

## RAY TRACING OF JOVIAN LOW FREQUENCY RADIATION

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N. Frank Six<sup>†</sup>  
Western Kentucky University  
Dept. Physics & Astronomy  
Bowling Green, KY 42101

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<sup>†</sup>Now with Universities Space Research Association  
139 McMurtrie Lane, Huntsville, AL 35806

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## INTRODUCTION

The radio emission from Jupiter in the decametric range (2-40 MHz) has been studied for three decades. It is known that this emission is correlated with particular longitude regions on the planet and with the position of the satellite Io. The Planetary Radio Astronomy experiment on the Voyager 1 and 2 spacecraft observed this emission, obtaining valuable new information.

The objectives of this study are the following:

- 1) calculate raypaths for decametric wavelength radiation in Jupiter's magnetosphere;
- 2) compare the model-dependent raypaths with the Voyager observations; and
- 3) deduce characteristics of the source regions and the influence of propagation effects.

Using a model of Jupiter's magnetized plasma environment, radiation raypaths have been calculated with a three-dimensional ray tracing program. It is assumed that energetic particles produce the emission in the planet's auroral zone at frequencies just above the electron gyrofrequencies. Families of rays have been launched at particular angles with respect to the magnetic field lines to generate conical sheets of radiation for various frequencies and various source locations. As the planet's magnetic field rotates, these warped sheets of radiation sweep past the observer, producing signatures in frequency versus time plots. These signatures match some of those found in the Voyager data. The greatest propagation effects occur in and around the source regions in Jupiter's auroral zone.

## TECHNICAL APPROACH

A major effort has been the development of a Jovian radiation path model using techniques which have proven successful in explaining the interactions of particles and waves in the terrestrial magnetosphere. The description of Jupiter's magnetic field, adopted for this study, is that published by Acuna and Ness (1976). A spherical harmonic analysis was used to calculate the components of  $\vec{B}$  and their derivatives. The plasma distribution chosen was that of Sentman and Goertz (1977) augmented by the Warwick torus (1979).

Radiation paths are generated by a three-dimensional ray tracing program based on the Stix cold plasma formulation of the index of refraction and Haselgrove's set of first order differential equations (1955), amenable to numerical solution. A source position (radial distance from the center of Jupiter, System III longitude, and System III latitude) from which waves of a specified frequency are to be launched is input, along with the specified launch angle (wave normal angle) with respect to the magnetic field. At the origin of the ray, the program calculates an index of refraction surface based on the plasma and magnetic field parameters. Next the program takes an incremental step in the direction perpendicular to the index of refraction surface, i.e., in the direction of propagation, and determines the coordinates of this new position on the raypath. Snell's law is used to conserve the component of the refractive index parallel to planes of constant electron number density. Another index of refraction surface is calculated at this new point and the procedure is repeated. In this manner, a raypath is

generated. The path of a ray through the magnetized plasma is determined by the following initial conditions: the frequency of the wave, the wave normal angle, the coordinates of the source (launch points), the propagation mode, and the magnetospheric model.

The Galilean satellite Io is known to have a pronounced modulating effect on the decametric radio emissions from Jupiter. Ground based and spacecraft observations of Jupiter are made from a coordinate system in which both the central meridian longitude of Jupiter and the central meridian longitude on which Io is located are changing rapidly. Observations in this coordinate system tend to mask features which are fixed or nearly fixed relative to Io itself. We have examined the data from the Planetary Radio Astronomy (PRA) experiment onboard the Voyager 1 and 2 spacecraft in a stationary coordinate system in which Io is fixed at particular central meridian longitudes of Jupiter. The reformatted data are equivalent to what an observer would detect if s/he could sample all longitudes around Jupiter's equatorial plane with the planet's rotation halted and Io stopped in its orbit.

