

URANUS RADIO EMISSIONS

Michael L. Kaiser

*Laboratory for Extraterrestrial Physics
NASA/Goddard Space Flight Center
Greenbelt, MD 20771, USA*

Abstract

An overview of the Voyager 2 Planetary Radio Astronomy instrument observations of the planet Uranus is presented. From these observations, a number of inferences have been made including the rotation period of the interior of the planet and the source locations of several of the radio components.

Introduction

Although Uranus was very secretive in revealing its radio signature (first signals detected only five days before Voyager 2 fly-by in January, 1986), it is surpassed only by Jupiter among the radio planets in the degree of radio complexity. In this paper, I will briefly describe the radio observations made by the Planetary Radio Astronomy (PRA) and Plasma Wave System (PWS) instruments during the approximately two week period centered on closest approach. A more complete description of the observations can be found in Leblanc et al. (1987). Following the description of the observations, I will illustrate some of the early results of the on-going data analyses. These illustrations will be incomplete, and will be centered primarily on results from the Goddard PRA group. A more complete picture of the PRA results can be obtained from the Uranus Special Issue of the Journal of Geophysical Research (December, 1987 edition).

Observations

With the exception of brief episodes of lightning-like sferics detected near closest approach (Zarka and Pedersen, 1986a), the Uranian radio emissions were all confined to the low band receiver of the PRA instrument. This receiver (see Warwick et al., 1977 for complete description) sweeps through the range from 1.2 to 1326.0 kHz in 70 equally spaced steps every six seconds. The actual measurements made are of power in the left hand (LH) circular and right hand (RH) circular senses of polarization. This polarization information combined with some knowledge of the radio source location (i.e. which magnetic hemisphere) allows one to deduce the mode of the emission, either ordinary (O) mode or extraordinary (X) mode.

Figure 1 shows a 4-day overview of the Uranus encounter (C.A. = closest approach) in dynamic spectrum format where increasing intensity is shown by increasing darkness. The striking dichotomy between the inbound observations from above the daylit hemisphere and the outbound observations from above the nighttime hemisphere is readily apparent. Prior to closest approach, the emission was confined to the lowest few channels and was

extremely weak. However, at about the time significant portions of the night hemisphere first became visible to Voyager 2 (near C.A.), the emission abruptly increased in both bandwidth and intensity. In that sense, Uranus resembles the earth, with the majority of its radio emissions beamed toward the night hemisphere.

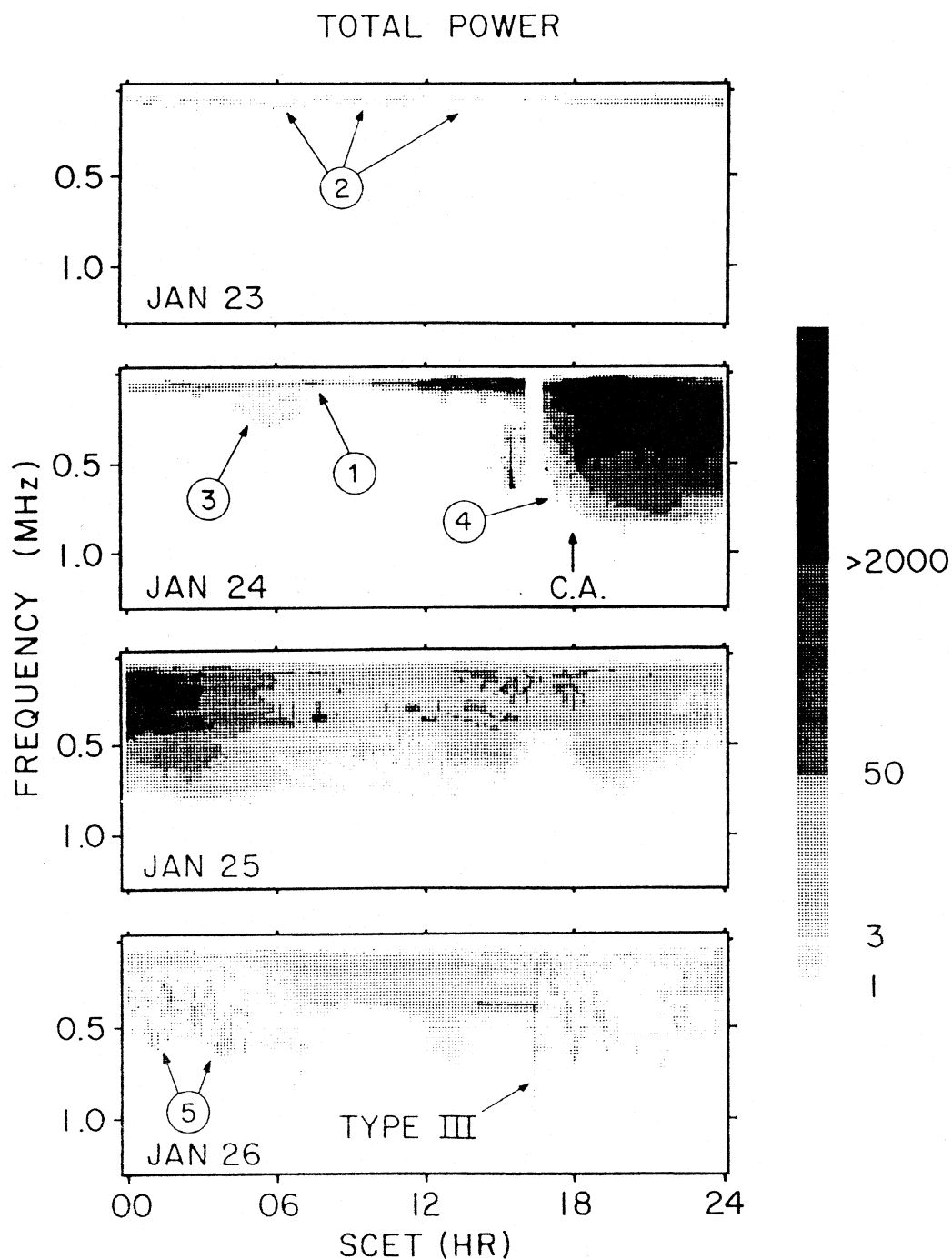


Fig. 1: Frequency versus time dynamic spectra from the Voyager 2 PRA instrument for the four day period near closest approach (C.A.) to Uranus. Five different spectral components are visible.

At least five distinct radio components are visible in Figure 1 and they are highlighted in subsequent figures. These components are numbered in approximately the order in which they were first detected. A complete description of components numbered 1, 2, 4, and 5 can be found in Leblanc et al. (1987), and component number 3 is described fully by Desch and Kaiser (1987). In addition to the five numbered components, Zarka and Pedersen (1986a) report the possible detection of lightning-like discharges essentially at frequencies above those shown in Figure 1.

Figure 2 shows components 1, 2, and 3 at a number of individual channels in a format which shows not only total power, but the sense of circular polarization. The polarization is that detected at the spacecraft in the radio astronomical sense (i.e. the tip of the wave vector rotates clockwise for a LH polarized wave approaching the observer). Component number 1 was actually first reported by the PWS team (Gurnett et al., 1986) and consists of extremely narrow bandwidth bursts with large temporal fluctuations. In the example shown, note that the emission is at least 30 dB above background in the RH channel at 59 kHz and is not seen in the next channel only 19 kHz higher in frequency. Leblanc et al. (1987) believe these low frequency bursts actually consist of two populations, one type has burst episodes of less than two minutes total duration, and the other contains burst episodes of much longer – tens of minutes – duration. These bursts were reported primarily during the inbound leg of the trajectory (i.e. dayside) although some were observed during the first few hours of the outbound trajectory (nightside).

