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ON THE NATURE OF S II EMISSION FROM JUPITER'S HOT PLASMA TORUS

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ABSTRACT

Hot-torus emission rates at the *Voyager 1* encounter in the 6731, 1256, 911, and the reclassified 765 Å ($3p^3\ ^4S^o$–$3p^2 3d\ ^4P$) transitions of S II indicate an effective electron temperature $T_e \approx 80{,}000$ K. This result is compatible with the value deduced from the *Voyager 1* UVS spectrum which is due mainly to ions other than S II. A set of 53 measurements of the S II red line doublet obtained $5.9 R_J$ from Jupiter shows strong, irregular fluctuations in intensity but no variation in the line ratio, except that expected from photon statistics. The doublet ratio is diagnostic of plasma density, and we adopt a recent revision of S II transition probabilities affecting such interpretations. We find the torus longitudinally uniform in density at $5.9 R_J$, which is consonant with the *Voyager* UVS findings but apparently contrary to predictions of the magnetic anomaly model. The observed S II brightness variations must be due to fluctuations in the S II mixing ratio in a region where S II is a minor constituent, but where S III is known to be a major plasma component. Since the electron properties are regular and variable only over a small range in the hot torus at $5.9 R_J$, the irregular variations of the S II component indicate that reactions other than with electrons control the sulfur ion partitioning. We suggest that as yet unidentified ion-ion and/or ion-atom reactions are responsible.

Subject headings: atomic processes — planets: Jupiter — planets: magnetospheres — plasmas

I. INTRODUCTION

Optical emission from sulfur and oxygen ions in the vicinity of Io's orbit permits both remote sensing of intrinsic plasma properties and mapping the spatial distribution of the various ion components (see Brown, Pilcher, and Strobel 1982 for a current review). One of the brightest ionic emissions is the sulfur red doublet at wavelengths λλ6716, 6731. Images and spectra recorded in this collisionally produced light have been used to infer (1) the S II spatial distribution; (2) the distribution of ion thermal speeds from Doppler line shape; (3) the electron temperature by brightness comparisons with shorter wavelength S II emission, and (4) the total plasma charge density from the intensity ratio of the doublet lines. In the first two topic areas, the ground-based studies have supported and extended the *Voyager* spacecraft findings (Bagenal and Sullivan 1981; Brown 1982*a*).

The third topic has drawn recent concern, particularly in regard to torus homogeneity. Close coupling, configuration-mixed calculations by Ho and Henry (1981) predicted a bright S II λ863 feature, whereas none was observed by the *Voyager* UVS. This seemed to imply that the electron temperature specifically controlling the S II emission is much lower than that responsible for EUV emission from S III and oxygen ions in the same line of sight through the torus. However, recent experimental work by Pettersson and Martinson (1982) has reclassified the strong S II "λ863" ($3p^3\ ^4S^o$–$3p^2 3d\ ^4P$) muliplet to 765 Å, and using the adjusted Ho and Henry calculation, we show below that the S II problem has been completely alleviated. Using the 765 and 911 Å emission rates from the reanalyzed *Voyager 1* EUV spectrum, the Moos and Clarke (1981) measurement of S II λ1256 emission and the Trafton (1980) measure of average 6731 Å emission at $6 R_J$, we find accord with a plasma electron temperature of 8×10^4 K, the same as was deduced by the Shemansky and Smith (1981) analysis of the *Voyager 1* UVS spectrum. The latter is dominated by emissions from sulfur and oxygen ion species other than S II.

On the fourth topic, Shemansky and Smith (1981) have pointed out that UV and visible studies apparently differ concerning possible mass variations in the hot plasma torus. The *Voyager* UVS experiment found that the brightest UV emission, [S III] λ685, varies ~40% with local time but <10% with magnetic longitude (λ_{III}), and this modulation is probably controlled by electron temperature, not plasma mass (Shemansky and Sandel 1982). On the other hand, ground-based observations of [S II] λλ6716, 6731 (including our current data set) find drastic brightness changes (~0.1 to ~1 kR) in space and

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time within the distributed plasma (Trafton 1980; Pilcher and Morgan 1980; Morgan and Pilcher 1982; Trauger, Münch, and Roesler 1980), and it has been argued that these variations, unlike the UV, do manifest plasma mass fluctuations: specifically, a density pattern in accord with predictions of the magnetic anomaly model. The optical S II emission has a greater radial range than the UV and extends into the cool, inner torus ($r < 5.5R_J$), but this conflict concerning brightness and possible density variability is well established solely on the basis of UV versus visible observations of the hot plasma torus region ($5.5R_J < r < 7R_J$). This outer region is the specific object of the current study. Our new observations probe the relationship between S II optical emission brightness and total plasma mass. Our strategy has been to examine $\lambda\lambda$6716, 6731 doublet emission from the particular column through the plasma tangent at Io's orbital distance ($r = 5.9R_J$) and to seek a correlation of that brightness with the electron density as implied by the line ratio. We find no dependence of these quantities that can be interpreted as plasma mass variation. During the observing period the S II red lines showed a strong intensity variation but with a relatively stable line ratio. This result is interpreted below as a variation of the mixing ratio of S II in the plasma, but a relatively constant plasma mass is required. We present model calculations of expected emission characteristics for comparison with the data, including a recommended change in atomic data for the S II $\lambda\lambda$6716, 6731 transitions.

The brightest spectra in the current data set have been analyzed earlier for the underlying distribution of S II ion speeds implied by their line shape, and we summarize those results. Brown and Ip (1981) pointed out high speed wings which imply the mean S II gyroenergy is an order of magnitude greater than would be deduced from the width of the central peak alone. Brown (1982*a*) decomposed a composite line shape in terms of three Maxwellians and found perpendicular temperatures $T_\perp = 2.7$, 28, and 192 eV with weights 0.28, 0.50, and 0.22, respectively. The line profile shows no evidence within the uncertainties of S II ions at the corotational pickup speed. Comparison with [S III] line widths indicates that S III is hotter than S II, so thermal equilibrium exists neither between nor within ion species in the hot plasma torus (see Shemansky and Sandel 1982).

Brown (1982*b*) analyzes the ion velocity information contained in the Doppler-shifted wavelength positions of the S II emission features in the current data set. He finds that observed ions do not corotate with Jupiter, but exhibit only 92 ± 5% of the System III angular velocity.

