Cassini UVIS Observations of the Io Plasma Torus. 
III. Observations of Temporal and Azimuthal Variability

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ABSTRACT

In this third paper in a series presenting observations by the Cassini Ultraviolet Imaging Spectrometer (UVIS) of the Io plasma torus, we show remarkable, though subtle, spatio-temporal variations in torus properties. The Io torus is found to exhibit significant, near-sinusoidal variations in ion composition as a function of azimuthal position. The azimuthal variation in composition is such that the mixing ratio of S II is strongly correlated with the mixing ratio of S III and the equatorial electron density and strongly anti-correlated with the mixing ratios of both S IV and O II and the equatorial electron temperature. Surprisingly, the azimuthal variation in ion composition is observed to have a period of 10.07 hours—1.5% longer than the System III rotation period of Jupiter, yet 1.3% shorter than the System IV period defined by Brown (1995). Although the amplitude of the azimuthal variation of S III and O II remained in the range of 2–5%, the amplitude of the S II and S IV compositional variation ranged between 5–25% during the UVIS observations. Furthermore, the amplitude of the azimuthal variations of S II and S IV appears to be modulated by its location in System III longitude, such that when the region of maximum S II mixing ratio (minimum S IV mixing ratio) is aligned with a System III longitude of $\sim200\pm15^\circ$, the amplitude is a factor of $\sim4$ greater than when the variation is anti-aligned. This behavior can explain numerous, often apparently contradictory, observations of variations in the properties of the Io plasma torus with the System III and System IV coordinate systems.

Subject headings: Jupiter, Magnetosphere; Io; Ultraviolet Observations; Spectroscopy

1. Introduction

The Io plasma torus is a dense ($\sim2000 \text{ cm}^{-3}$) ring of electrons and sulfur and oxygen ions trapped in Jupiter’s strong magnetic field, produced by the ionization of $\sim1$ ton per second of

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neutral material from Io’s extended neutral clouds. On ionization, fresh ions tap the rotational energy of Jupiter (to which they are coupled by the magnetic field). Much of the torus thermal energy is radiated as intense (∼10^{12} \, \text{W}) EUV emissions. The ∼100 \, \text{eV} temperature of the torus ions indicates that they have lost more than half of their initial pick-up energy. Electrons, on the other hand, have very little energy at the time of ionization and gain thermal energy from collisions with the ions (as well as through other plasma processes) while losing energy via the EUV emissions that they excite.

*In situ* measurements of the Io plasma torus from the Voyager, Ulysses, and Galileo spacecraft and remote sensing observations from the ground and from space-based UV telescopes have characterized the density, temperature and composition of the plasma as well as the basic spatial structure (see review by Thomas et al. (2004)). However, the azimuthal and temporal variability of the torus remains poorly determined. Extensive measurements of torus emissions made by the Ultraviolet Imaging Spectrograph (UVIS) on the Cassini spacecraft as it flew past Jupiter on its way to Saturn allow us to further examine the azimuthal structure of the plasma torus and its changes with time.

Analysis of torus spectral emissions provides estimates of plasma composition, temperature, and density, which can then be used to constrain models of mass and energy flow through the torus. Such models can be used to derive plasma properties such as source strength, source composition, and radial transport timescale (Delamere and Bagenal 2003; Lichtenberg et al. 2001; Schreier et al. 1998). Thus, one aims to relate observations of spatial and temporal variations in torus emissions to the underlying source, loss and transport processes. Towards this ultimate goal, we present an analysis of UVIS observations of the Io torus from 1 October 2000 to 14 November 2000.

1.1. Jovian Coordinate Systems

In order to understand the UVIS observations of azimuthal variability and periodicity, it is useful to briefly review the various Jovian coordinate systems (see also Dessler (1983) and Higgins et al. (1997)). Jupiter has no fixed surface features on which measurements of its rotation period can be based. Observations of the transits of Jovian cloud features by several late 19th century astronomers, among whom were Marth (1875) and Williams (1896), led to the adoption of the “System I” and “System II” rotation periods. The System I period, based on the rate of rotation of equatorial cloud features, was defined as 9^h\, 50^m\, 30.0034^s, while the System II period, based on the more slowly rotating cloud features at high latitudes, was defined as 9^h\, 55^m\, 40.6322^s (Dessler 1983). The prime meridians of the associated longitude grids for both coordinate systems were defined to be the Central Meridian Longitude at Greenwich noon on July 14, 1897.

Attempts to derive a rotation period based on the motion of the interior of the planet, rather than the cloud tops, met with little success until the discovery of decametric (DAM; ∼20 MHz) radio emissions from Jupiter by Burke and Franklin (1955). From this radio emission, Shain (1956)
obtained the first measurement of the Jovian rotation period based on the rotation of the magnetosphere. Subsequent observations improved the accuracy of the rotation period derived from radio emissions, and a period of $9^h 55^m 29.37^s$—the weighted average of several radio observations—was defined as the “System III” (1957) rotation period (Burke et al. 1962). With further observations, it gradually became clear that this period was in need of a slight revision. Riddle and Warwick (1976) reported the weighted average of radio observations obtained since the System III (1957) period was defined; their published value of $9^h 55^m 29.71^s$ became known as System III (1965) and was adopted by the International Astronomical Union (IAU) as the standard rotation period of Jupiter (Seidelman and Devine 1977). Recently, Higgins et al. (1997) reported that the System III (1965) rotation period should be further revised to $9^h 55^m 29.6854^s$, based on 35 years of radio observations of Jupiter. This difference results in a shift of $\sim 1^\circ$ in longitude every four years relative to System III (1965). Since this shift in longitude is far less than can be measured by UVIS during the Jupiter encounter and since the proposed revision to the System III period has not yet been uniformly adopted (Russell et al. 2001), all subsequent references to “System III”, corotation, or rotation with the magnetic field, will refer to the IAU accepted Jovian rotation period: System III (1965).

1.2. Variations with System III Longitude

For the purposes of modeling, the Io plasma torus is often assumed to be azimuthally symmetric. However there have been numerous observations of the Io torus that suggest that the torus exhibits significant variation with System III longitude. Here, we present a brief review of some of these observations. An additional discussion of observations of longitudinal asymmetries can be found in Thomas (1993).

Some of the earliest observations of the Io plasma torus found that the brightness of the [S II] 6716Å/6731Å doublet was correlated with System III longitude. Trauger et al. (1980) observed this [S II] doublet using the 5 m Hale telescope on the nights of 7–11 October 1976. They found that a region extending 90° in longitude and centered on $\lambda_{III} = 280^\circ$ was consistently fainter than the rest of the torus. The [S II] brightness peaked at $\lambda_{III} \approx 180^\circ$, although given the relatively large scatter in the data, this value is poorly constrained.

Using the 2.2 m telescope of the Mauna Kea observatory, Pilcher and Morgan (1980) observed the [S II] 6716Å/6731Å doublet over a three month interval that began in December 1977. The brightness of the [S II] doublet was found to vary with longitude by as much as a factor of 4. The peak brightness was observed in the longitude range of $160^\circ < \lambda_{III} < 340^\circ$. At other times, Pilcher and Morgan (1980) found the [S II] brightness to be more azimuthally uniform, with the transition between these two states taking approximately two weeks.

Trafton (1980) reported a similar azimuthal variation in the brightness of the [S II] 6716Å/6731Å doublet in widely-spaced observations between 19 January 1976 and 19 June 1979 using the Mc-
Donald Observatory’s 2.7 m telescope. The brightness was found to vary by about a factor of 5, with a peak located at \( \lambda_{III} = 260^\circ \).

