A Study of the Neutral and Ionized Io Tori

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1. Introduction

Historically, the discovery and the first observations of the neutral clouds, and then of the plasma tori near Io were made by ground-based spectroscopic observations about a decade ago (NaI: Brown, 1974; KI: Trafton, 1975; SII: Kupo et al., 1976). The neutral emission lines are due to resonant scattering of allowed transitions from the solar lines, while the optical emissions from the ionized tori are excited by collisions with electrons (the lines from 3000 Å to 10000 Å, including the visible, arise from forbidden transitions, while the far U.V. lines later observed from spacecraft are due to electron-excited, allowed transitions). The lines studied in the Io tori emissions are listed in Table 1, together with their reported intensity.

Images of the emitting areas have been obtained significantly later (NaI: Matson et al., 1978; SI: Pilcher et al., 1985).

There are quite a number of questions concerning the thermodynamic equilibrium of the sodium cloud (such as density and temperature, loss mechanisms in various cloud regions, lifetimes of the neutrals, mass loss rate, mass loading rate) for which we now begin to obtain the first answers through observations of the extent of the cloud, its east-west and north-south asymmetries, its longitudinal and temporal variations and its velocity fields, by means of imaging and high resolution spectroscopic methods. However, much remains unknown in a region close to the satellite itself, within a few arcseconds, where the observations are very difficult due to the high surface albedo of Io near the resonant lines of Na (5890–96 Å). We must recall that the first images were obtained with a ~17 arcsec and later with a ~10 arcsec coronographic mask. In this region, the presence of an unknown atomic sink is suspected (Brown, 1983).

There are presently two ways to get access to this region. The first one is spectroscopic in nature and is based on registration of the solar spectrum reflected by Jupiter or one of its sattellites: provided the incident ray has crossed the Io Na cloud before reflection, we observe the absorption Na line in the reflected solar Fraunhofer line with contamination by the continuum from Io. This method had been proposed by some of us (R. Prange, R. Ferlet, A. Vidal-Madjar and C. Emerich) for the 39th ESO observing period, but time was not allocated. It has once been successfully applied on Europa during the mutual phenomena, see Schneider et al., 1986. The second method employs mapping of the near surface environment of Io with a very narrow band filter and very good spatial resolution and stability, in order to improve the contrast between the diffused light from Io and the cloud line. This is one of the purposes of our present programme "Study of the ionized and neutral Io tori" at La Silla.

The potassium cloud is about 15 times fainter than the sodium cloud, and it obeys the same physical laws, except for the lifetime. Therefore, it has not been thoroughly studied. No imaging at all has been done of the oxygen cloud.

As for the ionized tori, only one systematical spatial/temporal survey has been achieved up to now (Pilcher et al., 1985) in the SII 6731 Å line. Few other images exist in SII and SIII, but they give rather contradictory results, especially what concerns longitude dependence of the emissions, and they seem to testify to temporal variations, not yet understandable due to the limited data.

2. Our Observing Programme at La Silla

Most of us are interested in the study of Jupiter's environment, and especially of the magnetosphere/atmosphere coupling. F. Paresce, J.C. Gérard and A. Vidal-Madjar have already been allocated observing time on the GTO programme of the Hubble Space Telescope

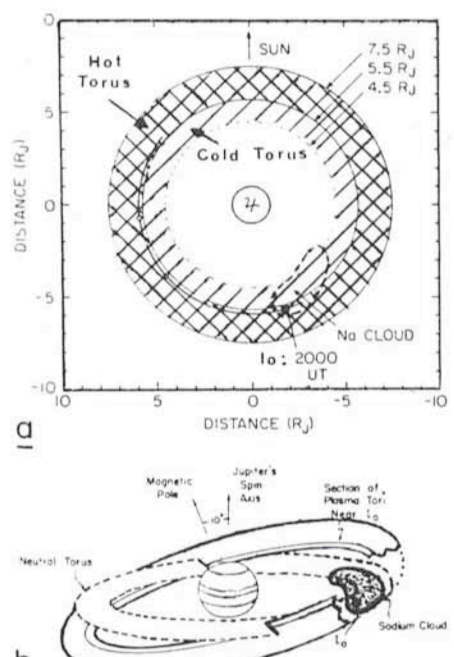

Figure 1: *Schematic geometry of the plasma and neutral tori illustrating the neutral cloud shape and how the ionized particles can kick the neutral species out. (A) Projection onto the plane of the ecliptic (adapted from Bagenal and Sullivan, 1981). (B) Perspective edge-on view (adapted from Trafton, 1980).*