II. SYNTHESIS OF S II EUV AND RED EMISSIONS

The *Voyager* EUV spectrum (see Shemansky and Smith 1981) contains no detectable emission at 863 Å, the wavelength assigned by Moore (1971) to the ($3p^3\ ^4S^o$–$3p^2 3d\ ^4P$) multiplet. The Pettersson and Martinson (1982) observations of a hollow cathode discharge also show no transition in S II at 863 Å, and those authors have concluded that the $3p^2 3d\ ^4P$ state has been misclassified and that the ($3p^3\ ^4S^o$–$3p^2 3d\ ^4P$) transition is indeed a strong emitter, but the multiplet lines occur at 765.69 Å (5/2), 764.42 Å (3/2), and 763.66 Å (1/2). This conclusion seems to be entirely consistent with the published literature; so far as we are aware, no multiplet in laboratory or solar spectra has been attributed to S II at 863 Å. We now attribute the peak in the EUV spectrum between 700 and 800 Å (Sandel *et al.* 1979, Fig. 3*b*; Brown, Pilcher, and Strobel 1982, Fig. 9*b*) to the S II λ765 multiplet, whereas it had been tentatively assigned to K III (Shemansky and Smith 1981).

A reanalysis of the *Voyager 1* EUV spectrum treated by Shemansky and Smith (1981), now using the Pettersson and Martinson (1982) reclassification, gives the intensities for S II λ765 and λ911 shown in Table 1. The observations near the time of *Voyager 1* encounter of S II λ1256 and λ6731 emission by Moos and Clarke (1981) and Trafton (1980), respectively, are also given. A collisional equilibrium model using the adjusted Ho and Henry calculations and assuming an electron temperature of 8×10^4 K was normalized to produce the Trafton (1980) 6731 Å intensity and yielded the predictions for the other multiplets indicated in Table 1. The reanalysis raises the estimated mean S II density to 120 cm^{-3} compared to the value 44 cm^{-3} given by Shemansky and Smith (1981) and produces a ratio [S II]/[e] = 0.075. The suite of S II observations is clearly compatible with a single effective electron temperature of 8×10^4 K, which is the temperature derived by Shemansky and Smith (1981) from the *Voyager 1* UVS spectrum mainly attributable to ions other than S II. The strong temperature sensitivity of the visible/UV line intensity ratios is illustrated in Figure 1. (Although the present intensity estimate for the S II λ911 transition is the same as that given by Shemansky and Smith (1981), the estimated S II number density obtained from the EUV data is increased by a factor of 2.5 as a result of the application of the new Ho and Henry 1981 collision strength.) We note that the comparison of the S II red and EUV lines must be made with special care given

TABLE 1

S II EMISSION LINE INTENSITIES IN IO PLASMA TORUS AT *Voyager 1* ENCOUNTER

λ (Å)	Multiplet	$4\pi J$ (R)	$4\pi J$ (R)[a]	Ω_{ij}
765	$3p^3\ ^4S^o$–$3d\ ^4P$	62[b]	59	7.2[c]
911	$3p^3\ ^4S^o$–$4s\ ^4P$	20[b]	19	1.6[c]
1256	$3p^3\ ^4S^o$–$3p^4\ ^4P$	43[d]	45	2.2[c]
6731	$3p^3\ ^4S^o$–$3p^3\ ^2D^o(3/2)$	242[e]	242	3.7[f]

[a] Model calculation at $T_e = 8 \times 10^4$ K (see Shemansky and Smith 1981) normalized to the Trafton (1980) 6731 Å intensity.
[b] Reanalysis of Shemansky and Smith 1981 *Voyager 1* spectrum.
[c] Collision strength (Ω_{ij}) at $T_e = 8 \times 10^4$ K from Ho and Henry 1981.
[d] From Moos and Clarke 1981.
[e] From Trafton 1980.
[f] Collision strength (Ω_{ij}) at $T_e = 8 \times 10^4$ K. See Shemansky and Smith 1981.

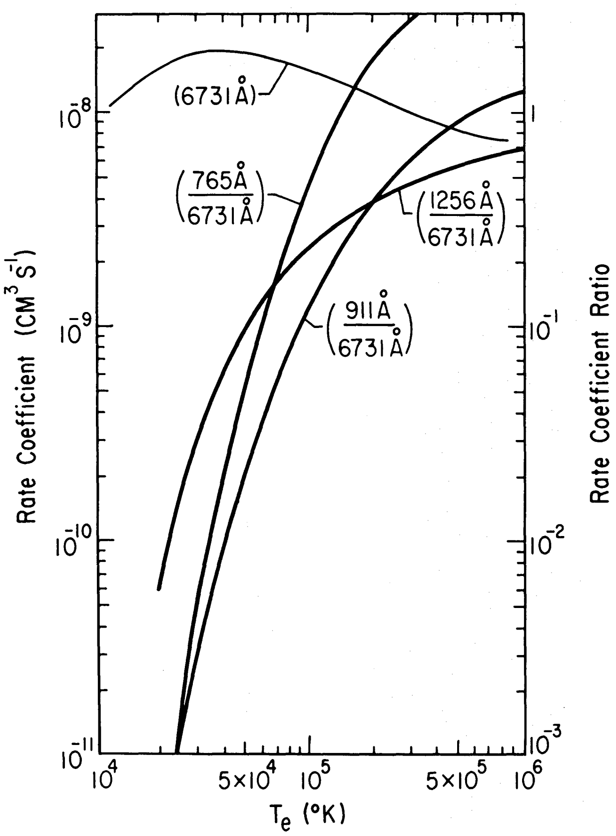

FIG. 1.—Thin curve is the rate coefficient for S II emission at 6731 Å (*left scale*). Bold curves are the ratios of three S II UV rate coefficients to that of 6731 Å (*right scale*). Intensity measurements near *Voyager 1* encounter are compatible with $T_e = 8 \times 10^4$ K.

to accurate pointing and instrumental fields of view because modeling predicts that the red line emissions, in particular, have a strong radial gradient in the hot torus, as discussed below.