Extensive observations of the Io plasma torus were made by the ultraviolet spectrometers (UVS) aboard the Voyager 1 and Voyager 2 spacecraft (Broadfoot et al. 1977, 1981). The initial search for variations in the UV brightness of the torus with System III longitude focused on the pre-encounter period of the Voyager 2 spacecraft, which took place from days 116–144 of 1979 (Sandel and Broadfoot 1982b). During the period of day 121/16:20 UT to day 123/14:00 UT, a weak (<10%) azimuthal variation in the brightness of the S\( III \) 685Å feature was observed. This variation had a peak brightness located in the range of \( 330^\circ < \lambda_{III} < 40^\circ \) and a minimum brightness in the range of \( 140^\circ < \lambda_{III} < 200^\circ \) and was seen only in the dusk ansa of the torus. Roughly two days later, during the period of day 123/18:00 UT to day 125/12:00 UT, a stronger azimuthal variation was seen in both the dawn and dusk ansae. However, the phase of the variation had shifted by \( \sim 60^\circ \) in longitude, such that the peak in brightness was located between \( 40^\circ < \lambda_{III} < 100^\circ \) and the minimum between \( 180^\circ < \lambda_{III} < 240^\circ \).

A short-term variation with System III longitude similar to that reported by Sandel and Broadfoot (1982b) has been found in spectra from the Voyager 1 UVS (Herbert and Sandel 2000). After analyzing 47 hours of Voyager 1 UVS spectra of the Io torus, Herbert and Sandel (2000) found that both the electron density and electron temperature vary with System III longitude. The electron density variation had an amplitude of about 12% with a peak near \( \lambda_{III} = 150^\circ \) and a minimum near \( \lambda_{III} = 320^\circ \). The electron temperature variation had an amplitude of about 7% with a peak near \( \lambda_{III} = 270^\circ \) and a minimum near \( \lambda_{III} = 80^\circ \).

Although Sandel and Broadfoot (1982b) found evidence for short-term azimuthal variations in the brightness of the S\( III \) 685Å feature, they reported no significant long-lived variation of torus brightness with System III longitude during the 44-day Voyager 2 pre-encounter period. However, such a long-lived System III variation was found by Sandel and Dessler (1988), who used a Lomb-Scargle periodogram analysis (Lomb 1976; Scargle 1982; Horne and Baliunas 1986) to search for periodicities in the Voyager 2 pre-encounter data. Using similar analysis techniques (Lomb-Scargle periodograms) Woodward et al. (1994) and Brown (1995) also discovered System III periodicities in their observations of the torus [S\( II \)] 6731Å emission.

Imaging observations of the torus in 1981 by Pilcher et al. (1985) showed that the brightness of the [S\( II \)] 6731Å line varied by a factor of 6 as a function of System III longitude. The peak brightness was found to be at \( \lambda_{III} \approx 170^\circ \), although a secondary peak at \( \lambda_{III} \approx 280^\circ \) was also evident.

Also in 1981, Morgan (1985) was able to simultaneously image the [S\( II \)] 6716Å/6731Å doublet, the [S\( II \)] 4069Å/4076Å doublet, and the [O\( II \)] 3726Å/3729Å doublet, using the Mauna Kea Observatory 2.2 m telescope. On observing runs that took place from 14–17 February 1981 and 20–23 March 1981, Morgan (1985) found the brightness of both [S\( II \)] doublets varied with System III longitude, with a peak at \( \lambda_{III} \approx 180^\circ \). However, no correlation of the brightness of the [O\( II \)]

Additional imaging of the Io plasma torus at the [S II] 6731Å emission was conducted by Schneider and Trauger (1995) over six nights from 31 January 1991 to 6 February 1991. They found the longitudes $150^\circ < \lambda_{III} < 210^\circ$ to be consistently $\sim 3–4$ times brighter than the longitudes $0^\circ < \lambda_{III} < 170^\circ$. More detailed examination revealed that the variation of brightness with longitude was weakest on 31 January 1991 with a poorly-constrained maximum near $\sim 120^\circ$. Three nights later, the variation with longitude was significantly stronger, and the peak had shifted to a longitude of $\sim 170^\circ$. Finally, on the last night of observation (5 February 1991), the amplitude of the longitudinal variation remained relatively large, and the peak had shifted further to a longitude of $\sim 210^\circ$. Schneider and Trauger (1995) interpreted the shift in phase of $\sim 18^\circ$/day as evidence for a possible 2.1% subcorotation (relative to rigid corotation) of a torus feature. Additionally, Schneider and Trauger (1995) proposed that the modulation of the amplitude of the longitudinal variation might explain why numerous previous observations had detected an enhanced brightness of S II in the “active sector” (a sector spanning roughly 90° in longitude centered around $\lambda_{III} \approx 180^\circ$): the amplitude of the variation is greatest when the peak lies within this region and is diminished when it lies outside.

Spectra of the Io torus obtained on 10–11 February 1992 showed that the brightness of the [S II] 6716Å/6731Å doublet and the S III 6312Å line were correlated. These spectral features peaked in brightness at a System III longitude of $\approx 180^\circ$ (Rauer et al. 1993).

In contrast to observations of the S III 685Å feature by the Voyager 1 and Voyager 2 UVS (Sandel and Broadfoot 1982b; Herbert and Sandel 2000), Gladstone and Hall (1998) found no correlation between the brightness of torus emission between 70–760Å and System III longitude.

Emission from the [S IV] 10.51 μm line was discovered in observations of the Io plasma torus on 25 May 1997 using the Infrared Space Observatory (Lichtenberg et al. 2001). The brightness of this feature was found to vary by $\sim 20\%$ with System III longitude with a poorly-constrained peak near $\lambda_{III} \approx 120^\circ$.

1.3. Subcorotating Torus Phenomena and “System IV”

In the 29 years since its discovery by Kupo et al. (1976), there have been numerous observations of phenomena occurring in the Io plasma torus having a period longer than the System III rotation period. There have also been several direct measurements of the torus plasma lagging corotation with System III. To place our results into proper context, we present a brief review of these observations.
1.3.1. Radio Emissions

The first indications that plasma in the Io torus might not be rigidly corotating with Jupiter’s magnetic field came from the Planetary Radio Astronomy (PRA) experiments aboard the two Voyager spacecraft. The Jovian narrow-band kilometric radiation (nKOM), first described by Kaiser and Desch (1980), is emitted from source regions lying in the outer Io plasma torus at radial distances of $\sim 8–9 \, R_J$. Kaiser and Desch (1980) found that the rotation period of Jovian narrow-band kilometric radiation (nKOM) source regions was 3.3% slower than the System III rotation period during the Voyager 1 encounter and 5.5% slower during the Voyager 2 encounter.

The initial analysis by Kaiser and Desch (1980) of the Jovian nKOM emissions observed by the Voyager PRA experiments covered only a relatively short period ($\sim 45$ Jovian rotations) during each spacecraft encounter. A statistical analysis of all detections of nKOM by both Voyager PRA experiments between 14 January 1979 and 31 December 1979 (the period when the spacecraft were within 900 $R_J$ of Jupiter) found that the rotation period of the nKOM sources was not constant (Daigne and Leblanc 1986). Rather, the rotation periods for individual nKOM sources varied between 0–8% longer than the System III rotation period with average values of 3.2% and 2.7% for Voyager 1 and Voyager 2, respectively. The large range of values reflects intrinsic variability in the rotation period of the nKOM sources rather than errors in measurement, which are estimated to be $\sim 1\%$. Although the rotation period of individual nKOM sources generally lagged the System III rotation period, the probability of observing nKOM emission was found to be significantly greater when the spacecraft were at System III longitudes of 40° and 300°.

