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ABSTRACT

Measurements of the polarization of terrestrial kilometric radiation obtained with planetary radio astronomy experiments on Voyager-1 and 2 during the early portions of each flight show the signals to be predominantly left-hand circularly polarized. Since these emissions were most probably generated above the Northern hemisphere auroral zone, we conclude that the radiation is emitted primarily in the extraordinary mode.

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INTRODUCTION

Recent satellite measurements have provided a nearly complete picture of the intense, nonthermal, kilometer-wavelength emissions from the magnetosphere. Although the terrestrial kilometric radiation (TKR) was discovered more than ten years ago (Benediktov et al., 1965), the first extensive discussion of these emissions was given by Gurnett (1974) who described the general morphological properties of TKR including the close association between the occurrence of the radio emission and discrete auroral arcs. The average source location and radiation pattern were subsequently studied in some detail by Kurth et al. (1975), Alexander and Kaiser (1976), and Green et al. (1977), and a comprehensive analysis of the average spectral properties was presented by Kaiser and Alexander (1977).

To obtain a complete description of a source of electromagnetic waves, we must measure both the intensity and polarization as a function of frequency and time, and none of the early satellite experiments were capable of direct measurements of polarization. An indirect estimate of the polarization of TKR was obtained by Green et al. (1977) based on ray tracing model calculations and by Gurnett and Green (1977) based on the observation of frequency cut-offs at low altitudes. In this paper we present the first direct measurements of the polarization of TKR as obtained from the Planetary Radio Astronomy (PRA) experiment on the Voyager-1 and 2 spacecraft.

Each of the two Voyager spacecraft carry a Planetary Radio Astronomy Receiver (PRAR) that has been designed primarily to provide detailed measurements of the spectrum and polarization of the low frequency radio emissions of Jupiter and Saturn (Warwick et al., 1977). Several workers (e.g. Kaiser and Stone, 1975) have called attention to the similarities between the properties of the terrestrial emissions and those observed for Jupiter and Saturn, and in that spirit we note that the results presented in this paper for the Voyagers' fleeting encounters with Earth may provide a benchmark against which to compare their later close encounters with the giant planets.

In this paper, we describe and illustrate the performance of the PRARs in measuring the polarization of TKR during the very early portion of the Voyager flights, and we summarize the observed polarization properties. Based on an indirect estimate of the probable source location we then determine the fundamental magnetoionic mode in which the radiation is emitted, and we comment briefly on the implications of these results. A more extensive discussion of the interpretation of the observed polarization properties of TKR is in preparation (Warwick, private communication).

INSTRUMENTATION

The technical characteristics of the PRAR have been discussed by Warwick et al. (1977) and by Lang and Peltzer (1977). We describe here only those parameters that are important for this study of TKR.

The PRA experiment utilizes a pair of orthogonal 10-meter monopoles. Signals from the monopoles are combined in 90-degree hybrids so that the processed output of the receiver is most responsive to a selected sense of circular polarization. The sensitivity is reduced by a factor of two for linear or randomly polarized signals and by more than 12 dB for the other sense of circular polarization.

Data samples are digitized every 30 ms, each sample being the result of true integration for the preceeding 25 ms. The sense of circular polarization to which the receiver responds is reversed between data samples. The low-frequency band of the receiver can be tuned to one of 70 frequency channels separated by 19.2 kHz through the range 1.2 kHz to 1326 kHz with a bandwidth at each frequency of 1 kHz. For the observations described here only two of the many possible receiver modes were utilized: fixed frequency and scanning. In the fixed frequency mode, 198 data samples were collected at one frequency during a 6.0-sec period. During the next 6 seconds a different frequency was used. In the scanning mode, the receiver stepped down through the 70 frequency steps, one step per data sample. Six seconds later the same frequency sequence was repeated. Once selected, each mode operated for some multiple of 48 sec. The total duty cycle was about 50% for the fixed frequency mode and 20% for the scanning mode during the early portion of the missions.

The data have been digitized on a pseudo-logarithmic scale with a digitization step of about 0.13 dB at low signal levels and 0.4 dB at high signal levels, the total dynamic range being nearly 60 dB. The noise fluctuation due to the receiver time constant, bandwidth product corresponds to about 0.8 dB. The threshold sensitivity is $\sim 10^{-19}$ W m^{-2} Hz^{-1}.

The ability to discriminate between the two senses of circular polarization is affected by a number of mechanisms. Internal to the receiver the crosstalk or coupling prior to the hybrids can reduce the discrimination. This effect has been measured and the channel separation is better than 20 dB under all conditions. There is also potential for coupling in the antenna system. This effect could not be tested prior to flight but indications from the observed data are that the effect is small. For a pair of orthogonal dipoles, perfect discrimination is achieved only for sources normal to the plane containing the dipoles, and there is no discrimination at all for sources lying in the plane of the dipoles. We are using orthogonal monopoles; yet, the effective dipoles are unlikely to be orthogonal (as indicated by theoretical computations and scale model testing). The directions from which perfect discrimination is achieved are different from the ideal case. We have observed events with degree of circular polarization $\sim$ 80% in either sense at times when the source-monopole geometry would suggest that at best 80% would be achieved. Hence the coupling between antennas and the displacement of the equivalent dipoles from the position of the monopoles contribute, we believe, a total effect no greater than the measurement uncertainty (0.8 dB), about 10% error in degree of circular polarization.

OBSERVATIONS

The two spacecraft were launched 16 days apart, Voyager-2 (V-2) on August 20 and Voyager-1 (V-1) on September 5, 1977. Both were launched so that they departed from Earth along trajectories over the dawn meridian. The data used in this paper were obtained during the first 8 days of V-2 and 10 days of V-1, during which both spacecraft remained essentially fixed in local time.