TABLE 1: *Neutral and ionized emissions of the Io tori.*

GROUND-BASED			FROM SPACE from Durrance et al. (1983)		
Species	Wavelength	Intensity	Species	Wavelength	Intensity
NaI	5890 Å 5896 Å	up to 30 KR	OI	1304 Å	3 R
KI	7665 Å 7699 Å	500 R	SI	1296 Å 1425 Å	1.3 R 2.5 R
OI	5577 Å	200 R	SII	1256 Å	4 to 40 R
CaI	4227 Å	≤5 kR	SIII	1199 Å 1729 Å	15 to 60 R 17 to 47 R
SII	6717 Å 6731 Å 4069 Å	400 R 50 R	OIII	1664 Å	3 to 12 R
OII	3726 Å 3729 Å	50 R	SIV	1406 Å	2 R
SIII	6312 Å 3722 Å	50 R			

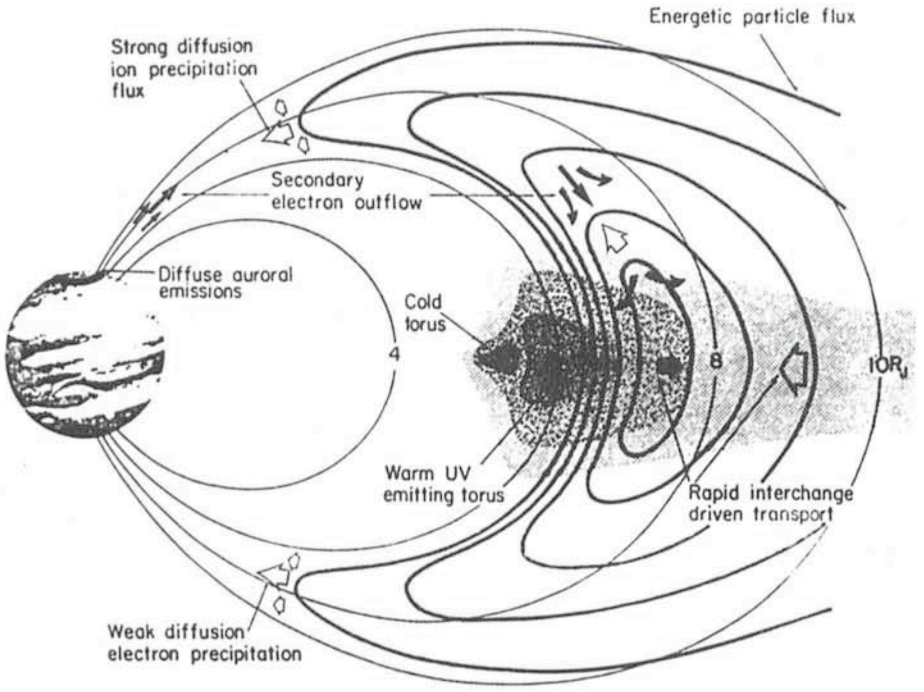

Figure 2: *Schematic meridian section of the Jupiter/Io magnetospheric coupled systems, showing the cold and hot tori. Io is on the ~ 6 R_J shell close to the peak of the hot torus (from Thorne 1981).*

(HST). Included in this programme is a high spatial (latitude-longitude) resolution (and then temporal survey) study of the H Ly α and H_2 We-Ly U.V. emissions excited by the precipitation of magnetospheric particles along field lines. Since these precipitations are (totally or partially) monitored by the Io tori, we had long ago suggested that a correlated study of the Jovian aurorae and of the Io tori would give a clue to these questions (Vidal-Madjar et al., 1982). There is currently no spacecraft which is able to observe simultaneously the auroral zone of Jupiter and the Io orbit, and we have therefore proposed to add ground-based observations of the Io tori in the visible to the U.V. auroral data expected from the HST. In order to prepare this programme, we have obtained two observing nights at ESO in September 1986 and then three more at the end of November 1986.