III. OBSERVATIONS

Table 2 is a log of 53 [S II] spectra obtained in the spring of 1981 using the Cassegrain echelle spectrograph (Chaffee 1974) and the intensified Reticon detector (Davis and Latham 1979) at the 60 inch (1.5 m) telescope of the Smithsonian's Fred L. Whipple Observatory (formerly Mount Hopkins Observatory). The 6716, 6731 Å emission lines were observed in the 84th echelle order at a reciprocal dispersion 0.04 Å pixel^{-1} or 2.7 Å mm^{-1}. Wavelength calibration was provided by exposures of a thorium-argon lamp, and the intensity calibration came from exposures of the Jupiter disk center, which was assigned a brightness 5.4 MR Å^{-1} on the basis of the reflectivity of Woodman, Cochran, and Slavsky (1979) and the solar spectral irradiance of Arvesen, Griffin, and Pearson (1969). Exposures were interleaved so that a torus exposure was separated from preceding and following calibration exposures of both kinds by no more than 20 minutes.

The entrance aperture, which measured 6″.7 × 0″.5 or 0.3 × 0.02R_J projected on the sky, was oriented celestial east-west in 1981 February and parallel to the Jupiter rotational axis in 1981 April. Moving the telescope under computer control, the aperture was offset from Jupiter 5.9R_J (Io's orbital distance), either east or west. For the 1981 February spectra, this offset was in the satellite plane. For the 1981 April spectra, the displacement was along a line estimated to be the intersection of the plasma's centrifugal symmetry surface with the plane of the sky. For this purpose, we assumed the centrifugal symmetry surface to be a plane passing through the center of Jupiter inclined by 7° toward λ_{III} (1965) = 200° (Hill, Dessler, and Michel 1974). The exposures were guided with estimated $\pm 0.2R_J$ upper limit error in the celestial east-west direction and much better north-south. This pointing deadband is discussed below as one possible source of S II intensity variation.

If the emitting S II ions corotated with Jupiter, the emission line wavelength positions could be inverted using the Doppler formula to give the actual axial distance from Jupiter at which a spectrum was obtained. Brown (1982*b*) performs this analysis on the current data set and finds the implied axial distance to be displaced inward toward Jupiter by $\sim 0.5R_J$ from the nominal offset axial distance of 5.9R_J. He argues that offsets were accurately positioned 5.9R_J east or west of Jupiter, but that the observed ions circulated at less than the corotational rate.

The emission line brightnesses were determined by integrating the recorded photoelectrons at each [S II] line position, subtracting the local continuum level, dividing by the integration time, and multiplying by a count rate-to-Rayleigh conversion factor separately for each emission line from the Jupiter disk spectra most closely spaced in time to the torus spectrum. The torus spectra contain no evidence of underlying scattered Fraunhofer continuum. The results are given in Table 2 as the brightness, $4\pi J$(6731 Å), and the line ratio, $4\pi J$(6716 Å)/$4\pi J$(6731 Å). The quoted uncertainties are the propagated Poisson-statistical uncertainties in the photoelectron integrations, $\pm N^{1/2}$, where N photoelectrons were recorded in the wavelength range over which the emission and Jupiter calibration signals were summed.

Figure 2 shows the observed $4\pi J$(6731 Å) versus λ_{III} (1965) of the intersection point of the line of sight with the plane of the sky through Jupiter. The apparent absence of a functional dependence of brightness on λ_{III} as reported by others could have been caused by two factors or their combination: (1) actual instability in the λ_{III} dependence of the emission rate at fixed distance from Jupiter during the observation period; (2) small random guiding errors which could have moved the spectrograph slit around on a field known from imagery to have steep spatial gradients in 6716, 6731 Å brightness (Pilcher 1980; Trauger 1981). We believe effect (2) was minor for two reasons. First, the data show no correlation between the observed brightnesses and Doppler speeds, whereas one is expected for guiding errors sampling

TABLE 2

LOG OF OBSERVATIONS

Identification	Date	UT[a] (hr)	Exposure (s)	Position[b]	λ_{III}[c]	$4\pi J(6731$ Å) (R)	$4\pi J(6716$ Å)/$4\pi J(6731$ Å)
779/32	1981 Feb 23	5.28	600	East	307°	630 ± 43	0.80 ± 0.09
780/2	1981 Feb 23	5.60	600	East	318°	493 ± 40	0.80 ± 0.11
780/4	1981 Feb 23	5.85	630	East	327°	745 ± 42	0.73 ± 0.07
781/10	1981 Feb 24	6.85	600	East	154°	229 ± 33	0.92 ± 0.21
781/11	1981 Feb 24	7.02	600	East	160°	146 ± 31	0.88 ± 0.30
781/12	1981 Feb 24	7.20	600	East	167°	129 ± 32	0.85 ± 0.33
781/21	1981 Feb 24	8.48	606	East	214°	135 ± 31	0.63 ± 0.29
781/22	1981 Feb 24	8.68	600	East	221°	139 ± 32	1.06 ± 0.36
782/6	1981 Feb 24	11.48	600	East	322°	954 ± 45	0.71 ± 0.06
782/7	1981 Feb 24	11.62	300	East	327°	810 ± 61	0.62 ± 0.09
782/8	1981 Feb 24	11.77	300	West	151°	148 ± 49	0.44 ± 0.39
854/11	1981 Apr 25	4.28	600	West	280°	447 ± 49	0.94 ± 0.16
854/12	1981 Apr 25	4.48	600	West	288°	494 ± 51	0.79 ± 0.13
854/13	1981 Apr 25	4.71	600	West	296°	534 ± 51	0.90 ± 0.13
854/16	1981 Apr 25	5.20	600	West	314°	467 ± 48	0.81 ± 0.13
854/17	1981 Apr 25	5.49	780	West	324°	498 ± 41	0.57 ± 0.09
854/18	1981 Apr 25	5.73	600	West	333°	116 ± 39	1.66 ± 0.67
854/21	1981 Apr 25	6.03	600	West	344°	324 ± 43	0.73 ± 0.17
854/22	1981 Apr 25	6.25	600	West	352°	61 ± 38	1.40 ± 1.08
854/23	1981 Apr 25	6.46	600	West	359°	184 ± 40	1.34 ± 0.38
854/24	1981 Apr 25	6.70	600	East	188°	531 ± 47	0.73 ± 0.11
854/27	1981 Apr 25	7.02	600	West	20°	227 ± 41	0.87 ± 0.24
854/28	1981 Apr 25	7.26	600	West	29°	269 ± 42	1.08 ± 0.23
854/29	1981 Apr 25	7.46	600	West	36°	330 ± 43	0.77 ± 0.17
855/1	1981 Apr 25	7.85	600	West	50°	523 ± 41	0.63 ± 0.10
855/2	1981 Apr 25	8.18	600	West	62°	332 ± 44	0.71 ± 0.16
855/3	1981 Apr 25	8.58	600	West	77°	387 ± 45	0.97 ± 0.17
855/6	1981 Apr 25	9.05	600	West	93°	518 ± 49	0.78 ± 0.12
855/7	1981 Apr 25	9.79	600	West	120°	358 ± 44	0.66 ± 0.15
855/8	1981 Apr 25	9.94	300	West	126°	413 ± 75	0.67 ± 0.22
855/11	1981 Apr 25	10.24	600	West	137°	728 ± 70	0.90 ± 0.13
855/12	1981 Apr 25	10.58	600	West	149°	174 ± 72	3.20 ± 1.40
855/17	1981 Apr 26	2.98	600	East	204°	616 ± 59	0.76 ± 0.12
855/18	1981 Apr 26	3.17	600	West	31°	127 ± 48	1.48 ± 0.71
855/19	1981 Apr 26	3.40	660	East	219°	754 ± 55	0.69 ± 0.09
855/20	1981 Apr 26	3.61	600	West	47°	254 ± 48	0.69 ± 0.24
855/23	1981 Apr 26	3.91	600	East	238°	233 ± 69	0.53 ± 0.35
855/25	1981 Apr 26	4.21	600	West	69°	293 ± 54	0.42 ± 0.21
855/26	1981 Apr 26	4.44	600	East	257°	398 ± 58	0.88 ± 0.20
855/27	1981 Apr 26	4.64	600	West	84°	559 ± 62	0.60 ± 0.13
856/2	1981 Apr 26	5.77	600	West	125°	234 ± 53	0.44 ± 0.27
856/3	1981 Apr 26	5.96	600	West	132°	619 ± 53	0.76 ± 0.11
856/4	1981 Apr 26	6.17	600	West	140°	255 ± 44	0.52 ± 0.20
856/7	1981 Apr 26	6.46	600	West	150°	739 ± 59	0.60 ± 0.09
856/8	1981 Apr 26	6.65	600	West	157°	637 ± 58	0.56 ± 0.11
856/16	1981 Apr 26	7.79	600	West	198°	459 ± 53	0.51 ± 0.13
856/24	1981 Apr 26	9.95	600	West	277°	300 ± 55	0.84 ± 0.24
856/25	1981 Apr 26	10.15	450	West	284°	180 ± 59	0.84 ± 0.43
856/28	1981 Apr 27	3.53	600	West	194°	859 ± 57	0.78 ± 0.08
856/29	1981 Apr 27	3.72	600	West	201°	543 ± 51	0.90 ± 0.13
856/30	1981 Apr 27	3.92	600	West	208°	1040 ± 60	0.57 ± 0.06
856/31	1981 Apr 27	4.12	600	West	216°	726 ± 56	0.75 ± 0.09
856/32	1981 Apr 27	4.40	600	West	226°	167 ± 47	0.98 ± 0.40