Component number 2 consists of the thin “line” of emission running near the top of each panel in Figure 1 for January 23 and part of January 24. It can be seen in Figure 2 as LH polarized emission extending up to about 100 kHz. The overall frequency extent of this component is roughly 20 kHz to over 200 kHz, but the intensity drops sharply on either side of 80–100 kHz so that it is below the detection threshold at the frequency extremes for all but a very few hours near closest approach. This component differs from the narrow band bursty emissions (component 1) not only in polarization, but in temporal character. Intensity variations for component 2 are slow with an poorly defined waxing and waning every 17.24 hr period. Component 2 was also detected by PRA during the outbound trajectory (e.g. see Figure 4), but the polarization was reversed relative to the inbound observations, the reversal occurring at approximately the time the spacecraft crossed from one magnetic hemisphere to the other.

Component 3, identified by Desch and Kaiser (1987), also shows a smooth temporal variation. However, this component was only observed on one occasion lasting 4–5 hours centered some 12 hours before closest approach when Voyager 2 was still above the dayside of Uranus. From Figure 2, it can be seen that component 3 is also LH polarized like component 2, but is much weaker and has its peak intensity several hours later than component 2. The overall frequency extent of this third component is from about 100 kHz to about 300 kHz with peak flux at 150 kHz.

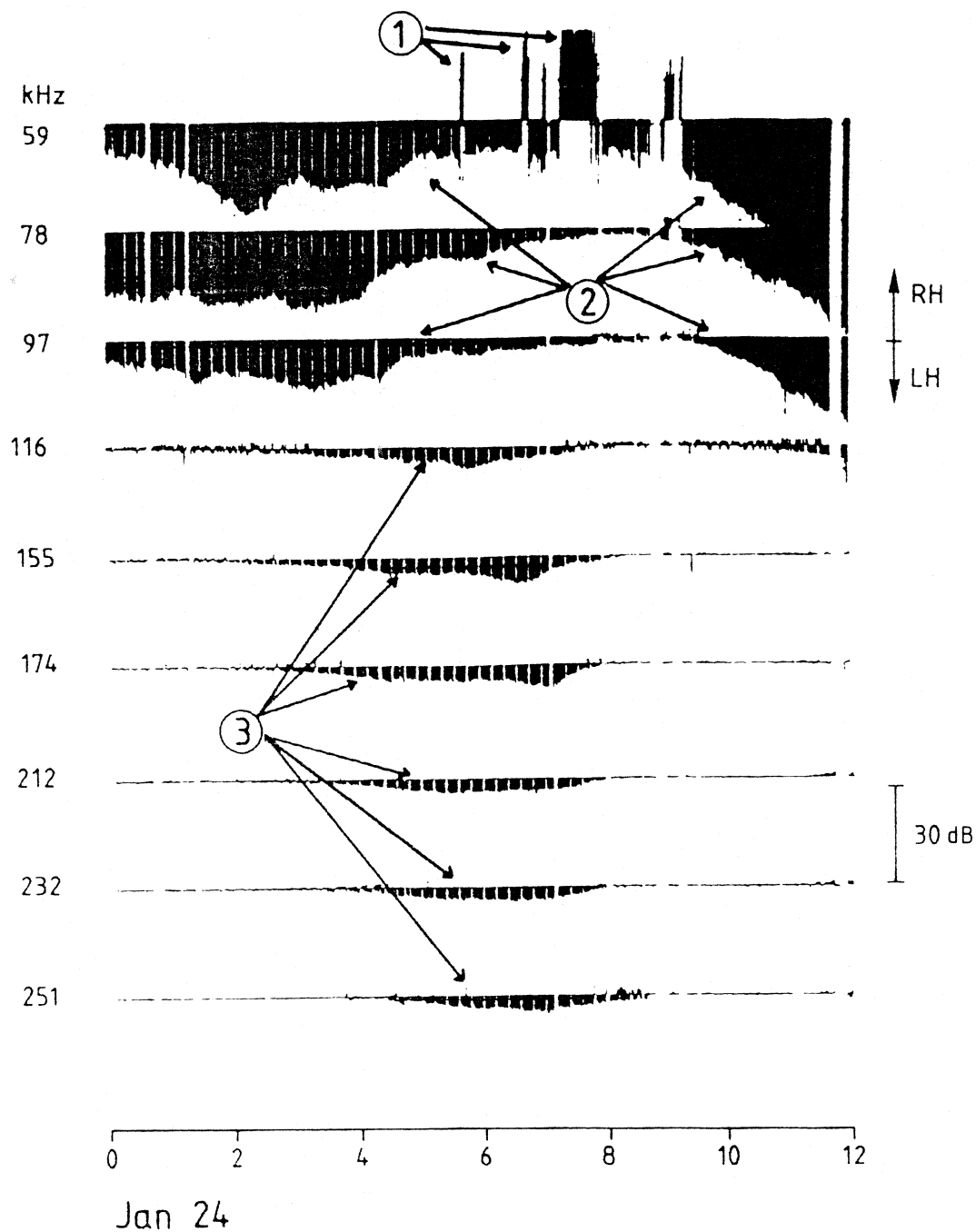


Fig. 2: Several of the low frequency channels from the Voyager 2 PRA instrument for the period just prior to closest approach when the spacecraft was still above the Uranian dayside. Intensity is coded so that the sense of circular polarization is indicated. Three of the five spectral components from Figure 1 are shown.

Figure 3 dramatically illustrates the difference between component 2 and component 3 as reflected in the apparent polarization axial ratio. Component 2 (narrowband emission) is more circularly polarized than component 3 (dayside emission); indeed their axial ratios measured at the same time do not even overlap.

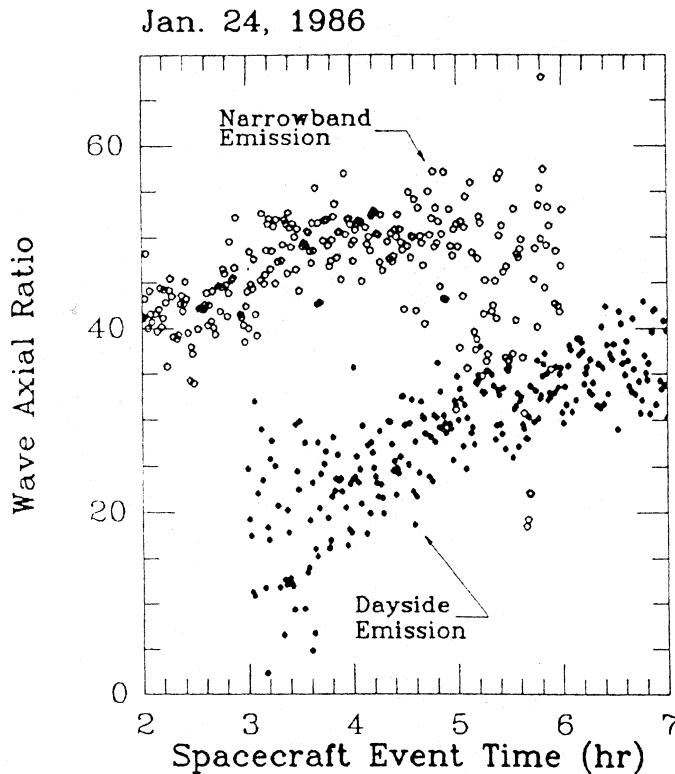


Fig. 3: The polarization axial ratio as a function of time for the narrowband smooth emission (component 2 of Figures 1 and 2) compared with the "dayside" emission (component 3).

Figure 4 corresponds to a period of time after Voyager 2 has swung around Uranus onto the outbound (nightside) trajectory. Shown are the polarized intensities of four PRA channels near 100 kHz. Examination of this interval of time in the total power dynamic spectra of Figure 1 suggests one radio component extending from essentially the lowest PRA frequencies to several hundred kilohertz. However, when the polarization information is added in Figure 4, it can be seen that a transition occurs near 80 to 100 kHz. The emission above 100 kHz is strongly LH polarized throughout the entire outbound trajectory. Below 80 kHz the emission is RH when observed from the outbound trajectory. Detailed examination (Leblanc et al., 1987; Lecacheux and Ortega-Molina, 1987) shows that component 2 is observed throughout the encounter, both inbound (LH) and outbound (RH), but suffers severe competition from the much more intense and broader bandwidth component number 4 which is visible only during the outbound portion of the trajectory.

