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 $\leq 1\,\%$ 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.

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