This type of observations is only possible within about two months of a Jovian opposition (most recently on September 10, 1986; the next will be in mid-October 1987) and during intervals of 3 to 6 successive nights, due to the 42.5-hour period of Io, which must be observed near the greatest elongation on either side of Jupiter. The length of the sequence as well as the amount of available observing hours per night decreases as one moves away from opposition, from about 9 to 10 hours on September 1, 1986, i.e. close to the centre of the best period, down to ~2 hours per night at the latter period in November.

The images were obtained with the 2.2-meter telescope at La Silla in the imaging mode, coupled with the RCA/CCD detector.

The strong emission from Io's continuum (illustrated in Figure 3) was significantly decreased by the use of an occulting mask in the telescope focal plane and centred on the image of Io. This coronographic mask, specially designed and built at the Space Telescope Science Institute in Baltimore to be mounted on the 2.2-m telescope, has been described in detail by Paresce and Burrows, 1987. It basically consists of a movable wedge, the angular width of which can be continuously varied from 2 arcseconds to 10 arcseconds and centred anywhere in the field of view. The positional angle can be changed, depending on the direction of the faint features to be observed. The associated optics introduce a magnification of 5, the resulting beam aperture is f/40, leading to negligible "beam aperture effects" in the very narrow band filters used. The pixel size on the sky is 7.23 × 10^{-2} arcsec and the field of view is about 23 by 37 arcsec, both well adapted for high-resolution imaging close to Io.

The use of the occulting mask centred on the bright source does not in itself eliminate the diffuse continuum close to the surface, as seen on Figures 4a and 4b. It is necessary to further decrease the transmitted continuum by means of very narrow band filters. Sophisticated interference filters or Fabry Perot interferometers can be used. During the runs of September and November 1986, we investigated the neutrals and concluded that a spectral resolution of 5 Å or better was desirable. We have therefore used a 5 Å sodium interference filter, centred at 5890 Å and lent to us by the Service d'Aéronomie (C.N.R.S., France) in order to obtain the sodium cloud image shown in Figure 6.

Moreover, the efficiency of the occulting mask critically depends on the actual spatial resolution and the image stability during the exposure, which usually lasts from 20 minutes to a few hours. This includes the seeing and the telescope guiding accuracy.

We obtained a reasonable measurement of the image widening by the overall seeing parameters from the measurement of the FWHM of a nearby stellar image. During the September and November runs, we found values of the order of 0.5 to 0.9 arcsec. Compared to the ~1 arcsec diameter of the object, these were indeed excellent observing conditions. We were therefore able to use 3.5 arcsec for the mask width.

The second point has turned out to be much more critical. As previously noted, once we had acquired a narrow band image of Io's continuum plus the sodium cloud emission, we had to eliminate the continuum contribution. We then imaged the diffuse light from Io through a broadband ESO filter, with Io

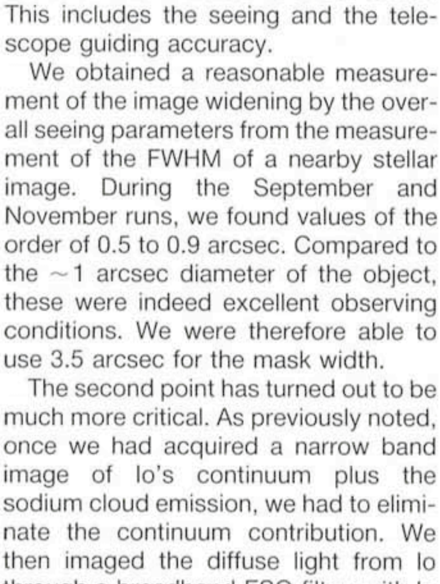

Figure 3: *Cuts through simultaneous images (exposure 1 minute) of Io and Europa on November 24, 1986. The angular diameters are very similar and the signals have been normalized to Io. The image was acquired with the 5 Å bandpass NaI filter and without the occulting wedge. The small difference between the profiles ~ 100 pixels left of the maximum (~ 7.5 arcsec) is due to Io's sodium cloud and gives an idea of the small contrast with the reflected continuum. The 3.5 arcsec wide arrow corresponds to the size of the mask which was used to obtain Figures 4 and 6.*