[a] Universal time at midpoint of observation.

[b] System III (1965.0) longitude at the exposure midtime of the intersection point of the observation line of sight with the plane of the sky through Jupiter.

[c] For 779/32, 780/2 and 4, 782/5 and 6, the position was $5.9R_J$ from Jupiter in the satellite plane. For all other exposures, the position was $5.9R_J$ from Jupiter along the intersection of the centrifugal symmetry surface with the plane of the sky through Jupiter.

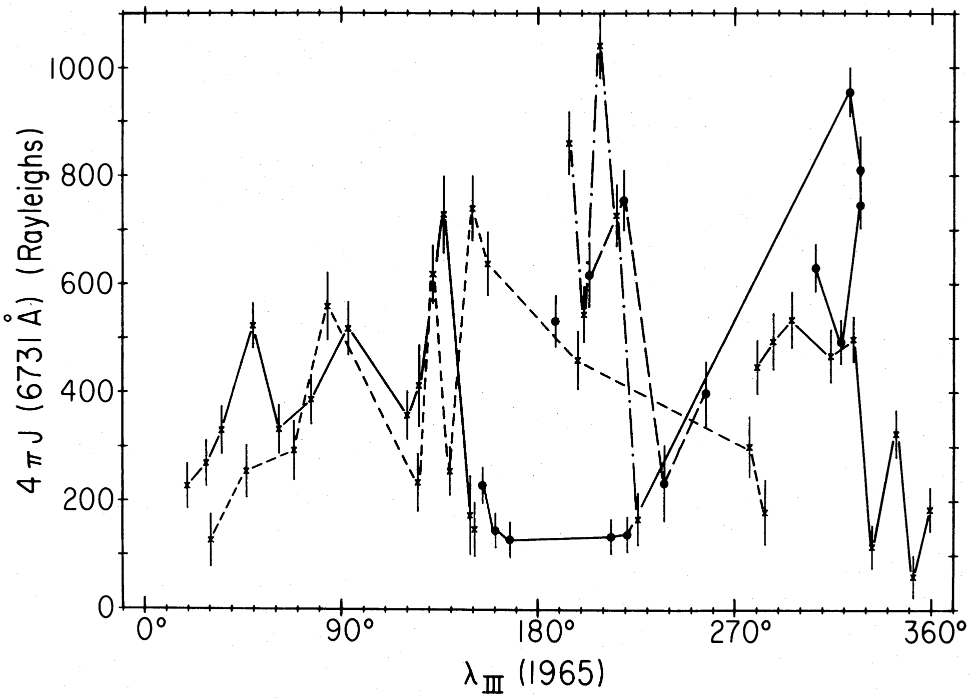

FIG. 2.—Observed S II λ6731 emission intensity at $5.9R_J$ vs. System III longitude. Dots and crosses indicate observations obtained east and west of the planet, respectively. Various lines connect consecutively obtained measurements. We find no evidence for a functional relationship between λ_{III} and S II red line intensity at $5.9R_J$.

radial gradients in both quantities (Brown 1982*b*). Second, we describe below modeling which predicts guiding errors which will produce a similar (and unobserved) correlation between S II brightness and the doublet intensity ratio. Using model comparisons, we will argue that guiding errors were small. The question of exactly what combination of radial, longitudinal, or secular changes produced the observed 10-to-1 brightness changes is separable from that concerning the relationship of mean electron density to the mean S II density along the line of sight. The data document large fluctuations in [S II] emission from a reasonably specific column through the torus, and now we intend to relate those variations to possible changes in electron density by examining the [S II] intensity ratio.