The order of magnitude greater sensitivity and direction-finding capabilities of the Unified Radio and Plasma Wave instrument (URAP) on the Ulysses spacecraft allowed the detection of six distinct nKOM source regions during the Ulysses encounter with Jupiter in February, 1992 (Reiner et al. 1993). These source regions were found to lie at radial distances of 7.0–10.0 $R_J$ and to have a rotation periods ranging from 3.0–8.6% greater than the System III period (again the range in values represents the variability of the individual nKOM sources, rather than measurement uncertainty). In addition, to the subcorotation period of nKOM source regions, URAP also detected a new component of the Jovian hectometer radiation (HOM) that recurs with a period 2–4% longer than the System III rotation period (Kaiser et al. 1996). Reexamination of Voyager 1 and Voyager 2 PRA data found similar results. Based partly on the spectroscopic observations of Brown (1995), which were concurrent with the Ulysses encounter, Kaiser et al. (1996) conclude that the new HOM component is the result of an HOM source region in the high-latitude regions of Jupiter being periodically blocked by a high-density region in the Io torus.

1.3.2. In Situ Plasma Measurements

In situ measurements of the bulk rotation velocity of the torus plasma have been made by the Plasma Science (PLS) instruments aboard the Voyager 1 and Galileo spacecraft and the URAP
instrument aboard the Ulysses spacecraft. The Voyager 1 PLS found that the torus plasma was within a couple percent of rigid corotation inside of 5.7 R_J, but between 5.9–10 R_J, deviations from corotation of up to 10% could not be ruled out (Bagenal 1985). The Ulysses URAP instrument measured two components of the dc electric field during its fly-through of the outer Io torus, and from this derived the flow speed of torus plasma (Kellogg et al. 1993). URAP found the plasma flow speeds to be generally close to corotation but with significant deviations having an rms value of 5.3 km/s. Finally, on five passes through the Io torus, the Galileo PLS observed that the bulk plasma flow lagged the corotation velocity by 2–10 km/s, with an average deviation of ∼2–3 km/s (Frank and Paterson 2001).

1.3.3. Spectroscopic Measurements

The first direct observation of a corotational lag in the Io torus plasma came from analysis of the Doppler shift of the [S II] 6716 Å/6731 Å doublet (Brown 1983). Using observations from two nights in February, 1981 and three nights in April, 1981, Brown (1983) found that the radial velocity of S II deviated from rigid corotation by 6%±4%, where the ±4% represents the variability of the derived corotation lag, rather than the measurement uncertainty.

Observations of [S III] 9531 Å emitted from the dusk side of the torus between 12 April 1982 and 30 April 1982 found that the torus brightness was not correlated with the System III rotation period, but rather with a period of 10.2±0.1 hours, 2.8% longer than the System III period (Roesler et al. 1984). These observations were obtained between 12 April 1982 and 30 April 1982 using a scanning Fabry-Perot spectrometer that had a field of view 2 R_J in diameter centered at a radial distance of 6 R_J. This was the first detection of a long-lived (roughly 43 rotations of Jupiter) periodic phenomenon in the Io torus at a period other than System III. A reanalysis of this data by Woodward et al. (1994) confirmed the existence of a 10.20 hour periodicity in the data and found a statistically significant secondary periodicity at the System III rotation period. Additional ground-based observations of [S III] 9531 Å and [S II] 6731 Å emission from the Io torus in March and April, 1981 by Pilcher and Morgan (1985) and Pilcher et al. (1985) were interpreted as requiring a torus rotation period a few percent longer than System III, consistent with Roesler et al. (1984).

The reported subcorotation of the nKOM source regions (Kaiser and Desch 1980), the 10.2-hour periodicity in the brightness of [S III] 9531Å (Roesler et al. 1984), and analysis of Voyager Ultraviolet Spectrometer (UVS) data (Sandel 1983), led Dessler (1985) to propose a new Jovian coordinate system known as “System IV” that rotates 3.1% slower than System III. The proposed System IV coordinate system was further refined by Sandel and Dessler (1988). Using a Lomb-Scargle periodogram analysis of the brightness of the Voyager 2 UVS 685 Å feature, (a feature dominated by three multiplets of S III though also containing emissions from S IV and O III), Sandel and Dessler (1988) found evidence for periodicity at both the System III period, and at a period of 10.224 hours, 3.0% longer than System III. In addition, Sandel and Dessler (1988) noted that the azimuthal variation in brightness was greatest when these two periods were aligned. The
observed period of 10.224 was used to define the System IV (1979) coordinate system. The prime meridian of the System IV (1979) coordinate system was defined such that the peak of the 685 Å emissions occurred near $\lambda_{IV}=180^\circ$. Recent analysis of 47 hours of Voyager 1 UVS spectra of the Io torus by Herbert and Sandel (2000) found both electron density and electron temperature to be organized in System IV longitude. However, the uncertainty in these quantities is larger than the observed System IV modulation.

The first observational program designed specifically to look for periodicities in the Io torus was undertaken in 1988 (Woodward et al. 1994). Woodward et al. (1994) observed emission of $[\text{S II}]$ 6731Å from the Io torus over a 35 day period using a Fabry-Perot spectrometer similar to that used by Roesler et al. (1984). After careful analysis of their data using weighted Lomb-Scargle periodograms, they found periodicity in the torus $[\text{S II}]$ intensity at 10.14±0.03 hours—a period intermediate of System III and System IV—and at 9.95 hours, consistent with the System III period.

In an effort to address the apparent inconsistencies between the previous spectroscopic measurements, Brown (1994b) observed the $[\text{S II}]$ doublet at 6717Å and 6731Å over a six month period in 1992 using a long-slit echelle spectrograph. To date, this remains the longest time baseline of torus observations, and it thus provides the most accurate measurement of the periodicities in the torus. Using the now ubiquitous Lomb-Scargle periodogram analysis, Brown (1995) found significant periodicity in the torus at both the System III period and a period of 10.214±0.006 hours—2.91% longer than the System III period. The latter period was found to remain constant between the radial distances of 5.875 and 6.750 $R_J$ and provides the basis for a minor revision to the System IV (1979) coordinate system known as System IV (1992). Subsequent references to “System IV” will refer to the System IV (1992) period defined by Brown (1995).

During the observing period, the variation of $[\text{S II}]$ line brightness with System IV longitude underwent a sudden phase shift of $\sim100^\circ$. The sudden shift in phase resulted in a spurious weak peak in the dawn ansa periodogram at a period of 10.16 hours—quite similar to the value reported by Woodward et al. (1994). By subdividing the data into two groups (before and after the sudden phase shift) the peak in the dawn ansa periodogram becomes 10.217±0.010 hours, consistent with the value of 10.214±0.006 hours obtained from the dusk ansa. In light of the discovery that the phase of System IV variations can shift rapidly, Woodward et al. (1997) reanalyzed their 1988 data and found a similar phase shift was responsible for the reported periodicity of 10.14±0.03 hours. By subdividing their data into two groups they found that the primary periodicity in the data was, in fact, at 10.2 hours, consistent with the System IV period.

Direct measurements of the radial velocity of the torus plasma as a function of radial distance were obtained by measuring the Doppler shift in the sum of all 222 spectra obtained in 1992 (Brown 1994a). The torus plasma was found to lag rigid corotation with System III, with the amount of corotational lag being a strong function of radial distance. The corotational lag reached a maximum deviation of $\sim4$ km/s in the range of 6–6.5 $R_J$. Between 6–7 $R_J$, the torus lags
corotation by an average of 2%. This measurement, coupled with the observation that the System IV period remained constant between 5.875 and 6.75 \( R_J \), led Brown (1995) to conclude that the System IV periodicity cannot be caused by plasma lagging corotation.

The radial velocity profile of the Io torus was measured again in October 1999 using the 3.5 m European Southern Observatory’s New technology Telescope (NTT) (Thomas et al. 2001). The radial velocities derived from \( S\,\text{II} \) and \( S\,\text{III} \) emission lines were in good agreement with the range in velocities measured by Brown (1983) and Brown (1994a), however the larger collecting area of the NTT telescope enabled Thomas et al. (2001) to place much smaller relative error bars on their radial velocity profiles. The radial velocity measurements of Thomas et al. (2001) represent a snapshot of the Io torus radial velocity profile (they were derived from a single integration) whereas the radial velocity profile of Brown (1994a) represents the average profile over a six-month period.