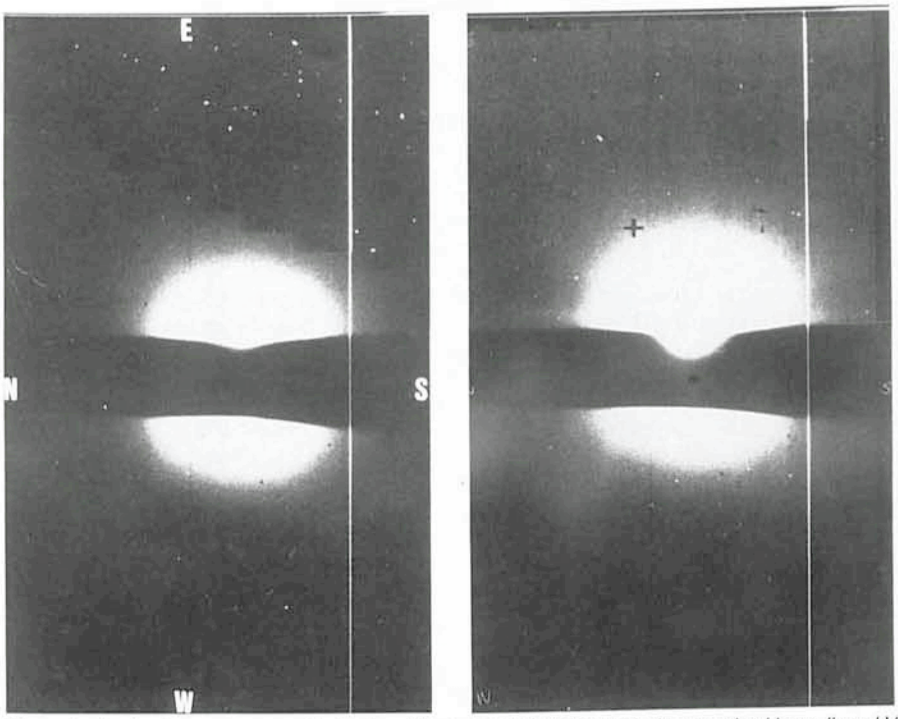

Figure 4: *1-minute exposures obtained on September 4, 1986, with the standard broadband V filter. Io is behind the occulting wedge, the width of which is 3.5 arcsec. One sees the wings of the distribution of the diffused continuum reflected by Io (Io's size = 1 arcsec), which must be subtracted by suitable image processing from the narrow band filter Na images of the neutral clouds. Figure b is shifted by about 0.3 arcsec from Figure a, perpendicular to the wedge. The observed difference in the diffused light distribution emphasizes the need of a very high pointing stability during long exposures.*

Figure 6: *20-minute exposure obtained on November 27, 1986, with a 5 Å bandpass filter centred on the 5890 Å NaI emission line. The circularly symmetric contribution of Io's continuum (cf. Figure 4) is easily distinguishable from the elongated sodium cloud. The orbit of Io is nearly in the NE-SW plane. Jupiter is outside the image in the SW direction.*

being carefully located in the same place, and we must subtract this reference image from the first one, as described by Paresce and Burrows. Figures 4a and 4b illustrate the difference introduced in the reference broadband images when the centre of Io is shifted by only 0.3 arcsec perpendicularly to the wedge. This means that the location accuracy and the spatial stability of the images must be of the order of a few tenths of arcsec (< 0.5 arcsec) during the active experimental sequence (narrow band + reference broadband image). This constraint on the guiding of the telescope is very severe for several reasons:

– First, the relative motion of Io in the sky, which must be introduced into the telescope computer for guiding, is fast and rapidly variable. For example, it can vary from 0 to ± 20 arcsec in α and ± 10 arcsec in δ during the same night. It is therefore necessary to adjust the guiding input parameters, approximately every 15 minutes.