Figure 5 shows this broad bandwidth component number 4 at higher frequencies, near its spectral peak of 400 kHz. Also shown is yet another nightside component labelled number 5 which happens to be in the same frequency range as component 4, but with strikingly different temporal characteristics. Component number 4 is relatively smoothly varying, reminiscent of components 2 and 3, whereas component 5 is quite bursty like component 1. Both of these nightside components extend over the range from at least 100 kHz, where the previously mentioned confusion with component 2 occurs, to as high as 850 kHz. At frequencies above approximately 300 kHz, a precipitous several hour long intensity decrease is evident (see Figure 6) in both components, but particularly component 4, the smoothly varying component.

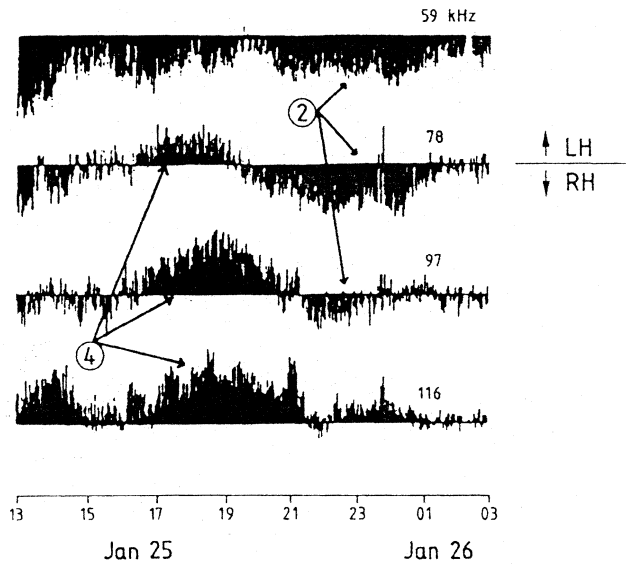


Fig. 4: Several of the low frequency channels from the period after closest approach when the spacecraft was above the night-side of Uranus. A polarization difference between the lowest frequencies and those above 100 kHz is evident, indicating that the two spectral components (2 and 4) are merged together.

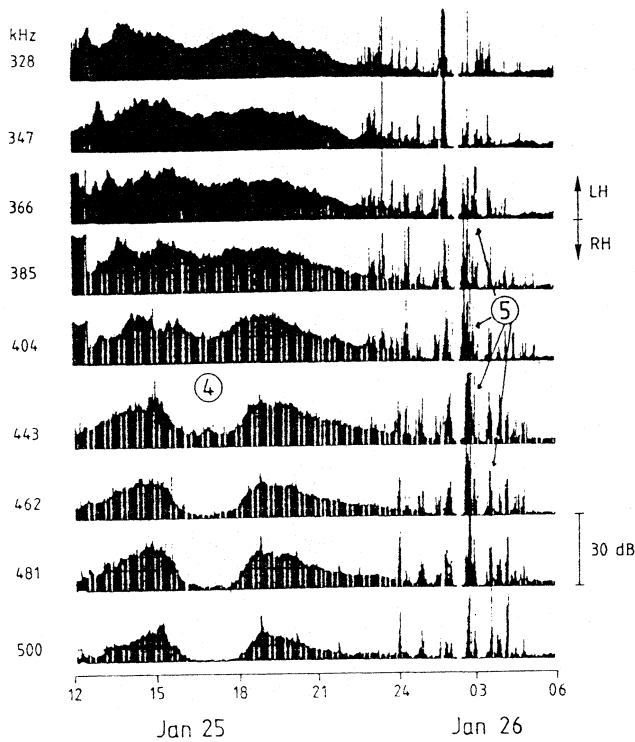


Fig. 5: Several of the mid-frequency channels from the PRA instrument showing the two dominant nightside components (4 and 5 from Figure 1). The smooth component (4), shows a dramatic intensity dropout at frequencies above about 300 kHz. The bursty emission (component 5), is concentrated during intervals when the spacecraft is near the magnetic equator.

Table 1

URANUS RADIO EMISSIONS

	COMPONENT	F (PEAK)	MEDIAN POWER	POL.	COMMENTS
1	BURSTY LF	60 kHz	<10 MW	RH	INBOUND ONLY, SOURCE UNKNOWN
2	SMOOTH LF	60 kHz	4 MW	LH(in) RH(out)	SOURCE UNKNOWN, NEAR EQUATOR ?
3	"DAYSIDE"	150 kHz	1/2 MW	LH	ONE EVENT - MAY BE OTHER END OF #4 FIELD LINE
4	SMOOTH HF	400 kHz	10 MW	LH	NIGHT AURORAL ZONE 17.24 HR PERIOD
5	BURSTY HF	400 kHz	>20 MW	LH	OBSERVED NEAR EQUATOR

ALSO

SPORADIC LIGHTNING RF ABOVE 1 MHz
NARROWBAND "TONES" NEAR 5 kHz

Table 1 summarizes the basic observable properties illustrated in Figures 1 through 5.

Just one step removed from a direct observation is the determination of a planet's intrinsic rotation period from periodic modulations in the radio emissions. The line of reasoning is that the emissions are locked to the planet's magnetic field which emanates ultimately from the planet's core. Since it is assumed that the planet's core rotates rigidly, therefore, it is assumed that the radio emission rotates rigidly. This line of reasoning has been used successfully at Jupiter and Saturn where the radio defined rotation periods are the ones used by virtually all investigators.

In the case of Uranus, both the narrow band smooth emission (component 2) and the broad band smooth emission (component 4) wax and wane in intensity with a roughly 17.3 hour period. However, the total span of data for Uranus is scarcely two weeks, so that simple power spectral analysis of the intensity modulations would not produce a very accurate rotation period. Instead, Desch et al. (1986) used the previously mentioned intensity dropout in the high frequency portion of the broad band smooth emission along with an analysis of the magnetic field itself to produce an extremely accurate rotation period.

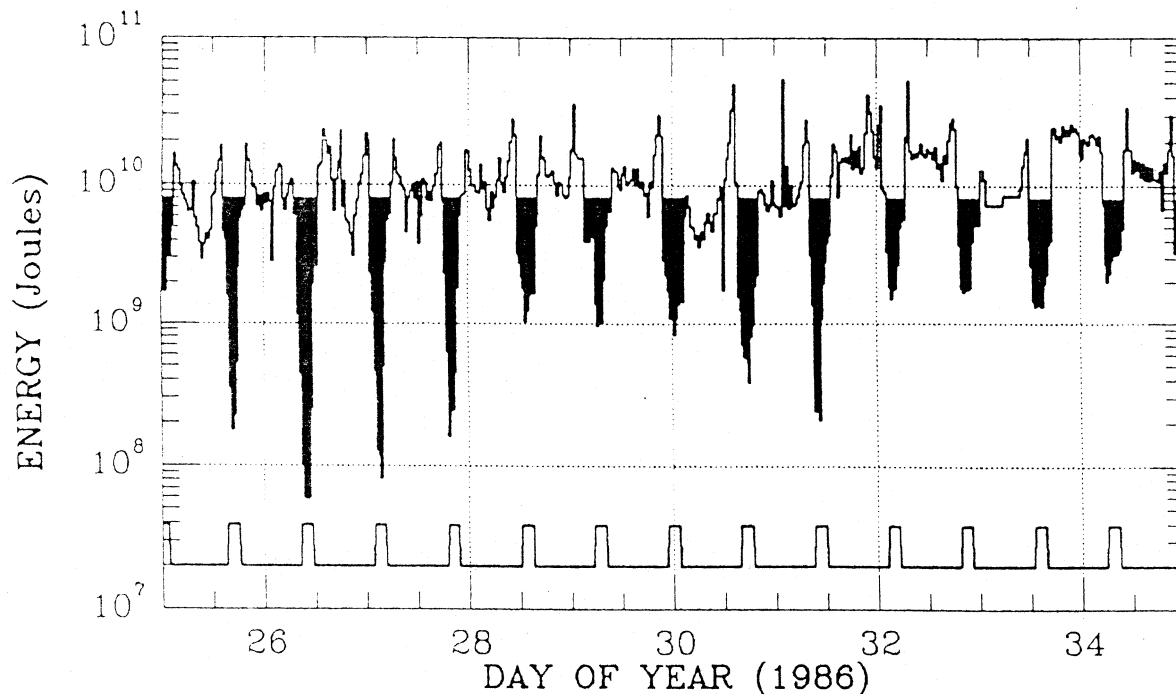


Fig. 6: Total energy of component 4 in Joules as a function of time clearly showing the rotation modulation of the nightside Uranian radio emissions. A 17.24 hour clock is superimposed below the data.