Finally, a multi-year campaign to determine the long-term variability of torus \([S\,\text{II}] 6731\,\text{Å} \) and \(6716\,\text{Å} \) emissions has been carried out by Nozawa et al. (2004). Using small telescopes (diameters of 28 cm and 35 cm), Nozawa et al. (2004) obtained data in four observing seasons between 1997 and 2000. Using Lomb-Scargle periodogram analysis, they found periodicities of 10.18±0.06 hours in 1998, 10.29±0.14 hours in 1999, and 10.14±0.11 hours in 2000, all within measurement uncertainty of the 10.214 hour System IV period. Data from the 2000 observing season were acquired between 15 December 2000 and 5 January 2001, concurrent with the Cassini spacecraft’s closest approach with Jupiter, but more than 30 days after the data presented in this paper were acquired.

2. Observations and Data Analysis

The data used in this paper were obtained by the Cassini spacecraft’s Ultraviolet Imaging Spectrograph (UVIS) (Esposito et al. 2004) between 1 October 2000 and 15 November 2000 (DOY 275–320) during the inbound leg of Cassini’s Jupiter flyby. During this period, while the spacecraft was between 1100 \( R_J \) and 600 \( R_J \) from the planet (1 \( R_J \)=71,492 km), 1904 spectrally-dispersed images of the Io torus, in its entirety, were acquired. All of these spectral images have an integration time of 1000 seconds. The duty cycle for UVIS consisted of six 20-hour blocks. During blocks 1, 2, 5, and 6 UVIS observed the Io torus for 9 consecutive hours followed by 11 hours of downlink and observations of other targets. Blocks 3 and 4 consisted of 28 hours of torus observation followed by 12 hours of downlink and other observations. This cycle was repeated nine times. Additional information about this dataset, including examples of the observing geometry, images of the raw and processed data, and descriptions of the data reduction and calibration procedures used, can be found in Steffl et al. (2004).

Since the encounter distances were so large, the spatial resolution of this dataset is relatively coarse (0.6–1.1 \( R_J \) per detector row). We therefore limited our analysis to spectra from the ansa region on both sides (dawn and dusk) of the torus. The ansa region was defined as the part of the torus subtended by the brightest row on the detector, plus the two neighboring rows. Spectra
contained in these three rows were averaged together to obtain the ansa spectrum. The decreasing
distance of the Cassini spacecraft to Jupiter during the observation period meant that the range
of projected radial distances in the Io torus from which the ansa spectra were extracted went from
4.5–8.0 \(R_J\) on 1 October 2000 to 5.2–7.0 \(R_J\) on 15 November 2000.

The Io torus spectral model described in Steffl et al. (2004) was used to derive the ion com-
position, electron temperature, and electron column density from the spectra extracted from each
ansa of the torus. Spectra from the dawn and dusk ansae of the torus are fit independently of
each other and yield statistically identical results. For clarity of presentation, all figures (with the
exception of Fig. 2) show results from only one of the torus ansae.

Since the long axis of the UVIS entrance slit was oriented parallel to the Jovian equator,
information about the latitudinal distribution of the Io torus is convolved with spectral information
along the dispersion direction of the detector. To separate theses effects, we assume a Gaussian
scale height for the torus plasma, the value of which is a parameter fit by the model. Additionally,
we assume that the scale heights for all ion species present in the torus are equal. Although this
last assumption is somewhat unphysical, given the relatively coarse spatial resolution of the UVIS
dataset, it has no significant effect on our results.

3. Results

3.1. Temporal Variation in Torus Composition

Figure 1 shows how the mixing ratios (ion density divided by electron density) of four ion
species in the torus: \(S^{\text{II}}\), \(S^{\text{III}}\), \(S^{\text{IV}}\), and \(O^{\text{II}}\), and electron temperature vary with time during the
observation period. The most obvious long-term change is that the mixing ratio of \(S^{\text{II}}\) falls from
0.10 to 0.05 over a 45-day timescale, while the mixing ratio of \(S^{\text{IV}}\) increases from 0.02 to 0.05 over
the same period. The mixing ratios of \(O^{\text{II}}\) and \(S^{\text{III}}\), the two dominant ion species in the torus,
remain relatively constant. The temporal changes in the composition of the torus plasma coupled
with observations by the Galileo Dust Detector System of a four-orders-of-magnitude increase in
the amount of dust emitted from Io (Krüger et al. 2003) led Delamere et al. (2004) to propose
a factor of 3–4 increase in the amount of neutral material available to the torus on, or around,
4 September 2000. Torus chemistry models including such an increase in the neutral source rate
(along with a corresponding increase in the amount of hot electrons in the torus) can closely match
the observed changes in plasma composition with time.

3.2. Azimuthal Variations in Torus Composition

Over the 45-day inbound staring period, the long-term variations of torus parameters with
System III longitude are relatively small. The relative variation of the EUV luminosity of the
Fig. 1.— Ion mixing ratios (ion column density divided by electron column density) and electron temperature versus time, as derived from the dusk ansa of the torus. Owing to uncertainty in the absolute calibration of the UVIS Extreme Ultraviolet (EUV) channel below 800 Å, the electron temperature is presented in relative units. Results from the dawn ansa are similar.
torus ansae with System III longitude is only about 5%, with a maximum near \( \lambda_{III}=120^\circ \) and a secondary peak near \( \lambda_{III}=270^\circ \) (Steffl et al. 2004). The relative variations of electron density and electron temperature with System III longitude are shown in Fig. 2. Like the EUV luminosity, both electron density and electron temperature show long-term variations of only \( \sim5\% \). In contrast, however, the variations of both electron density and electron temperature show a single, clearly defined peak with a single, clearly defined minimum. Although there is a large amount of scatter in the individual data points, the average variation in electron density is clearly anti-correlated with the average variation in electron temperature: the electron density has a maximum value near \( \lambda_{III}=160^\circ \), while the electron temperature has a minimum value near \( \lambda_{III}=170^\circ \).

Although the torus exhibits relatively small variations with System III longitude on long timescales, azimuthal variations of up to 25% are observed on timescales of a few days. This can be seen in the high-frequency component of the curves in Fig. 1. All four ion mixing ratios, as well as the relative electron temperature and column density, exhibit near-sinusoidal variations with a period close to that of the 9.925-hour System III (1965) rotation period of Jupiter. This can be more readily seen in Fig. 3, which shows the mixing ratios of S II, S III, S IV, and O II; the electron temperature, and the electron column density as derived from the dusk ansa of the torus over a typical three day period (DOY 276.5–279.5). Results from the dawn ansa are virtually identical to those from the dusk ansa presented here, but the phase is shifted by 180°. For ease of comparison, we present these quantities normalized to their average value over the three day period. The overplotted solid curves are best-fit sinusoids to the data. These sinusoids have a period equal to the System III rotation period of Jupiter.

The mixing ratios of S II and S IV, and the electron temperature and column density show variations of roughly 25% over this three day period, while the mixing ratios of S III and O II show variations near the 5% level. In addition, the variations of S II, S III, and electron column density are close to being in phase with each other, while at the same time, they are nearly 180° out of phase with the variations in S IV, O II, and electron temperature. The strong anti-correlation between the mixing ratios of S II and S IV can also be seen in the brightnesses of individual spectral features. Figure 4 shows the integrated luminosity from the dusk half of the torus for two pairs of S II and S IV lines. Since the spectral features in each pair are close to each other in wavelength, they have roughly the same excitation energies and therefore are unaffected by variations in electron temperature. Additionally, the confidence interval analysis presented in Fig. 8 of Steffl et al. (2004) shows that the S II and S IV mixing ratios derived from the spectral fitting model are only very weakly correlated and therefore, the strong anti-correlation of these quantities cannot be merely an artifact of the spectral fitting model.