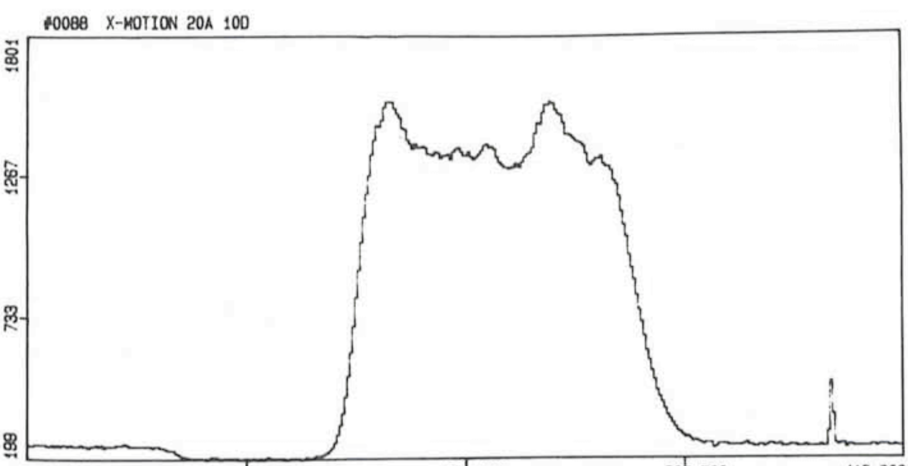

Figure 5: *Calibration of the guiding motion of the telescope: A constant drift velocity $d\alpha/dr$ = 20 arcsec per hour and $d\delta/dt$ = 10 arcsec per hour is introduced and the signal from a star near Io is acquired during a 20-second exposure. The two-dimensional trail on the CCD detector provides the velocity scalings in α and δ. The intensity cut along the X-axis shows that the motion is not entirely uniform.*

– Second, the scaling factor between the input parameters and the real (actual) $d\alpha/dt$, $d\delta/dt$ of the line of sight on the sky must be perfectly known and regularly controlled. This was one by acquiring a star, introducing a standard motion drift in the computer and directly calibrating on the CCD the displacement of the star during the exposure time.

– Third, the motion of the telescope monitored by this calibrated "motion drift" must be uniform at the needed accuracy. Figure 5 which represents the photometric signal from the star during the above procedure shows that it is not perfectly regular, and probably introduces some "positional blur".

This delicate calibration study is obviously not a standard one, and it had to be done with the active support of the Operations Group at La Silla. It is good to report that the achieved results are already much better than those obtained by the procedures used by other groups, who report stabilities of 1 to 2 arcsec during an exposure, see Pilcher et al., 1985. The efforts at ESO should therefore be continued.

At the end of the November 1986 run, we obtained our first image of Io's sodium cloud, shown in Figure 6. The occulting mask was only 3.5 arcsec wide and the exposure lasted 20 minutes.

The data processing is now in progress with the use of reference broad-

Io's Tori and their role in the Jovian magnetosphere/atmosphere dynamics

Io is the innermost Galilean satellite of Jupiter. It travels along an orbit at the distance of 5.9 R_J from the centre of Jupiter (R_J is the Jovian radius) which corresponds approximately to an angular distance of 2 arcminutes as seen from the Earth. Its angular diameter is about 1 arcsecond (~3,600 km) and its visual brightness $m_v \simeq 5.1$.

Contrarily to most other "moons" which look like telluric planets or icy bodies, Io has a very special surface due to the fresh lava spread by its active volcanoes over the mineral crust. It is presently supposed to be mainly composed of a mix of silicate regoliths, basalts, with frozen SO_2, S_2O, polysulfur oxydes and alkali sulfides (Gradie, 1985; Hapke, 1986; McEwen et al., 1986). A continuous, significant ejection of materials is observed, either by direct volcanic emissions or by sputtering of the surface compounds by energetic magnetospheric particle impact. It results in an atmosphere which mainly consists of oxygen, various sulphur molecules (S, S_2, S_3), SO_2 and metallic species (Na, K) with a ≤1% mixing ratio. Its size could be a few Io radii according to recent models and observations (Chrisey et al., 1986; Summers et al., 1985; Schneider et al., 1986; Ballester et al., 1986).

