VOL. 7, NO. 1 GEOPHYSICAL RESEARCH LETTERS JANUARY 1980

SPATIAL AND TEMPORAL STUDIES OF JOVIAN KILOMETRIC RADIATION

W. S. Kurth[1], D. A. Gurnett[1,2], and F. L. Scarf[3]

[1]Department of Physics and Astronomy, The University of Iowa, Iowa City, IA 52242
[2]On leave at the Institute of Geophysics and Planetary Physics,
University of California, Los Angeles, CA 90024
[3]TRW Defense and Space Systems Group, One Space Park, Redondo Beach, CA 90278

Abstract. Plasma wave measurements taken during the Voyager 1 and 2 Jupiter encounters are used as a basis for synoptic studies of Jovian kilometric radiation. The studies reveal the existence of a shadow zone near the magnetic equator within which kilometric radiation is seldom or weakly observed. This shadow is presumably cast by the Io plasma torus whose density is high enough to refract electromagnetic waves generated either near the torus or closer to Jupiter. At 56.2 kHz this shadow zone has a half width of about 10°. In addition to a latitudinal shadow zone, there occasionally appear to be long-lived longitudinal variations of kilometric radiation intensities. That is, individual features may reappear on successive rotations at nearly constant System III longitudes. This may imply longitudinally asymmetric structures in the kilometric source region or intervening magnetosphere such as the Io torus which corotate and have lifetimes of up to several days. Some of the features appear to drift to higher longitudes with increasing time suggesting deviations from corotation ranging up to a few percent. Gross changes in the character of Jovian kilometric radiation on time scales of a few days imply dramatic changes in the inner Jovian magnetosphere on the same time scale and may be indicative of magnetospheric substorms or changes in plasma injection rates from Io.

Introduction

The detection of a new component of the Jovian radio spectrum in the kilometric wavelength regime was reported after the Voyager 1 encounter of Jupiter [*Scarf et al.*, 1979; *Warwick et al.*, 1979a]. The emission ranges in frequency from several kHz to nearly 1 MHz as measured by the plasma wave and radio astronomy receivers on Voyager 1. *Kurth et al.* [1979] described Jovian kilometric radiation as consisting of a low level, continuum-like background with relatively intense, discrete features which usually, but not always, drift to lower frequencies with time. *Kurth et al.* [1979] also carried out synoptic studies of the kilometric emission and demonstrated that the majority of events detected by Voyager 1 at 56.2 kHz were within about 45° of 200° System III (1965) longitude λ_{III} and that there was little, if any, Io control of the emission. Two possible source locations were enumerated by *Kurth et al.*: first, the Io plasma torus, since it was the location of intense electrostatic waves which might couple into the electromagnetic radiation; and second, regions closer to Jupiter at high latitudes, which were suggested because the radiation was most often detected at higher magnetic latitudes.

Gurnett et al., [1979] emphasized the importance of a latitudinal effect in the detection probability for Jovian kilometric radiation and explicitly suggested that the magnetic equatorial region was a shadow zone where the radiation could seldom be observed.

In this paper further evidence is presented indicating the presence of a magnetic equatorial shadow zone for kilometric radiation at 56.2 kHz using observations from both Voyagers 1 and 2. We shall argue that for a large range of reasonable source locations the Io plasma torus is the most likely cause for the shadow. Accordingly, it is reasonable to look for temporal variations which might be associated with temporal changes in the source region or intervening plasma regions. Evidence for both small scale irregularities and gross temporal fluctuations of the inner Jovian magnetosphere is presented and the implications of these variations are examined.

Evidence for an Equatorial Shadow Zone

The earliest reports of Jovian kilometric radiation from Voyager 1 observations indicated the maximum probability of detection of the emission occurred when the spacecraft was near 200° System III longitude, λ_{III}, i.e., when the northern magnetic pole was tilted toward Voyager. A secondary occurrence peak occurred near $\lambda_{III} = 20°$ when the southern pole was tilted toward the observer [*Scarf et al.*, 1979; *Warwick et al.*, 1979a; *Kurth et al.*, 1979]. *Gurnett et al.* [1979] interpreted this apparent longitudinal dependence as primarily a latitudinal effect and argued that there is a shadow zone in the region near the magnetic equator within which Jovian kilometric radiation is only infrequently observed. Synoptic studies now lend additional support for the concept of a magnetic equatorial shadow zone for Jovian kilometric radiation.

