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Two-Dimensional Transport Studies for the Composition and Structure of the Io Plasma Torus

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Two-Dimensional Transport Studies for the Composition and Structure of the Io Plasma Torus

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I. Introduction

The overall objective of this project is to investigate the roles of local and spatially extended plasma sources created by Io, plasma torus chemistry, and plasma convective and diffusive transport in producing the long-lived S^+, S^{++} and O^+ radial "ribbon" structures of the plasma torus, their System III longitude and local-time asymmetries, their energy sources and their possible time variability. To accomplish this objective, two-dimensional [radial (L) and System III longitude] plasma transport equations for the flux-tube plasma content and energy content will be solved that include the convective motions for both the east-west electric field and corotational velocity-lag profile near Io's orbit, radial diffusion, and the spacetime dependent flux-tube production and loss created by both neutral-plasma and plasma-ion reaction chemistry in the plasma torus. For neutral-plasma chemistry, the project will for the first time undertake the calculation of realistic three-dimensional, spatially-extended, and time-varying contributions to the flux-tube ion-production and loss that are produced by Io's corona and extended neutral clouds. The unknown two-dimensional spatial nature of diffusion in the plasma transport will be isolated and better defined in the investigation by the collective consideration of the foregoing different physical processes. For energy transport, the energy flow from hot pickup ions (and a new electron source) to thermal ions and electrons will be included in investigating the System III longitude and local-time temperature asymmetries in the plasma torus. The research is central to the scope of the NASA Sun-Earth Connection Roadmap in Quest II Campaign 4 "Comparative Planetary Space Environments" because it addresses key questions for understanding the magnetosphere of planets with high rotation rates and large internal plasma sources and is of considerable importance to the NASA Solar System Exploration Science Theme. In this regard, Jupiter is the most extreme example with its rapid rotation and with its inner Galilean satellite Io providing the dominant plasma source for the magnetosphere. The research work is furthermore highly relevant to the scientific goals and the ongoing interpretation of data for the Jupiter system acquired by a host of ground-based facilities, the Hubble Space

Table 1. Three-Year Research Plan

Investigation	Year 1	Year 2	Year 3
Step 1: Calculations for Iogenic plasma sources & lifetimes	Calculate Outer Source ion/energy productions, ion loss lifetimes, and explore Inner Sources.	Complete Outer Source calculations; continue to explore impact of molecular sources and sinks for the plasma torus chemistry.	
Step 2: Transport studies for $N_i L^2$	Add corotational-lag convection to transport equations; perform exploratory calculations.	Undertake major transport calculations for the spatial structure of the torus for an Inner Source and also Outer Source atomic sources and important molecular contributions; publish results.	
Step 3: Transport studies for $\mathcal{E}_i$ and $N_i L^2$	--	Initiate energy transport studies; explore power of Outer Source and Inner Source and torus System III longitude and local-time asymmetries.	

Telescope, the Voyager, Ulysses, and Galileo missions, and by the Cassini mission in its recent Jupiter flyby. The three-year research plan is summarized in Table 1.

II. Summary of Work Performed in the Second Quarter

In the second quarter, research has been performed at a reduced level. Efforts have included (1) the preparation and presentation of a paper at the Spring American Geophysical Union (AGU) Meeting, and (2) the initiation of an assessment of the basic nature of the radial structure of the peak electron density (i.e., electron ribbon structure) in the plasma torus measured during the J0 encounter of the Galileo spacecraft with Jupiter and how it compares to the electron ribbon structure measured by the Voyager 1 spacecraft.

2.1 Europa Paper Presented at the 2004 Spring AGU Meeting

A paper (Marconi and Smyth 2004) entitled "Europa's Hydrogen Atmosphere" was presented at the spring AGU Meeting during the week of May 17-21, 2004 in Montreal, Canada. The paper provided a preliminary assessment of the nature of the bound atmosphere and extended neutral clouds of Europa and their possible impact on the plasma torus. As noted in the prior progress report, the distinctly different ion density signatures in the Voyager 1 epoch plasma torus between the so-called "ramp region" (7.4 to 7.8 R_J) and Europa's orbit (9.4 R_J) indicate that Europa's neutrals may play a significant role in altering the ion composition and in determining the electron and ion temperature structures in this spatial region. A paper suitable for publication is in development.

