Ground-based observations of the [SII] 6731 Å emission lines of the Io plasma torus

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Abstract. The Io Plasma Torus (IPT) is a doughnut-shaped structure of charged particles, composed mainly of sulfur and oxygen ions. The main source of the IPT is the moon Io, the most volcanically active object in the Solar System. Io is the innermost of the Galilean moons of Jupiter, the main source of the magnetospheric plasma and responsible for injecting nearly 1 ton/s of ions into Jupiter's magnetosphere. In this work ground-based observations of the [SII] 6731 Å emission lines are observed, obtained at the MacMath-Pierce Solar Telescope. The results shown here were obtained in late 1997 and occurred shortly after a period of important eruptions observed by the Galileo mission (1996-2003). Several outbursts were observed and periods of intense volcanic activity are important to correlate with periods of brightness enhancements observed at the IPT. The time of response between an eruption and enhancement at IPT is still not well understood.

Keywords. Io; Io Plasma Torus; Instrumentation; Volcanism; Jupiter magnetosphere

1. Introduction

Jupiter is a complex system and has an unique interaction with its innermost moon, Io. Jupiter has the largest magnetosphere in the Solar System and Io is immersed within it. Io has an intense volcanic activity and its volcanism is due to tidal heating produced by its forced orbital eccentricity. It is mainly generated by Jupiter's gravitational pull but also, in a smaller scale, by the other Galilean moons (Europa and Ganymedes) (Lopes & Williams, 2005). Io's volcanic plumes expel a considerable amount of material to the atmosphere. The release of lava flows and plumes produces Io's patchy atmosphere, which is mainly composed by SO_2, SO, S, O (Mendillo *et al.*, 2004). A significant fraction of the material lost to the atmosphere escapes as neutral atoms and molecules, mainly oxygen and sulfur atoms. The material which escapes from the gravitational pull of Io forms a neutral cloud that extends for several Jupiter's radii. The neutrals follow Io in its orbit about Jupiter until they are ionized through electron impact and charge exchange (Wilson *et al.*, 2002). Once ionized, the ions are accelerated to the nearly co-rotational flow of the ambient plasma, forming a torus of ions surrounding Jupiter, the so called Io Plasma Torus (IPT).

2. Overview

The Io Plasma Torus (IPT) is a ring-shaped cloud of S^+, S^{++}, S^{+++}, O^+, O^{++}, and a small concentration of other ions. Material escaping from Io creates an environment in constant change. Its physics can only be understood by measuring and correlating the variations in its structure and properties such as density, temperature and state of motion (Herbert *et al.*, 2003). The conditions in the plasma torus are highly variable both spatially and temporally due to the dynamic environment at Io and in the magnetosphere. The plasma torus can be observed in the extreme ultraviolet (EUV) emission and in the optical wavelengths. Optical emissions come from interactions between thermal electrons and sulfur ions. The optical emission traces the densest part of the torus, the EUV traces the hottest part of the torus. It is most dense around Io's orbit ($\sim 5.9~R_J$). Therefore, from observations it is possible to obtain the temporal and spatial variability of the Io plasma torus (Lopes & Williams, 2005).

Kupo *et al.*, 1976 were the first to identify the individual forbidden emission lines of sulfur ([SII], λ 6731 $\mathring{A}$, 6716 $\mathring{A}$). Since then a number of ground-based observations were obtained. The plasma torus variability is still not well understood, this is partially because to the lack of continuous observations. From the IPT is possible to observe both sides of the torus simultaneously and monitor the positions of maximum brightness relative to the center of Jupiter. Another effect possible to obtain during observations is the brightness asymmetry produced by the modified electron density and temperature. The IPT variability is believed to be related to Io's volcanic activity as it does not occur steadily. Jupiter's magnetic field confines the plasma torus toward the equator, not by the strength of the magnetic mirror, but by centrifugal forces (Bagenal & Sullivan, 1981), causing the plasma torus to tilt, mainly due to the inclination of the planet magnetic field (10° inclination from Jupiter's rotation axis), but also by the planet rapid rotation ($\sim$ 10 hours). The torus extends along the field lines to $\pm~1~R_{Io}$ from the centrifugal equator (Bagenal, 1989). At the torus, it is estimated that the ions remain there up to a time relative to 100 revolutions of Jupiter, which means that every rotation of the torus through the neutral cloud adds only 1 % of new plasma (Connerney *et al.*, 1993).

