JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 92, NO. A10, PAGES 11,273–11, 76, OCTOBER 1, 1987

Reply

W. S. Kurth and D. A. Gurnett

Department of Physics and Astronomy, The University of Iowa, Iowa City

F. L. Scarf

TRW Space and Technology Group, Redondo Beach, California

1. Introduction

Kurth et al. [1986] presented analyses of observations of continuum radiation at Jupiter which indicated that the emission at 3.11 kHz was modulated in a clocklike fashion and not by the spatial location of the Voyager spacecraft with respect to the plasma sheet. *Barbosa* [1987] comments that the data are supportive of the latter interpretation and suggests a model incorporating a shadow in the magnetic equator of Jupiter to explain the modulations due to the sheet even when the spacecraft is well beyond the hinge point in the plasma sheet. In this reply we support our initial conclusion and test the model proposed by Barbosa. We conclude that the 3.11-kHz observations are not well ordered by the model proposed by Barbosa and that the clock model provides a superior organization of the data.

2. Analyses of the Models

2.1. *The Clock Model*

Kurth et al. [1986] proposed that the intensity of the Jovian continuum radiation at 3.11 kHz was modulated in clocklike fashion with periods near both 5 and 10 hours. Since the fundamental (10 hour) period of this model is the synodic period of Jupiter's rotation and is basically the same as that which would control a plasma sheet model as proposed by *Barbosa* [1987], it is not sufficient to look for a one-to-one correspondence between a plasma sheet indicator (such as a minimum in the magnetic field as used by Barbosa) and continuum radiation peaks. Rather, the differences in the two models are more subtle. Hence, we employ a means of analysis similar to that used by *Kurth et al.* [1986] which enables the examination of the phase of the peaks within a Jovian rotation. Specifically, we plot the position of the Voyager spacecraft in system III longitude and radial distance at times of local maximum in the continuum radiation.

Kurth et al. [1986] concluded that the 3.11-kHz continuum radiation peaked in intensity when the subsolar system III longitude λ_{III} was about 95° and a secondary peak occurred when the subsolar system III longitude was about 315°. The position of the spacecraft in λ_{III} when peaks occur, then, is simply a function of the local time of the spacecraft. Given the variation of local time of the spacecraft provided by the ephemeris data, λ_{III} at the times of peak emissions in the clock model is given by

$$\begin{aligned}\lambda_{\mathrm{III}} &= 95^\circ + 15^\circ(12 - \mathrm{LT})\\ \lambda_{\mathrm{III}} &= 315^\circ + 15^\circ(12 - \mathrm{LT})\end{aligned} \qquad (1)$$

where

$$\mathrm{LT} = 12 + (\lambda_{\mathrm{sun}} - \lambda_{s/c})/15^\circ$$

λ_{sun} and $\lambda_{s/c}$ are the longitudes of the sun and spacecraft, and LT is in the usual units of hours. Actually, a magnetic local time definition would be more accurate here; however, with only a 3° inclination of the rotational axis from the ecliptic pole and 10° inclination of the magnetic dipole, the errors introduced are minimal and certainly are not crucial to the argument.

Figures 1*a* and 1*b* show the locations of the peaks of continuum radiation at 3.11 kHz from *Kurth et al.* [1986] in system III longitude and radial distance and curves indicating the solution to (1) for both the primary and secondary peak. According to the clock model of Kurth et al., the peaks should fall along these curves as they seem to do very well. Note that the curves are not least squares fits to the data and hence are not subject to the reconsideration of a few "anomalous" points questioned by Barbosa (although we have eliminated a point used by Kurth et al. which is actually a Bernstein emission as pointed out in the comment). The only free parameters are the subsolar system III longitudes at the peaks (95° and 315°), which would change a minimal amount by the inclusion or rejection of one or two questionable points in the averages calculated by Kurth et al.