IV. THE $4\pi J$(6716 Å)/$4\pi J$(6731 Å) INTENSITY RATIO

The intensity ratio $4\pi J$(6716 Å)/$4\pi J$(6731 Å) is a classical diagnostic indicator of electron density in astrophysical emission nebulae. It was first applied to the Jupiter problem by Brown (1976), who concluded the plasmasphere was dense ($2000 < n_e < 6000$ cm^{-3}), contrary to *Pioneer* data (Frank *et al.* 1976) but as confirmed subsequently by *Voyager*. Pilcher and Strobel (1982) and Brown, Pilcher, and Strobel (1982) review optical indicators of plasma density and summarize their generally good correspondence to *Voyager* in situ measurements.

Figure 3 shows contours of constant $4\pi J$(6716 Å)/$4\pi J$(6731 Å) plotted versus electron density and temperature as computed using the collisional equilibrium model of Shemansky (1980) with a recommended change in the fine structure ($3p^3\ ^4S^o$–$3p^2 3d\ ^2D^o$) transition probabilities. This recommended change in atomic data stems partly from the Miller (1974) observations of the O II λλ3726, 3729 and S II red line doublets in the Cygnus Loop, and partly from the present observations

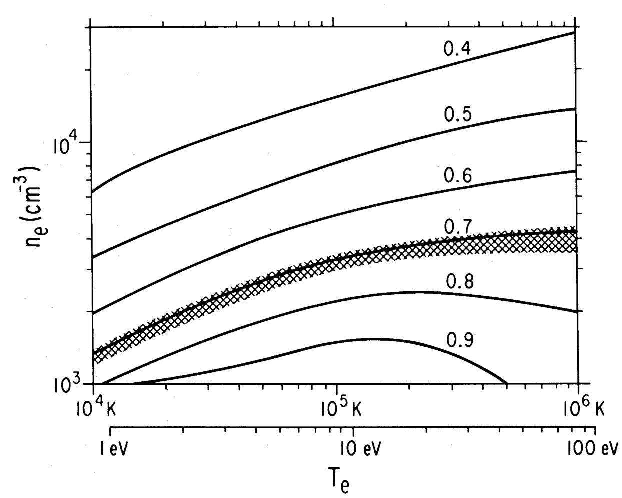

FIG. 3.—Contours indicate constant values of the S II red doublet ratio, $4\pi J$(6716 Å)/$4\pi J$(6731 Å) vs. electron density and temperature according to the calculations of Shemansky (1980). Crosshatched area is the current measurement of the average doublet ratio along a $5.9R_J$ line of sight.

as explained below. The Cygnus Loop observations are used here as a comparative standard since it is a low density supernova remnant where a greater degree of homogeneity is expected in comparison to planetary nebulae (see Saraph and Seaton 1970). The original analysis by Miller (1974) using early collision strengths calculated by Osterbrock show that electron densities calculated with the S II red lines are factors of 4–7 higher than those obtained from the O II lines for his three observational positions on the Loop. The most recent collision strengths obtained by Pradhan (see Shemansky and Smith 1981) largely correct this discrepancy, with the exception of the higher temperature position 3 of the Miller observation. A correction of $\sim 25\%$ to the S II line transition probabilities provides the best match of the Cygnus Loop S II and O II observations. The inclusion of apparently more accurate transition probabilities for the O II and S II terms recently obtained by Eissner and Zeippen (1981), Zeippen (1982), and Mendoza and Zeippen (1982) provide an improved match to the Cygnus Loop S II and O II observations. The new atomic data for O II provide the correct $[r(\infty)]$ line ratio at the high density limit (Zeippen 1982), but it is not clear that this is true for the S II lines, and we require more observational data for confirmation.

The ability to verify the suggested correction to the S II transition probabilities on other data is limited. The results improve the correspondence of the O II and S II plasma diagnostics of Morgan and Pilcher (1982), but uncertainty in radial location of those measurements limits the usefulness of this check.

The weighted average of our ratio measurements is 0.71 ± 0.02, where the uncertainty is the estimated standard deviation of the mean. $\chi^2 = 52.2$ with 52 degrees of freedom, and one expects a χ^2 in excess of that value 47% of the time, assuming only random errors and no systematic effects. In other words, the observed variation in the intensity ratio is satisfactorily accounted for by photon noise only, and other sources of variability must be small. To determine how small, we performed the following statistical experiment. For each data point, a random number was computed from a Gaussian distribution with zero mean and standard deviation σ_{ext}, and this number was added to the measured intensity ratio. The averaging and χ^2 analysis was then performed again, still using the *a priori*, photon-statistical uncertainties to normalize the residuals. By repeating this process many times for different σ_{ext}, we found the effect of this additional variability on the χ^2 probability:

σ_{ext}:	0.00	0.04	0.07	0.1
$P(\chi^2)$:	0.47	0.3	0.1	<0.01 .

From this exercise we place an upper limit to a possible underlying variability in the intensity ratio of $\sigma_{\text{ext}} < 0.07$.

The observed values of $4\pi J(6716\ \text{Å})/4\pi J(6731\ \text{Å})$ are plotted versus λ_{III} and $4\pi J(6731\ \text{Å})$ in Figures 4 and 5. It is corollary of the foregoing discussion of the data dispersion that we find no evidence for longitude or brightness dependence in the measured ratio, and these figures display that result.

The stability of the mean line ratio, shown as interval averages in Tables 3 and 4, can be used to estimate the

