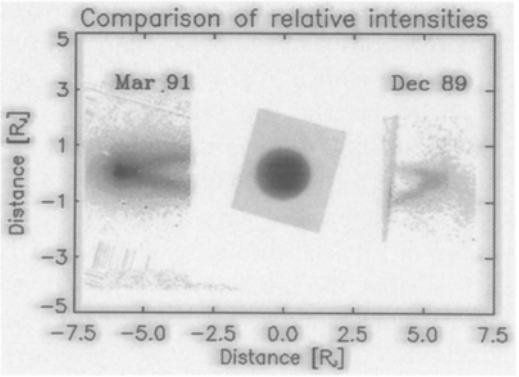
The Voyager data made it apparent that a more rigorous analysis was required to interpret the ground-based observations and in post-Voyager studies by Trauger (1984a) and Morgan (1985a,b) considerable effort was made to relate their results to Voyager observations. Trauger provided plots of the radial intensity distribution for [SII] and [SIII] obtained during the 1983 opposition. The peak electron density was slightly higher than would have been predicted from Voyager PLS observations and the [SIII] intensity near the ribbon was higher than PLS measurements would suggest but, within the uncertainties associated with the two data sets, they provided a broadly similar picture.

The data from Morgan (1985b), on the other hand, showed that the torus emissions did vary substantially from year to year. Morgan compared his data, taken between February and May 1981, with the results from Voyager and found that his measured intensities at 6731 Å were up to a factor of 3 lower than predicted by the Voyager PLS observations. He suggested that in 1981, the torus beyond 5.7 R_J was 1.5 to 2 times denser with lower S^+ and O^+ mixing ratios and that the warm outer torus was about 2 times cooler than during Voyager 1 encounter. (The contemporary data from Brown and Shemansky (1982) gave intensities in closer accord with those predicted by a Voyager-type model but Morgan's results were supported by data acquired by Oliversen (1983).)

Recent advances in imaging of the torus through its forbidden line emission have emphasized the magnitude of the changes that occur from year to year. Figure 13 gives an example. The [SII] 6731 Å image from December 1989 gave a peak intensity of 400 R centred at around 5.4($\pm$0.1) R_J from Jupiter. The January 1991 data gave a peak intensity of around 1.5 kR with a maximum at 5.9 R_J. The data indicate that the ribbon was more intense during the 1990–91 Jupiter opposition than during the 1989–90 opposition. Unpublished imaging data obtained by Schneider and Trauger show the torus during the 1988–89 opposition to be similar in form to that seen in January 1991 (N. M. Schneider, personal communication). This data set also appears to show a weaker torus emission during the 1989–90 opposition. Models of the [SII] emission based on Voyager data and on the "1981" model of Morgan (1985b) are shown in Figure 13 for comparison.

The models fit the data quite well. The double maximum in the Voyager type model is evident in the 1991 ground-based data but not in the 1989 data. The 1989 data fits well with Morgan's "1981" model although in both cases the intensities are greater than the models would predict.

Trauger (1984a) has pointed out that his observations of [SII] in 1983 indicate a far higher SII concentration in the torus than observations made in 1976 (Trauger *et al.*, 1980). Although the two data sets were acquired with different instrumentation, the evidence for a change in torus conditions appears strong. Data presented by Trafton (1980) obtained over a four year period including the Voyager



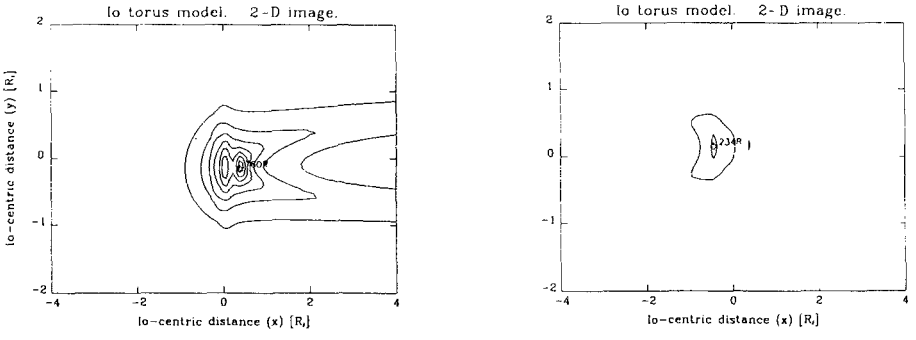


Fig. 13. Two images of the [SII] plasma torus obtained by Jockers and co-workers. The images were taken 15 months apart with similar equipment. The appearance of the torus has changed dramatically with a sharp increase in intensity at 5.9 R_J between December 1989 (right) and March 1991 (left). The data to the left is superior in signal to noise and size of field due to improvements in the equipment. Models of the two images are shown below. The appearance and intensity of the March 1991 image are well fit using a Voyager-type model. A better fit for the image from Dec 1989 is obtained using Morgan's "1981" model.

fly-by appear to support this. In order to provide a more quantitative comparison of the spectrograph data taken at many different Jovicentric distances and plasma latitudes, the [SII] 6731 Å intensities have been computed (using a Voyager-type model based on the scheme described in previous sections) at the positions in the torus where Trafton placed his slit. On separating the data into groups and comparing the ratio of observed to the predicted emission, several interesting points arose. Firstly, the data taken on 28 Feb 1979 and 1 March 1979, a few days before the Voyager 1 closest approach, gave a ratio of the sum of the observed to the predicted intensities of 1.2. The absolute calibration of Trafton's data should be good to about 25% so that the predictions of the Voyager type model are consistent with the observations made just five days before the Voyager 1 fly-by. However, data obtained on 30 and 31 January 1979 give a ratio of 2.9 and data acquired between 19 January 1976 and 17 March 1978 give a ratio of observed to predicted of only 0.5. Hence, Trafton's data appears to support Trauger (1984a)'s claim of reduced [SII] emission in 1976 although the averaging of data obtained over several years may be misleading. Thirdly, the data also suggest that the [SII] emission was substantially brighter in January 1979 just 5 weeks before the Voyager fly-by. Morgan and Pilcher (1982) obtained long slit spectrograph data 4 days before Trafton in this period but the derived intensities are difficult to interpret.

Other evidence for long term variability is present in Voyager, Pioneer, and IUE data sets. The UVS experiment on Voyager 2 indicated a 50% higher electron density during its fly-by than during the Voyager 1 fly-by (Shemansky, 1987), a rise comparable to that suggested by Morgan (1985b) in his interpretation of his 1981 data beyond 5.8 R_J. IUE observations of the torus in the early 1980's were reviewed by Moos *et al.* (1985). They concluded that T_e in the warm torus was quite stable over a five year period between March 1979 and March 1984. A comparison of the relative intensities of the sulphur emissions revealed some significant changes. Of particular interest is the sharp increase in all emissions at the beginning of 1981. The ratio of the SII 1256 Å line to other emission lines (SIII at 1729 Å and SIV at 1406 Å) jumped by nearly a factor of 2 for this observing run and Skinner *et al.* (1984) observed a very strong north pole aurora the following day. The ground-based observations of the lower temperature and higher density of the warm torus in the following months may be correlated. Similarly, in February 1989, IUE observations showed relatively high SII 1256 Å intensity. By November, the brightness had returned to a lower level when [SII] 6731 Å observations indicated that the torus was in a similar state to that seen in 1981. Another leap in the 1256 Å brightness occurred in March 1991 (McGrath, personal communication). Figure 13 shows the high intensity of the 6731 Å line at this time.

The marked change in the conditions in the torus in 1981 compared to Voyager offers an explanation for the observations of Brown *et al.* (1983b) who found an [OIII] 5007 Å upper limit of around 5 R thereby contradicting the predicted brightness of ≈50 R (Table II) which can be derived from the PLS observations

(Bagenal, 1985). The only upper limit for O^{2+} at the time of Voyager fly-by other than the PLS observation is a value of $110\,cm^{-3}$ (corresponding to about 200 R) from IUE observations (Strobel, 1989). It should be noted that the reaction

$$OII + e \rightarrow OIII + 2e \tag{17}$$

is extremely sensitive to T_e (Shemansky, 1987) and hence the lower electron temperature in 1981 may have led to a lower [OIII] intensity.

The Hopkins Ultraviolet Telescope (HUT), which was flown in December 1990 on the Astro-1 mission on board the space shuttle Columbia, provided a 2σ detection of the OIII] 1661 Å and 1666 Å lines from which an [OIII] 5007 Å intensity of 11 ± 5 R (Table II) was derived (Moos *et al.*, 1991). The data shown in Figure 13 indicate that the torus during the 1990–91 opposition was Voyager-like and hence this would argue that O^{2+} is not usually as abundant in the torus as the Voyager results would suggest. On the other hand, HUT will have seen emission from the edge of the warm inner torus and the warm outer torus. The spatial distribution determined by Bagenal (1985) would indicate a peak [OIII] 5007 Å brightness at around 5.6 R_J. As both Moos *et al.* (1991) and Strobel (1989) state, further constraints on the [OIII] 5007 Å emission are urgently required.

Other variations are also apparent in the IUE observations which recorded a significant decrease in n_e between February and July 1983. Trauger (1984a) obtained [SII] and [SIII] data during this period but no discussion of variability within this data set has so far appeared.

A re-analysis of data from the Pioneer 10 particle experiments suggests that the Pioneer observations are at least qualitatively in agreement with the Voyager results. Intriligator and Miller (1981) have presented evidence for SIII and OIII in the data but a detailed quantitative comparison has not been published although Intriligator and Miller (1982) does contain a reference to the source strength of the torus being "so much greater in 1979 than in 1973". Their interpretation indicates that n_e peaked at roughly Io's orbit. The Pioneer 10 UV experiment, however, showed strong emission near 4 R_J (Carlson and Judge, 1974; 1975) which was initially interpreted as indicating a hydrogen torus. A detailed re-evaluation of this data in the light of the Voyager findings has not yet appeared although indications are that the torus at the time of Pioneer 10 fly-by was probably different from the Voyager state. The effect of the torus on the radio signals from the Pioneer 10 spacecraft was close to the noise level and no conclusions with regard to the scale and magnitude of the torus at the time of the fly-by have been reached (Levy *et al.*, 1981; Campbell and Synnott, 1985).

7.5. "Pulsations"

Ultra-low frequency (ULF) pulsations are a common feature of magnetospheric dynamics. It now appears that they are also present in the Jovian magnetosphere, (e.g. Khurana and Kivelson, 1989; Glassmeier *et al.*, 1989). Of particular relevance

for plasma torus physics are ULF waves observed by Glassmeier *et al.* (1989) using Voyager 1 magnetometer measurements. Wave activity was enhanced when Voyager 1 entered the torus and periodicities of ≈ 800 s and ≈ 1200 s were evident. The observations were interpreted as toroidal and poloidal eigenoscillations of the entire torus (i.e. as twisting and breathing modes). The difference in the eigenperiods of both modes points toward decoupled oscillations with very large azimuthal wavelength.

The authors suggested that the variability in the magnitude of the deviation from corotation of the torus observed by Brown (1983) (see Section 7.3) was possible evidence for at least the twisting mode in ground-based observations. One other possible method of identifying these ULF pulsations would be to observe the azimuthally symmetric contraction and expansion (breathing) of the torus.