We suggest that the excellent correspondence between the modeled position of the peaks and the observed peaks provides a good measure of confidence in the clock model proposed by *Kurth et al.* [1986] to explain the periodicities. Note that the model curves in Figure 1 are quite flat at large radial distances when the local time of the spacecraft does not change appreciably; hence the flatness of the trend in the peaks at large distances is a prediction of the model and can not be used to distinguish the model from that proposed by *Barbosa* [1987] as suggested therein.

2.2. *The Rotating Disk Model*

Barbosa [1987] suggests that the inner portion of the plasma sheet, acting like a rigid disk, might cast a radio shadow at larger radial distances, even though the plasma sheet eventually bends over at large distances to follow (more or less) the forces acting upon the tail by the solar wind. The model explicitly assumes that the (dominant) continuum

Paper number 7A9129.
0148-0227/87/007A-9129$02.00

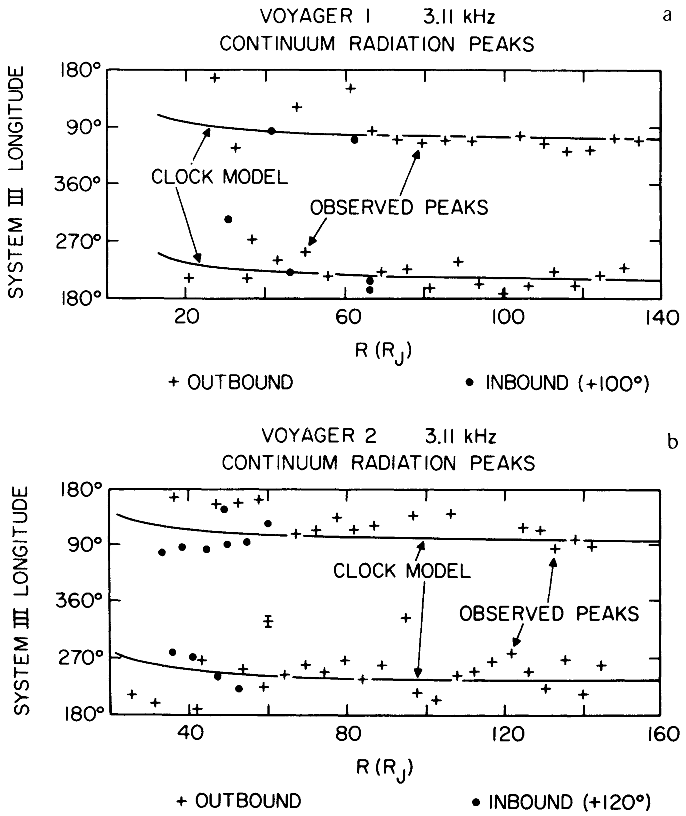

Fig. 1. (*a*) A comparison of the observed position of peaks in Jovian continuum radiation at 3.11 kHz as a function of system III longitude and radial distance of Voyager 1 [*Kurth et al.*, 1986] to the position of peaks predicted by the clock model suggested by *Kurth et al.* [1986]. (*b*) Same as Figure 1*a* except for Voyager 2.

source region is at the edge of the plasma sheet contrary to the conclusions of both *Kurth et al.* [1986] and *LeBlanc et al.* [1986]. We were intrigued by the Barbosa model, however, and chose to ignore this inconsistency in order to test the model's viability on other grounds.

The key to testing the *Barbosa* [1987] model lies in understanding the implication of his Figure 3. At small radial distances (inside about 80 R_J), amplitude variations in the continuum radiation are due to the spacecraft passing directly through the plasma sheet twice per Jovian rotation. Beyond 80 R_J, when a nonequatorial spacecraft may not pass directly through the sheet twice per Jovian rotation, a radio shadow is cast which is coplanar with the inner, rigid magnetodisc. Hence Barbosa predicts that minima in the continuum intensity should be observed when the Voyager spacecraft are near this plane and maxima should be observed above and below it.