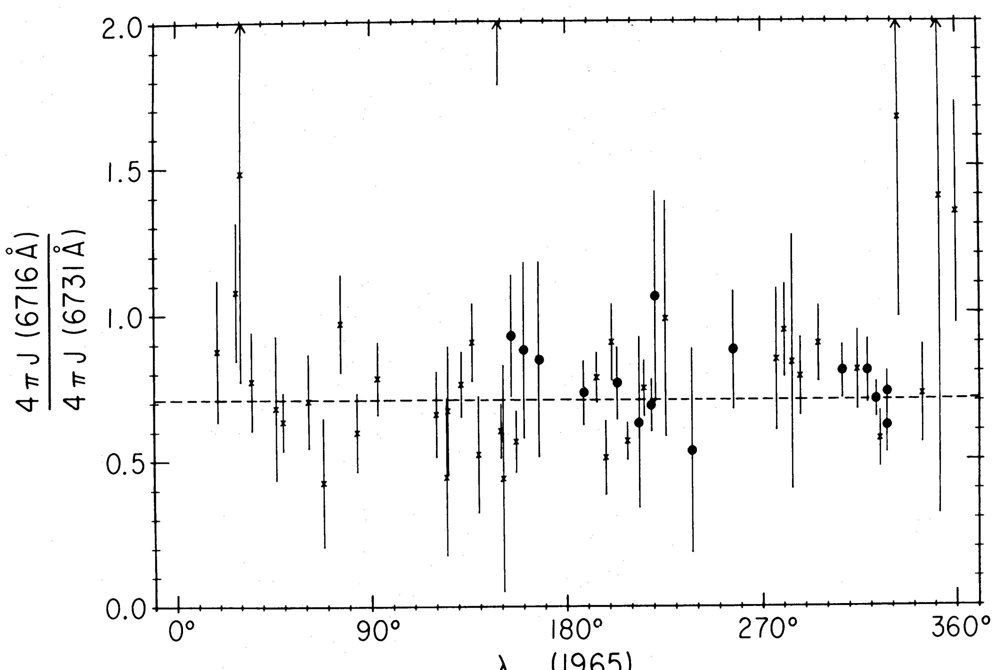

FIG. 4.—This paper's S II red doublet ratio measurements at $5.9R_J$ vs. System III longitude. Error bars terminated with arrows indicate continuation beyond plot domain. Dots and crosses indicate observations obtained east and west of the planet, respectively. Fluctuations are consistent with photon-statistical random errors in the intensity measurements, and no additional variability is evidenced.

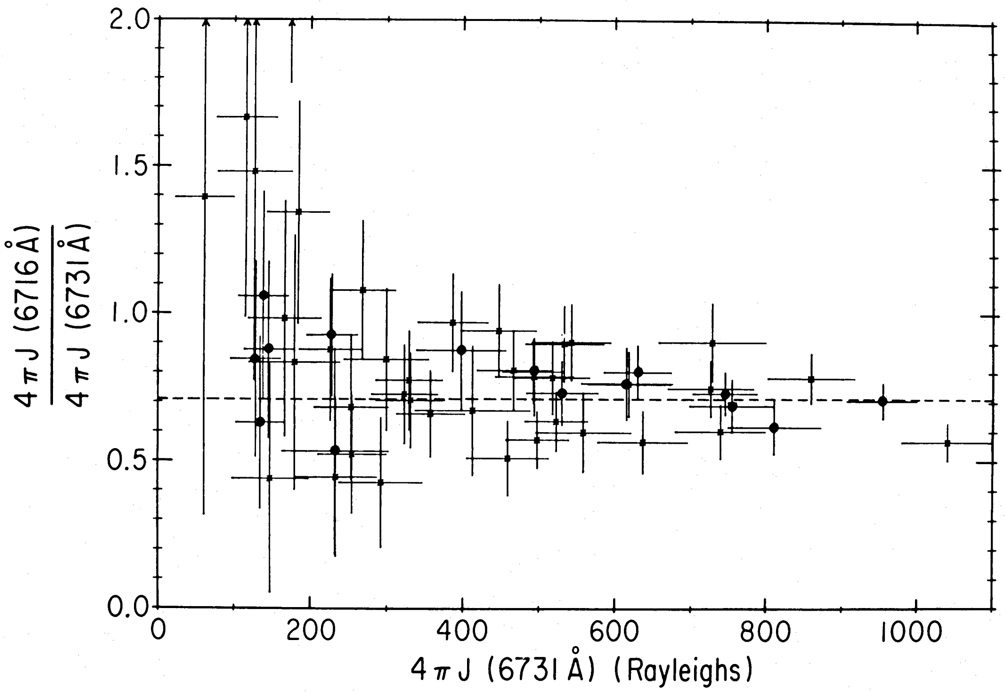

FIG. 5.—This paper's S II red doublet ratio measurement vs. the intensity of one line, $4\pi J(6731$ Å). Error bars terminated with arrows indicate continuation beyond plot domain. Dots and crosses indicate observations obtained east and west of the planet, respectively. We find no evidence for a functional relationship, which indicates *S* II brightness is decoupled from inferred plasma density for observations at 5.9 R_J.

instrument pointing accuracy using a model of the electron density–temperature structure of the torus. Smyth and Shemansky (1982) have constructed such model distributions on the basis of *Voyager* EUV and plasma science observations. The model calculation of S II red line emission for *Voyager 2* encounter conditions at a $5.9R_J$ line-of-sight position yields $4\pi J(6716$ Å$)/4\pi J(6731$ Å$) = 0.76$, and the values calculated at $6.1R_J$ and $5.7R_J$ are 0.80 and 0.67, respectively. The expected intensity variation over the same $\pm 0.2R_J$ excursion in pointing position is approximately a factor of 3. In this model, we have assumed a constant [S II]/[e] mixing ratio, so a probable decrease in that ratio with increasing radial position would increase the predicted intensity variation. The lack of a distinct correlation between the line ratio and the intensity as expected from the

TABLE 3

S II RED LINE DATA

RADIAL DISTANCE (R_J)	CURRENT OBSERVATIONS		*Voyager 2* ENCOUNTER MODEL CALCULATION[a]	
	$4\pi J(6731$ Å) (R)	$4\pi J(6716$ Å$)/4\pi J(6731$ Å)	$4\pi J(6731$ Å) (R)[b]	$4\pi J(6716$ Å$)/4\pi J(6731$ Å)
5.7	...	...	767	0.67
5.8	...	...	553	0.72
	>800	0.66 ± 0.04	...	...
	600–800	0.72 ± 0.03	...	...
5.9	400–600	0.73 ± 0.03	425	0.76
	200–400	0.75 ± 0.05	...	...
	0–200	0.93 ± 0.12	...	...
6.1	...	...	300	0.80
6.3	...	...	200	0.85
6.5	...	...	146	0.88

[a] Smyth and Shemansky 1982.

[b] Normalized to the mean observed value of 425 ± 230 R. The model then gives [S II]/[e] $= 7.1 \times 10^{-2}$. See text.

TABLE 4

LONGITUDINAL WEIGHTED AVERAGES OF S II RED LINE RATIO

λ_{III} (1965)	$\frac{4\pi J(6716\ \text{Å})}{4\pi J(6731\ \text{Å})}$
0°–90°	0.72 ± 0.05
90°–180°	0.69 ± 0.04
180°–270°	0.70 ± 0.03
270°–360°	0.74 ± 0.03

model calculations supports our view that pointing excursions probably did not contribute substantially to the observed intensity variations.