As possible sources for the observed eigenoscillations Glassmeier *et al.* (1989) discuss temporal variations of the torus mass loading rate, amongst others. An alternative explanation for these ultra low frequency waves might be Io's interaction with the Jovian magnetospheric plasma (e.g. Neubauer, 1980), an explanation favoured by Southwood and Fazakerley (1991). They suggest that the oscillations discussed by Glassmeier *et al.* arise from Io's motion through the plasma creating a substantial disturbance to the flow up to at least 0.5 R_J downstream of Io. A wake of this scale is apparent in recent 3-D MHD calculations of the Io-torus interaction by Linker *et al.* (1988) (Section 11). Periodic perturbations in the wake have been predicted by Smith and Wright (1989) (see also Wright and Smith, 1990). The standing Alfvén wave pattern due to the Io-plasma interaction itself (e.g. Neubauer, 1980; Gurnett and Goertz, 1981) has been observed by Walker and Kivelson (1981) on the basis of Pioneer 10 observations. Hence, rather than being oscillations of the entire torus, Io may be the source of the detected oscillations.

The integration and read out times required to obtain good signal to noise with CCD imagers will tend to smear out periodicities of the order of 10 min duration in ground-based CCD observations. Any straylight background from Jupiter will also have a detrimental effect for the analysis of the data. However, detection of these pulsations may be possible with modern photometers or photon counting detectors and so a test of the pulsation theory from ground should, in principle, be possible.

7.6. Extreme line ratios

On several occasions, observations of extreme line ratios for the [SII] red doublet (<0.4, the theoretical lower limit according to computed transition probabilities) have been reported (e.g. Trafton, 1980, and Morgan, 1985a). These observations have been interpreted as the result of "clumps" of plasma in the magnetic field which lead to extreme values of n_e. The mechanism by which this process can

occur is unclear although Morgan (1985a) suggests that up to 3% of the plasma in the torus could be contained within clumps of $n_e > 5 \times 10^4\ \mathrm{cm}^{-3}$. Ground-based imaging of the torus should reveal the presence of such clumps but apparently they are not immediately obvious in imaging data so far obtained (Schneider, personal communication; Debi Prasad, personal communication).

8. Torus Energy Balance

In the previous Sections, it was argued that the torus exhibits several or perhaps even a range of stable states and two models of the torus producing significantly different intensity distributions for [SII] were described. The models are, however, no more than empirical fits to the data with no real description of the underlying physics of the mass and energy balance of the torus. A realistic model requires adequate descriptions of the diffusion processes by which ions populate the cold inner and warm tori, the ion partitioning (which includes detailed knowledge of the charge exchange reaction rates which, in some cases, are strongly temperature dependent), the radiative cooling processes, and the source of new mass for the torus as a whole.

For several years after the Voyager fly-bys, it was widely assumed that the only source of power for torus emissions was derived from the ionization of neutrals and subsequent acceleration to corotation velocity, so called "ion pickup" (Smith and Strobel, 1985; Barbosa *et al.*, 1983). However, revised calculations of the radiative loss rates of particularly S^+ have led to the conclusion that ion pickup is insufficient to sustain radiative losses from the warm torus (Smith *et al.*, 1988; Shemansky, 1988a) and that around 50(±25)% of the energy input to the torus must have another origin.

Gehrels *et al.* (1981) reported measurements made by the Voyager cosmic ray subsystem (CRS) in Jupiter's magnetosphere and concluded that oxygen and sulphur ions which diffuse outward from the vicinity of Io are accelerated in the region around 17 R_J after which inward diffusion can occur. Gehrels and Stone (1983) showed that the inward diffusion could provide sufficient energy to drive the Jovian aurora. However, the precipitation of these ions into the Jovian ionosphere occurs too far from Io's orbit to have a significant effect on the optical emissions although less energetic particles may play a role. Eviatar and Barbosa (1984) proposed that a small percentage of fast neutrals, generated by charge-exchange processes in the inner magnetosphere, are re-ionized and picked up in the outer magnetosphere and that these ions subsequently diffuse inward to provide a source of energy for the inner magnetosphere and aurora (see Paranicas *et al.* (1990) and review by Bagenal (1992)). Cheng (1986) has pointed out that the ionization of fast neutrals must occur farther out in the magnetosphere than Eviatar and Barbosa (1984) propose in order to explain the Voyager LECP observations of fast neutrals (Kirsch *et al.*, 1981). A detailed model description of these processes

showing the method by which the warm torus is energized has so far not been published.

The cold torus, on the other hand, has been explained in Barbosa and Moreno (1988) by a straightforward diffusion process with no requirement for an additional energy source. The authors noted that the efficient depletion of S^+ by the reaction:

$$S^+ + SO \rightarrow S + SO^+ \tag{18}$$

indicates that molecular clouds of SO_2 and SO are important in the immediate vicinity of Io despite the fact that photodissociation is a major sink for these species. The remaining difficulty with this model is that electron impact dissociation and/or ionization of molecular species was not discussed. These processes probably have a significant effect on the distribution and required source rates of SO_2 and SO.

In view of the variations evident in the torus considerable attention has recently focussed on possible mechanisms by which the torus remains stable despite substantial changes in its composition and/or temperature (e.g. Richardson and Siscoe, 1981; Huang and Siscoe, 1987; Cheng, 1988). Our current knowledge of the processes involved in stabilizing both the mass supply and loss rates has been extensively covered in the recent review by Schneider *et al.* (1989a).

9. Neutrals in Region B

In the traditional picture, neutrals escape from Io by torus species sputtering the atmosphere and/or surface of Io (Matson *et al.*, 1974; Haff *et al.*, 1981). Electron impact ionization of neutrals then occurs to provide mass and energy for the torus emissions. The sodium lifetime against ionization in the immediate vicinity of Io (corresponding roughly to Region A) is thought to be ≤ 1 h (Brown, 1981b; Shemansky, 1980). Neutrals that survive drift slowly away from Io into regions where the lifetime is longer to form the extended (Region B) neutral clouds. The sodium and potassium clouds are the most readily observed from the ground due to the efficient resonant scattering of sunlight by these atoms (Sections 1, 6.2, and 9.4) and their morphologies have been the most thoroughly studied. In this Section, the physical processes affecting the brightness and morphology of the Region B clouds will be discussed resulting in a simple model of the clouds which can be compared to ground-based observations.

9.1. Detected neutral species

The sodium and potassium neutral clouds were discovered in the mid-1970's by Brown (1974) and Trafton (1975b), respectively (see Table II). Searches for the spectral signature of other alkali metals were also made but no confirmed emissions have been found although published upper limits are generally not that low (see Table V). The IRIS observation of gaseous SO_2 in the atmosphere of Io (Pearl *et*

al., 1979) led to a search for oxygen and sulphur neutral clouds. Brown (1981a) found evidence for a neutral oxygen torus near Io's orbit by observing the 6300 Å emission line which results almost exclusively from collisional excitation of O^0. This is a particularly difficult observation due to the Earth's atmospheric airglow but further study of this line is required to constrain models of the energy balance, ion partitioning, and composition of the torus. The Doppler shift resulting from the orbital velocity of the neutrals ($\approx 17.4\ \mathrm{km\ s^{-1}}$) can be used to separate the two emissions, although one must also take into account the velocity of Jupiter with respect to the observer which can be as high as $\pm 30\ \mathrm{km\ s^{-1}}$.

Both the neutral oxygen cloud (1304 Å) and the sulphur cloud (1429 Å) have been detected in the UV by Durrance *et al.* (1983). Some collisionally excited [SI] lines are present in the visible but they are expected to be weak. The Voyager observations of Io show that sulphur compounds dominate its surface and, probably, its atmosphere. The torus itself contains vast quantities of sulphur and oxygen which must be replenished at a rate of $\approx 10^{30}\ \mathrm{amu\ s^{-1}}$ ($\approx 4 \times 10^{28}\ \mathrm{atom\ s^{-1}}$) (Hill, 1980). PLS observations indicate that sodium is only a trace constituent in the torus. Furthermore, the electron impact ionization rate coefficient for S is at least a factor of 2 lower than for Na above 10 eV and as much as an order of magnitude lower for $T_e < 10$ eV. The rate coefficients for neutral oxygen are lower still (Brown *et al.* (1983a) and references therein). Hence, both the sulphur and oxygen clouds are expected to be at least two orders of magnitude more dense than either the sodium or potassium clouds. The oxygen cloud should form a complete torus around Jupiter as the lifetime against ionization and (more significantly) charge exchange, even in the densest parts of the torus, is probably greater than 12 hours, thereby explaining the detection of the OI 1304 Å line in the torus when Io was at the opposite ansa. Despite these differences and our comparative ignorance concerning the ejection mechanism from Io, it is frequently assumed that sodium is a tracer for the more abundant species in the neutral clouds.

Both SO_2 and SO clouds are to be expected in the immediate vicinity of Io due to the presence of SO_2 in Io's atmosphere and their detection would provide constraints on theoretical models of the torus and its production (see e.g. Barbosa and Moreno, 1988) but both these molecules are difficult to observe and their lifetimes will be comparatively short due to electron impact ionization and dissociation and photo-dissociation (see above).

9.2. Neutral lifetimes in the torus

The spatial extent of the Na cloud was the subject of many papers prior to the Voyager fly-bys. The Region B cloud is "banana-shaped" with most of the neutrals seen inside the orbit of Io. This led several authors to suggest that the neutral source had to be on or close to the Jupiter facing hemisphere (e.g. Smyth and McElroy, 1978). The discovery of the distribution of plasma in the torus changed this picture radically when it became clear that the neutral distribution was heavily

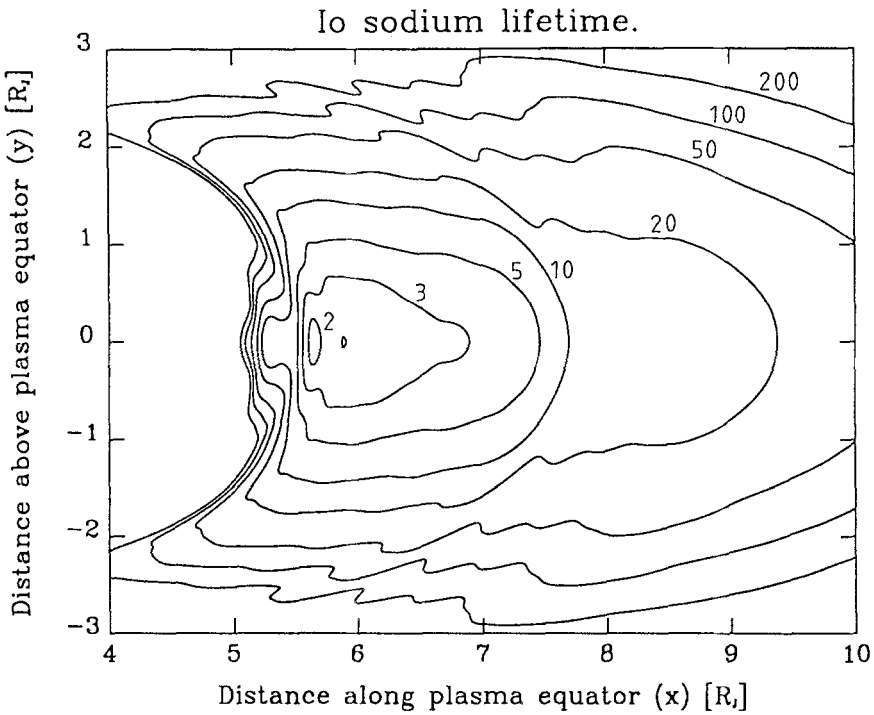
influenced by the sink. The rate coefficient for electron impact ionization rises sharply with T_e (see Brown *et al.*, 1983a) and references therein). T_e outside the orbit of Io was much higher than around 5.5 R_J so that a neutral on a trajectory taking it inside the orbit of Io had a correspondingly higher lifetime. This is illustrated in Figure 14 (top) which shows the lifetime of Na against electron impact ionization for the electron density distribution derived from Voyager PLS results.