We turn to *Behannon et al.* [1981] for a survey of several of the proposed models for the plasma sheet at Jupiter and utilize their formulation of the rotating disk model to organize the Voyager observations. We stress that while all would agree that the rotating disk model is a valid model of the plasma sheet only close to the planet, it provides an excellent description of the Barbosa shadow plane at large distances; hence we choose it for our analysis.

In Figures 2*a* and 2*b* we plot the position of the Voyager spacecraft above the rotating disk z as a function of ρ $(=(x^2 + y^2)^{1/2})$. For z, we use the formulation for the position of the rotating disk [*Behannon et al.*, 1981]:

$$z_d/\tan \alpha = x \cos \phi + y \sin \phi \qquad (2)$$

and subtract that from the z component of the spacecraft from the ephemeris. The x, y, and z are all defined as they are in the work by *Behannon et al.*, where z is measured parallel to the rotation axis of the planet, x is measured positively in the antisunward direction in the equatorial plane, and y completes the right-handed system. The α is the tilt of the dipole (taken as 10° here), and ϕ is the angle from sunward of the projection of the dipole in the equatorial plane, measured in the right-hand sense.

In order to desensitize the analysis to the difficulty of choosing the peak in the events, we have plotted with heavy lines time intervals when the 3.11-kHz emission was enhanced in relation to surrounding local minima. The heavy lines represent (approximately) the upper half of individual peaks as represented on a logarithmic display. The plasma sheet model proposed by *Barbosa* [1987] would predict that relative minima should be centered about the rotating disk ($z = 0$) and the peaks should be found above and below this plane. This effect is confirmed close to the planet in Figure 2*a* but is generally not seen otherwise. For the early outbound pass of Voyager 1, the plasma sheet density was near 3 kHz and totally cut off the radio emission. Beyond ~50 R_J there are many occasions when emission peaks lie in the plane of the disk. We point out that there are numerous relative minima at high elevations off the rotating disk plane which are not explained by the Barbosa model.

In order to place the rotating disk model analysis in a more direct comparison with the clock model analysis above, we have calculated the times when the Voyager 1 trajectory crossed the plane of the rotating disk and then found the system III longitude and radial distance in the ephemeris for those times and plotted those points on Figure 3. The solid diamond symbols represent the rotating disk interception positions, hence, locations where Barbosa would predict minima in the 3.11-kHz continuum radiation. The upper line of diamonds is just a repetition of the lower set for continuity over the longitude range of the plot. Superimposed on the figure are the observed 3.11-kHz minima as given by *Kurth et al.* [1986]. While a few points overlap to within the errors of locating the minima, there is general disagreement between the model prediction and the observed minima.

The upper pair of model minima lines in Figure 3 tend to straddle the observed minima near 0°, while there is little, if any, correspondence with the set of minima near 180°. In addition, the two populations of observed points are more evenly spaced (closer to 180° apart) than the two model populations. The analysis in Figure 3 can be compared with that in Figure 1, and it is clear that the clock model predicts the location of continuum radiation peaks much more accurately than the plasma sheet model predicts the location of minima.

The compulsion to invoke some plasma sheet model to explain the continuum radiation intensity variations is so strong, even to us, that the failure of the rotating disk shadow model begs the question of whether a high-fidelity model of the current sheet, itself, might organize the data better. As mentioned above, the rotating disk model used above to represent Barbosa's shadow plane does not accurately describe the plasma sheet at large distances. We returned to the *Behannon et al.*

[1981] analysis of the various models for a more realistic version in order to determine whether the data might be ordered simply by the sheet without the need of the Barbosa shadow. Behannon et al. rate the so-called rocking plane/rotating disk (RP/RD) model to be generally superior to other models, especially at distances within about 70 R_J, since it fit the observed positions of the current sheet most consistently. Since many of our observations are beyond 70 R_J, we thought it prudent to use the bent version of the RP/RD model, which should limit the vertical flapping of the RP/RD model at large distances.