Additionally, Io is embedded in the Jovian magnetosphere and the neutral species which have been sputtered out are rapidly dissociated and ionized by the ambient hot plasma and give rise to ions which are immediately trapped by the magnetic field lines and are the major source of feeding of the inner Jovian magnetosphere.

This produces two classes of features:

***1. Neutral clouds** (Na, K, O, S) escaping from Io's atmosphere at low velocity (~2 to 3 km s^{-1}), which roughly accompany it in its motion in the geographic (rotational) equatorial plane of Jupiter (Figure 1). The shape and size of these clouds depend on the ejection parameters related to the gravitational interaction of Io and of Jupiter, on the solar flux pressure (which is suspected to induce east-west asymmetries depending on the phase of Io) and on particle interactions, the more effective being ionizing collisions with electrons and ions of the magnetosphere and charge exchange with the ions trapped in the ionized tori when they intersect the geographic equatorial plane (see later). Depending on their lifetimes against such processes and diffusive rates, the neutral clouds can look like limited areas extending essentially forward Io along its orbit (for lifetimes of the order of a few tens of hours, i.e. the typical "banana shape" sodium cloud schematically drawn on Figure 1a), or like complete tori as in the model-predicted ones for OI, for lifetimes of hundreds of hours (Smyth and Schemansky, 1983) or SI (Durrance et al., 1983). Escaping accelerated jets are also occasionally observed with velocities greater than 50 km/s, giving evidence of charge-exchange with fast ionized species of the ionized tori.*

***2. Ionized tori,** which are caused by the pick-up of the newly created ions by the magnetosphere. Since the magnetic field lines are rigidly rotating with the planet, their velocity at the Io jovicentric distance is about 4 times that of Io (76 ± 6 km s^{-1} between 5.5 R_J and 6.5 R_J, and ~17 km s^{-1} respectively), and the ions are immediately accelerated by the differential velocity. Due to this shorter rotation period and their longer lifetimes (from one hundred hours for SII to one thousand hours for SIII and OII; Pilcher et al., 1985) they give rise to closed tori of SII, SIII, SIV and OII, OIII in the magnetic equatorial plane of Jupiter, which differ by ~10° from the geographic one (Figure 1b). The low ionization level species OII and SII are mainly observed inwards of Io's orbit, while the higher ionization level ones are almost exclusively observed outside of it, giving rise to the so-called "cold" and "hot" tori (Figures 1a and 2).*

However, differences in the longitudinal dependence of the densities of the various ions seem to be present in the small data sets now available. For example, the shorter lifetime SII species exhibits a significant, two maxima longitudinal variation, while most of the time SIII does not. This is tentatively attributed to local plasma sources which are related to the Jovian magnetic anomaly, to the intersection with the orbits of the neutral clouds or to collisions with magnetospheric electrons of given energy (Pilcher et al., 1985). As in any plasma,, the ratio of the intensity of selected emission lines can give information on the electronic temperature and density (T_e, n_e) as a function of the location.

Finally, these rotating ions interact with the Jovian magnetosphere, for which they constitute the major source of energy and mass loading, thus playing a key role in the dynamics of the magnetosphere and, beyond it, of the Jovian atmosphere. Here are some of the processes by which Io may control the Jovian environment (summarized in Figure 2):

- *by diffusion in pitch-angle, the ions from the tori are a significant source of auroral emissions in the upper atmosphere of Jupiter, competing with the solar wind input;*
- *secondary electrons are created and are mirrored back towards the equator to populate the magnetosphere of a warm electron component;*
- *plasma instabilities are expected to appear along the magnetic flux tube of Io, again accelerating particles; and*
- *radial diffusion of the ions also takes place (rapidly outwards, slowly inwards), thereby feeding a large region in the magnetosphere.*

band images such as those shown in Figure 4.

Acknowledgements

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