2.2 Plasma Torus Structure at the Galileo Spacecraft J0 Pass

The electron density determined along the Galileo J0 trajectory from data acquired by the Plasma Wave Subsystem (PWS) instrument (Gurnett et al. 1996; Bagenal 1997) and the ion density determined from data acquired by the Plasma Analyzer (PLS) instrument (Frank and Paterson 2000) are compared in Figure 1. The electron density from the PWS data is shown in red on the inbound Galileo trajectory and in light blue on the outbound Galileo trajectory and is determined by a distinct narrow band of emission at the local electron upper hybrid frequency $f_{UH} = (f_p^2 + f_c^2)^{1/2}$, where f_p is the plasma frequency and f_c is the cyclotron frequency estimated from the local magnetic field. The inbound and outbound electron densities were, however, acquired over a significantly different angular range of System III longitudes, as indicated in Figure 1. The stair-step nature of the PWS electron density profile is caused by quantization in frequency. The ion density (dark blue), acquired only along the inbound Galileo trajectory and determined by fitting the PLS *in situ* ion data for an assumed ratio of ion mass (AMU) to ion charge (M/Q) of 16, has been multiplied by a factor of 1.5 in Figure 1 to adjust for the higher ion charge-state reflected in the electron density. The adjusted ion density profile is then in excellent agreement with the inbound electron density profile determined from the PWS data and thus provides an added level of confidence in the measured structure of the plasma torus.

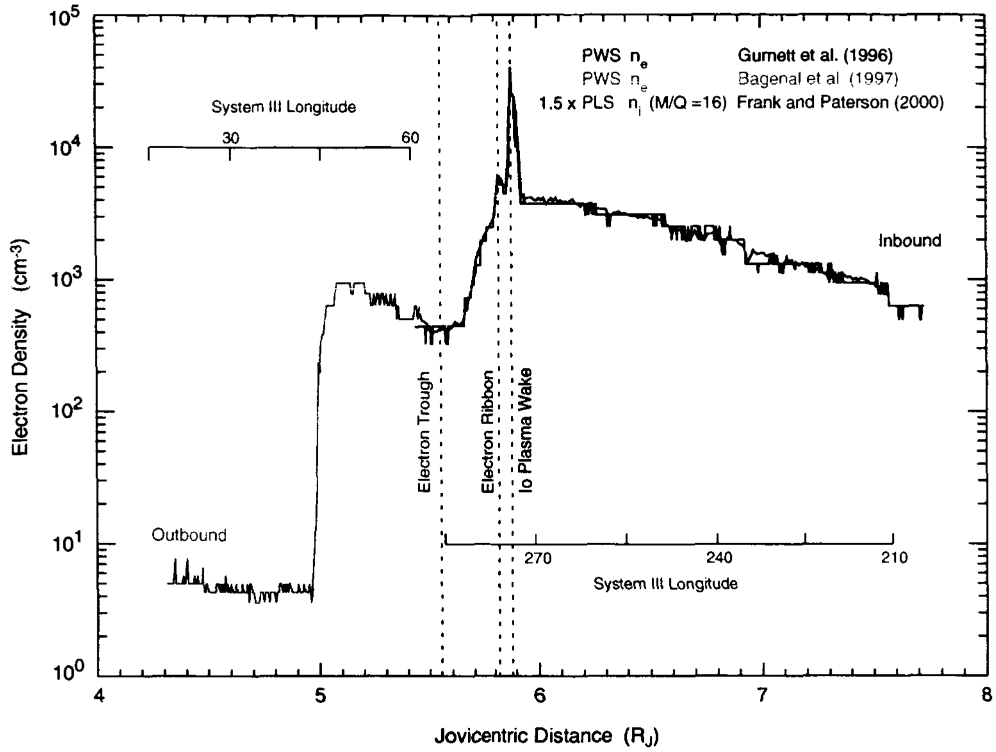

Figure 1. Electron and Ion Densities along the Galileo Spacecraft J0 Trajectory. The electron density determined from the PWS data is shown in red along the Galileo inbound trajectory and in light blue along the Galileo outbound trajectory. The ion density (dark blue), acquired only along the Galileo inbound trajectory and determined by fitting the PLS *in situ* ion data for an assumed M/Q of 16, has been multiplied by a factor of 1.5 to adjust for the higher ion charge-state reflected in the electron density.

The electron density along the spacecraft trajectory in Figure 1 increases radially inward at a rather uniform rate between the Jovicentric distances of ~7.7 R_J to 5.95 R_J, with the inner boundary occurring just before the Galileo spacecraft closest approach at 5.884 R_J to Io located at 5.876 R_J. The electron density peak with a maximum value of ~40,000 cm^{-3} at 5.818 R_J is the Io plasma wake signature, and it is followed by a secondary peak of ~5,000 cm^{-3} at 5.818 R_J which we propose is the electron ribbon signature of the plasma torus. For smaller Jovicentric distances, the electron density then has a relative minimum of ~400 cm^{-3} at ~5.5 R_J which is the electron trough. The electron ribbon and electron trough structures have the same distinct signatures in both the inbound PWS and PLS data. Along the Galileo outbound trajectory, an inner electron peak of ~1000 cm^{-3} is also present at a Jovicentric radial distance of ~5.2 R_J and is similar in structure to the inner electron peak measured by the Voyager 1 spacecraft.