The bent RP/RD model, described by *Behannon et al.* [1981] as

$$z_s/\tanh(\alpha) = a \operatorname{sech}(x/a) \tanh(x/a) \cos\phi + b \tanh(y/b) \sin\phi \qquad (3)$$

reduces to the rotating disk at small radial distances and the rocking plane at larger distances, again, limited at very large distances by the influence of the solar wind. In (3), a and b are parameters determined by fitting the data and are 10 and 64 R_J, respectively, for Voyager 1 and 32 and 94 R_J for Voyager 2 [*Behannon et al.*, 1981]. Using (3), it is straightforward to compute the distance of Voyager above the bent RP/RD sheet and plot that as a function of ρ as we did for the rotating disk model in Figure 2. The results are given in Figures 4*a* and 4*b*.

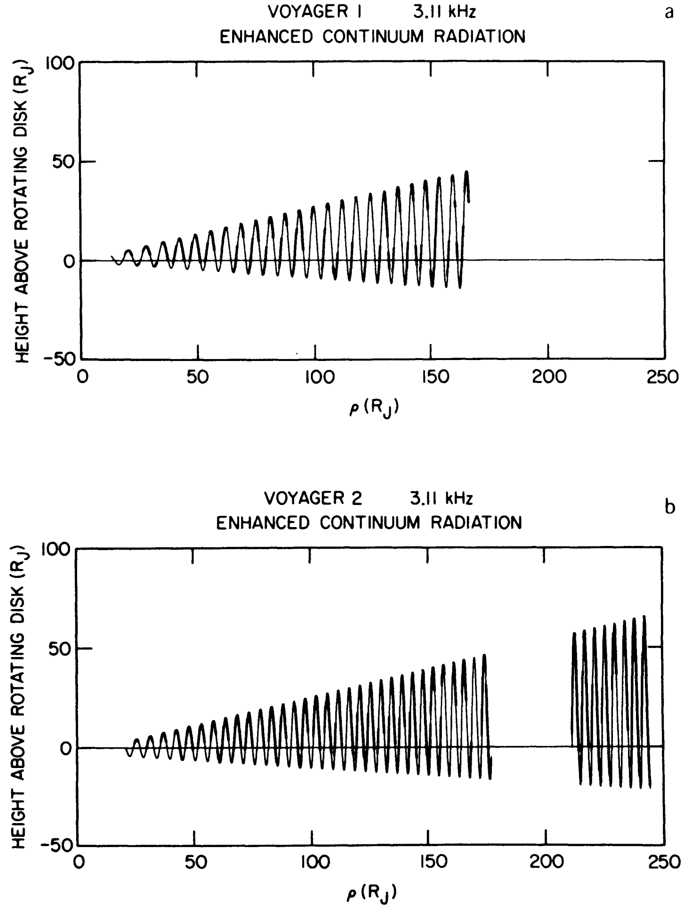

Fig. 2. (*a*) The position of Voyager 1 in cylindrical coordinates for the rotating disk model with heavier lines representing the locations where enhanced continuum radiation at 3.11 kHz was detected. At small radial distances, the radiation is located above and below the rotating disk. At larger radial distances, the model proposed by *Barbosa* [1987] would predict minima in the continuum radiation centered around $z = 0$ with enhanced radiation above and below the plane. Clearly, maxima are often seen at or near the $z = 0$ plane, and minima are often seen large distances above the plane, suggesting that the rotating disk model does not order the data well. (*b*) Same as for Figure 2*a* but for Voyager 2.