Voyager 2 provides a more suitable data set with which to study latitudinal effects since its trajectory lies in a plane inclined about 7° with respect to the zenographic equator on the inbound leg, ~ 4° greater than the inclination of the Voyager 1 trajectory. The results of a synoptic study of the Voyager 2 observations during the inbound portion of its Jovian encounter are presented in Figure 1. Illustrated are the positions of Voyager 2 in magnetic cylindrical coordinates at times when radio emissions were detected by the plasma wave instrument. Z_M is the distance from the magnetic equatorial plane and ρ_M is the Jupiter-spacecraft distance projected into the magnetic equatorial plane. Voyager 2's trajectory confines observations between magnetic latitudes from about −3° to 17°.

As clearly demonstrated in Figure 1 the 56.2 kHz emission is observed almost exclusively above about 10° magnetic latitude. However, there are deviations from a perfectly conical shape to the shadow zone. For example, within about 100 R_J of Jupiter the boundary appears to lie nearly parallel to the equatorial plane. We interpret this effect and other deviations from a simple shadow zone as temporal changes in either the source or the portion of the magnetosphere casting the shadow. We also acknowledge the presence of longitudinal variations, particularly between 50 and 100 R_J in addition to the latitudinal effect shown in Figure 1. The longitudinal variations will be discussed in greater detail in the next section.

Since Voyager 2 approached Jupiter at a local time of about 9.5 hours, the shadow zone depicted in Figure 1 is only a measure of the zone at that local time. The shadow effect, however, is seen at other local times via the inbound and outbound trajectories of Voyager 1 and the outbound leg of Voyager 2 at about 10.5, 4.3, and 3 hours, respectively. For example, the outbound Voyager 1 observations are shown in Figure 2 and illustrate an equatorial shadow with a half width of about 10°, although the effect is less striking and conditions are more variable than in Figure 1. The Voyager 2 outbound leg near 3 hours local time

Paper number 9L1566.
0094-8276/80/009L-1566$01.00

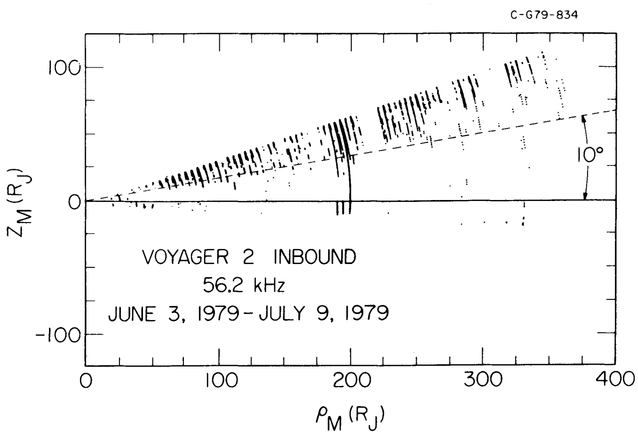

Fig. 1. Positions of Voyager 2 with respect to the Jovian magnetic equator when kilometric radiation was observed at 56.2 kHz. Notice the region within about 10° of the equator is a very unlikely place from which to observe the radiation. The Voyager 2 inbound passage was at a local time of about 9.5 hours.

shows the smallest apparent shadow zone with a half width between ~ 5° and ~ 8°. It is not possible to determine whether this represents a local time effect or a temporal variation in the size of the shadow zone.

The shadow zone is undoubtedly the result of a propagation effect such as the refraction of electromagnetic waves by a high density region between the observer and the source. *Green and Gurnett* [1980] use this information in an attempt to locate the kilometric radiation source region using ray tracing techniques.

Temporal Variations of Jovian Kilometric Radiation

As suggested in the previous section, there are variations in the appearance of Jovian kilometric radiation which we interpret as temporal fluctuations in either the source of the radiation or the intervening plasma regions casting the shadow. It is important to mention at this point that the temporal variations addressed in this paper are on much larger time scales than the temporal structure (i.e., drifting features) reported by *Kurth et al.* [1979] and *Warwick et al.* [1979b].