The trajectories of the Voyager 1 spacecraft on March 5, 1979 and the Galileo spacecraft for the J0 pass on December 7, 1995 are compared in Figure 1. For the Voyager 1 spacecraft, *in*

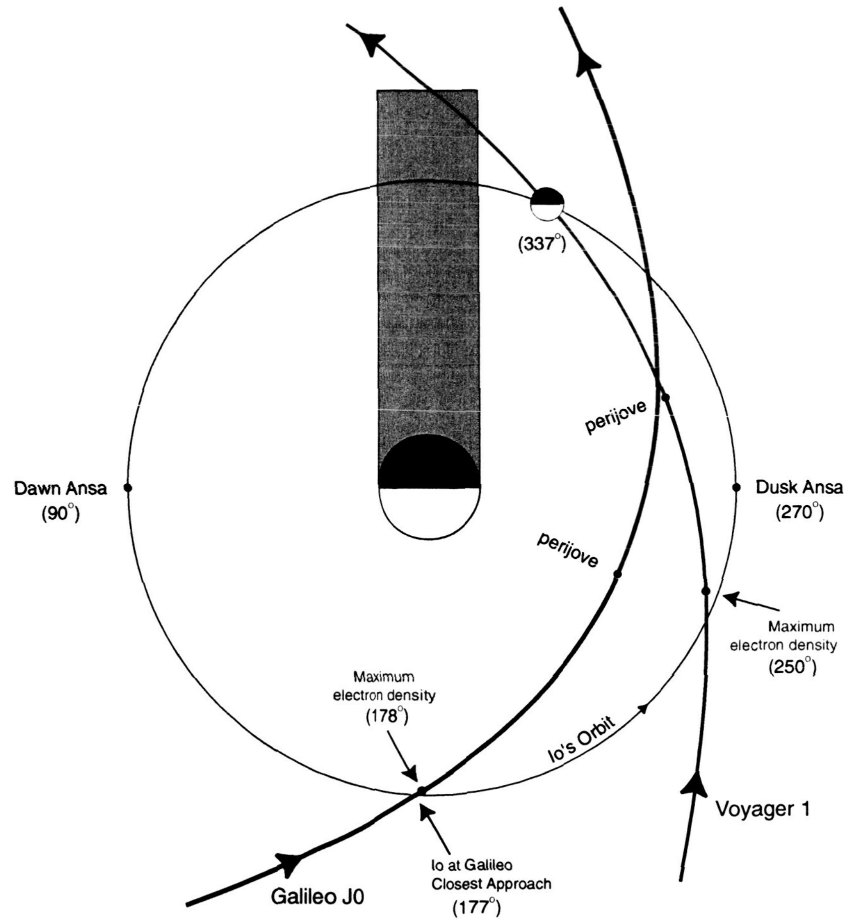

Figure 2. Spacecraft Trajectories Past Jupiter of Galileo for the J0 Pass and of Voyager 1. For each spacecraft, its Jovicentric radial location along the inbound trajectory (red) and the outbound trajectory (blue) in a heliocentric coordinate system is shown in proper spatial relationship to Io's orbit, Jupiter, and Jupiter's shadow. The location of the measured maximum electron density (electron ribbon) along each inbound spacecraft trajectory is indicated to scale. This location occurs for Voyager 1 at a heliocentric phase angle of 250° well before its closest encounter with Io on the outbound trajectory at 337° and occurs for Galileo at a heliocentric phase angle of 178° near noon just after its closest approach to Io at 177°.

situ ion data were acquired by the PLS instrument only along the inbound (red) trajectory while electron data were acquired along the inbound (red) and outbound (blue) trajectories by both the PLS and PWS instruments. Hence, the best Voyager 1 description of the plasma torus (Bagenal 1994) is based essentially on inbound measurements near the dusk ansa. As indicated in Figure 2, the maximum electron density measured by the Voyager 1 spacecraft was obtained on its inbound trajectory at a heliocentric phase angle of 250° and a radius of 5.663 R_J, which is inside of Io's orbital radial distance of 5.905 R_J. The close encounter of the Voyager 1 spacecraft with Io occurred somewhat later on the outbound trajectory at a heliocentric angle of 337°. The maximum electron density measured by the Galileo spacecraft other than the much larger peak for the Io plasma wake was obtained on its inbound trajectory at a heliocentric phase angle of 178° and a radius of 5.818 R_J, which was just inside of Io's orbit at 5.876 R_J. For all of the above radial locations, the value 1 R_J = 71,492 km that was adopted in the Galileo mission epoch has been used here. The location of the maximum electron density measured by the Voyager 1 and Galileo spacecrafts is therefore separated in local time by a heliocentric phase angle of 72° and is seen to be much closer to Io's orbit near noon than near dusk.