Figure 6 shows the modulation of the broad band smooth component in terms of energy (Joules) versus time. The shaded regions correspond to the dropouts. At the bottom, an artificial 17.24 hour clock is shown aligned with the dropouts. Least squares analysis of the dropout repetition resulted in a value of 17.239 ± 0.009 hours. Analysis of the spherical harmonic coefficients describing the magnetic field indicated that a best fit was obtained when the rotation period was 17.29 ± 0.20 hours, thus providing good evidence that the implicit assumption of a connection between the radio emissions and the magnetic field is real.

Determination of the intrinsic rotation period for any planet is of fundamental importance in a number of research fields. For the outer gaseous planets, this determination relies solely on the radio technique because features in the clouds can move rapidly with respect to rotation in either direction. Prior to the 17.24 hour PRA determination for Uranus, published values for the rotation period ranged from 10 hours to 24 hours, with 15.57 hours being the nominally adopted value. The PRA result had two immediate consequences, namely, the few discrete clouds observed by the Voyager 2 imaging system (Smith, B.A. et al., 1986) were shown to be moving rapidly in a prograde direction, contrary to pre-encounter ideas, and the internal structure of Uranus as deduced from the rotation period combined with the observed oblateness was shown to be less centrally condensed than previously thought.

Source locations

The direct observations reported in the last section answer questions about the properties of Uranian radio emission but they do not tell us such fundamental facts as the source locations. In the frequency range of the Uranian emissions, the PRA antennas (two 10-m orthogonally mounted monopoles) provide virtually no directional information. Therefore, source location determination for Uranus (as well as the other planets visited by Voyager) is done by inference and is subject to interpretation.

Perhaps the most progress in source location determination at Uranus has occurred for the broadband smooth (#4) component due to its exclusive occurrence over the night hemisphere and the ubiquitous intensity dropout. Figure 7 shows another example of the dropout as a function of frequency for several PRA channels. Also indicated on the figure is the time of passage of the South magnetic dipole tip, i.e. the time at which the sub-Voyager point is on the same Uranographic longitude meridian as the dipole tip. The dropout is clearly asymmetric with respect to the dipole tip passage, suggesting that the source location is not symmetric about the dipole tip as would be the case, for example, of a filled auroral oval.

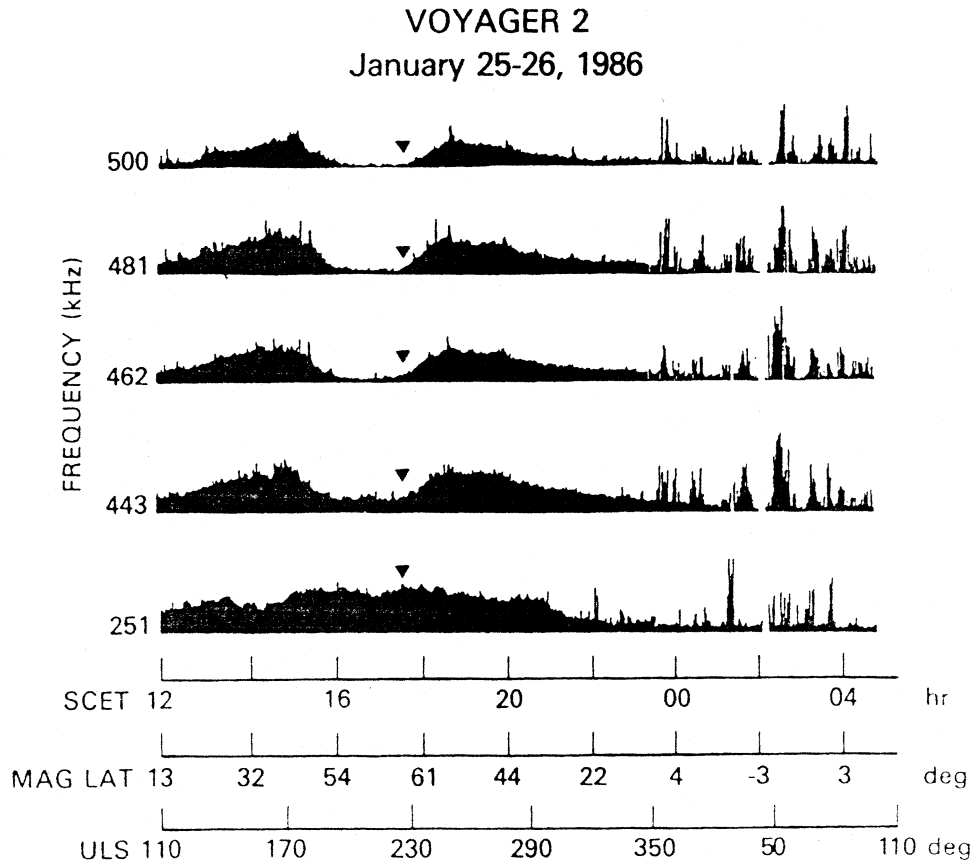


Fig. 7: Another example of components 4 and 5 showing the time of passage of the South magnetic dipole tip (arrow), i.e. the time at which the sub-spacecraft longitude and the longitude of the dipole tip are the same. This dipole tip passage is clearly not in the center of the dropout.