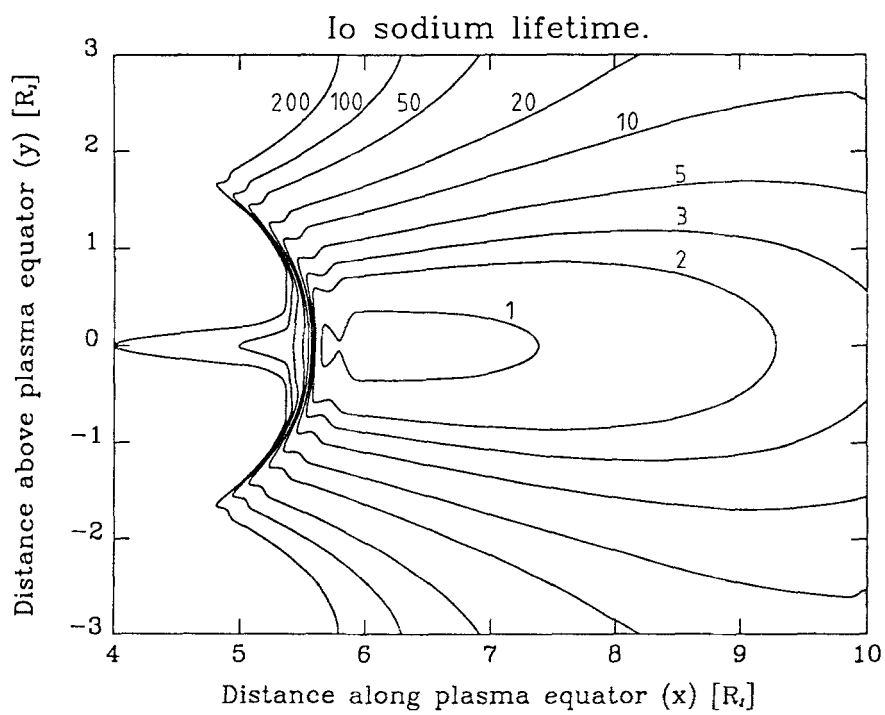
The lifetime of neutrals close to Io varies with the position of Io relative to the OTD. The amplitude of this variation for Na is around 30% (see Figure 15) with a mean of $\approx$2.7 h for the Voyager electron density distribution. The dawn–dusk electric field has a further influence on the lifetime by reducing n_e and T_e when Io is at eastern elongation (Section 4.3) which results in the cloud being $\approx$25% brighter at eastern elongation than at western elongation (Smyth and Combi, 1988a).

In view of the variability of the torus, one should ask whether this has a significant effect on the Na lifetime. By using the "1981" model of Morgan (1985b) and solving the equations for diffusive equilibrium (Section 4.1), the sodium atom lifetime for this distribution of n_e and T_e can be computed. The result is compared to the lifetime derived from the Voyager model in Figure 14. The "1981" model gives a substantially shorter lifetime which suggests that, for a constant supply rate, observed variations in the plasma torus should produce noticeable intensity variations in the sodium cloud. The Region B cloud has often been noted for its stability (e.g. Brown *et al.*, 1983a; discussion by Schneider *et al.*, 1989a) which argues that the Na supply rate varies according to the plasma conditions. However, the accuracy of the absolute photometry for these observations requires verification and a re-analysis of these data is almost certainly warranted. It would be surprising if plasma conditions modulate the sodium cloud over a period of 42.5 hours due to the dawn-dusk asymmetry but do not modulate the cloud over longer timescales.

The minimum lifetimes of K, S, and O against electron impact ionization in the torus are 1.1 h, 4.4 h, and 40.0 h respectively for a Voyager-type model. These values indicate that while charge exchange reactions play a relatively minor role in shaping the slow neutral sulphur cloud, they are the dominant reaction for the removal of neutral oxygen. Figure 16 shows the neutral oxygen lifetime against the combined effects of charge exchange and electron impact ionization for a Voyager-type torus. The charge exchange reactions modelled in the calculation

Fig. 14. The lifetime of neutral sodium against electron impact ionization varies with position in the Io plasma torus due to variations in electron density and temperature. The diagrams show the lifetime in hours relative to the plasma equator for two models of the torus. The Voyager model (top) gives a minimum lifetime of about 2 h on the plasma equator at 5.9 R_J. The "1981" model (bottom) of Morgan (1985b) generally gives lifetimes around a factor of 2 shorter indicating that variations in the plasma torus should have a significant influence on the observed intensity of the neutral sodium cloud.


Io sodium lifetime.
Distance above plasma equator (y) [R_J]
Distance along plasma equator (x) [R_J]
200
100
50
20
10
5
3
2
0
3
2
1
0
-1
-2
-3
4
5
6
7
8
9
10


Io sodium lifetime.
Distance above plasma equator (y) [R_J]
Distance along plasma equator (x) [R_J]
200
100
50
20
10
5
3
2
1
3
2
1
0
-1
-2
-3
4
5
6
7
8
9
10

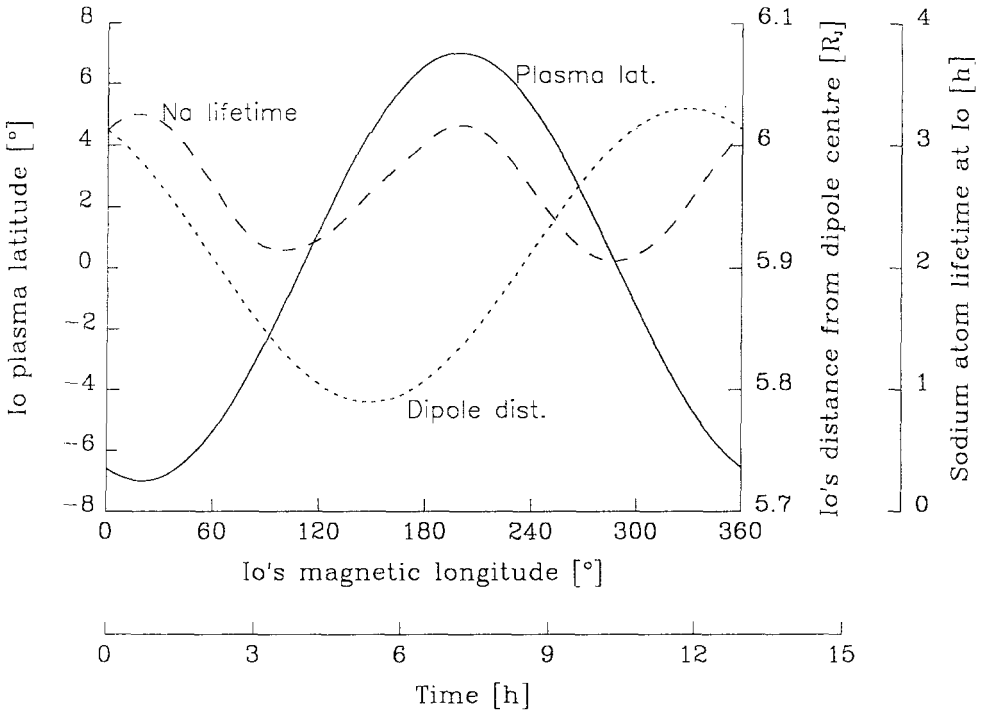


Fig. 15. The variation in the sodium atom lifetime at Io due to the effects of the offset tilted dipole field. The plasma latitude at Io varies with a period of 13 h which, when combined with the distance from the dipole centre produces a modulation of the Na lifetime at Io of more than 50%.

are shown in Table VII. Note that neutrals produced by charge exchange reactions will have high velocities and leave the system. The minimum lifetime is 14.2 hours. Use of the more recent reaction rate coefficients of McGrath and Johnson (1989) would not substantially affect this result.

9.3. Solar radiation pressure

Goldberg *et al.* (1978) pointed out that the Region B cloud is not a mirror image of itself when observed at two Io orbital phases separated by 180°. Smyth (1979) suggested that solar radiation pressure would be sufficient to explain this effect. The resonant scattering process involves the absorption of solar photons at a fixed wavelength which is followed by almost immediate emission. For the present purpose, it can be assumed that all angles of emission are equally probable. (Chamberlain (1990) provided a more detailed analysis showing that the scattering phase function varies by $\approx 10\%$ with phase angle). Hence, there is a transfer of momentum which modifies the trajectory of the sodium atom. The acceleration of the neutral (a_n) in [cm s^{-2}] is given by (Hunten *et al.*, 1988):

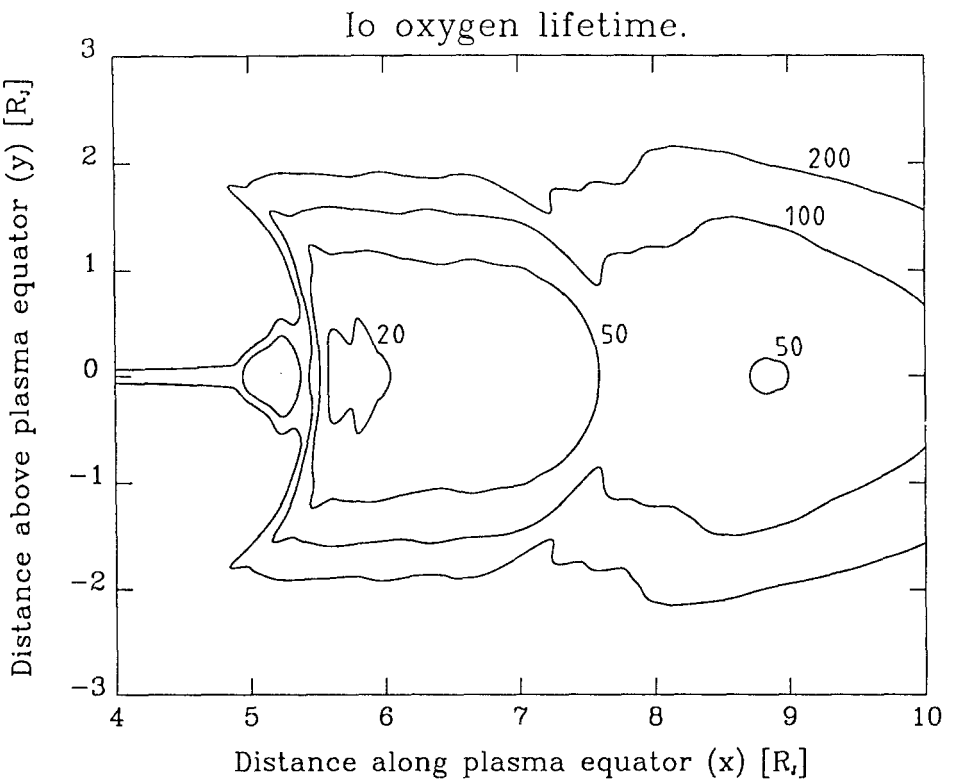


Fig. 16. The lifetime of neutral oxygen (in hours) against the combined effects of electron impact ionization and charge exchange reactions for a Voyager-type torus. The latter provides the dominant influence.