The Voyager encounter trajectories provide a good opportunity to study the temporal variations of a radio emission such as kilometric radiation. When the spacecraft are at radial distances greater than about 50 R_J there is only a radial component of motion with respect to the planet to a high order of accuracy.

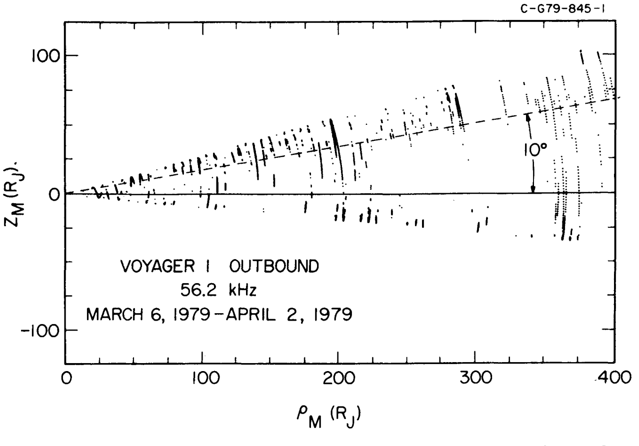

Fig. 2. Evidence for an equatorial shadow zone based on observations during the Voyager 1 outbound trajectory at about 4.3 hours local time.

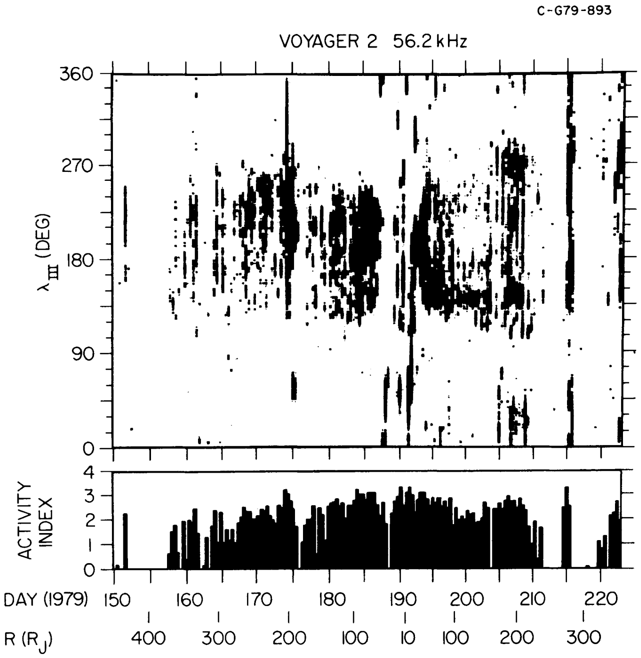

Fig. 3. A synoptic study of the temporal fluctuations of Jovian kilometric radiation based on the Voyager 2 encounter observations. The upper panel shows the intensity of 56.2 kHz emissions as a function of time and System III longitude. Gross changes in the character of the emission are apparent on time scales of a few days. The lower panel shows the relative degree of kilometric radiation activity for each rotation and demonstrates the highly variable nature of the emission.

Hence, as the spacecraft approaches or recedes, it remains at nearly constant latitude and local time. Besides a smooth R^{-2} dependence, only temporal and longitudinal variations are visible in the data set. The upper panel of Figure 3 is a display of Voyager 2 data within ~ 450 R_J organized to separate out longitudinal variations and allow a straightforward analysis of the gross temporal variations of Jovian kilometric radiation at 56.2 kHz. The data are sorted by System III longitude, λ_{III}, and time (or rotation number). That is, the intensity of kilometric emissions is plotted as a function of λ_{III} with data from each successive rotation of Jupiter plotted to the right of the previous rotation. This is in a sense a series of snapshots of Jupiter at 56.2 kHz taken once per Jovian rotation. The darkest areas represent the most intense signals. In the lower panel an index of the relative kilometric radiation activity is plotted as a function of time. This index will be described below.