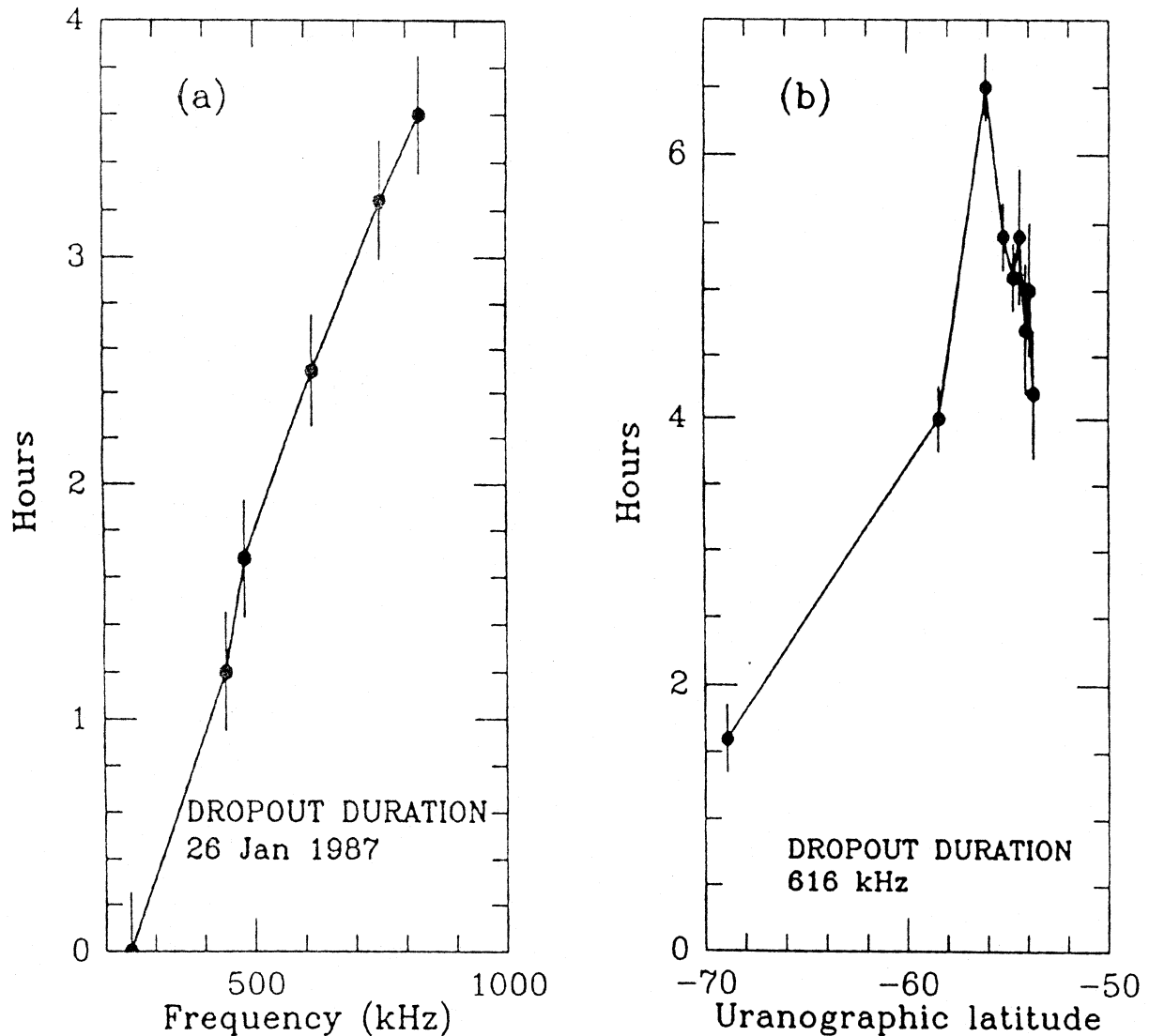


Fig. 8: Left panel shows typical dropout duration as a function of frequency. Below 300 kHz, the dropout is filled in. Right panel shows, for a fixed frequency, the dropout duration as a function of sub-spacecraft latitude. Maximum duration occurred when Voyager 2 was at approximately -56° latitude.

Kaiser et al. (1987) pointed out that the dropout has both a latitude and a frequency dependence as illustrated in Figure 8. Panel a) of Figure 8 shows that the dropout duration is longer at higher frequencies, whereas panel b) shows that the longest duration dropout occurred when the sub-Voyager latitude was -56° .

Several PRA teams have addressed the source location of this component and the reader is referred to the Journal of Geophysical Research Uranus Special Issue mentioned previously for the details. Although different techniques are used in the analysis by the various authors, the deduced source locations are in general agreement. I will take the work of Kaiser et al. (1987) to illustrate the type of analysis used in low frequency source location determination.

Kaiser et al. (1987) made two crucial, but supportable, assumptions. The first is that the emission from component 4 occurs at or near the electron gyrofrequency. Since the emission was observed to be strongly LH polarized and was clearly associated with the magnetic southern hemisphere, Warwick et al. (1986) concluded that it was X mode. Also, since the electron plasma frequency is likely to be much less than the electron gyrofrequency at most altitudes over the Uranian night hemisphere, the X mode cutoff frequency is approximately equal to the electron gyrofrequency. The second assumption had to do with the nature of the dropout itself. Kaiser et al. (1987) assumed that the dropout was due to a hollow emission pattern with the hole in the pattern oriented parallel (or antiparallel in this case) to the magnetic field direction in the source region. Hollow emission patterns like this had previously been observed in association with X mode radio sources both at the earth and at Jupiter.

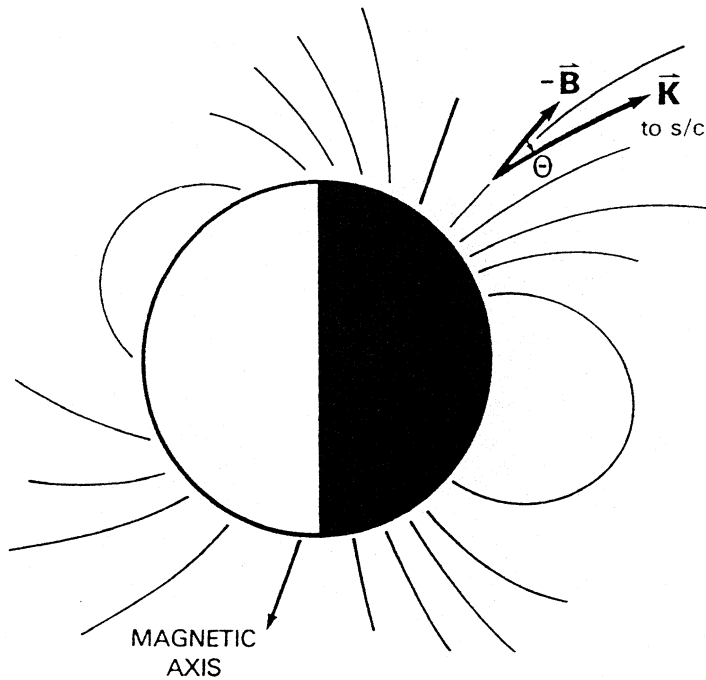


Fig. 9: An illustration of the calculation of the angle (θ) between the direction of the magnetic field and the direction of the spacecraft for a particular altitude corresponding to a particular electron gyrofrequency. This calculation was made for all field lines emanating from the night side of Uranus.

Armed with these two assumptions and the offset tilted dipole magnetic field model of Ness et al. (1986), Kaiser et al. (1987) performed the calculations illustrated in Figure 9. They calculated the angle between the direction of the magnetic field at a specified gyrofrequency altitude and the direction of the spacecraft for the entire night hemisphere of Uranus. As a starting point, they used the geometry corresponding to the time of the center of the maximum duration dropout, when Voyager 2 was at -56° latitude. They searched for the location in the magnetic field where the angle was approximately 180° .

Figure 10 shows the results of this calculation in terms of contours of equal angle projected down the field lines to the cloud tops. As can be seen, the region where the angle is nearly 180° is a small area not far from the South dipole tip. Kaiser et al. (1987) concluded that the center of the component 4 source region has its magnetic footprint at the center of the contours.

Comparison of the dropout duration with the variation in the angle between the proposed source-center footprint and the spacecraft led Kaiser et al. (1987) to conclude that the overall extent of the source was small, corresponding to the darkened footprint shown in Figure 11 (top panel). This source is situated mostly on closed field lines, the approximate break between open and closed occurring at $L=18$ (Ness et al., 1986). The opposite end of this bundle of field lines reaches the cloud tops at the Uranographic equator, near the present day terminator. This unique arrangement led Curtis et al. (1987) to speculate that the nightside radio emission is driven by diurnal variations in the altitude of the atmosphere near this opposite footprint.

Also shown in the top panel of Figure 11 is the location of the "radio horizon" corresponding to the footprint of field lines making a 90° angle to the spacecraft at the time the component 4 was first detected. The agreement between this radio horizon and the deduced source region is remarkable.

In the bottom panel of Figure 11, the radio horizons that apply to the first detection and subsequent episodes of the broad band bursty component (#5) are shown. Here only regions of exclusion can be determined such that the source must lie on the side of the horizons indicated by the arrows. Kaiser et al. (1987) speculated that the source of the bursty emissions was probably on higher L shells than the source of the smooth emissions, perhaps on open field lines.

Desch and Kaiser (1987) attempted to deduce the source location of the weak component observed above the dayside hemisphere (component 3). Figure 12 shows the spacecraft-planet geometry at the time of the observation. The spacecraft was near maximum northern magnetic latitude so the nightside source regions determined for components 4 and 5 were blocked from view by the planet itself. Desch and Kaiser concluded that the emission was likely to be O mode since it was observed to be LH and was associated with the magnetic northern hemisphere. Desch and Kaiser conjectured that this component might be on the conjugate field lines of the nightside broad band smooth component. Figure 13 shows the conjugate footprint of the nightside radio source as determined using the offset tilted dipole model (left panel) and the more sophisticated quadrupole model of Connerney et al. (1987). Also shown are radio horizons for the time of onset of the dayside component (02:00) and the end time (08:00). Particularly for the quadrupole model, the correspondence between emission onset and first visibility of the conjugate footprint region is impressive. The end time horizon does not correspond to a visibility horizon, but may signal the quenching of the radio source via the Curtis et al. (1987) mechanism due to heating and subsequent rising of the atmosphere at the footprint.