TABLE VII

Charge exchange reactions and rates in the Io plasma torus which contribute to the loss neutral oxygen from the atomic clouds (rate coefficients from Brown *et al.* (1983b) and Shemansky (1987))

Reaction	Rate coefficient [$cm^3 s^{-1}$]
$O^+ + O \rightarrow O^* + O^+$	1.2×10^{-8}
$O^{2+} + O \rightarrow O^+ + O^+$	2.0×10^{-10}
$S^+ + O \rightarrow S^* + O^+$	6.0×10^{-11}
$S^{2+} + O \rightarrow S^+ + O^+$	6.0×10^{-9}
$O^{2+} + O \rightarrow O^* + O^{2+}$	5.0×10^{-9}
$S^{3+} + O \rightarrow S^{2+} + O^+$	4.4×10^{-9}
$S^{3+} + O \rightarrow S^+ + O^{2+}$	5.6×10^{-9}

$$a_n = \left(\frac{\pi e^2}{m_e c}\right) \frac{h}{m_n \lambda} \pi F_\nu \frac{f}{R^2} \tag{19}$$

where πF_ν is the solar flux at 1 AU at the resonant frequency in the rest frame of the atom (in [photon $cm^{-2}\,s^{-1}\,Hz^{-1}$]), R is the heliocentric distance in [AU] (Jovian mean heliocentric distance is 5.203 AU), m_n is the mass of the neutral atom in [g], f is the oscillator strength of the transition, λ is the wavelength of the transition, and $(\pi e^2/m_e c)$ is the integrated absorption coefficient per atom for unit f-value and equal to $2.647 \times 10^{-2}\,cm^2\,s^{-1}$. For sodium atoms at Jupiter, this can be approximated by (following Smyth, 1979):

$$a_n \approx 0.55(\gamma_{D_1} + 1.98\gamma_{D_2}) \tag{20}$$

where γ_{D_2} is the ratio of the solar flux at the excitation wavelength of the atom in its rest frame to that of the continuum for the D_2 line (at 5890 Å) and γ_{D_1} is the corresponding ratio for the D_1 line (5896 Å) (Brown and Yung, 1976). The solar continuum at Na D-line wavelengths is $\approx$22 photon $cm^{-2}\,s^{-1}\,Hz^{-1}$ at Jupiter. γ_{D_2} and γ_{D_1} are strongly dependent upon the velocity of the scattering atom with respect to the Sun as Figure 1 indicates.

Smyth and Combi (1988a) have shown that the orbital asymmetry of the sodium cloud noted by Goldberg *et al.* (1978) is well explained by the influence of solar radiation pressure on the cloud.

9.4. Neutral brightnesses

The orbital velocity of the neutral clouds with respect to the Sun gives a wavelength shift for the resonant frequency in a Sun-centred reference frame. The solar flux in the rest frame of the atom can be determined from Kurucz *et al.* (1984). γ can then be computed allowing conversion from [atom cm^{-2}] into [rayleigh] using the formula (Brown and Yung, 1976):

$$E = gN \tag{21}$$

where $E/10^6$ is the omni-directional emission rate in [rayleigh], N is the column density in [atom cm^{-2}], and g is a factor defined by:

$$g = \left(\frac{\pi e^2}{m_e c}\right) \frac{\pi F_\nu}{R^2} f \gamma \tag{22}$$

These expressions are only valid for an optically thin neutral cloud. This condition may not hold very close to Io where the Na column abundance may exceed $2\,10^{11}$ atom cm^{-2} (an intensity of $\approx$50 kR for $\gamma_{D_2} = 0.5$). Beyond this limit, the intensity increase with column abundance is non-linear for temperatures greater than 1000 K (Brown and Yung, 1976; Schneider, 1988). Broadening of the emission line profiles and a decrease in the D_2/D_1 (5890/5896) line ratio, which in the

TABLE VIII
Influences on the apparent distribution of neutral sodium in Io's environment

Phenomenon	Influence on the appearance of the cloud	Included in Smyth and Combi (1988a)
Source distribution	?	Yes
Gravitational potentials of Jupiter and Io	Strong	Yes
Solar radiation pressure	Strong	Yes
Electron impact ionization	Strong	Yes
Charge exchange	?	No
Soft collisions	Weak	No
Dissociative recombination	Possibly strong	No
Offset tilted dipole	Strong	Yes
Dawn–dusk electric field	Strong	Yes
Observing geometry	Strong	Yes
Resonant scattering	Strong	Yes
Distribution of outflow velocities	Strong	Yes

optically thin case is ≈ 2 (the ratio of the oscillator strengths for the two lines is 1.985 ± 0.004 (Gawlik *et al.*, 1979)), also occur. Maximum observed sodium D-line emission intensities are between 20 and 60 kR (Schneider *et al.*, 1989a) so that, for most purposes, optical thickness effects can be ignored beyond a few r_{Io} from the surface (but see Section 10). Values of g for several resonance lines can be derived from Table VI.

For the visible [OI] emission at 6300 Å, collisional excitation dominates over resonant scattering so that a classical five-level collisional equilibrium calculation must be performed as for visible torus emissions (Section 5). Similarly, UV emissions of SI in the Region B cloud result from collisional excitation and require an equilibrium calculation. The emissions will therefore be dependent upon n_e and T_e in the torus.

9.5. Models of neutrals in region B and comparison with observation

Models of the distribution of neutrals in the Jovian magnetosphere must describe several features of the system. A comprehensive model of the neutral clouds has been constructed by Smyth and Combi (1988a,b) and the processes this model can take into account are shown in Table VIII. In this model, trajectories of particle packets are computed in the presence of the gravitational fields of Jupiter and Io taking into account the influence of solar radiation pressure. Loss by electron impact ionization has been studied using the OTD field including the effects of the dawn-dusk electric field.

By adopting isotropic outflow of sodium at velocities of around 2.6 km s^{-1} from a simulated exobase 2600 km from the centre of the satellite at a rate of $\approx 10^{26}$ Na atom s^{-1}, the main features of the neutral Na cloud evident in observations

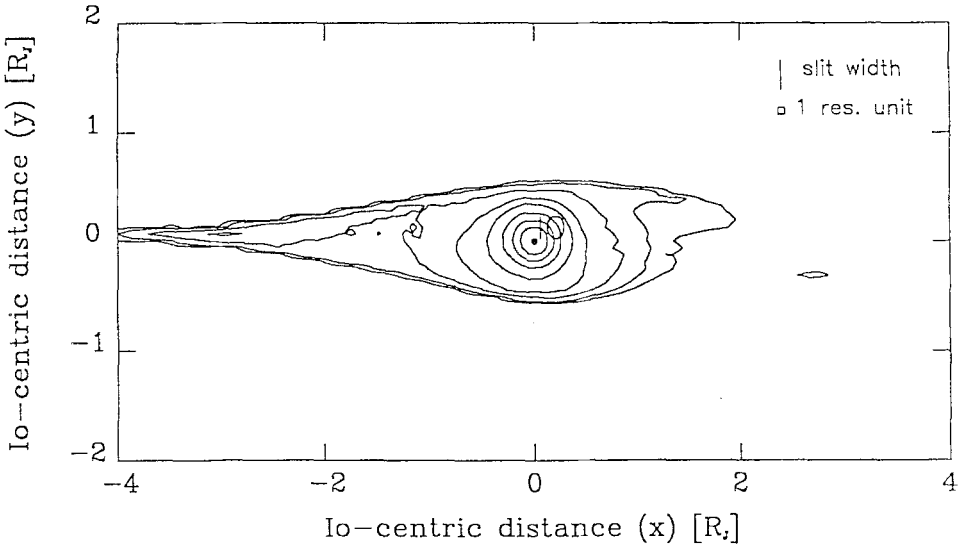


Fig. 17. Model of the Io Region B sodium cloud which shows the elongated shape of the cloud. The model parameters are $\theta_{Io} = 300.4°$, $\lambda_{III}(Io) = 248.9°$, source strength $= 2 \times 10^{26}$ atom s^{-1}, $v = 2.6$ km s^{-1}. Contours are in [rayleigh] with levels at 0.2 kR, 0.4 kR, 1 kR, 2 kR, 4 kR, 10 kR, 20 kR, 40 kR. Optical thickness effect are not included. A "bite" appears to have been taken out of the cloud 2 R_J east (left) of Io which is caused by the intersection of the extended cloud with the centre of the torus. Note also the concentric nature of the isophotes near the source in this isotropic emission model.

as far back as 1976 (e.g. Murcray and Goody, 1978) are well reproduced. A model calculation for the sodium cloud based on the method adopted by Smyth and Combi is shown in Figure 17. The extent of the emission in front of Io in its orbital motion is the result of gravitation combined with the slow initial outflow velocity which barely exceeds Io's escape velocity ($v_{esc} = 2.56$ km s^{-1} from Io's surface and $v_{esc} = 1.78$ km s^{-1} from the simulated exobase). The non-uniformity of the sink is sufficient to explain the relative enhancement of intensity inside the orbit of Io which, prior to the Voyager observations, appeared to require a non-isotropic source (e.g. Smyth and McElroy, 1978). Smyth and Combi (1988a) also demonstrated that the east–west brightness asymmetry of the Region B sodium cloud (Bergstralh *et al.*, 1975; 1977) is a natural consequence of the effect of the dawn–dusk electric field on the principle sink, thereby eliminating the need for a time variable source (Thomas, 1986). (The absence of a diurnal modulation of the Na abundance in eclipse measurements of the near-Io environment (Schneider *et al.*, 1991a; Section 10) is also evidence against a time variable source.)

Although well modelled, some details associated with the slow sodium cloud remain unclear. A monoenergetic source of 2.6 km s^{-1} is insufficient to explain sodium observed more than 0.5 R_J above the equatorial plane. Smyth and Combi (1988a) overcome this by using a distribution of velocities. However, images frequently show that the cloud is more strongly asymmetric about the equatorial plane than the model would suggest. Images in Pilcher *et al.* (1984) and Jockers

et al. (1991) are good examples of this. It will be seen in Figure 17 that the isophotes are concentric about Io out to around 0.75 R_J from Io. This is persistent in the model independent of λ_{III} (Io) which tends to argue for an anisotropic source or a modified sink near Io not present in the model. The asymmetry may be a side effect of the directional features discussed in Section 11.

The concentric isophotes in the model are the result of isotropic outflow before other effects included in the model begin to have a visible effect. However, spectra obtained soon after the discovery of the cloud tended to suggest that the emission mechanism was somewhat more complicated. The first spectra were provided by Brown and Chaffee (1974). These data indicated that the line width was only marginally greater than the instrumental function ($\approx$200 mÅ). Trafton (1975a), using a 22.5 × 1.2 arcsec slit centred on Io, concluded that the D-line emission was slightly shifted in wavelength when compared to an Io-centred rest frame. A red shift, corresponding to about 1 km s^{-1}, was observed when Io was close to western elongation and a blue shift of similar magnitude was apparent at eastern elongation (Trafton and Macy, 1977). Carlson *et al.* (1978), who placed their slit $\approx$16 r_{Io} ahead of the satellite to eliminate effects of the scattered light from Io's continuum, supported this conclusion from which they suggested that sodium emission was principally from the leading hemisphere of Io. There was also evidence for high ($\geq$10 km s^{-1}) velocity wings (or "skirts") in the data presented by both Trafton (1975a) and Trafton and Macy (1977).