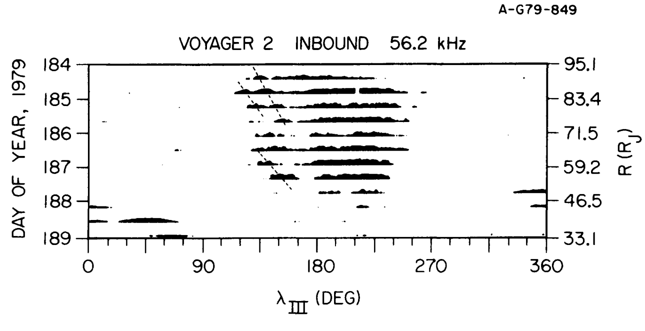

Fig. 4. A display of Jovian kilometric radiation intensities as a function of System III longitude for successive rotations of Jupiter. Notice several features appear to drift to higher longitudes with time corresponding to deviations from rigid corotation of the source field lines of about 1%.

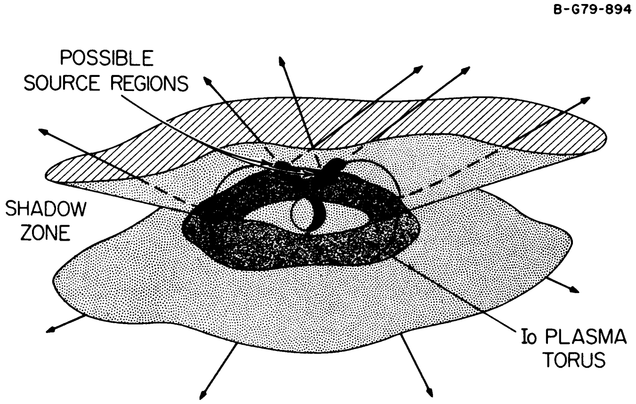

Fig. 5. A schematic representation of the formation of a shadow zone for kilometric radiation caused by the Io torus which may have longitudinal and temporal variations in density and size.

The most obvious trend in Figure 3 is a growth in average signal strength as Voyager 2 approaches Jupiter. But more interesting is the fact that the growth is not steady. Instead, the entire character of the emission varies on time scales of a few days from virtually undetectable to bright and continuous and then to sporadic and weak. Notice that near day 152 there is continuous emission from $\lambda_{III} = 195°$ to 250°. For the next ~ 6 days, virtually no emission is detected. Then, starting near day 157 is a period of relatively weak, sporadic activity which lasts until about day 162. Following a brief, 2-day period of virtually no activity, sporadic emissions begin again and build in intensity until day 174 when there is bright and continuous emission over the range $120° \lesssim \lambda_{III} \lesssim 360°$. This highly time-variable character is evident throughout most of the 74-day period displayed in the upper panel. We caution the reader that near day 190 the spacecraft is at small radial distances and near high density regions where propagation effects are extremely important. In the region within about 50 R_J, the variations cannot be identified as purely temporal fluctuations. Also, some of the emissions near day 190 are not kilometric radio emissions, but plasma waves in various modes.

The kilometric radiation activity index in the bottom panel of Figure 3 is a crude integral of the intensity of kilometric radiation activity present during a given Jupiter rotation which is sensitive to both the intensity of emission at a particular longitude and the range of longitudes illuminated during that rotation. Hence, a rotation with continuous weak emission could have the same index as a rotation during which a narrow but intense beam is observed. This index serves as an aid in interpreting the upper panel and shows the sporadic nature of Jupiter as a radio source at 56.2 kHz. One interesting observation is the drastic reduction of kilometric activity on days 162, 176, 188 and 204 which corresponds to a 14-day periodicity and is suggestive of a correlation with a 2-sector structure in the solar wind.