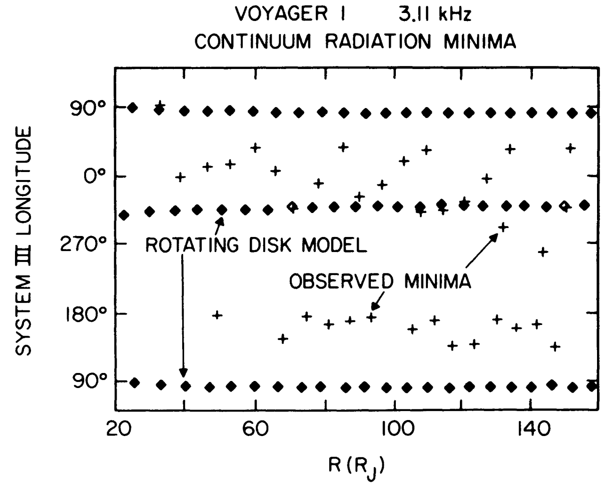

Fig. 3. The location of observed minima in the 3.11-kHz continuum radiation reported by *Kurth et al.* [1986] in system III longitude and radial distance coordinates compared to the locations predicted by the shadow model proposed by *Barbosa* [1987]. Note that while a few of the points are predicted very accurately by the model, most of the observed minima show little consistency with the model.

The effect of the more complex model is to reduce the magnitude of the excursions out of the plane, owing to the nonrigid behavior of the sheet at large distances. At even larger distances the inclined trajectory eventually takes the spacecraft high enough so that no traversals are possible due to the limited flapping of the sheet. There is some trend for the enhanced 3.11-kHz continuum radiation emissions to be found above and below the bent RP/RD sheet while the spacecraft is close to Jupiter, but there is no clear organization at larger distances. We suggest that the analysis in Figure 4 further supports our position that (except close to Jupiter where plasma sheet plasma frequencies are close to 3 kHz) the position of Voyager with respect to the plasma sheet is not important in the modulation of the intensity of the continuum radiation.

3. Discussion

It is natural to try to associate the Jovian continuum radiation intensity modulation to the position of the observer with respect to the plasma sheet. In fact, *Leblanc et al.* [1986] have done successfully just that in their consideration of the emission at 1.2 kHz. Our initial attempts at understanding the modulations at higher frequencies (3.11 kHz) were similarly directed. Since the the differences in the timing of the observed intensity variations between the clock model and a plasma sheet model are small with respect to the fundamental period of 10 hours, however, the analysis is not straightforward; attempts to study the timing by looking at individual sheet crossings (using either minima in the lower-frequency continuum radiation or the magnetic signature of sheet crossings) are hampered by the fact that simple one-to-one correspon-

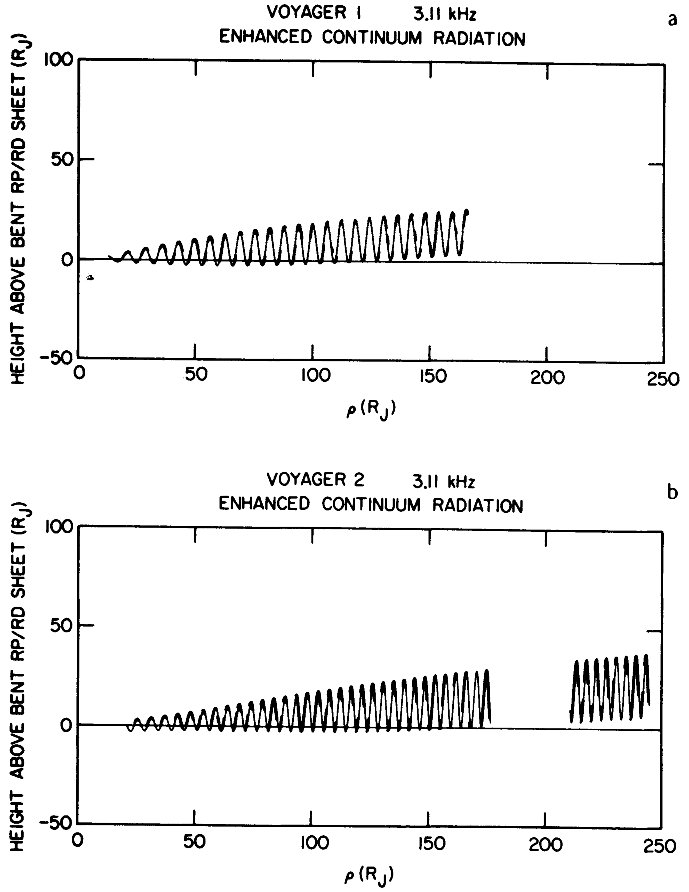

Fig. 4. (*a*) The position of Voyager 1 in cylindrical coordinates based on the bent RP/RD model of the current sheet. This model fairly accurately reproduces the location of the current sheet, even to large radial distances [*Behannon et al.*, 1981]. Locations where enhanced continuum radiation is observed are highlighted with heavy lines showing little organization along the $z = 0$ plane as would be expected if the continuum radiation amplitude were modulated by the presence of the plasma sheet. (*b*) Same as Figure 4*a* but for Voyager 2.