Figure 14 summarizes the source location studies to date performed by the Goddard

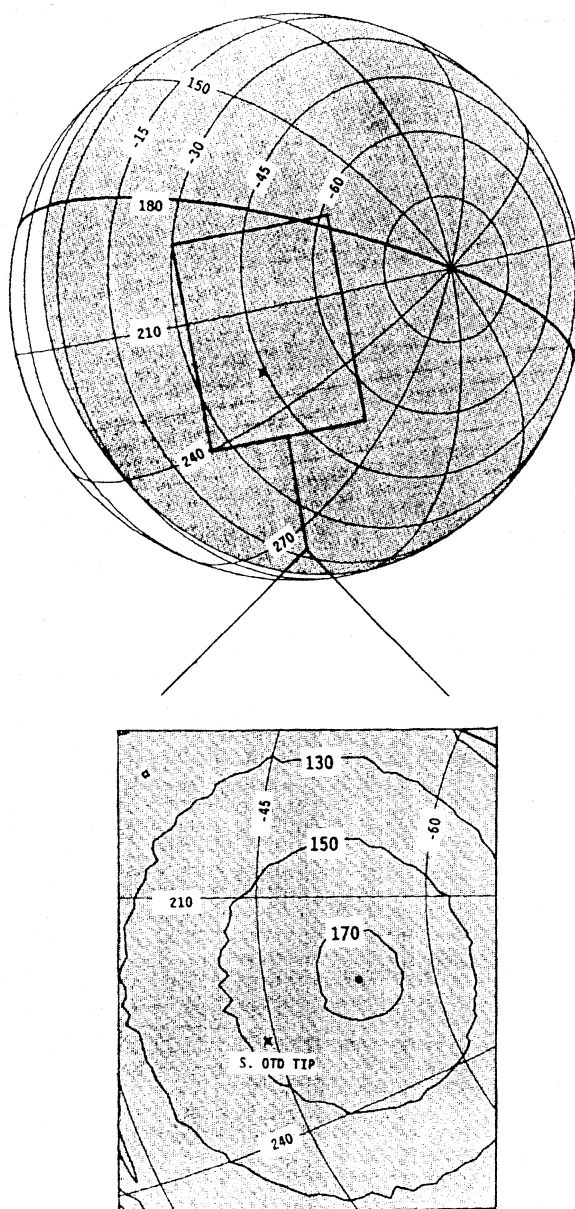


Fig. 10: Contours of equal angle between the field direction and the spacecraft direction projected along the field down to the cloud tops. The inset shows that the two vectors are nearly antiparallel for field lines arising from a very small area near the South dipole tip.

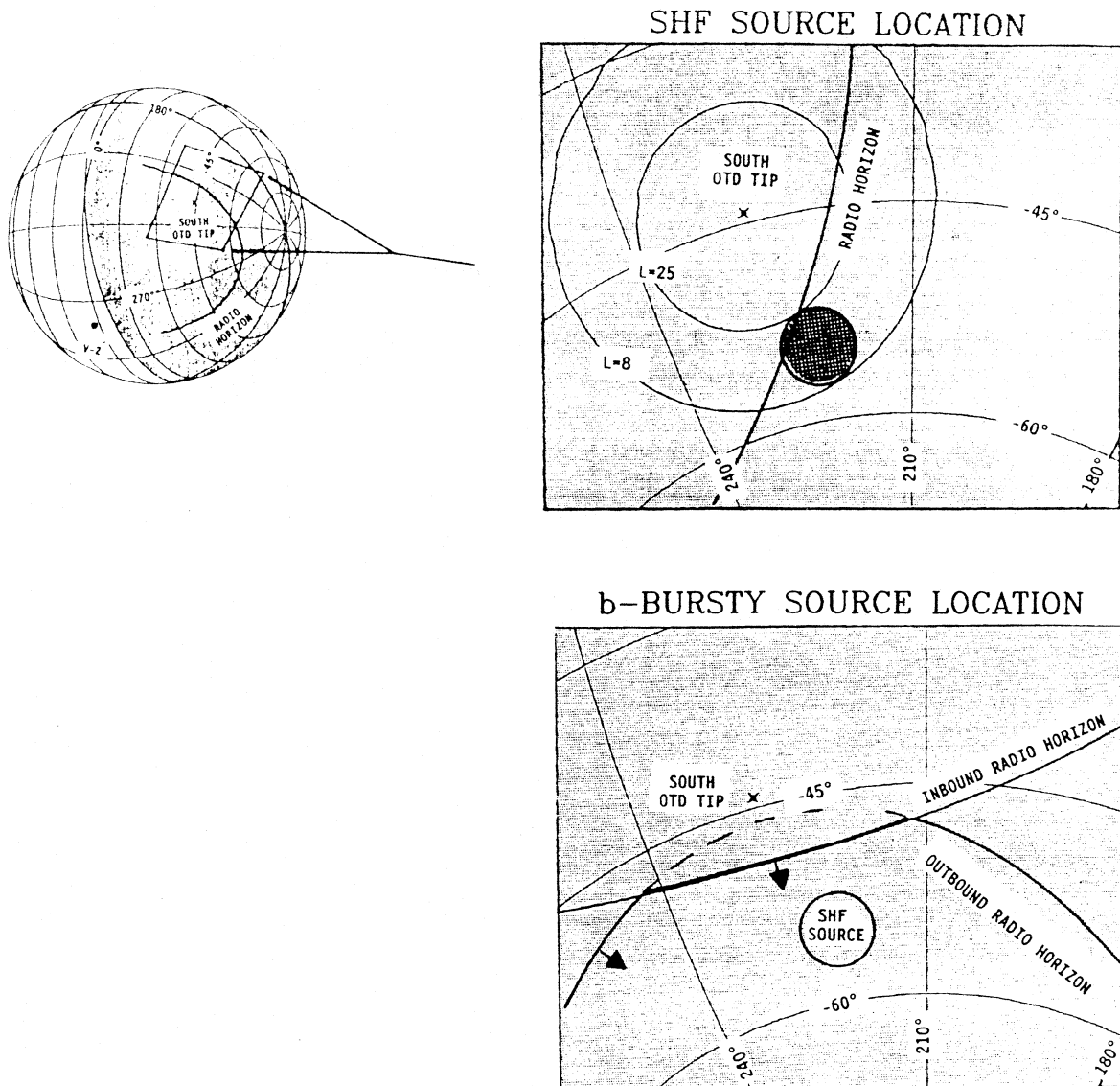


Fig. 11: Consideration of dropout duration suggests that the source of component 4 has its magnetic footprint within the darkened circle, probably on closed field lines. A source in this location is impressively consistent with the time of first detection of this source as indicated by the "radio horizon" line. In the bottom panel, times of visibility of the bursty nightside source (component 5) only serve to exclude regions for a possible source location. Also shown is the source footprint proposed for the smooth high frequency (SHF=component 4) emission.