Given that the only significant production mechanism for S IV is the electron impact ionization of S III (which becomes more efficient at higher temperatures for values typical of the Io torus):

\[
S^{2+} + e^- \rightarrow S^{3+} + 2e^-
\]  

(1)
Fig. 2.— Relative torus electron density and electron temperature versus System III longitude from both dawn and dusk ansae. Values have been normalized to the azimuthally-averaged value at the time each observation was made. The solid lines represent the average of the data in 10° longitude bins. Both electron density and electron temperature show a long-term correlation with System III longitude of ∼5%. Although the scatter of the individual data points is considerable, on average, the electron density is anti-correlated with the electron temperature.
Fig. 3.— Relative ion mixing ratios, electron temperature, and electron column density for a typical 3-day period obtained from the dusk ansa. Values are normalized to the average value over the 3-day period. The best-fit sinusoids for this period are overplotted. Note the strong anti-correlation of S II with S IV and equatorial electron temperature with equatorial electron column density.
Fig. 4.— Integrated luminosity for two pairs of closely-spaced S II and S IV spectral features from the dusk half of the torus. Although the error bars for an individual spectral feature are significantly larger than the error bars for the mixing ratios derived from the simultaneous fit to all spectral features (i.e. Fig 3), the anti-correlation of S II and S IV is readily apparent.
it is not surprising that the S IV mixing ratio is positively correlated with electron temperature. For S II, electron impact ionization is both a source and a loss process:

\[ S + e^{-} \rightarrow S^+ + 2e^- \]  \hspace{1cm} (2)
\[ S^+ + e^- \rightarrow S^{2+} + 2e^- \]  \hspace{1cm} (3)

As the electron temperature increases the loss rate of S II via Eq. 3 more rapidly than the production rate via Eq. 2, S II should show an anti-correlation with electron temperature, which is what is observed. A similar anti-correlation between parallel ion temperature and equatorial electron density has been reported by Schneider and Trauger (1995). This anti-correlation results from the increased radiative cooling efficiency of the torus with higher electron densities.

One of the historical difficulties in understanding the Io plasma torus has been to separate phenomena that are legitimately time variable from those that are the result of spatial variations in the torus that rotate in and out of the observation’s field of view. Since the observed variations have a period very close to the rotation period of Jupiter, and since the timescales for chemical processes, such as charge exchange, ionization, recombination, etc., which produce significant changes in the Io torus are generally much longer than this (Shemansky 1988; Barbosa 1994; Schreier et al. 1998; Delamere and Bagenal 2003; Delamere et al. 2004), the only plausible explanation is azimuthal variability.

In order to quantify the azimuthal variations in composition, we fit generalized cosine functions to the ion mixing ratios obtained within a 50-hour window centered on each data point (e.g. the sinusoidal curves in Fig. 3):

\[ M_i(\lambda_{III}) = A_i \cos(\lambda_{III} - \phi_i) + c_i \]  \hspace{1cm} (4)

where \( M_i \) is the ion mixing ratio at the torus ansa; \( A_i \) is the amplitude of the compositional variation; \( \phi_i \) is the phase of the variation, i.e. the longitude of the compositional maximum; and \( c_i \) is a constant offset, i.e. the azimuthally-averaged value. The amplitude, phase, and constant offset were allowed to vary, while \( \lambda_{III} \), the System III longitude of the ansa (dawn or dusk), is determined from the time of the observation. Since we are using the System III longitude of the ansa to determine the phase of the compositional variation, we are implicitly assuming that the period of the variations is the 9.925 hour System III Jovian rotation period. The 50-hour window was chosen as a compromise between the need for enough data points to produce a robust fit to the data and the need to minimize the effects of the actual temporal changes in torus composition evident from Fig. 1. The results of the sinusoidal fits are insensitive to the size of the sliding window used for windows smaller than \( \sim 100 \) hours. Although there is some scatter in the data, the simple sinusoidal fits provide a good match to the conditions in the Io torus.
3.3. Torus Periodicities

3.3.1. Drift of Phase With Time

The locations of the peak mixing ratio, i.e. the phase ($\phi_i$) of the azimuthal variation, for each of the four ion species are plotted versus time in Fig. 5. As in Fig. 3, the phase of the azimuthal variation for S II tracks with that of S III, while the phase of S IV tracks roughly with the phase of O II, both of which are shifted approximately 180° from the phase of S III and S II. All four of the main ion species in the torus exhibit phase increases that are roughly linearly with time. Since the System III coordinate system is a left-handed coordinate system (System III longitude increases clockwise when viewed from the north, such that the sub-observer longitude increases with time for an observer fixed in inertial space. See Dessler (1983) for more information.) an increase in phase with time implies that the pattern of compositional variation is rotating more slowly than Jupiter’s magnetic field. The linear nature of the phase increase implies that the rate of the subcorotation of the compositional variation is approximately uniform during the observation period.

The difference in angular frequency, $\Delta \Omega$, between the subcorotating compositional variation and the magnetic field of Jupiter (System III) can be derived from the slope of the phase increase
Fig. 6.— Linear fit to phase increase with time. The solid curve represents the phase of azimuthal variations in composition. The solid line is the line best fit to this data. The dotted line represents the slope (the intercept of this line is arbitrary) the data would have if the plasma in the Io torus were subcorotating at the System IV period defined by Brown (1995).

with time. We used a single linear function to fit the slope of the phase increases for each of the three sulfur ion species (both dawn and dusk ansae) simultaneously. The resulting fits are presented in Fig. 6. The dotted lines show the slope that would be observed if the compositional variations in the torus plasma were rotating at the System IV period defined by Brown (1995). The value of ∆Ω derived from the three sulfur ion species is 12.5°/day, corresponding to a period of 10.07 hours—1.5% longer than the System III period of 9.925 hours. At a radial distance of 6 R_J, this corresponds to a drift of 1.1 km/s relative to the magnetic field. The value of ∆Ω derived from the UVIS data is slightly less than half the previously reported values of ∆Ω ∼24.3°/day, which are the basis for the System IV period (Sandel and Dessler 1988; Woodward et al. 1994; Brown 1995).

Although the phase increase is roughly linear, especially for S III, there are several deviations from linearity. For example, O II appears to have a greater slope in the period before DOY 295 than after, S II and S IV show an increase in slope during the period of DOY 291-309, and all four ion species show a decrease in slope after day 310.
Fig. 7.— Lomb-Scargle periodogram of UVIS dusk ansa S II data. The primary peak of the periodogram is found below the System III rotation frequency, but above the System IV rotation frequency of Brown (1995).

3.3.2. Periodograms

In order to examine our data for periodicities, we have constructed Lomb-Scargle periodograms (Lomb 1976; Scargle 1982; Horne and Baliunas 1986) using the fast algorithm of Press and Rybicki (1989). The periodogram created from the UVIS dusk ansa S II data is shown in Fig. 7. Periodograms created using from the S III, S IV, or O II data are quite similar; likewise, periodograms made from the dusk ansa data are virtually indistinguishable from periodograms made from the dawn ansa data. The periodogram has a very large peak near a frequency of 0.10 h$^{-1}$, with smaller peaks occurring near 0.05 h$^{-1}$ and its harmonics. A secondary peak, located at Io’s orbital frequency of 0.024 h$^{-1}$, is seen only in the S II data, in contrast to Sandel and Broadfoot (1982a) who report a strong correlation of the brightness of the S III 685Å feature with Io’s phase. No other significant peaks are present in the UVIS periodograms.