High velocity wings were, however, almost completely absent in spectra of emission from the immediate vicinity of Io (within an impact parameter of $\approx 0.5 r_{Io}$ of the centre of the satellite) presented by Schneider (1988) suggesting that the high velocity component observed by Trafton and Macy (1977) and Carlson *et al.* (1978) came from a more remote source (Section 11). Schneider confirmed the shift of the velocity peak relative to an Io rest frame but estimated the velocity to be 0.30 ($\pm$0.15) km s^{-1}, somewhat lower than Trafton and Macy (1977) determined, but still significant when compared to isotropic radial outflow. This suggests that the source requires a more sophisticated treatment although the influence of Jupiter's gravitational field on the velocity distribution along the line of sight has not been fully quantified.

10. Constraints on Io's Atmosphere and Corona

Io's atmosphere and surface are the ultimate sources of the neutrals in the atomic clouds so that the nature of the atmosphere is of considerable significance to the study of the system. However, the atmosphere has been the subject of conjecture for many years (Johnson and Matson, 1988). The equilibrium vapour pressure model proposed after the initial detection of an SO_2 atmosphere (Pearl *et al.*, 1979) was modified by Fanale *et al.* (1982) to take into account the effects of regional cold-trapping. The surface pressure of SO_2 in this model decreases by six

orders of magnitude from the sub-solar point to the nightside. A more detailed model of regional cold-trapping has recently been presented by Ingersoll (1989). Matson and Nash (1983) proposed that sub-surface cold trapping would reduce the atmospheric pressure much further and suggested that all SO_2 seen by the IRIS experiment came from a near-by volcanic plume. An atmosphere resulting from volcanic outgassing has also been proposed (Moreno *et al.*, 1991). In this case, the observed surface pressure would vary substantially depending on the proximity of the observation to a volcanic vent.

Recent observations at microwave wavelengths have suggested that the model of Fanale *et al.* (1982) may be most appropriate for Io's atmosphere (Lellouch *et al.*, 1990) and IUE observations (Ballester *et al.*, 1990) also support the presence of a collisionally thick atmosphere at least above the dayside hemisphere.

Several models of the upper atmosphere and corona have been presented. McGrath and Johnson (1987), following earlier work by Sieveka and Johnson (1984; 1985; 1986), have suggested that energetic particle sputtering is responsible for the escape of Iogenic neutrals. This requires that the plasma in the torus penetrates the near-Io environment such that sputtering can occur from the exobase. Equilibrium vapour pressure and regional cold-trapping atmospheric models imply that the exobase varies from dayside to nightside so that the sputtering loss would be modulated by Io's orbital phase. Further modulation would be expected if the ion concentration in the torus were to vary significantly. Alternatively, Summers *et al.* (1989) have concluded that thermal escape alone is sufficient to provide the observed source rates. However, by analogy with cometary interactions, the outflow from the satellite does not appear to be sufficient to stand off the combined plasma and magnetic pressures (the latter dominates) of the torus unless an additional mechanism, such as an intrinsic magnetic field, is present. A thermal escape mechanism would, on the other hand, provide a stable source for Na (and therefore presumably O and S also) but requires that the Region B cloud vary according to the prevailing torus conditions.

Optical studies of Region A of the sodium cloud, which could provide information on the nature of the interaction, are hindered by the comparable brightness of Io's surface. Isotropically scattering sodium atoms in an optically thick cloud around Io would appear like a Lambertian surface and since the surface of Io itself is roughly Lambertian, it is almost impossible to distinguish between the two (Brown *et al.*, 1975). Schneider *et al.* (1987; 1991a) have attempted to probe the upper atmospheric abundance of Na in an ingenious manner. Every six years, the Earth passes through the equatorial plane of Jupiter. The most recent occurence was in 1991. Around this time, the Galilean satellites can pass very close to each other in projection and eclipses of one satellite by another can occur. Schneider *et al.* (1991a) took advantage of this phenomenon in a highly unusual way to probe the atmosphere of Io. The method was to obtain spectra of Europa as Io passed between Europa and the Sun with the objective of observing neutral sodium

in absorption in Europa's spectrum. The sodium column abundance at impact parameters less than 5.6 r_{Io} from eclipse observations in August and September 1985 were well fit by a power law distribution according to:

$$N = 2.6\,10^{12} b^{-2.48} \tag{23}$$

where N is the column abundance in [Na atom cm^{-2}] and b is the impact parameter in r_{Io} thereby appearing to confirm the presence of a collisionally thick atmosphere. The maximum observed column abundance was $\approx 2 \times 10^{12}$ atom cm^{-2} which corresponds to between 150 and 300 kR in emission ($\gamma = 0.6$) so that at points within $4r_{Io}$, optical thickness must be taken into account. Schneider *et al.* (1991a) have compared their data to several models of Io's upper atmosphere. Eclipses measurements were obtained above both the leading and the trailing hemispheres of Io. The lack of a significant difference between these data argues against the sputtering mechanism of McGrath and Johnson (1987) in its basic form due to the absence of a diurnal modulation of the Na abundance (cf. Section 9.5). The asymmetry of the near-Io Na velocity distribution also argues against a sputtered source.

It is widely assumed that Io's well developed ionosphere, first identified by Kliore *et al.* (1974; 1975) using data from the Pioneer 10 radio occultation experiment, is produced by plasma torus electrons impacting and ionizing Io's neutral atmosphere. Kumar (1980) successfully modelled the ionosphere by assuming an impacting flux of 20–100 eV electrons (although the precise nature of the interaction including the plasma transport process was not considered). Evidence for collisional excitation of neutral sulphur and oxygen at UV wavelengths has been presented by Ballester *et al.* (1987) while recent detections of [OI] emission from Io in the visible at 6300 Å have been made by Schneider *et al.* (1989b) and Scherb and Schultz (1991). If one assumes that the emission is derived from collisional excitation by torus electrons in the immediate vicinity of Io, then an atmospheric column density of $\approx 1.7 \times 10^{15}$ cm^{-2} could be determined from the intensities observed by Scherb and Schultz (1991). This value is close to that expected for a collisionally thick atmosphere and is in reasonable agreement with the data of Ballester *et al.* (1987). (It should be noted, however, that 6300 Å emission can also be produced by dissociation of O_2.) Scherb and Schultz (1991) point out the need to determine the spatial distribution of the [OI] emission and have adopted the method of Potter and Morgan (1990) in an attempt to determine if the emission comes from an extended corona or from a bound atmosphere. First efforts appear to show that the emission is more extended (in the form of a corona) which would agree with Voyager observations of cool electrons in the vicinity of Io (Sittler and Strobel, 1987). It should be noted, however, that the intensity determined by Schneider *et al.* (1989b) was a factor of four lower than that found by Scherb and Schultz (1991). This discrepancy currently remains unresolved.

Several papers have considered the interaction between Io and the magnetosphere from the point of view of the flow of plasma past Io. An analytical non-

linear description of the standing Alfvén wave pattern far from Io was provided by Neubauer (1980). The first self-consistent numerical model was that of Wolf-Gladrow *et al.* (1987) which was used to investigate the effect of Io's conductivity on the flow pattern close to Io itself. Linker *et al.* (1988; 1989; 1991) have also constructed a three-dimensional MHD model which has been used to study the wave modes and the effects of mass loading on the flow. Southwood and Dunlop (1984) had already pointed out that ion pickup in the immediate vicinity of Io leads to a disruption of the flow past Io. Linker *et al.* (1989) showed that the flow speed will be greatly decreased in the vicinity of Io while later simulations demonstrated the reduced flow speed in the Alfvén wings. At this stage, however, a detailed model of the pickup process has not appeared. As Linker *et al.* (1989) were principally concerned with the effect of mass loading on the plasma, their simulations were restricted to either a spherically symmetric neutral density distribution or a modelled exosphere with mass loading proportional to the neutral density. As they point out, this is not a complete description of the ionization and mass loading process. Ground-based observations suggest that magnetospheric electrons (and presumably ions) reach the exobase of Io's atmosphere. On the other hand, the velocity and spatial distribution of neutrals suggests a thermal escape mechanism rather than sputtered ejection. A detailed description of this interaction is a requirement for future study of the ejected material.

11. Directional Features in the Neutral Emission

"During the period of Voyager 1 encounter there appeared a region of enhanced emission intensity projecting outward from Io's orbit and inclined to the orbital plane." This remark by Goldberg *et al.* (1980) was the first reference to directional high velocity features in the Io sodium cloud. These features are at present the subject of considerable interest since their formation may be strongly influenced by the interaction between Io and the plasma torus.

The directional features appear as intense, almost collimated "jets" of neutral sodium frequently directed out of the equatorial plane. The features are clearly evident in the images presented by Goldberg *et al.* (1984) and were the subject of an investigation by Pilcher *et al.* (1984). Out of the plane emission requires velocities substantially higher than those of the slow "banana-shaped" cloud originally associated with the Region B observations of, for example, Murcray and Goody. The apparent linearity of the features shown by Pilcher *et al.* argued for only small gravitational perturbations and hence high velocity. They concluded that emission of 10^{26} atom s^{-1} at a velocity of ≈ 20 km s^{-1} would explain their observations. Spectral observations and velocity resolved imaging indicated neutral velocities of up to 50 km s^{-1} (e.g. Trauger, 1984b).

Pilcher *et al.* (1984) also showed that the direction of the jet was a function of Io's magnetic longitude. Northerly directed jets were preferred between λ_{III}

(Io) $\approx 140°$ and $300°$ with southern jets preferred at other times. Broadly similar results were obtained by Schneider (1988). The velocity and collimation tended to support charge exchange as the probable production mechanism. Charge exchange in the vicinity of Io had already been suggested as a significant source of neutrals for the clouds (Ip, 1982). Sodium ions in the torus would charge exchange with neutrals in the atmosphere by the reaction:

$$Na^+ + Na \rightarrow Na^* + Na^+ \tag{24}$$

In this reaction, little of the kinetic energy of the incoming ion is lost as the charge exchange takes place so that one would expect neutral sodium velocities of around $57\ \mathrm{km\ s^{-1}}$ with respect to Io from this reaction. Subsequent modelling of the flow of plasma near Io showed that, at least at the flanks where most of the interaction was expected to take place, flow velocities were even higher (Wolf-Gladrow *et al.*, 1987 and cf. Barnett, 1986). Spectra of the jets showed, however, that the mean velocity of the fast neutrals was somewhat less than the relative corotation velocity (see Schneider (1988) and Schneider *et al.* (1989a), Figure 43). Several hundred high resolution spectra of the cloud have been obtained by Cremonese *et al.* (1992) which frequently show fast sodium neutrals travelling at up to $80\ \mathrm{km\ s^{-1}}$ in the immediate vicinity of Io but most of the high velocity neutrals ($v > 5\ \mathrm{km\ s^{-1}}$) travel at velocities of between 30 and $40\ \mathrm{km\ s^{-1}}$ with respect to Io (e.g. Figure 18). The charge exchange process only remains viable if the interaction with Io is sufficient to slow the plasma flow to these velocities. As noted in the previous section, this may occur in Io's wake, if mass loading is significant, or above the poles where the Alfvén wing forms (Wolf-Gladrow *et al.*, 1987; Linker *et al.*, 1988; 1989; 1991).