The structure of the plasma torus measured along the Galileo J0 trajectory is therefore characterized for increasing radial distances by three features: an inner electron peak followed by an electron trough followed by the maximum peak in the electron density (electron ribbon). This sequence of three features is the same radial structure that was measured by the Voyager 1 spacecraft for the plasma torus as shown in Figure 3 and discussed in the prior progress report. The only significant difference is that the electron ribbon is located closer to Io's orbit near noon than near dusk, as would be expected due to the dusk-to-dawn displacement of the plasma torus produced by the east-west electric field. This exact displacement will be studied in more detail later in the project, and this study will provide insight into the nature (magnitude and vector orientation) of the east-west electric field and the earlier ambiguous efforts of Bagenal et al. (1997) to address this matter.

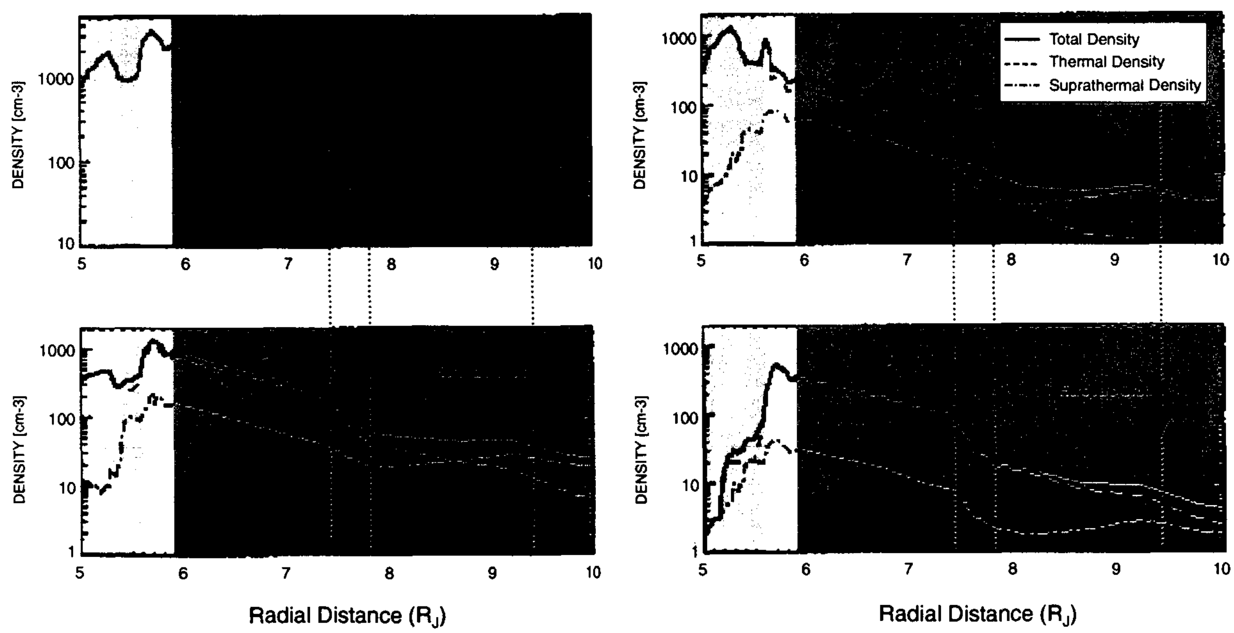

Figure 3. Electron and Ion Densities in the Plasma Torus. Thermal, suprathermal and total densities of the plasma torus at the centrifugal equator determined by Bagenal (1994) from Voyager 1 measurements are shown for electrons, O^+, S^+ and S^{++}. The cold torus (blue), Io high-density (ribbon) region (white), and warm torus (red) as well as the locations of the so-called "ramp region" (~7.4 – 7.8 R_j) and Europa's orbit are indicated.

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Research efforts in the second quarter have been focused upon a preliminary exploration of the likely impact of Europs's local atmospheres and neutral clouds on the plasma torus and the initiation of an assessment of the basic nature of the radial structure of the electron density in the plasma torus during the J0 encounter of the Galileo spacecraft with Jupiter.

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