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# Morphology of the Io Plasma Torus inferred from Dual Uplink-Dual Downlink calibration during Juno mission

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## Abstract

The volcanic activity of Io, the innermost Galilean moon of Jupiter, ejects gas in the magnetosphere of the planet, mainly oxygen, sulfur and their compounds. This gas is quickly ionized by means of various physical processes (e.g: charge exchange) and then it remains tied to the planetary magnetic field, creating a dense toroidal-shaped cloud of plasma known as *Io Plasma Torus* (IPT) near Io's orbital distance ($\sim 5.9R_J$). The geometry of the IPT is governed by the interplay among centrifugal force, gravity and radial diffusion of plasma across Jupiter's magnetic field, which is nearly dipolar in the inner magnetosphere and tilted of about $10°$ with respect to the rotation axis. Thus, the midplane of the IPT must lie between the equatorial plane of Jupiter and its magnetic equator because of the balance between the centrifugal force and the magnetic constraint [1], while the radial distribution of plasma can be described by a diffusion coefficient [2].

Juno is following a highly eccentric, nearly polar low-altitude orbits, thus the radio communication with the ground station must cross the IPT during perijoves (Fig.1). Being a dispersive media, this introduces a distinctive signature in the differential Doppler shift measurements (Fig.2), which is defined as

$$f_{R,X} - f_{R,Ka}\Big(\frac{f_{T,X}}{f_{T,Ka}}\Big), \qquad (1)$$

where $R$ and $T$ stand for "received from the ground station" and "transmitted by the spacecraft" respectively, while $X$ and $Ka$ are the frequency bands. The quantity in (1) depends on the time derivative of the total electron content (TEC) along the path of the two-frequency downlink [3].

On one side, the signature of the IPT in the Doppler measurements can potentially introduce a bias in the orbit determination solution if not properly calibrated in the X/X configuration (in the Ka/Ka configuration the bias is negligible [4]), which may cause errors in determining the spacecraft ephemeris and the gravity harmonics of Jupiter . On the other side, it can be used to investigate the structure of the plasma cloud because of the relation between Doppler shift and TEC. Thus, there are both engineering and physical interest in employing radio observables to determine the structure of the IPT. Juno mission is particularly well suited to do this because of the many occultations it is performing.

The IPT is subdivided in different regions with different physical characteristic (e.g: temperature, ion composition). Here we assumed that the electron density in each of these regions can be modelled (in cylindrical coordinates) by a double-gaussian function similar to the one used in [3],

$$N_i exp\Big[-\Big(\frac{r-R_i}{W_i}\Big)^2 - \Big(\frac{z-Z_i}{H_i}\Big)^2\Big]^1, \qquad (2)$$

and we will show pro and cons of using only radio observables to fit this model alongside the results obtained by the occultations available so far. Indeed, the TEC is a line-of-sight integrated quantity along the downlink path, so it depends - roughly speaking - on the product of the peak electron density and the spatial extension of the IPT. We were able to decouple these two characteristic quantities taking into account the slight inclination of the downlink path with respect to the centrifugal equator and exploiting multiple occultations performed by Juno at different poloidal angle of the IPT (Fig.3). Nevertheless, the available geometry cannot give a complete scan all around the IPT: this implies that the complex structure of the outer torus (i.e: the ribbon, the warm and the extended torus, as

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[1] $N_i$ is the peak electron density of the $i$-th region, $R_i$ and $Z_i$ are the radial location and offset from the midplane of the peak density, while $W_i$ and $H_i$ are the typical width in the radial and $z$ direction.

identified by PLS instrument on *Voyager 1* [1]) cannot be retrieved, because the signature of each region is too mixed up with the others. However, we were able to distinguish the cold inner torus from the warm outer one and their characteristic parameters in (2).

Irregardless of the limits on the retrieval of a well-resolved morphology, we are able to constrain the radial structure of the IPT using only radio measurements. Besides, Juno is the second orbiter of the Jupiter system, so its data can be used to observe a possibile short-term variability of the IPT (the spacecraft performs a closest approach every $\sim$ 53 days) as well as a longitudinal modulation. In the end, data from Juno are compared with past missions in order to rule out (or "rule in") non-periodic secular variations, whose underlying physical mechanism may deserve further investigation.

To conclude, we remark that differential Doppler shift measurements are a powerful tool for investigating the IPT on their own, but their benefits can be further improved by other observables such as direct plasma measurements and spectroscopy, which can put additional constraints on the morphology of the IPT.

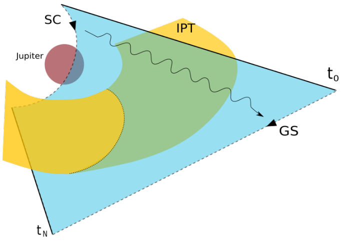

Figure 1: Sketch of the downlink crossing the IPT seen in a frame integral with the IPT. The blue area is the plane spanned by the the paths of the radio signal during each perijove.

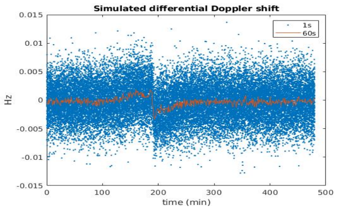

Figure 2: Simulated differential Doppler shift measurements: the Io's signature is clearly visible at $t =\approx$ 200.

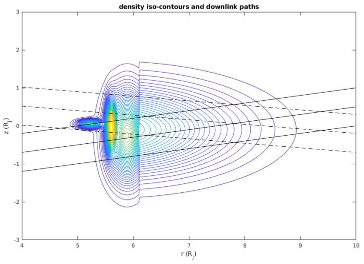

Figure 3: Sketch of the density isocontoursof the IPT alongside paths of the radio signal during two perijoves (solid and dashed black lines) with different poloidal angles.

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