The gross temporal variations of Jovian kilometric radiation shown in Figure 3 may prove to be an important diagnostic probe of the inner Jovian magnetosphere. Fluctuations in the intensity of auroral kilometric radiation at the Earth have been shown to correlate well with the occurrence of discrete auroral arcs, [*Gurnett*, 1974] and the auroral electrojet index, A_E [*Voots et al.*, 1977]. It is thought that the terrestrial emission is intimately associated with auroral processes such as inverted-V electron precipitation events [*Green et al.*, 1979]. While we do not propose there exists a direct analogy between the terrestrial and Jovian emissions, there is significant reason to expect the Jovian radio emissions to be indicative of conditions within the inner magnetosphere. The frequency range of the kilometric radiation locates the source either in the Io plasma torus or even closer to Jupiter (see *Green and Gurnett* [1980]). In the Discussion section we shall suggest the variations observed in the kilometric radiation intensities may be indicative of either magnetic substorms in the Jovian magnetosphere or changes in the plasma injection rates from Io.

Additional information may be gleaned from a display such as in the upper panel of Figure 3. Presumably knowledge of the source or intervening magnetosphere can be gained by studying the occurrence of features which reappear on successive rotations at the same or slightly different longitudes. The reappearance of detailed structures indicates relatively long-lived features either in the source region or in the obscuring 'clouds' between the source and the observer. For example, the rotations occurring between about day 184 and day 187 indicate emission over the entire range from ~ 125° to ~ 255° System III longitude with the exception of about a 10° interval near $\lambda_{III} = 170°$ where the emission is much weaker. This feature drifts to higher longitudes at a rate of about 1° per rotation. A possible interpretation is that the torus has local structure and is enlarged or more dense at $\lambda_{III} \sim 170°$ and, hence, casts a larger shadow than the remainder of the torus. The longitude shift can be explained by a deviation from corotation of about 0.3% by the hypothetical structure near $\lambda_{III} = 170°$. Deviations from corotation have been reported by *McNutt et al.* [1979] for plasma outside Io's L-shell.

A strikingly persistent feature is present at $\lambda_{III} \simeq 140°$ from day 194 to day 208. This corresponds to a particularly intense emission observable only in a narrow range of longitudes. The field lines associated with this feature evidently corotate rigidly with the planet. A good example of an emission which exhibits a systematic drift in longitude can be seen at $\lambda_{III} \simeq 270°$ near day 222. This feature drifts from ~ 250° to ~ 280° over the period of three rotations giving a drift rate of about 10° per rotation. Since λ_{III} increases to the west, a drift to larger λ_{III} is counter to the direction of corotation. In this case the field lines associated with the emission rotate at a rate of 3% less than that for rigid corotation. Figure 4 is a detail of the data between days 184 and 189 shown in a slightly different format than in Figure 3. Here the log of the intensity is represented as the vertical height of a bar, again plotted as a function of λ_{III} and time (or rotation number) with each successive rotation plotted below the previous rotation. Notice the feature near $\lambda_{III} \simeq 150°$ in the first four rotations displayed shows an obvious drift to larger λ_{III} corresponding to a 1% deviation from corotation. Other drifting features are identified by dashed lines indicating the direction of apparent motion. Figure 4 also shows that the character of the emission even though present from one rotation to the next, may change drastically from smooth and featureless to a very bursty nature within one rotation.

Discussion

We have presented evidence which strongly indicates the existence of a shadow zone within which Jovian kilometric radiation is seldom or weakly observed. Evidence given by *Kurth et al.* [1979], *Scarf et al.*, [1979] and *Warwick et al.* [1979a] indicates the source of the radiation lies near or within the Io plasma torus or at high latitudes closer to Jupiter. Hence, the Io plasma torus is the only identifiable structure in the Jovian magnetosphere with high enough densities and at a suitable distance from Jupiter to obstruct electromagnetic waves in the kilometric range. We suggest that the torus, then, is the obstructing structure, regardless of the detailed location of the source of Jovian kilometric radiation. The relative positions of possible source regions with respect to Jupiter and the torus and the resulting shadow zone are shown schematically in Figure 5. Here, the cone-like surfaces represent the low-latitude limits for the detection of the radio emission. At higher latitudes the radiation is observable although the extent to which the cones are illuminated at high latitudes is not known. The torus and illumination cones have been distorted to indicate that variations in the torus size or density will affect the shape of the emission cone. The emission regions shown here are suggested by the ray tracing results of *Green and Gurnett* [1980].