The spectra presented by Cremonese *et al.* (1992) also show the reproducibility of the fast sodium phenomenon. By combining the orbital period of Io (42.48 h) and the rotation period of Jupiter (9 h 55 m 29.7 s) it is apparent that the same value of λ_{III} (Io) recurs every 12.95 h. θ_{Io} recurs every 42.48 h giving the same geometry for observations of the cloud. These two periods are not commensurate but a close alignment to the initial condition occurs after 31.86 days. Hence, observations of Io taken this length of time apart should be made under similar geometrical and magnetic conditions. Cremonese *et al.* (1992) showed that spectra taken in January and February 1989 did indeed appear remarkably similar with substantial quantities of high velocity sodium apparent. Observations taken two months earlier at the same geometrical configuration but with Io at a different magnetic longitude showed no evidence for fast sodium within the slit.

An alternative means of providing fast neutral velocities below the relative corotation velocity is through elastic (soft) collisions (Brown *et al.*, 1983a). This process, however, cannot adequately explain the evident collimation of the directional features and hence it seems improbable that it is a dominant mechanism in the production of "jets".

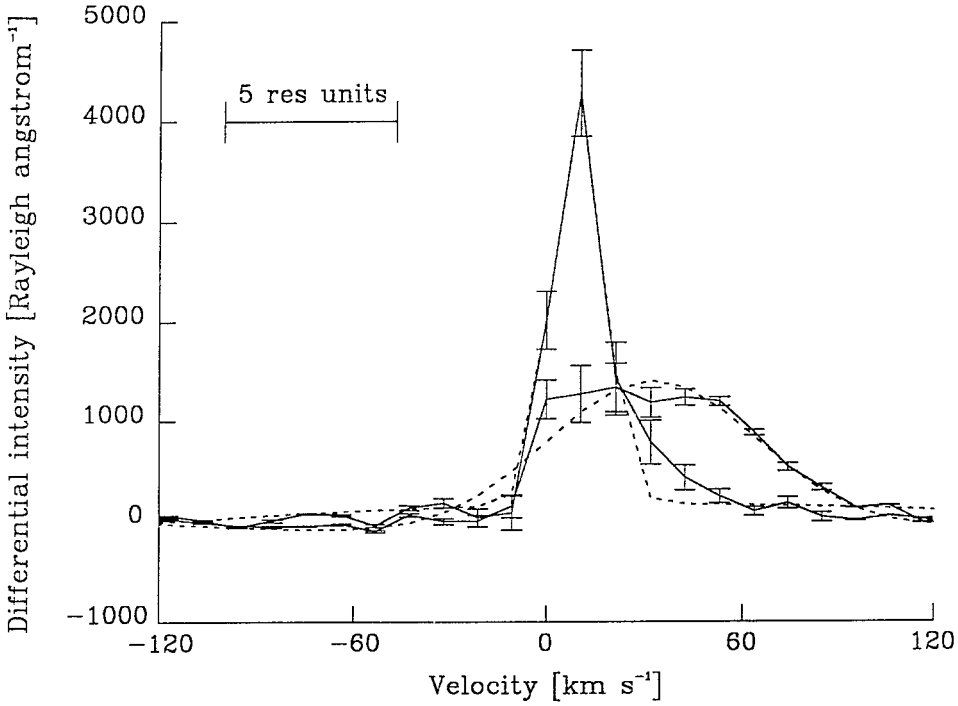


Fig. 18. Spectrum of the neutral sodium cloud at 0.75 R_J from Io. Note the two maxima in the velocity distribution. The low velocity component corresponds to the slow sodium cloud presumably generated by energetic particle sputtering of the upper atmosphere of Io. The high velocity component is centred at around 40 km s^{-1} (Cremonese *et al.* 1991).

Schneider *et al.* (1991b) have recently suggested a further possibility. The quality of ground-based images of the Na cloud has increased over the past 5 years due to improvements in the detectors and in the technique. Recent images by Schneider *et al.* (1991b) show the neutral Na "jet" very clearly as a narrow structure which can appear curved near the ansae of the plasma torus although several R_J from Io (Figure 19). Schneider *et al.* (1991b) suggest that fast neutral Na must therefore be generated locally to explain the curved appearance of the "jet". They propose dissociative recombination or dissociation of a sodium-bearing molecular ion in the torus as the means by which the fast Na is produced. The molecular ion is preferred to Na^+ principally because dissociative recombination rates of molecular ions have far higher rate co-efficients than the sum of the dielectronic and radiative recombination co-efficients of Na^+. The orientation of the jet is described by the trajectory freshly created ions follow after creation in the immediate vicinity of Io (Cummings *et al.*, 1980). Freshly created ions oscillate about their equilibrium latitude (for most purposes, the plasma equator) with an amplitude dependent upon the latitude of their injection until a significant number of collisions have occurred. The period of the oscillation was treated as a free parameter in the

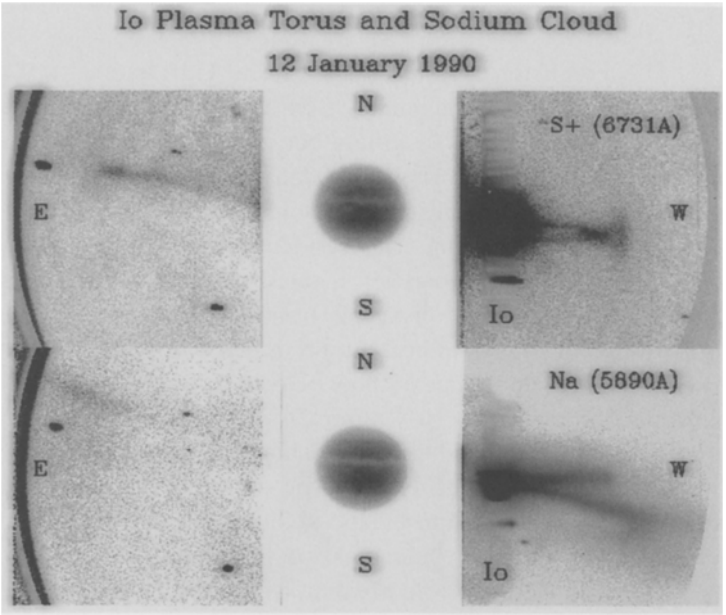


Fig. 19. The orientation of the fast sodium jet compared to the position of the [SII] plasma torus (from Schneider *et al.*, 1991b; copyright 1991 by the AAAS).

model of Schneider *et al.* (1991b) and a value of 5.6 h was derived. The existence of an extended source of fast neutral sodium may be supported by the fact that the column density of high velocity neutrals in spectra given in Cremonese *et al.* (1992) was found to decrease less steeply than b^{-1}.

The nature of the molecular ion remains unknown but NaO^+ and NaS^+ are obvious candidates. The latter may be derived from Na_2S which was suggested as a surface constituent and possible atmospheric constituent on the basis of sputtering experiments by Chrisey *et al.* (1988). The lifetime of the molecular ion is probably too short (of the order of 4–8 h from Schneider's imaging data) to allow build-up of a significant population in the torus so the absence of its signature in the Voyager PLS data would not be surprising. A difficulty for the molecular ion theory is the creation mechanism since, if the source is a parent molecule, the ionization rate must be of the same order as the dissociation rate to limit the required abundance of the parent molecule to reasonable concentrations. The apparent abundance of molecular ions may well have profound implications for the aeronomy of the upper atmosphere of the satellite and for the plasma-atmosphere interaction.

12. Sodium Remote from Io

The discovery of Na emission several R_J from Io by Trafton *et al.* (1974) marked the beginning of the study of Na remote from Io. Observations by Brown and Schneider (1981) revealed that Na atoms between 10 and 20 R_J from Io had acquired line of sight velocities of up to 100 km s^{-1}. It is now evident that these high velocity neutrals were probably derived from the directional features or "jets" discussed in the previous Section. The residence time of fast neutrals within regions of high electron impact ionization is relatively short ensuring a substantial population of Na atoms at great distances from Jupiter. Mendillo *et al.* (1990) showed the extent of the cloud indicating intensities of 10 R at a radial distance of more than 200 R_J. Assuming an outflow velocity of 74 km s^{-1}, they derived a fast sodium production rate of 4×10^{26} atom s^{-1} which is a factor of 4 greater than the values derived from fast sodium observations near Jupiter by Brown and Schneider (1981) and Pilcher *et al.* (1984). The outflow velocity cannot be much lower than 20 km s^{-1} as the Jovian escape velocity from Io's orbit is 25 km s^{-1} and gravitational effects for low velocities would distort the appearance of the remote cloud so that deviations from the simple r^{-1} law demonstrated so clearly by Mendillo *et al.* (1990) would be present. Cremonese *et al.* (1992) derived a fast sodium production rate within a few r_{Io} of Io of only 5×10^{25} atom s^{-1} at times of high fast sodium abundance. This may be consistent with the observations of Mendillo *et al.* (1990) if fast sodium is produced from an extended source as Schneider *et al.* (1991b) suggest. Flynn *et al.* (1991) have recently reported evidence for time variability in the extended nebula which may have an impact on the source mechanism of fast sodium.

13. Further Research

There has been a considerable advance in our observational capabilities in recent years due to improvements in both equipment and technique. These improvements have led to a wealth of new data but several questions remain concerning the torus and its interaction with Io. There are many areas where new research is needed both at the telescope and in the laboratory.

13.1. New Optical Observations

13.1.1. *Torus Composition*

A major priority of future ground-based research should be the observation of [OIII] 5007 Å emission. A detection or a strict upper limit would provide significant new input to the argument over the O^{2+} content of the cold inner torus. The O^{2+} concentration may vary strongly both with time (due in part to variations in T_e) and position in the torus so that a persistent search must be undertaken. When undertaking such observations it will also be necessary to determine the state of

the torus at the time by monitoring other lines. This would have the added benefit of providing an inventory of major torus ions. Morgan (1985b) was able to provide a consistent description of the torus by carefully monitoring several lines. More than 10 years have passed since those observations.

The published upper limit for emission from most other species in the torus is around 500 R (ClIII is an exception). This limit was set 15 years ago and although more recent unpublished surveys suggest upper limits of ≤ 100 R, a re-evaluation should be performed. Searches for carbon and nitrogen species will be relevant for the formation of Io and for the aeronomy of its atmosphere. Silicon compounds are expected on the surface (Clow and Carr, 1980; Johnson *et al.*, 1988) and sputtering of the surface or of material above volcanic vents may provide a source of Si for the torus although no evidence of Si was found in the magnetosphere by the Voyager LECP experiment (Krimigis and Roelof, 1983). Better upper limits on these species and on resonant scattering from alkali metals would constrain abundances and possibly escape mechanisms.

13.1.2. *Long-Term Monitoring*

Long-term infra-red monitoring of Io has been performed for more than 10 years (e.g. Sinton *et al.*, 1983) and the accumulated data analysed to determine the frequency and scale of volcanic events. Optical observers tend to study the torus for periods of 4 to 5 days perhaps 3 times a year. It is now apparent, however, that a dedicated monitoring program is required for the torus. It would be extremely informative to watch the torus as it changes from one state to another, giving information on the timescales involved which would, in turn, provide further constraints on the factors determining its stability. Such a program would also provide the opportunity for comparisons between data sets. Detailed comparisons between the IR data and torus observations, for example, have never been made. "What influence does varying volcanic activity have on the torus?" remains an often asked but as yet unanswered question.