Using the 04 magnetic field model, we have investigated the variation of source altitude with longitude around Jupiter at selected emission frequencies, assuming an oblate spheroid for the cloudtop surface. We have concluded that, in certain ranges of longitude, the higher frequency radiation ( $f \gtrsim 20$  MHz) originating from lower altitudes will be affected by the Jovian ionosphere. As a result of this study, a model ionosphere was added to the ray tracing program.

## REVIEW OF RESULTS

1. Calculated Raypaths. An examination of the catalog of decametric radiation sheets generated by the ray tracing procedures described in Publication 4 reveals that signatures such as those observed by the Voyager PRA experiment can be reproduced. The radiation sheets are warped by the plasma near the planet and by the twist (azimuthal asymmetry) in the magnetic field such that overlapping occurs. An observer riding with Voyager intermittantly crosses thin sheets of radiation as the source co-rotates with the planet. It is as though the observer were viewing the ruffles in a twirling ballerina's tutu. The Io plasma torus has minimal effect at decametric wavelengths. The major distortion by plasma occurs at higher latitudes nearer the surface of the planet. This is also the region of greatest azimuthal asymmetry in the magnetic field.

In the one case tested, the high frequency limit of the decametric emissions has been predicted. The Voyager 2 data of July 16, 1979, reveals a well defined boundary to the highest frequencies observed. The rays for frequencies just below this boundary propagated through the magnetized plasma, as expected. The rays that were generated for frequencies above the cutoff did not propagate. The altitude of the 25 MHz source point at this latitude is approximately 12,400 km, presumably above the Jovian ionosphere. We conclude that the high frequency limit to the emission, in this case, is imposed by the R-X cutoff.

The growth-rate of the emission process causes the radiation to be confined to narrow sheets which are contoured by the plasma near Jupiter and by the azimuthal twist in the magnetic field,

resulting in bends and ruffles like the familiar shapes of "auroral curtains", but on a grander scale. The intersection of these calculated sheets of radiation with the spacecraft produce arc-like signatures like those detected by Voyagers 1 and 2. Both the shape and the location (in longitude) of the low curvature arcs in the data are predicted by Doppler-shifted gyro-emission with all frequencies launched at a wave normal angle of approximately  $90^\circ$ . Decametric arcs of higher curvature appear to represent a different class of event. Initial studies imply that these higher curvature features are reproduced by allowing the wave normal angle to vary as a function of the wave frequency. It is suggested that these events could be produced by higher energy electrons whose gyro-emission is relativistically beamed closer to the B-field direction, i.e., launched with smaller wave normal angles.

2. Io-Centered Coordinate System. Voyager spectrograms have been generated as a function of frequency and spacecraft longitude for a constant Io phase. In this coordinate system, we find multiple lanes of radio emission which are highly correlated with the orbital position of Io. This analysis supports an earlier conclusion that the decametric radiation emanates in thin sheets from regions associated with the foot of the Io flux tube. The principal radio "sources" A, B, and C are easily identified in this coordinate system.

On close inspection of the Voyager data, transformed into this Jupiter-Io stationary coordinate system, one finds that the Io-dependent decametric radiation occurs in two or more wide

frequency bands of emission on each side of the instantaneous Io flux tube. As the sub-Io point on Jupiter moves to different longitudes, a result of the planet's rotation and Io's orbital motion, the wide band emissions also move to different longitudes. The longitudinal width of the emission regions detected by the spacecraft varies (sometimes as broad as 30 degrees), and the maximum frequency measured in each of the regions is not always the same for a fixed sub-Io longitude.

3. Emission Cone. Io-dependent decametric radiation, emanating as hollow emission cones from source regions at the feet of Io-threading field lines reproduces the signatures of the wide band emissions in the Voyager frequency-longitude spectrograms for sub-Io longitudes in the range  $200^{\circ}$ - $260^{\circ}$ . Two distinct arc-like structures in the Voyager spectrograms make up the cone "edges" (radiation sheet intersections with the plane of Voyager's trajectory). The edge of the cone at higher longitude than Io is always composed of vertex-late arcs; the other edge at lower longitudes is composed of vertex-early structures.