The sensitivity of the S II λλ6731 and 765 line emission rates to radial position in the model calculation is shown in Figure 6. The electron density distribution in the *Voyager 2* model peaks at $5.25R_J$ ($n_e = 2000$ cm^{-3}, $T_e = 1.7 \times 10^4$ K) in the cold torus and at $5.7R_J$ ($n_e = 5000$ cm^{-3}, $T_e = 5.5 \times 10^4$ K) in the hot torus, with the temperature of the majority electrons rising to $T_e = 3 \times 10^5$ K at $8R_J$. The 765 Å emission, which peaks at $5.7R_J$, shows a much less pronounced variation than the 6731 Å line. The 6731 Å intensity peaks at $5.25R_J$ (1.6 kR) in the model because S II is the majority ion in the cold torus ([S II]/[e] = 0.7) and a minor ion ([S II]/[e] = 0.07) in the hot torus, as discussed below. Figure 7 shows the rather strong model-predicted dependence of $4\pi J$(6716 Å)/ $4\pi J$(6731 Å) on the radial position of the line of sight. Accurate application of the S II red lines as indicators of plasma torus properties clearly requires an accurate pointing control system.

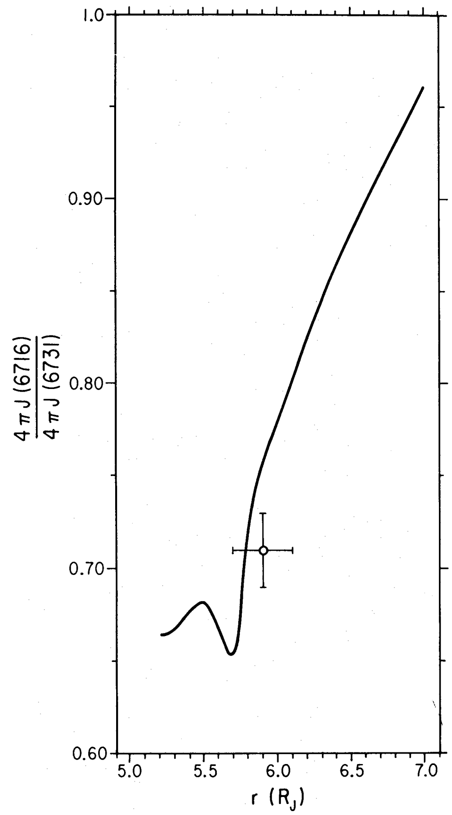

FIG. 7.—Model of Smyth and Shemansky (1982) giving the expected S II red line ratio vs. radial distance from Jupiter of the observational line of sight. Plotted point with error bars is the weighted mean value of the present observations.

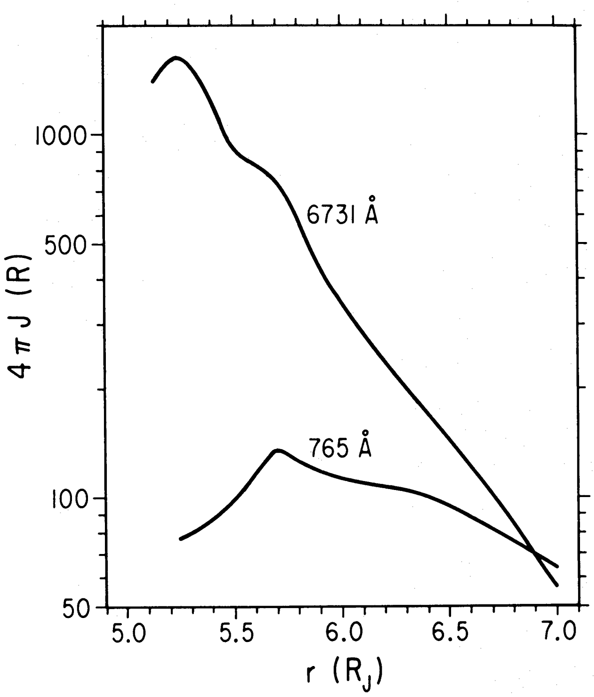

FIG. 6.—Model of Smyth and Shemansky (1982) giving the expected S II λ6731 and λ765 intensities vs. radial distance of the observational line of sight from Jupiter. The model refers to the *Voyager 2* encounter epoch, with a peak electron density of 5000 cm^{-3} at $5.7R_J$. See text for a discussion of [S II]/[e] ratio in the calculation.

The measured mean 6731 Å brightness of 425 ± 230 R in the current data is substantially higher than the Trafton (1980) value at $6.0R_J$ for the time of *Voyager 1* encounter, but it is compatible with the increased plasma density and decrease in electron temperature reported by Sandel *et al.* (1979) at *Voyager 2* encounter (see Brown 1981). The mean S II mixing ratio implied by the current data is [S II]/[e] = 0.070 based on the Smyth and Shemansky (1982) model calculation. The value [S II]/[e] = 0.075 obtained from the reanalysis of the Shemansky and Smith *Voyager 1* spectrum is very nearly the same. The application of the earlier atomic data (Shemansky and Smith 1981) to the electron density dependence of $4\pi J$(6716 Å)/$4\pi J$(6731 Å) would require a substantially lower [S II]/[e] ratio. Since it is unlikely that the mean [S II]/[e] ratio would be smaller at a time of lower electron temperature and higher plasma density, we conclude that the recommended changes in S II $3p^3\ ^2D^o$ relative line transition probabilities are reasonable.

V. DISCUSSION

The effective electron temperature derived from hot torus S II visible and UV emissions is consistent with that derived from *Voyager* UVS spectra of the dominant plasma ions. The magnitude and λ_{III} uniformity of the electron density implied by the S II red doublet ratio observations at $5.9 R_J$ are also consonant with the *Voyager* UVS findings. The hot torus S II ions are apparently a minor plasma constituent in collisional contact with the same electron population as the dominant UV emitters. Thus, we find no evidence for strong plasma density or temperature inhomogeneities in the present data.