The study of periodicities also requires many observations covering several months to eliminate aliases and provide good statistics. Periodicities deviating significantly from System III may be indicative of corotation breakdown and mass loading providing further information on the dynamics of the magnetosphere. Some studies of these phenomena (e.g. Woodward *et al.*, 1991) are continuing.

One should perhaps bear in mind that periodograms are difficult to interpret due to aliasing and one should be careful to avoid biasing the data. Analysis of the same data set with an alternative technique (e.g. maximum entropy), while time consuming, may prove informative.

13.1.3. *Plasma near Io and Pulsations*

Modelling of the interaction of the plasma torus with Io's atmosphere predicts considerable modification of the flow parameters within 0.5 R_J of Io (Linker *et*

al., 1989). A search for modification of plasma velocities and densities in the immediate vicinity of Io may be fruitful in constraining the models of the interaction. The observations are by no means trivial because of straylight from Io. The integration path length through parts of the torus unaffected by the interaction may also mask out any visible modifications to the flow. Evidence for a significant wake would tend to support the interpretation made by Southwood and Fazakerley (1991) of low frequency waves in the Voyager magnetometer observations. Alternatively, a search for eigenoscillations of the Jovian magnetosphere may now be possible using photon counting detectors. Their existence would tend to support Glassmeier *et al.* (1989)'s interpretation of the Voyager magnetometer data.

13.1.4. *Atmospheric Species*

The recent observations of [OI] emission at 6300 Å (Schneider *et al.*, 1989b; Scherb and Schultz, 1991) are still somewhat controversial in that the detections gave differing fluxes for the emission. This may indicate either observational error or variability and clearly further observations are required. Observations during Io's eclipse behind Jupiter may prove to be useful in determining the origin of the emission and whether the aeronomy of the atmosphere is controlled by the equilibrium vapour pressure of SO_2. However, the line of sight velocity of Io during this period will be very small making separation of this line from the atmospheric airglow line difficult. Observations with Hubble Space Telescope may, however, be a useful alternative. Further input may come from HST UV observations of sulphur and oxygen species in Io's atmosphere. Several detailed proposals have already been made. Additional microwave observations of the SO_2 SO, H_2S, and CO components would also provide significant constraints on the composition and variability of Io's atmosphere (Lellouch *et al.*, 1992)

13.1.5. *Beyond* $7R_J$

Measurements of torus intensities beyond 7 R_J from Jupiter are rarely reported as the signal level drops rapidly with Jovicentric distance. Trauger (1984a), for example, showed the intensity of the [SIII] emission dropped as $\propto e^{-r/2}$ (where r is the Jovicentric distance in R_J) and was below 200 R at 7 R_J. Although measurements at great distances from Jupiter may be useful for studies of the radial diffusion of torus ions, it seems improbable that there is sufficient signal beyond about 8 R_J. This may be good enough, however, to study the sharp increase in electron density between 7.2 and 7.8 R_J seen in the Voyager PLS data (Figure 8).

Detection of a Europa torus from ground-based observation would appear improbable.

13.2. Old observations and related studies

13.2.1. *Re-Evaluation of Pioneer 10 Data*

There appears to be little doubt that torus conditions during the Pioneer 10 fly-by were different from those during the Voyager fly-by but a detailed re-evaluation of all available data has yet to appear. This re-evaluation should take into account data from the UV spectrometer, the plasma analyser, and the radio data. I understand that at present only the UV data is being re-assessed. Further study may give a self-consistent picture of the torus during the December 1973 fly-by.

13.2.2. *Voyager Observations*

Voyager URS data have analysed for composition and periodicities in the SIII 685 Å line. Studies of other possible time-dependent phenomena and spatially-resolved measurements have not yet appeared. Synthesis of the PLS/UVS data continues to provide information on the ion distribution within the torus (e.g. Bagenal *et al.*, 1992). There are apparently some images of the sodium cloud taken by the imaging sub-system which have not been fully studied. These data may be important as Goldberg *et al.* (1980) have already pointed out the presence of directional features in ground-based observations taken during the Voyager 1 fly-by.

13.2.3. *Re-Evaluation of Old Ground-Based Observations*

As has been shown in Section 7.4, further re-evaluation of old observations of the torus in the light of the Voyager results may provide information on its long-term stability. A study of this sort should also seek access to the several unpublished or partially published data sets which have been acquired over the past 20 years. The different equipment and calibration techniques adopted will make this a difficult task.

A similar re-assessment of the stability of the sodium cloud is highly desirable. This has been addressed, in a preliminary sense, by Schneider *et al.* (1989a) but a more detailed study is needed to evaluate whether the sodium cloud is indeed modulated by variations in the torus.

13.2.4. *Atomic Data*

Shemansky (1990) has stressed the requirement for improved atomic data. As recently as 1988, for example, modifications to the computed radiative cooling coefficients of known torus species radically altered the interpretation of the torus energy balance (Shemansky, 1988a, b; Smith *et al.*, 1988). Collision strengths and transition probabilities for the principle ions in the torus have been the subjects of considerable research recently, motivated in part by the Io problem (e.g. Tayal *et al.*, 1987) but charge exchange rates remain rather uncertain with McGrath and Johnson (1989) being the only recent source of quantitative data (Shemansky,

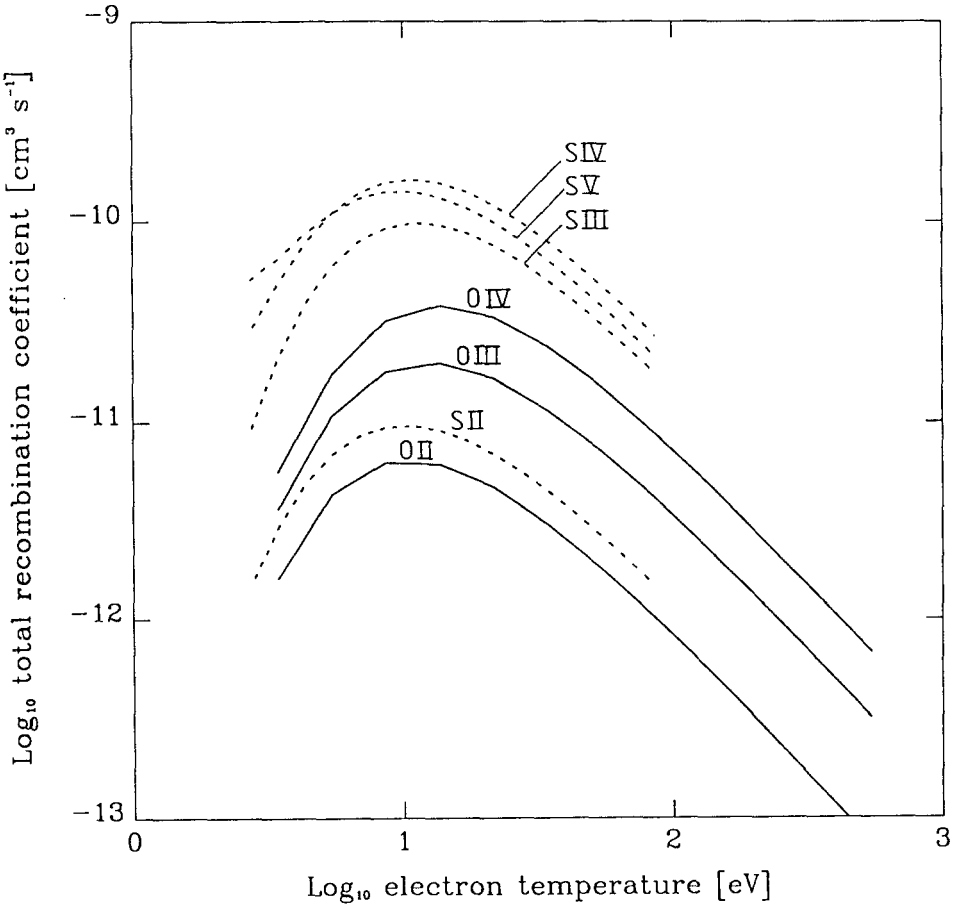


Fig. 20. Dielectronic recombination rate coefficients for major torus species taken from Badnell (1989; 1991).

1990). Recombination rate coefficients for the principle torus ions have been the subject of recent investigations by Badnell (1989; 1991) and Roszman (1989). The results of Badnell's calculations are plotted in Figure 20 (cf. Brown *et al.*, 1983a, Figure 6.11). Roszman (1989) points out, however, that his results for O^{2+} differ from Badnell's by about 30% which could lead to significant differences in model calculations. Clearly, further work on these coefficients is needed. Data on dissociative recombination of sodium-bearing molecular ions is also now required.

13.2.5. *Modelling of the Neutral Clouds*

Models of the sodium cloud have, in the past, assumed that the sink (the plasma torus) is constant with magnetic longitude. The evidence for variations in the torus have been documented above and recent unpublished work suggests that imaging data requires a variable sink (W. H. Smyth, personal communication). Modelling

of the Region B cloud has so far shed little light on the source distribution as most variations can be modelled by variations in the sink. It is surprising that the inferred non-uniform nature of the atmosphere and/or corona of Io (Section 10) which forms the immediate source of the neutrals in Region B should lead to an almost uniform source independent of Io's orbital phase. However, the region in the immediate vicinity of Io is extremely difficult to study and although there are several theories, an accepted model of the neutral source region has not yet emerged.

The importance of fast sodium in the magnetosphere of Jupiter is a relatively recent discovery and detailed modelling is only just beginning. The implications of the "molecular ion" theory are far reaching, requiring revised models of the aeronomy of Io's atmosphere, of the interaction of the torus with the upper atmosphere, and of the source distribution for the remote sodium cloud in the magnetosphere. The observations may also have implications for the energetics of the torus as a whole.

14. Concluding Remarks

Ground-based observations of emissions from the magnetosphere of Jupiter and the extended atmosphere of Io have considerably enhanced our knowledge of phenomena associated with the Jupiter system. In combination with earth orbiting observations and results from the Voyager spacecraft, a picture of the system has emerged which is summarized schematically in Figure 21. As can be seen from the preceding section however, a great deal of work remains to be done in several areas. The importance of fast neutral phenomena has only just been recognized, details of the interaction between Io and Jupiter's magnetosphere remain unclear, the energy supply mechanism for torus emissions has not been adequately modelled, and the stability of the system, in spite of its variability, is rather poorly understood. Co-ordinated observations at several wavelengths, which may provide further understanding of the processes involved, are starting to be performed on a more regular basis although these data have yet to be fully exploited.

Results from the Galileo orbiter will inevitably provide a vast quantity of additional data, particularly concerning the outer magnetosphere, during its two years of *in situ* measurements. But even during this time there will be room for further ground-based support because Galileo will only pass inside the orbit of Io once during its entire mission in order to avoid damage to the spacecraft from the hazardous radiation environment while the duty cycles for several of the experiments used to study the torus will be restricted. Thus, ground-based observations will continue to provide the context within which the spacecraft results will be placed.