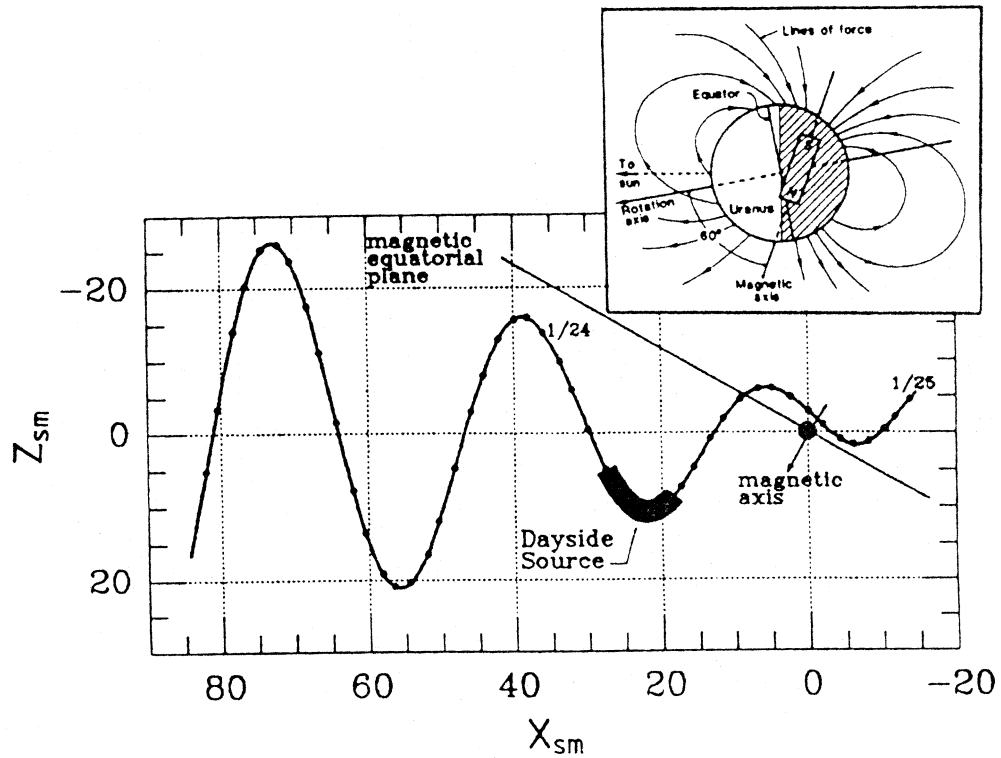


Fig. 12: The inbound portion of the trajectory of Voyager 2 relative to the Uranian magnetic dipole equator. The darkened band near minimum latitude represents the time during which component 3 was detected.

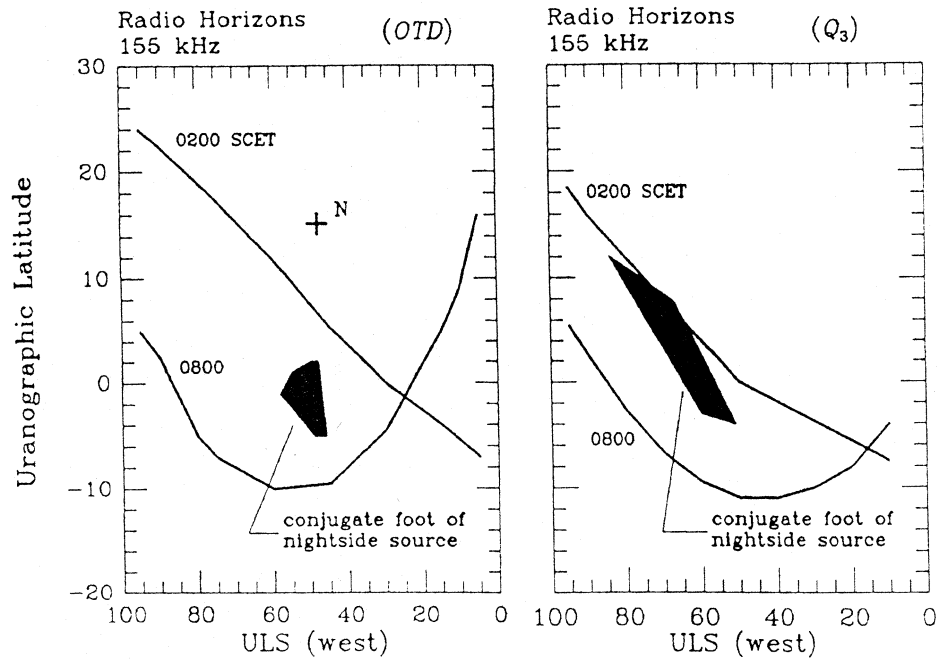


Fig. 13: The footprint of the nightside smooth component shown in Figure 11 is projected along the magnetic field (offset tilted dipole model in left panel, quadrupole model in right panel) to the other hemisphere near the equator and near the terminator. The lines labelled 0200 and 0800 indicate the visibility horizons at the start and end of the emission episode, respectively.

Space Flight Center PRA group. The nightside smooth source, emitting in the X mode, is confined to a small region near the South dipole tip. The beam pattern shown corresponds to the observed beam pattern at about 600 kHz. The conjugate footprint of this same field line may contain the dayside source emitting in the O mode. If this is indeed the case, it represents a very nice example of the Doppler shifted relativistic cyclotron mechanism of Wu and Lee (1979) operating in drastically different environments. On the nightside, the magnetic field strength is large and the plasma density is (presumably) small so that the gyro to plasma frequency ratio favors the growth of X mode waves. For the conjugate point, the magnetic field strength is much less due to the drastic offset of the dipole and the plasma density is very large (Tyler et al., 1986) due to the presence of sunlight. The gyro to plasma frequency ratio could be approximately equal to one, where O mode waves have a much higher growth rate than X mode waves.

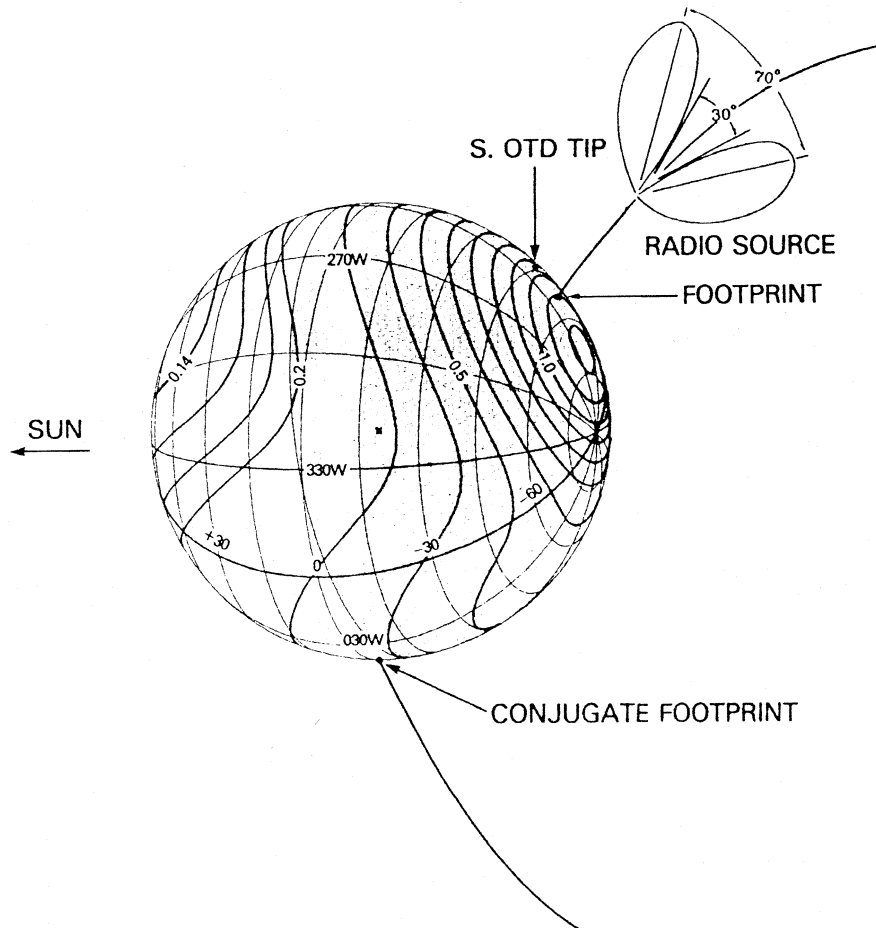


Fig. 14: Artists conception of the source locations of the smooth nightside emission and the dayside emission at the conjugate footprint. The emission beam illustrated for the nightside emission corresponds to a frequency of about 600 kHz.