The lower panel of Fig 7 shows the region around the primary peak in more detail. The locations of the System III and System IV frequencies are also shown. The sharp peak seen in the upper panel actually consists of two closely spaced but separate peaks: the primary located at a frequency of 0.099277 h$^{-1}$ (period of 10.073 h) and the secondary at 0.10061 h$^{-1}$, slightly below the System III frequency of 0.10076 h$^{-1}$. The periods obtained from the frequency of the peak in
The periodograms are given in Table 1.

<table>
<thead>
<tr>
<th>Ion Species</th>
<th>Dusk Ansa</th>
<th>Dawn Ansa</th>
</tr>
</thead>
<tbody>
<tr>
<td>S II</td>
<td>10.073 ± 0.0036 h</td>
<td>10.073 ± 0.0039 h</td>
</tr>
<tr>
<td>S III</td>
<td>10.057 ± 0.0125 h</td>
<td>10.061 ± 0.0140 h</td>
</tr>
<tr>
<td>S IV</td>
<td>10.067 ± 0.0039 h</td>
<td>10.073 ± 0.0039 h</td>
</tr>
<tr>
<td>O II</td>
<td>10.049 ± 0.0188 h</td>
<td>10.051 ± 0.0203 h</td>
</tr>
</tbody>
</table>

Table 1: Peak Periodogram Values and Uncertainties

$^a$ 3σ uncertainty derived from the 99.7% value of synthetic datasets

The probability that the tallest peak in a Lomb-Scargle periodogram is the result purely of Gaussian-distributed noise in the data (also known as the false alarm probability) can be derived from the height of the tallest peak according to the equation:

$$F = 1 - \left[1 - \exp^{-h}\right]^{N_i} \quad (5)$$

where $h$ is the height of the tallest peak and $N_i$ is the number of independent frequencies in the periodogram. It is worth noting that Eq. 5 is only valid for the tallest peak, and cannot be used to assess the significance of any other peaks present in the periodogram, such as the peak near the System III frequency.

While it is relatively straightforward to use Eq. 5 to obtain the significance of the primary peak in a Lomb-Scargle periodogram, it is much trickier to obtain an estimate of the uncertainty in the frequencies of the peaks present, $\Delta f$. Kovács (1981) derives several expressions for calculating the $\Delta f$ from standard periodogram methods, the derivation assumes the data contain only a single periodic signal with Gaussian noise, even data spacing, and no gaps in the data. Although Baliunas et al. (1985) found that these expressions were still valid in the case of unevenly sampled data, the UVIS data contain numerous gaps in the data and may also contain signals at multiple frequencies, rendering this approach invalid.

An order-of-magnitude estimate of $\Delta f$ can be made by assuming that $\Delta f$ is equal to the difference in frequency between a periodic signal that completes $n$ cycles during the observing period and one that completes $n + \frac{1}{2}$ cycles. The UVIS inbound staring mode observing period lasted slightly less than 1066 hours, which leads to a $\Delta f$ of $4.69 \times 10^{-4}$ h$^{-1}$. For a signal with a period of $\sim$10 hours, this corresponds to an uncertainty of 0.05 hours.

This method of estimating $\Delta f$ is clearly an oversimplification as it fails to account for the actual sampling rate or the level of noise present in the data. We therefore adopt the approach of Brown (1995) and use synthetic data sets to estimate the uncertainty in our determination of frequency. We constructed 1000 synthetic data sets containing a single periodic signal with a period of 10.073 hours. This signal had an amplitude similar to that observed by UVIS and was sampled at the
Fig. 8.— Comparison of real UVIS S II data from the dusk ansa with synthetic data. The synthetic data consist of a sinusoidal variation with a period of 10.073 hours with added Gaussian noise sampled at the same times as the UVIS observations. The amplitude of the sinusoidal variation in the synthetic data changes with time in order to match the real UVIS data.

We created a Lomb-Scargle periodogram from each synthetic dataset. An example of a periodogram created from one of the synthetic datasets is presented in Fig. 9. Like the periodogram created from the real data, c.f. Fig. 7, the synthetic periodogram contains a large peak near $0.10 \, \text{h}^{-1}$ with secondary peaks near $0.05 \, \text{h}^{-1}$ and $0.15 \, \text{h}^{-1}$. The presence of the secondary peaks in the synthetic periodogram implies that they are the result of what Horne and Baliunas (1986) call “spectral leakage”—side lobes caused by the data sampling and the finite observation period. Since there is a 20-hour periodicity in the actual data sampling, it should not be surprising that spectral power from the primary peak is aliased to these frequencies.

For each synthetic periodogram, we recorded the difference between the frequency of the peak and the frequency of the periodic signal actually present in the synthetic data. We assigned the 68.3%, 95.5%, and 99.7% values a significance of $1\sigma$, $2\sigma$ and $3\sigma$, respectively. This method yielded
Fig. 9.— Periodogram from synthetic S II data. The primary peak is displaced slightly from the actual period in the synthetic data. The secondary peaks near 0.05 h$^{-1}$ and 0.15 h$^{-1}$ found in Fig. 7 also appear in this periodogram, suggesting that they are spurious peaks due to the sampling of the UVIS data.
a 3σ estimate of Δf for the dusk ansa S II periodogram of 3.56×10⁻³ h⁻¹ or 0.0354%. The corresponding 3σ estimate of the uncertainty in the periods derived from the peak frequency of the periodograms are given in Table 1. Like Brown (1995), we find that our estimates of Δf derived from the synthetic data sets are much smaller than the order-of-magnitude estimate of Δf derived from the length of the observation period. However, given that the slope of the phase increase with time shown in Fig. 6 varies over the observing period, it is doubtful whether this result has any real physical significance. To illustrate this point, we divided the observing period into three equal parts and made periodograms from the data in each. The resulting periods derived from the periodogram peaks are given in Table 2. The ion S II provides an extreme example, with a period that varies from 9.996–10.137 hours. This effect can be readily seen in the varying slope of the S II curve in Fig. 6. Since the value of the period derived from the location of the periodogram peak depends on both the time and the duration of the observation window, it should be used with some caution.

Table 2: Peak Periodogram Values of Subdivided Data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>S II</td>
<td>All</td>
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<td>10.073</td>
</tr>
<tr>
<td></td>
<td>Beginning</td>
<td>10.019</td>
<td>10.014</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>10.137</td>
<td>10.137</td>
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<td></td>
<td>End</td>
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<td>9.992</td>
</tr>
<tr>
<td>S III</td>
<td>All</td>
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<td>10.061</td>
</tr>
<tr>
<td></td>
<td>Beginning</td>
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<td>10.059</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>10.032</td>
<td>10.041</td>
</tr>
<tr>
<td></td>
<td>End</td>
<td>10.023</td>
<td>10.028</td>
</tr>
<tr>
<td>S IV</td>
<td>All</td>
<td>10.067</td>
<td>10.073</td>
</tr>
<tr>
<td></td>
<td>Beginning</td>
<td>10.041</td>
<td>10.032</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>End</td>
<td>10.014</td>
<td>10.014</td>
</tr>
<tr>
<td>O II</td>
<td>All</td>
<td>10.049</td>
<td>10.051</td>
</tr>
<tr>
<td></td>
<td>Beginning</td>
<td>10.028</td>
<td>10.050</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
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<td>10.010</td>
</tr>
<tr>
<td></td>
<td>End</td>
<td>9.983</td>
<td>9.974</td>
</tr>
</tbody>
</table>

3.4. Amplitude Variations and System III Modulation

Figure 10 shows the relative amplitude of the azimuthal variation in composition \((A_i/c_i)\) derived from the sinusoidal fit to the mixing ratios of the 4 main torus ion species (cf. Section 3.2). All four ion species have non-zero amplitude for the entire observation period, suggesting that azimuthal variation in plasma composition is an omnipresent feature of the Io torus. The amplitudes
for the relatively minor species of S II and S IV, show dramatic changes with time. From the start of the UVIS observations on day 275, the amplitude of the azimuthal variation in torus composition for both S II and S IV increases rapidly with time. When the amplitudes reach their peak value around day 279, they are nearly a factor of two greater than when first observed. After reaching their peak value, both amplitudes fall rapidly to a minimum value around day 293, at which time they are roughly 1/4–1/3 of their peak value. The amplitudes of the two ion species again increase quickly until day 300 when the S II amplitude levels out and the amplitude of S IV decreases somewhat. By day 306, the amplitudes of both ion species are increasing again, reaching a peak around day 308.