3. Data & Preliminary results

Ground-based observations imply that the spatial distribution of SII inside Io's orbit is generally wedge-shaped. The apex of the ansa as observed from the ground corresponds to the maximum SII density (Pilcher 1980, Bagenal & Sullivan, 1981). The results here presented are from the [SII] 6731 $\mathring{A}$ emission lines. They were observed at the McMath-Pierce Solar Telescope (MMPST) during September and October of 1997. A total of 276 science (Jupiter) images were obtained. In Figure 1 is possible to observe the dawn (east) and dusk (west) ansae of the IPT. From the dawn side 154 images were analyzed, while for the dusk side 122 images were analyzed. The method to obtain the ansae brightness (dawn and dusk) was a photometric box around it (Figure 1). A method for processing [SII] torus data was developed during this work, as well as the routines used for basic image calibrations (bias and flat field) and the corrections necessary due to observations obtained from Earth's surface.

Once the [SII] images were fully reduced and analyzed, it was obtained a time sequence for 1997. The results in Figure 2 presents the average intensity the dawn and dusk ansa sides per day of observation. The abscissa shows the day of the year (DOY), from 240 to 320, versus intensity in Rayleighs (R). It is possible to observe a higher intensity on the dusk side when comparing the results between September and October. The highest

Figure 1. Image observed in October 11, 1997 at the McMath-Pierce Solar Telescope. Jupiter is at the center of the image, attenuated by a neutral density filter. The dawn and dusk ansae are at the borders of the image, delimited by a box. The box area was the region used to obtain each ansa brightness.
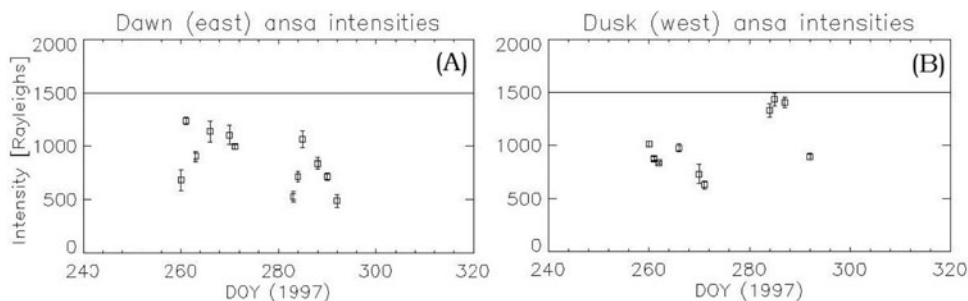
Figure 2. Variations of the ansae intensity of the 6731 Å emissions at dusk side (A) and dawn side (B). A total of 154 frames from the east ansa and 122 frames from the west ansa were used. Average [SII] intensity at dusk side shows slightly increase in October when compared with September observations and also for the same period when compared with the dawn side.

intensities observed are 1332 R at day 284 (October 11, 1997), 1434 R at day 285 (12 October 1997) and 1403 R at day 287 (October 14 1997). The highest intensity observed at the dawn ansa was 1238 R at 261 (18 September 1997).

Future Works: The next steps are to process the rest of the ground-based observations (1998-2003) and apply the Lomb-Scargle periodogram to obtain Jupiter's periodicities to study System's III and IV. Once the [SII] brightness time series is complete, the next step is to correlate it with the thermal emissions of Io's surface obtained with the Near Infrared Mapping Spectrometer (NIMS) during the Galileo mission (1996-2003).

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