dence does not address the phase differences between the two models. Analyses such as those in Figures 1 and 3 are designed to highlight these phase differences as a solid basis for differentiation between the two models.

We have attempted to analyze individual continuum radiation peaks using relatively high resolution magnetic field data and find (as pointed out by *Barbosa* [1987]) numerous individual examples where one model or the other fails outright as well as trends which are difficult to follow from one sheet crossing to another. The synoptic studies presented herein are much more useful in testing the models than the consideration of the details of individual cases.

In this reply we have reiterated the conclusion of *Kurth et al.* [1986] that the clock model is the best model for the 3.11-kHz continuum radiation modulation, using different approaches in the analysis than used in the original work. *Barbosa's* [1987] shadow model represented a new idea which merited further examination but does not order the data as well as the clock model; we suggest that it is not a useful model. It should be emphasized that Barbosa's model assumes a dominant source of continuum radiation at the edges of the plasma sheet and is contrary to the conclusion of *Leblanc et al.* [1986] and *Kurth et al.* [1986] that the dominant continuum radiation souce is near the magnetopause.

Finally, while we agree wholeheartedly with *Barbosa* [1987] on the applicability of the magnetodisc model to a number of Jovian phenomena, including the cutoff of low-frequency continuum radiation close to Jupiter, we are surprised to hear that *Barbosa et al.* [1979] laid the clock model to rest, especially in view of the incorporation of Voyager results with the original Pioneer results leading to the confirmation of the clock model [*Schardt et al.* 1981] as applied to electron fluxes in the boundary layer and beyond the magnetopause. It would appear that both the clock model and the magnetodisc models have some validity for certain (generally nonintersecting) sets of observations.

Acknowledgments. The research at the University of Iowa was supported by NASA through contract 957723 with the Jet Propulsion Laboratory. The research at TRW was supported by NASA through contract 957805 with the Jet Propulsion Laboratory.

REFERENCES

Barbosa, D. D., Comment on "Periodic amplitude variations in Jovian continuum radiation" by W. S. Kurth et al., *J. Geophys. Res.*, *92*, this issue, 1987.

Barbosa, D. D., D. A. Gurnett, W. S. Kurth, and F. L. Scarf, Structure and properties of Jupiter's magnetoplasmadisc, *Geophys. Res. Lett.*, *6*, 785, 1979.

Behannon, K. W., L. F. Burlaga, and N. F. Ness, The Jovian magnetotail and its current sheet, *J. Geophys. Res.*, *86*, 8385, 1981.

Kurth, W. S., D. A. Gurnett, and F. L. Scarf, Periodic amplitude variations in Jovian continuum radiation, *J. Geophys. Res.*, *91*, 13523, 1986.

Leblanc, Y., D. Jones, and H. O. Rucker, Jovian 1.2-kHz nonthermal continuum radiation, *J. Geophys. Res.*, *91*, 9995, 1986.

Schardt, A. W., F. B. McDonald, and J. H. Trainor, Energetic particles in the predawn magnetotail of Jupiter, *J. Geophys. Res.*, *86*, 8413, 1981.

D. A. Gurnett and W. S. Kurth, Department of Physics and Astronomy, The University of Iowa, Iowa City, IA 52242.

F. L. Scarf, TRW Space and Technology Group, One Space Park, Redondo Beach, CA 90278.

(Received May 22, 1987;
accepted June 10, 1987.)