The ion species O II and S III also show variations in amplitude with time, but less dramatically than for S II and S IV. The amplitudes for these ion species remain in the range of 1–6% during the observing period. Given that O II and S III are the primary ion species for oxygen and sulfur in the Io torus and that S III serves as an intermediate product of the chemical processes that convert S II into S IV (or vice versa), this is not surprising. Neither O II nor S III show a well-defined amplitude peak around day 279, although both have amplitude peaks coincident with the amplitude peaks of S II and S IV on day 308.
Fig. 11.— Relative amplitude of the azimuthal compositional variations as a function of time. The color of the plotting symbols represents the location (in System III longitude) of the peak mixing ratio. Line segments and numbers mark the locations of the three intervals used in Fig. 12.

The period of time between the peaks of S II amplitude is \( \sim 29 \) days—the same period as the beat between the 9.925-hour System III rotation period and the observed 10.07-hour periodicity. This suggests that the amplitude of the azimuthal variation in torus composition might be modulated by System III. To illustrate this, the amplitude of the compositional modulation as a function of time is plotted separately for each species in Fig. 11. The color of the plotting symbols represents the System III phase of the azimuthal variation, i.e. the location of the mixing ratio peak, for each ion species. The steady increase of phase with time is readily apparent in all four ion species. The peaks in amplitude of S II occur at a phase of \( \lambda_{III} \approx 210^\circ \). The S II amplitude minimum occurs at a phase of \( \lambda_{III} \approx 30^\circ \). Conversely, the amplitude peaks for S IV occur at a phase of \( \lambda_{III} \approx 30^\circ \), while the amplitude minimum occurs at a phase of \( \lambda_{III} \approx 210^\circ \).

Figure 12 shows the modulation of the amplitude of the compositional variation by System III longitude in a graphical manner for the three times marked in Fig. 11. In contrast to Fig. 11,
which shows the values of amplitude and phase derived from the sinusoidal fits, Fig. 12 shows the actual mixing ratio observed in each 10° System III longitude bin, relative to the azimuthal average. During periods 1 and 3, the mixing ratio of S II shows a strong enhancement in the longitude sector $\lambda_{III}=180–270^\circ$ and a strong depletion in the longitude sector $\lambda_{III}=340–70^\circ$. During the same periods, the mixing ratio of S IV shows a strong enhancement between $\lambda_{III}=330–60^\circ$ and a strong depletion between $\lambda_{III}=180–270^\circ$. During period 2, S II shows a very weak enhancement between $\lambda_{III}=320–50^\circ$ and a weak depletion between $\lambda_{III}=160–250^\circ$, while S IV shows an enhancement between $\lambda_{III}=160–250^\circ$ and a slight depletion between $\lambda_{III}=330–60^\circ$.

4. Discussion

Initial analysis of the UVIS observations of the Io torus found long-term azimuthal variations in EUV brightness (Steffl et al. 2004), electron density, and electron temperature (Fig. 2) on the order of $\sim 5\%$. However, over shorter timescales (a few days) the torus is found to exhibit azimuthal variations in ion composition of up to 25%. Significant azimuthal compositional variations were present during the entire observing period, suggesting that this is the natural state of the Io torus. Although the primary torus ion species of S III and O II displayed azimuthal variations of only a few percent, S II and S IV showed azimuthal variations of up to 25%. Models of the torus that treat the mixing ratios of these ion species as azimuthally uniform must therefore be used with some caution. Similar caution must be exercised when attempting to apply in situ measurements obtained in one azimuthal region to the torus as a whole. This may help to explain some of the wide range in electron densities measured by the Galileo PLS (Frank and Paterson 2001).

The azimuthal variations in the composition of the Io torus are observed to have a period of 10.07 hours—1.5% longer than the System III rotation period of Jupiter and 1.3% shorter than the System IV period. In ultraviolet, optical, and near-infrared observations of S II and S III obtained between 1979 and 1999, the 10.21 hour System IV period remained remarkably constant (Roessler et al. 1984; Sandel and Dessler 1988; Brown 1995; Woodward et al. 1997; Nozawa et al. 2004), which suggested that this period might be somehow intrinsic to the Jovian magnetosphere. The presence of a strong periodicity at 10.07 hours (and corresponding lack of any periodicity at the System IV period), is therefore rather surprising. While both Brown (1995) and Woodward et al. (1997) observed abrupt changes in the phase of the azimuthal variation in brightness of [S II] 6731Å which caused their initial analysis to identify a spurious periodicity of 10.16 hours, it is evident from Fig. 5 that no such change in phase occurred during the UVIS observations.

Given the phenomenological similarity between the UVIS 10.07 hour periodicity and the System IV periodicity, we propose that the same physical mechanism is responsible for both. It is plausible that the factor of 3–4 increase in the amount of neutrals supplied to the torus in September 2000 (Delamere et al. 2004) altered the mechanism responsible for producing the System IV period in such a manner that a 10.07 hour period was produced. Based on measurements of Iogenic dust by the Galileo Dust Detector System (Krüger et al. 2003), such events occur relatively infrequently (only
Fig. 12.— Graphical representation of the modulation of the amplitude of the azimuthal variation with System III longitude. For each time interval, the torus has been divided into 36 10° longitude bins. Each bin is colored according to its deviation from the average mixing ratio during that time interval. Intervals 1 and 3 correspond to periods of maximum amplitude, while interval 2 corresponds to minimum amplitude. The locations of these intervals are marked in Fig. 11.
one event of this magnitude was detected during 6.5 years of observations). If future observations of the Io torus detect periodicity at the 10.21 hour System IV period (and not at 10.07 hours), it would suggest that the intermediate period observed by UVIS was a result of the neutral source “event” that occurred in September 2000. Ground-based observations in December 2000 (roughly one month after the end of the UVIS staring-mode observations presented in this paper) found the brightness of torus [S II] 6712Å and 6731Å emissions varied with a period of 10.14±0.11 hours (Nozawa et al. 2004), which suggests the torus periodicity might have been returning to the “typical” System IV period. However, given the relatively large uncertainty in this value, it is consistent with both the 10.07 hour period measured by UVIS and the canonical 10.21 hour System IV period, so no firm conclusions can be drawn.

It is important to reiterate that we do not (and can not) directly measure the rotation speed of the torus plasma with UVIS. Rather, we derive the rotation period of azimuthal variations in the composition of the Io torus. This value will be affected by both the actual rotation speed of the plasma and any spatial/temporal changes in the plasma composition resulting from torus chemistry.