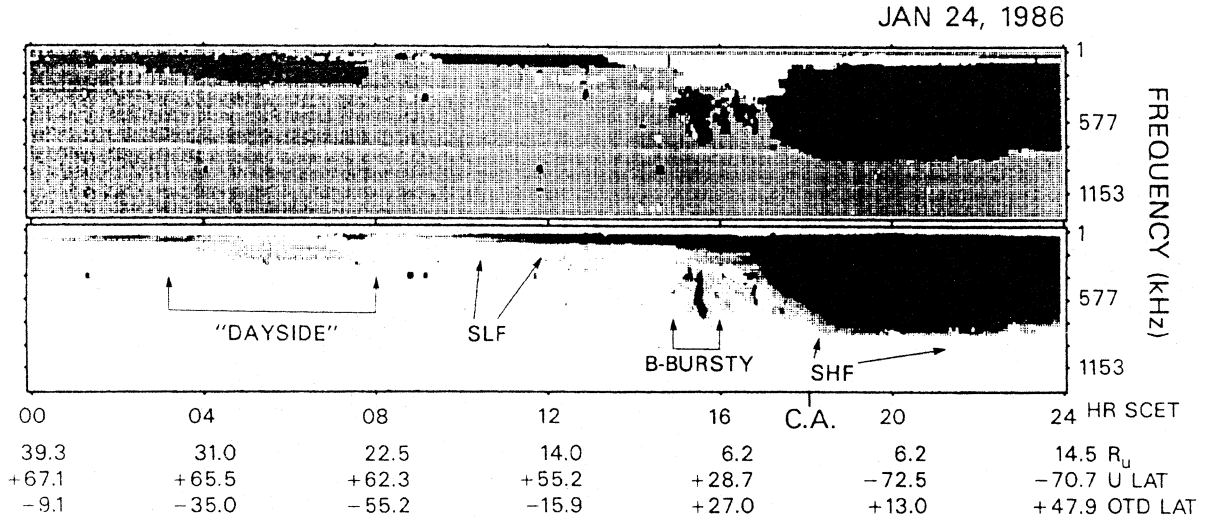


Fig. 15: Dynamic spectra of the day of closest approach. The bottom panel is total power, similar to the second panel of Figure 1. The top panel shows the sense of polarization with white depicting RH, black for LH and gray for unpolarized. The smooth low frequency (SLF=component 2) emission abruptly changes polarization just after mid day at almost precisely the time the spacecraft passes through the magnetic equator from the magnetic northern to the southern hemisphere.

Finally, some work is in progress (Leblanc et al., 1987; Lecacheux and Ortega-Molina, 1987) concerning the source location of the narrow band smooth component (#2). The major clue to the source location lies in correct interpretation of the polarization signature. Figure 15 shows, again, a dynamic spectrum of the day of closest approach. Also shown is a false color panel depicting the sense of polarization detected at the spacecraft coded such that white corresponds to RH and black to LH. Just after mid day, it can be seen that the smooth low frequency (SLF) component changes from black to white, i.e from LH to RH. This change corresponded almost exactly to the time of passage of the spacecraft through the local magnetic equator. These workers reasoned that the polarization reversal was caused by a change from obtuse to acute (or vice versa) in the angle between the vector from the source to the spacecraft and the magnetic field direction in the source. Figure 16 illustrates the possible source locations; essentially every field line in the plane of the figure (to first approximation) fulfills the criteria of being perpendicular to the vector to the observer. In addition, there is a region at the magnetic equator surrounding the planet (i.e. out of the plane of the figure) where the angle reaches 90° .

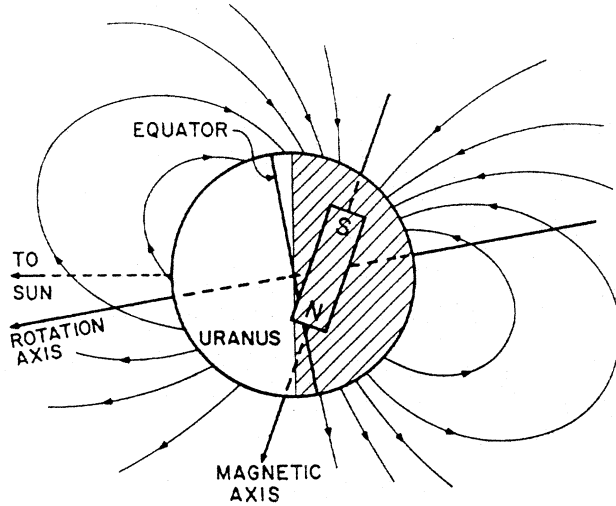


Fig. 16: The vector from the viewer is perpendicular to all field lines in the plane of this figure (to first approximation), and also to all field lines crossing the magnetic equator in a circle out of the plane of this figure. In principle, the source location of component 2 could be anywhere where the angle is 90° at the time of the polarization reversal.

Leblanc et al. (1987) and Lecacheux and Ortega-Molina (1987) made the assumption that the emission was generated at the local electron gyrofrequency and concluded that a source region above the North dipole tip was more consistent with the data than one above the South dipole tip. They did not investigate possible solutions at the magnetic equator, nor did they investigate other assumptions, e.g the emission is at the plasma frequency or twice the plasma frequency. Clearly more work is in progress on this source.

To my knowledge, there is no work in progress concerning the source location of the narrow band bursts (component 1).

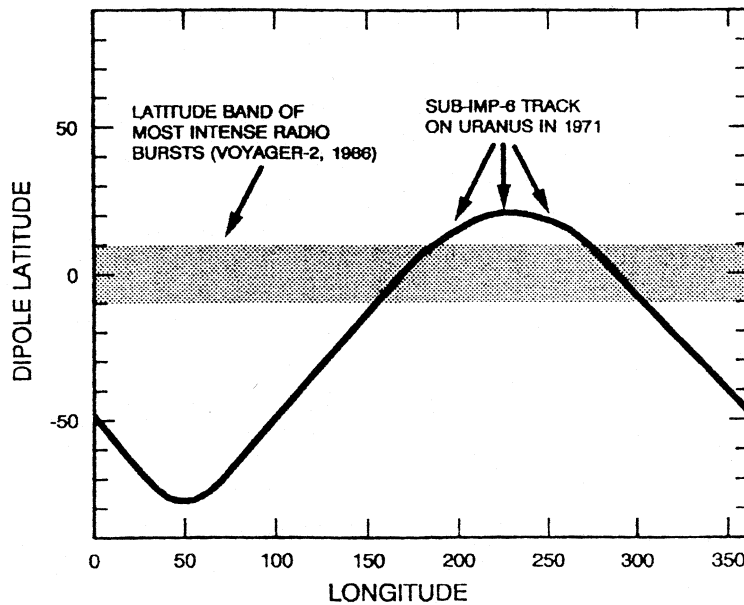


Fig. 17: Magnetic latitude versus longitude of the sub-earth point for a typical Uranian day in 1971 when the IMP-6 spacecraft may have detected radio bursts. Also shown in the shaded band is the region where the nightside bursty emission (component 5) is most prevalent.

Future work

It is now just eighteen months since the first unambiguous detection of Uranian radio emission, and much work is still in progress within the PRA team. Recently, NASA has funded additional investigators to also help with the analysis of Uranian radio emissions, so perhaps by the time of the Third Graz Workshop on Planetary Radio Emissions, there will be much more to report.

I have been intrigued by the question, "did the PRA detection truly represent the first detection of Uranian radio emissions?". More than ten years before the Voyager 2 encounter, Brown (1976) reports the possible detection of bursts of emission near 500 kHz using the earth-orbiting IMP-6 satellite. This paper was often discounted in subsequent years because there was no verification. Upon reexamination of that early work, combined with what we now know, I'm not so certain. Figure 17 shows the sub-earth point on Uranus in terms of magnetic latitude and longitude. During the time of the IMP-6 observations reported by Brown, the sub-earth track passed through the shaded region every rotation. It is in this shaded region, near the magnetic equator where Voyager 2 observed most of the broad band bursty (component 5) radio emission. This component waxes and wanes considerably in intensity, so it may be within the realm of possibility that Brown did indeed detect Uranus more than a decade before the Voyager detection. The sub-earth track intersects this "active" band again in 1995 and for many years thereafter, so it may be possible to collect more observations of Uranus at that time.