4. Magnetic Field Models. The ray tracing results show that the principal controlling agent of the radiation sheet morphology is Jupiter's B-field structure in the source region. The pointing of the emission cone axis is determined by the B-field direction in the source region.

The null centered at System III longitude =  $30^{\circ}$  in the probability histograms (earth-based observations) appears to be a manifestation of the zone of avoidance created by the asymmetric



location of Jupiter's magnetic poles. Since the poles are not separated by  $180^\circ$  of longitude, the stop zone produced by the Jovian ionosphere shadows those longitudes in the range  $15^\circ$ - $45^\circ$ .

The magnetic field models used for the ray tracing calculations are only approximations to the actual planetary magnetic field at low altitudes. The displacement of the measured UV auroral zone from the model-generated Io footprint is an indication of the uncertainty in our knowledge of the B-field.

5. Decametric Source Locations. In a comparison of model ray tracings with Voyager observations for constant sub-Io longitudes of  $260^\circ$  and  $300^\circ$ , we have identified spectral features in the emission with source locations in both the northern and southern hemispheres of Jupiter. We find that the emission traditionally designated "Io-B" originates at the Io flux tube footprint in the northern hemisphere when the sub-Io longitude =  $260^\circ$ . The emission which has been traditionally designated "Io-C" emanates from source regions at the feet of the Io flux tube in both northern and southern hemispheres when the sub-Io longitudes are  $260^\circ$  and  $300^\circ$ . The traditional "non-Io-A" emission is, in fact, Io related at both sub-Io longitudes investigated. When the sub-Io longitude =  $260^\circ$ , this emission emanates from the southern hemisphere flux tube footprint. When the sub-Io longitude =  $300^\circ$ , the emission originates from the flux tube footprint in the northern hemisphere.

The two pairs of traditional "sources" B-C and C-D are believed to correspond to the four intersections, in the observers plane, of two hollow emission cones which emanate from the north and south footprints of the Io flux tube.

In addition to the Io flux tube sources, there are sources which are independent of Io's orbital position. The highest frequencies ( $f > 36$  MHz) emerge near longitude  $255^\circ$ , consistent with a polar cap source location near longitude  $215^\circ$  in the northern hemisphere. The maximum concentration of plasma in the Io torus occurs in this longitude range. It is plausible to suspect that a weak region in the planet's magnetic field allows deeper penetration of energetic electrons which generate the higher frequency gyro emissions at this location.

## PUBLICATIONS

The following reports and publications in the open literature are the major products of the research performed under contract NAS8-34424.

1. "Ray Tracing Studies of Jupiter's Magnetosphere," NASA/ASEE Summer Faculty Research Fellowship Program, Marshall Space Flight Center, 1981, F. Six.
2. "Magnetospheric Ray Tracing Studies," NASA/ASEE Summer Faculty Research Fellowship Program, Marshall Space Flight Center, 1982, F. Six.
3. "Analysis of the Voyager Observations of Jupiter's Decametric Radio Emission," NASA/ASEE Summer Faculty Fellowship Program, Jet Propulsion Laboratory, California Institute of Technology, 1983, F.Six.
4. "Three Dimensional Ray Tracing of the Jovian Magnetosphere in the Low-Frequency Range," J. Geophys. Res., 89, 1489, 1984, J. D. Menietti, J. L. Green, S. Gulkis, and F. Six.
5. "The Io Decametric Emission Cone," Radio Sci., 19, 556, 1984, J. L. Green.
6. "Jovian Decametric Arcs: An Estimate of the Required Wave Normal Angles from Three-Dimensional Ray Tracing," J. Geophys. Res., 89, 9089, 1984, J. D. Menietti, J. L. Green, S. Gulkis, and F. Six.
7. "Ray Tracing of Jovian Decametric Radiation from Southern and Northern Hemisphere Sources: Comparison with Voyager Observations," J. Geophys. Res., 92, 27, 1987, J. D. Menietti, J. L. Green, N. Frank Six, and S. Gulkis.