Evidence has also been presented which shows Jupiter to be a sporadic emitter of kilometric radiation. The sporadic nature may be directly associated with the source mechanism or perhaps the obstructing torus. Either possibility suggests variations in the kilometric radiation may be indicative of gross changes in the inner Jovian magnetosphere. By analogy from terrestrial radio emissions, we suggest these changes may be manifestations of magnetic substorm activity. An alternate possibility is that the rate of plasma injection from Io changes, for example, by a change in the extent and/or character of volcanic activity, which in turn causes changes in the torus as an obstructing medium or directly affects the radiation emission mechanism.

Finally, the presence of long-lived features in Jovian kilometric radiation intensity profiles which drift to larger System III longitudes with time indicates shadowing structures or source regions which are on field lines which do not rigidly corotate. If it is actually the source regions which do not corotate, then the extent of deviation from corotation may help to isolate which field lines harbor the emission source. It is expected that field lines within Io's L-shell corotate, but that field lines passing through the plasma torus may be mass-loaded and, hence, may not rigidly corotate. Some evidence of this effect has already been reported by *McNutt et al.* [1979].

Further detailed analyses of Jovian kilometric radiation observations promise to provide a powerful tool with which to monitor the dynamics of the inner Jovian magnetosphere.

Acknowledgements. We wish to thank R. L. West for his data analysis effort in this study and acknowledge J. L. Green for stimulating discussions concerning the interpretation of the observations. The research at the University of Iowa was supported by NASA through Contract 954013 with the Jet Propulsion Laboratory and through Grant NGL-16-001-043 from NASA Headquarters. The research at TRW was supported by NASA through Contract 954012 with the Jet Propulsion Laboratory. A portion of this research was performed while one of us (D. A. Gurnett) was on leave at the Institute of Geophysics and Planetary Physics, University of California, Los Angeles.

References

Green, J. L. and D. A. Gurnett, Ray tracing of Jovian kilometric radiation, *Geophys. Res. Lett.*, this issue, 1980.

Green, J. L., D. A. Gurnett and R. A. Hoffman, A correlation between auroral kilometric radiation and inverted-V electron precipitation, *J. Geophys. Res.*, *84*, 5216, 1979.

Gurnett, D. A., The Earth as a radio source: Terrestrial kilometric radiation, *J. Geophys. Res.*, *79*, 4227, 1974.

Gurnett, D. A., W. S. Kurth and F. L. Scarf, Plasma wave observations near Jupiter: Initial results from Voyager 2, *Science*, *206*, 987, 1979.

Kurth, W. S., D. D. Barbosa, F. L. Scarf, D. A. Gurnett and R. L. Poynter, Low frequency radio emissions from Jupiter: Jovian kilometric radiation, *Geophys. Res. Lett.*, *6*, 747, 1979.

McNutt, R. L., Jr., J. W. Belcher, J. D. Sullivan, F. Bagenal, and H. S. Bridge, Departure from rigid co-rotation of plasma in Jupiter's dayside magnetosphere, *Nature*, *280*, 803, 1979.

Scarf, F. L., D. A. Gurnett and W. S. Kurth, Jupiter plasma wave observations: An initial Voyager 1 overview, *Science*, *204*, 991, 1979.

Voots, G. R., D. A. Gurnett and S.-I. Akasofu, Auroral kilometric radiation as an indicator of auroral magnetic disturbances, *J. Geophys. Res.*, *82*, 2259, 1977.

Warwick, J. W., J. B. Pearce, A. C. Riddle, J. K. Alexander, M. D. Desch, M. L. Kaiser, J. R. Thieman, T. D. Carr, S. Gulkis, A. Boischot, C. C. Harvey and B. M. Pedersen, Voyager 1 planetary radio astronomy observations near Jupiter, *Science*, *204*, 995, 1979a.

Warwick, J. W., J. B. Pearce, A. C. Riddle, J. K. Alexander, M. D. Desch, M. L. Kaiser, J. R. Thieman, T. D. Carr, S. Gulkis, A. Boischot, Y. Leblanc, B. M. Pedersen, and D. H. Staelin, Planetary radio astronomy observations from Voyager 2 near Jupiter, *Science*, *206*, 991, 1979b.

(Received October 23, 1979;
accepted November 13, 1979.)