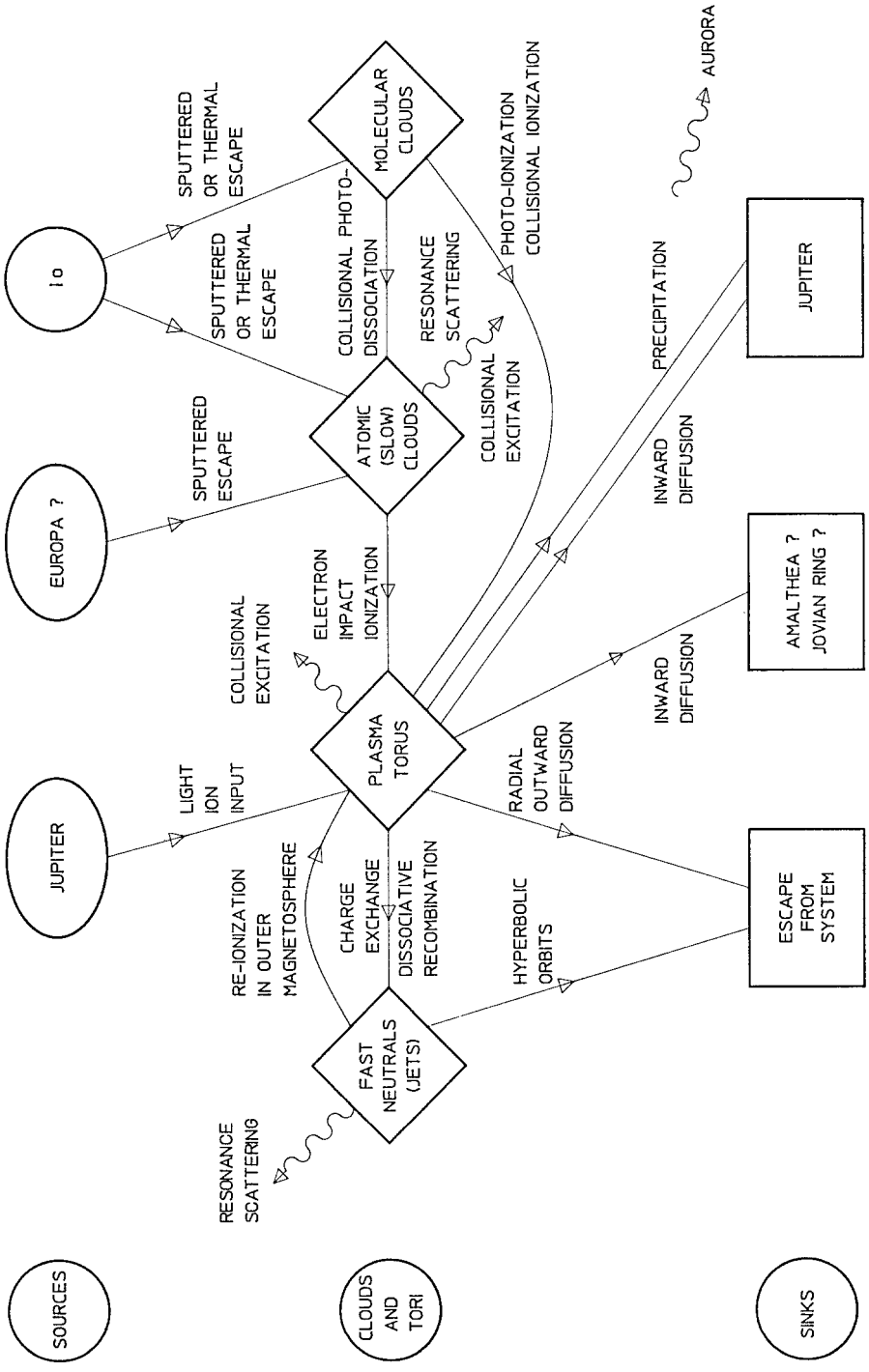


Fig. 21. A schematic diagram of the interactions between Iogenic material and Jupiter's magnetosphere. The top row of phenomena corresponds to sources of mass in the magnetosphere. The bottom row contains the sinks while the central row shows the observable phenomena and their interactions.

Appendix: Basic Quantities of the Jupiter System and Geometry

In this appendix, definitions are provided for basic quantities and co-ordinate systems in common use in the study of the Io-Jupiter system (see also Dessler, 1983).

The geometric position of Io in its orbit around Jupiter for a ground-based observer is described by an orbital phase angle θ_{Io} which gives the angular departure of Io from superior geocentric conjuction (SGC) (see Figure A1). Io resides in the equatorial plane of Jupiter and hence this is referred to as the equatorial system. The latitude of a point in this Jupiter-centred system is denoted by ψ_e. Io completes one orbit of Jupiter in this system every 1.769 days at a distance of 5.91 R_J from the centre of the parent planet.

The magnetic coordinate system describes the position of a point relative to the offset tilted dipole (OTD) approximation of Jupiter's magnetic field. The zero longitude meridian in this system is set by definition to co-incide with the zero longitude meridian of System III (1965.0) and the angular departure from this meridian in a left handed system is denoted by λ_{III} i.e. looking down from above Jupiter's north pole, longitude increases clockwise (Dessler, 1983). The angular velocity of System III is 1.7585×10^{-4} rad s^{-1}. The magnetic dipole is tilted relative to the Jovian spin axis by $9.8 \pm 0.3°$ towards $\lambda_{III} = 200°$. The dipole is offset towards $\lambda_{III} = 149 \pm 6°$ by 0.12 ± 0.02 R_J which causes a further modulation of the magnetic latitude by $\pm 0.2°$ near the equator.

A special case in this system describes the magnetic longitude of the earth in the magnetic coordinate system i.e. the λ_{III} of the sub-Earth point. This is known as the central meridian longitude and is denoted by λ_{III} (CML). λ_{III}(Io) is used to refer to the magnetic longitude of Io in this co-ordinate system. The magnetic latitude of an object in this system is denoted by ψ_m.

The macroscopic motion of the ions in the plasma torus do not follow the magnetic equator precisely because the ions are of sufficiently low energy that centrifugal force must be taken into account (Hill *et al.*, 1974). In the centrifugal co-ordinate system the longitude is identical to that of the magnetic coordinate system but the tilt of the system relative to the spin equator is only about 2/3 of that of the magnetic system. Hence, the latitude of a point relative to the centrifugal equator is different from ψ_m and is denoted by ψ_c. Observations of the orientation of the torus suggest that the plasma density is at a maximum between the centrifugal equator and the magnetic equator. I will refer to this as the "plasma equator" and denote latitude with respect to this plane as ψ_p. It should be noted that the plasma distribution about this plane will not be strictly symmetrical (Vasyliunas, 1983) although in interpretation of both ground-based and Voyager observations it is usually assumed to be so.

Torus observers have occasionally used the term "plane of sky longitude" (abbreviated to PSL) which describes the λ_{III} meridian in the image plane. As two

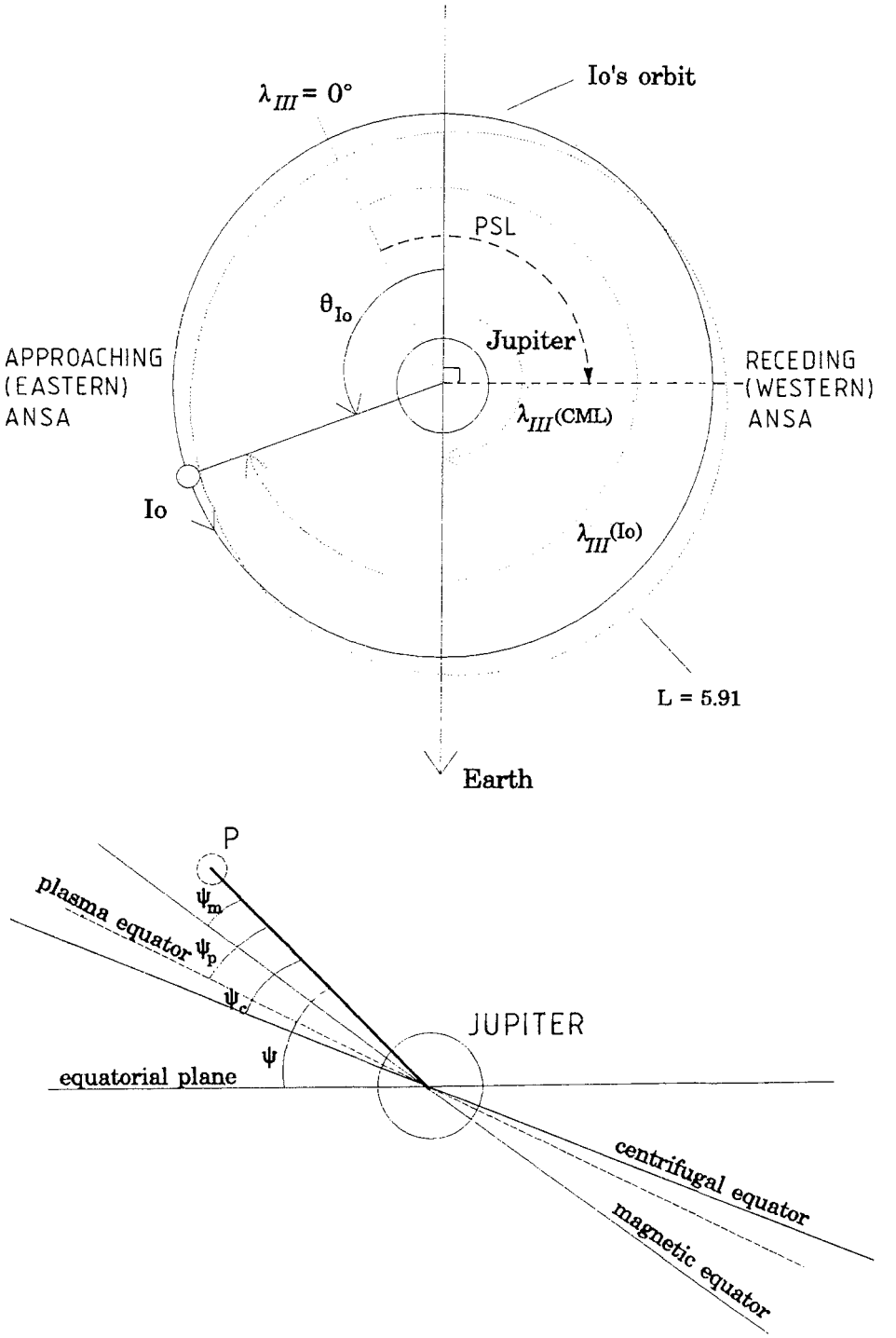


Fig. A1. The definition of coordinate systems used in studies of the Jovian system. The diagram left shows the system seen from north of the ecliptic plane. The symbols used to describe latitude in the various system are shown in the diagram to the right.

meridians satisfy this description (PSL = λ_{III}(CML) $\pm$ 90°) it remains necessary to specify which side of the torus is being observed.

Some phenomena (e.g. the dawn–dusk asymmetry) are best described in terms of the direction with respect to the Sun-planet line. It should therefore be noted that the phase angle (Sun–Jupiter–Earth) can vary by $\pm$ 11° due to the Earth's heliocentric orbit. Some confusion can also arise from use of terms such as "western elongation" or "western ansa". Elongation refers to the angular distance between Jupiter and a moon. When the moon appears to follow Jupiter in its daily motion it is in "eastern elongation". When the moon precedes Jupiter it is in "western elongation". Greatest elongation (or GE) refers to the point when the Jupiter-Earth-moon angle is at a maximum although this is frequently abbreviated in literature to just "elongation". Ansae refer to the parts of the torus visible on either side of Jupiter. Again, ansae are usually qualified as western or eastern. However, this terminology can be confusing in the spacecraft era when observations can be made from widely different phase angles. Use of "approaching ansa", indicating the ansa which would appear blue-shifted due to the corotation velocity, and "receding ansa" provides a better description.

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