The insensitivity of the S II line ratio to the strong observed variations in 6731 Å line intensity is a matter of special importance. As Table 3 and Figure 5 indicate, the relative constancy of $4\pi J(6716 \text{ Å})/4\pi J(6731 \text{ Å})$ over the 200–800 R intensity range rules out any comparable change in electron density averaged along the line of sight through the luminous region. Radial errors in the pointing system can cause distinct, coupled variations in line intensity and line ratio according to the model calculations shown in Figures 6 and 7 and Table 3, and images of the S II emission spatial distribution support this result (Pilcher 1980; Pilcher *et al.* 1981; Trauger 1981). Although some part of the observed intensity variation may be due to pointing motion, the dominant cause must be strong variations in S II mixing ratio, since electron density fluctuations are ruled out, and the 6731 Å rate coefficient is insensitive to electron temperature (Fig. 1). The azimuthal uniformity in $[e]$ (Fig. 4) also suggests that the radical and irregular 6731 Å intensity variations (Fig. 2) are due to fluctuations in longitude and in time of the S II mixing ratio.

By contrast to S II, there is evidence that the hot torus S III concentration is uniform in longitude and stable in time: the 685 Å brightness varied $<10\%$ with λ_{III} and was unchanged over a 0.5 yr period of reduced *Voyager* UVS data (Shemansky and Sandel 1982). Also, since S III is a major hot torus constituent, the constancy of the S II red doublet ratio is indirect testimony to S III azimuthal uniformity. Therefore, we are led to the conclusion that the hot torus [S II]/[S III] ratio displays strong secular and spatial variability. The ionization partitioning of sulfur is apparently not entirely controlled by the uniform and stable electron population responsible for producing photoemission. A decoupling of the singly and doubly ionized sulfur populations is also implied by the measured ion temperatures; S III appears to be substantially hotter than S II (Brown 1982*a*). A plasma controlled entirely by electron collisions and ion diffusive loss requires that S III ions be substantially cooler than the S II ions (see Shemansky and Sandel 1982).

It has been suggested elsewhere that charge exchange reactions share control of ion partitioning in the central, dense region of the hot torus (Brown, Pilcher, and Strobel 1982; Brown, Shemansky, and Johnson 1983), and the current work supports the view that ion-ion and ion-atom reactions are important for the plasma torus. Transient events must drive the fluctuations in the observed [S II]/$[e]$ ratio. Variations in electron temperature are unlikely as a forcing function, since the EUV transitions, which have the most sensitive dependence on this parameter, show no irregular variations (Shemansky and Sandel 1982). We suggest the [S II] fluctuations are due to sporadic injection of neutrals into the torus and subsequent ion-atom reactions, although presently known reactions do not appear adequate. Several charge exchange reactions involving O I and S I and the more highly charged ions produce S I, in addition to direct electron ionization of S II (Brown, Shemansky, and Johnson 1983); however, no presently known heavy body reaction dominates the electron loss process converting S II to S III. Both S II and S III are produced at the expense of S IV in an injection event, but the net effect on the S III population is not clear in this nonlinear system. Thus, the behavior of the plasma in response to a transient injection event is not obvious and requires detailed calculation. The relaxation time of the S II population in the dense region of the hot torus is estimated to be 7–14 days (Brown, Shemansky, and Johnson 1983). Strong variations on this time scale are thus possible and compatible with the present observations and earlier work such as that of Morgan and Pilcher (1982). The number of neutrals injected at a given time must be low enough in order not to produce more than a 5% change in electron temperature, a constraint imposed by the EUV observations. We believe this condition is not a serious impediment to the proposed mechanism to produce relatively strong, independent variation in S II population, but the major question remains concerning the net response on a time scale of a few days of the higher ions to an injection event.

The present data obtained at $5.9 R_J$ show no functional relationship between λ_{III} longitude and S II red line intensity. A strong relationship has been reported in earlier work at a variety of radial distances for Jupiter (Trafton 1980; Pilcher and Morgan 1980; Morgan and Pilcher 1982; Trauger, Münch, and Roesler 1980); however, a plot of the 6731 Å emission measurements listed by Trafton (1980) at $6 R_J$ also shows no apparent λ_{III} dependence. Future narrow-band imagery should establish the radial ranges in which stable λ_{III} intensity variations may exist, and, for this purpose, it will be particularly important to remove geometrical viewing effects caused by Jupiter's inclined magnetic pole.

We emphasize the importance of accurately determining radial position for S II red line observations since interpretations depend critically on this quantity (Figs. 6, 7). Relatively small pointing instabilities can produce strong emission variations from a constant torus plasma according to the model calculations. EUV observations are much less sensitive to this effect because the increasing electron temperature with increasing radial distance from Jupiter increases emission efficiency and tends to compensate for the opposite gradient in the torus density. It is noteworthy in particular that the

S II red line emissions do not show an easily measurable effect at the location of the hot torus density peak (Fig. 6) according to the *Voyager 2* model.

This paper draws attention to the interpretive point, namely, how variations in S II brightness are to be understood whether they are systematic in λ_{III} or not. Previous studies have assumed the intensity variations reflect change in total plasma density (Dessler 1980; Pilcher and Morgan 1980; Pilcher *et al.* 1981; Hill, Dessler, and Maher 1981; Hill, Dessler, and Goertz 1982; Shemansky and Sandel 1982). Such a connection seems likely in the cool, inner torus where S II is a dominant constituent, but it remains to be established through a demonstration of the intensity dependence of the doublet ratio with geometrical effects removed. We have shown that there exists a strong S II emission variability in, but not necessarily confined to, the hot torus and that these fluctuations are not caused by changes in total density.

VI. CONCLUSIONS

The hot torus emissions of S II over nearly a decade of energy, from 765 to 6731 Å, appear to be compatible with a single effective electron temperature, and that temperature is consistent with independent *Voyager* findings in the same region. Our 6716, 6731 Å spectra obtained at $5.9R_J$ show large intensity variability but display a doublet ratio which is invariant within the uncertainties. Since the doublet ratio is diagnostic of electron density, we find no variability in [*e*] in the observed torus volume. The S II emission variability must be caused by changes in S II mixing ratio and therefore in the [S II]/[S III] ratio. We suggest this decoupling of the S II and S III ion populations may be caused by as yet unidentified ion-ion or ion-atom charge exchange reactions. We conclude that a careful reassessment is due concerning the nature of S II brightness variations in other portions of the Jovian plasmasphere. In particular, existing arguments assuming that S II intensity manifests plasma density, which have arisen in support of the magnetic anomaly model, must be buttressed by clear evidence that such a functional relationship exists.

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