If the 10.07 hour periodicity in the UVIS data were produced directly by the subcorotation of torus plasma, the plasma, when averaged over the UVIS field of view and weighted by its EUV emissions, would need to lag the local corotation velocity by 1.5% (~0.19 km/s/R_J). In order to maximize signal-to-noise in the torus spectra, spectra from three rows on the detector were averaged together, as described in Section 2. If, however, spectra are extracted from just a single row on the detector, the same 10.07 hour periodicity is evident throughout the observing period, despite the factor of 3 decrease in the size of the field of view. Furthermore, this holds true for both the dawn and the dusk ansae of the torus which look at slightly different ranges of radial distance. Given these considerations and the changes in viewing geometry of the UVIS observations over the 45-day observing period, the only feasible way to produce such a periodicity directly from subcorotating plasma is if the deviation from corotation were constant with radius. This, however, is not supported by observations of the radial velocity of S II that show a strong variation in the subcorotation speed of the plasma with radial distance (Brown 1994a; Thomas et al. 2001). The Io torus must have been in a radically different state during the Cassini encounter than it was in 1992 (when the observations of Brown (1994a) were made) and 1999 (when the observations of Thomas et al. (2001) were made) if the subcorotation of the torus plasma is directly responsible for the periodicity in the UVIS data. Since there are also theoretical arguments against producing such periodicities in the torus directly from plasma subcorotation, i.e. that energy must be supplied continuously to the torus in just the right place and amount to keep the pattern coherent despite the changes in radial distance (Dessler 1985; Sandel and Dessler 1988), we consider this possibility unlikely.

Instead, the UVIS observations are entirely consistent with the theory proposed by Brown (1994b) that the System IV periodicity is the result of the pattern speed of a compositional wave propagating through the Io torus. While the individual particles of the torus lag corotation by
an amount appropriate for their radial distance, the group velocity of the compositional wave lags rigid corotation by 1.5%.

The amplitude of the azimuthal variation in composition appears to be modulated by its position relative to System III longitude. During times when the peak (minimum) in S II (S IV) mixing ratio is aligned with a System III longitude of \(210° \pm 15°\) the amplitude of the azimuthal variation in composition is enhanced. When the peak (minimum) in S II (S IV) mixing ratio is aligned with a System III longitude of \(30° \pm 15°\), the amplitude of the variation is diminished, i.e. the torus becomes more azimuthally uniform. Since UVIS observed only 1 1/2 modulation cycles, it is difficult to say whether the apparent modulation by System III longitude is real or just coincidental. However, similar modulations in the brightness of the S III 685Å feature observed by the Voyager 2 UVS, the probability of detecting nKOM emission with the Voyager PRA instruments, and the brightness of torus S II [6731Å] emissions were reported by Sandel and Dessler (1988) and Schneider and Trauger (1995) and may also be present in the data of Pilcher and Morgan (1980).

In light of the UVIS observations of a subcorotating azimuthal variation in composition whose amplitude is modulated by its position relative to System III longitude, several apparently contradictory observations of the Io torus can be explained. First, because the azimuthal variation subcorotates relative to System III, the phase of the variation (i.e. the location of peak) should be observed over the full 360° range of longitude. However, because the amplitude of the azimuthal variation is greatest when the peak in S II mixing ratio is located near \(\lambda_{III} = 200°\) azimuthal variations in the brightness of S II emissions will be preferentially detected in the “active sector” centered around \(\lambda_{III} = 200°\).

The detection of azimuthal variability in the brightness of the S II [6716Å/6731Å and 4069Å/4076Å] doublets but not in the brightness of the O II [3726Å/3729Å] doublet (Morgan 1985), arises from the fact that the amplitude of the azimuthal variation of the S II mixing ratio ranges from 10–25% while the amplitude of the azimuthal variation of the O II mixing ratio is \(\leq 5\%\). The correlation of S II brightness with S III brightness observed by Rauer et al. (1993) is also consistent with the correlation of the S II and S III mixing ratios observed by UVIS.

The two week transition between azimuthally varying and azimuthally uniform states observed by Pilcher and Morgan (1980) is just the manifestation of the modulation period, assuming that the modulation period was \(\sim 14\) days (which corresponds to the beat between the 9.925 hour System III period and the 10.214 hour System IV period). The \(\sim 14\) day modulation period of the amplitude of the azimuthal compositional variation also explains why Morgan (1985) observed a strong azimuthal variation in the brightness of the torus S II 6731Å emission with a peak near \(\lambda_{III} = 180°\) during the period of 14–17 February 1981, while Brown and Shemansky (1982) detected no significant azimuthal variation in the same emission line on 23–24 February 1981. Furthermore, the subcorotation and amplitude modulation of the azimuthal variation in composition explains why the Voyager 2 UVS observed only a weak azimuthal variation in the brightness of the S III 685Å feature with a peak between \(330° < \lambda_{III} < 40°\) on day 122 of 1979 (the amplitude of the
azimuthal variation was at a minimum), a stronger azimuthal variation (the azimuthal variation had reached its minimum amplitude with the S III peak near 20° and was increasing in amplitude) with a peak between 40° < λ_{III} < 100° on day 124 of 1979 (assuming the azimuthal pattern had the 10.2 hour System IV period, the phase should increase by \sim 24°/day), and no significant System III variation when the spectra were averaged over the 44 day pre-encounter period (the System III longitude of the peak varies with time). Whereas the failure of Gladstone and Hall (1998) to detect any significant variation in the brightness of torus emissions with System III longitude results from the averaging of EUVE data obtained during the interval from 19–24 June 1996. During this time, the peak of the azimuthal variation would have shifted by over 120° in System III longitude.

Finally, it is also interesting to note that the two largest torus EUV luminosity events reported by Steffl et al. (2004) occurred on days 280 and 307, near the modulation peaks. During these events, which last for roughly 20 hours, the power radiated by the Io torus in the EUV increases rapidly by \sim 20% before gradually returning to the pre-event level. Since several other brightening events occurred throughout the 45-day observing period, the timing of the two largest events may be coincidental.

The next step is to model the UVIS observations by extending the torus chemistry model of Delamere et al. (2004). Preliminary results suggest that the interaction of a subcorotating (at 10.07 hours), azimuthally-varying source of hot (\sim 55 eV) electrons with a corotating (i.e. fixed in System III), azimuthally-varying source of hot electrons can produce torus behavior that is both qualitatively and quantitatively similar to the UVIS observations. The 28.8 day modulation period arises naturally from the beating of the 10.07 hour period with the 9.925 hour System III period. While it is not too difficult to imagine a source mechanism capable of producing hot electrons in amounts that vary as a function of System III longitude, it is far from obvious what could cause an additional, azimuthally-varying pattern of hot electrons to rotate with a period 1–3% slower than the System III period. At present we know of no suitable physical mechanism capable of producing such behavior.

5. Conclusions

We have presented an analysis of the temporal and azimuthal variability of the Io plasma torus during the Cassini encounter with Jupiter. Our main conclusions are:

1. The torus exhibited significant long-term compositional changes during the UVIS inbound observing period. These compositional changes are consistent with models predicting a factor of 3–4 increase in the amount of neutral material supplied to the torus in early September, 2000. These results are discussed in more detail by Delamere et al. (2004).

2. Persistent azimuthal variability in torus ion mixing ratios, electron temperature, and equatorial electron column density was observed. The azimuthal variations in S II, S III, and
electron column density mixing ratios are all approximately in phase with each other. The mixing ratios of S IV and O II and the torus equatorial electron temperature are also approximately in phase with each other, and as a group, are approximately 180° out of phase with the variations of S II, S III, and equatorial electron column density.

3. The phase of the observed azimuthal variation in torus composition drifts 12.2°/day, relative to System III longitude. This implies a period of 10.07 hours, 1.5% longer than the System III rotation period. This period is confirmed by Lomb-Scargle periodogram analysis of the UVIS data.

4. The relative amplitude of the azimuthal variation in composition is greater for S II and S IV. These species have relative amplitudes that vary between 5–25% over the observing period. The major ion species, S III and O II, have relative amplitudes that remain in the range of 2–5%.

5. The amplitude of the azimuthal compositional variation appears to be modulated by its position relative to System III longitude such that when the peak in S II mixing ratio is aligned with a System III longitude of 210±15° the amplitude is enhanced, and when the peak in S II mixing ratio is aligned with a System III longitude of 30±15° the amplitude is diminished.

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