TKR was easily detected each day by both spacecraft. Signal strengths exceeding 1 dB above threshold occurred on some days as often as 40% of the time. Figure 1 is a representative example of a TKR "storm" observed from V-1. Panels (a), (b), and (c) are dynamic spectra constructed from 48-sec averages of scanning mode data, whereas, panels (d) and (e) show 48-sec averages of fixed frequency mode data (at 250 kHz) for the same day, Sept. 10, 1977.

For this day, the results are unequivocal: TKR is strongly LHC polarized with virtually no RHC emission. The obvious bursts of TKR at 02^h, $06\text{-}12^h$, 16^h and 24^h appear to consistently show that the LHC channel signal exceeds the RHC signal by some 6 to 7 dB (near the maximum channel difference possible for the antenna-source geometry for Sept. 10, 1977). For the full 18-day span analyzed for this report, we found the LHC signal exceeded any RHC signal for more than 80% of the time. Furthermore, the degree of polarization of the TKR signal has been observed to reach at least 95%.

Although Figure 1 is a good representation of most of the early Voyager data, there are a few examples of strong RHC emission such as that shown in Figure 2. These data, which are presented in the same format as Figure 1, (but with LHC and RHC labels reversed because of differing antenna-source geometry) were obtained by V-2 the day following launch and represent the most complex period observed by either spacecraft as of this writing. Panel (c) of Figure 2 clearly indicates that both LHC and RHC emission occurred almost simultaneously across the frequency band from about 100 kHz to 600 kHz.

Figure 3 is a summary of the observations as a function of UT from both spacecraft for the first ten days of V-1 and eight days of V-2. For both V-1 and V-2 we find that the maximum occurrence rate and the maximum polarized signal strength are nearly coincident with the attainment of highest geomagnetic latitude by each spacecraft. This result is consistent with the findings of Green et al. (1977) who indicated that the TKR "beam" is centered at about 70° geomagnetic latitude. Although the daily average occurrence rates of TKR are comparable for the two spacecraft (27% for V-1, 25% for V-2), the daily average channel differences (0.7 dB LHC for V-1, 0.3 dB LHC for V-2) indicate that the TKR was, in general, more intense during the V-1 observation period. Additionally, for V-2, there are periods centered roughly around minimum latitude for which the RHC channel significantly exceeded the LHC channel. However, inspection of the daily dynamic spectra like those in Figures 1 and 2 has shown that the periods of RHC signals in the 22-02 hr UT bins were contributed almost entirely by the complex day shown in Figure 2, August 21, 1977.

DISCUSSION

Before we can determine the base mode of the TKR emission, we must deduce from which hemisphere, North or South, the signals are emanating. Although the PRA experiments have no direction finding capabilities, indirect evidence strongly suggests that the emissions discussed here come from the Northern hemisphere. Figure 3 clearly shows a correlation between both the occurrence rate and signal strength of TKR and sub-spacecraft geomagnetic latitude with maximum TKR occurring near maximum northern latitude. Additionally, Figure 6 of Green et al. (1977) indicates that for the latitudes of the Voyagers, the Northern auroral zone is much more likely to be the TKR source region than the Southern zone. If this inference of a Northern source region is indeed correct, then the magnetoionic mode for most of the TKR (i.e., that which is observed to be LHC polarized) is the extraordinary (X) mode. Extraordinary mode emission beamed from the Northern hemisphere would be left-hand polarized because the wave vector will have a component antiparallel to the magnetic field vector. This is the same mode predicted by Green et al. (1977) from ray tracing modelling considerations and deduced by Gurnett and Green (1977) from observation of frequency cut-offs. Most of Jupiter's decametric emission is thought to be emitted also in the extraordinary mode.

One possible explanation for the August 21, 1977 RHC events observed by V-2 is that they are ordinary (O) mode from the Northern hemisphere. However, this is not the only possibility. In Figure 3, we see that the RHC events are most prominent near the South point of the sub-spacecraft ground track, even though the minimum latitude is 30° N. This may indicate that the emission is from the Southern auroral zone. Although V-2 is even further North than V-1, the spacecraft local time of approximately 6.5 hr places V-2 somewhat further from the center of the TKR beam (70°N, 21 hr LT) than V-1 (LT ≅ 5.5 hr), so that Northern hemisphere emission should be slightly less intense at V-2 than at V-1, thus allowing the Southern hemisphere emissions to be observed. Close inspection of Figure 2 leads one to believe that the RHC and LHC emissions are independent from one another almost as if two separate competing source regions (such as a Northern and Southern source) were involved.

Of the several theories currently published to explain TKR, the theories by Benson (1975), Palmadesso et al. (1976), and Jones (1977) predict exclusively O-mode emission and thus are at considerable odds with the majority of the Voyager observations. The theory promoted by Gurnett (1974) and Green et al. (1977) has the emission in the X-mode with the emission at 3/2 times the local electron gyrofrequency. The Doppler shifted coherent cyclotron theory of Melrose (1976) also has emission in the X-mode with a typical frequency of about 1.2 times the local electron gyrofrequency. The statistical turbulence theory of Barbosa (1976) and the spikey turbulence theory of Maggs (1977) predict emission in both the X and O modes.

At this time we are not able to produce further evidence lending support or lack of support for any of the theories predicting X-mode radiation. However, after detailed analyses of the frequency-by-frequency observations have been done, we may be able to provide a more rigorous assessment. Some of the theories depend on the ratio of gyrofrequency to plasma frequency in the source region which implies that the polarization percentage should vary with frequency. After careful calibration is performed, we should be able to measure this parameter throughout the TKR band.

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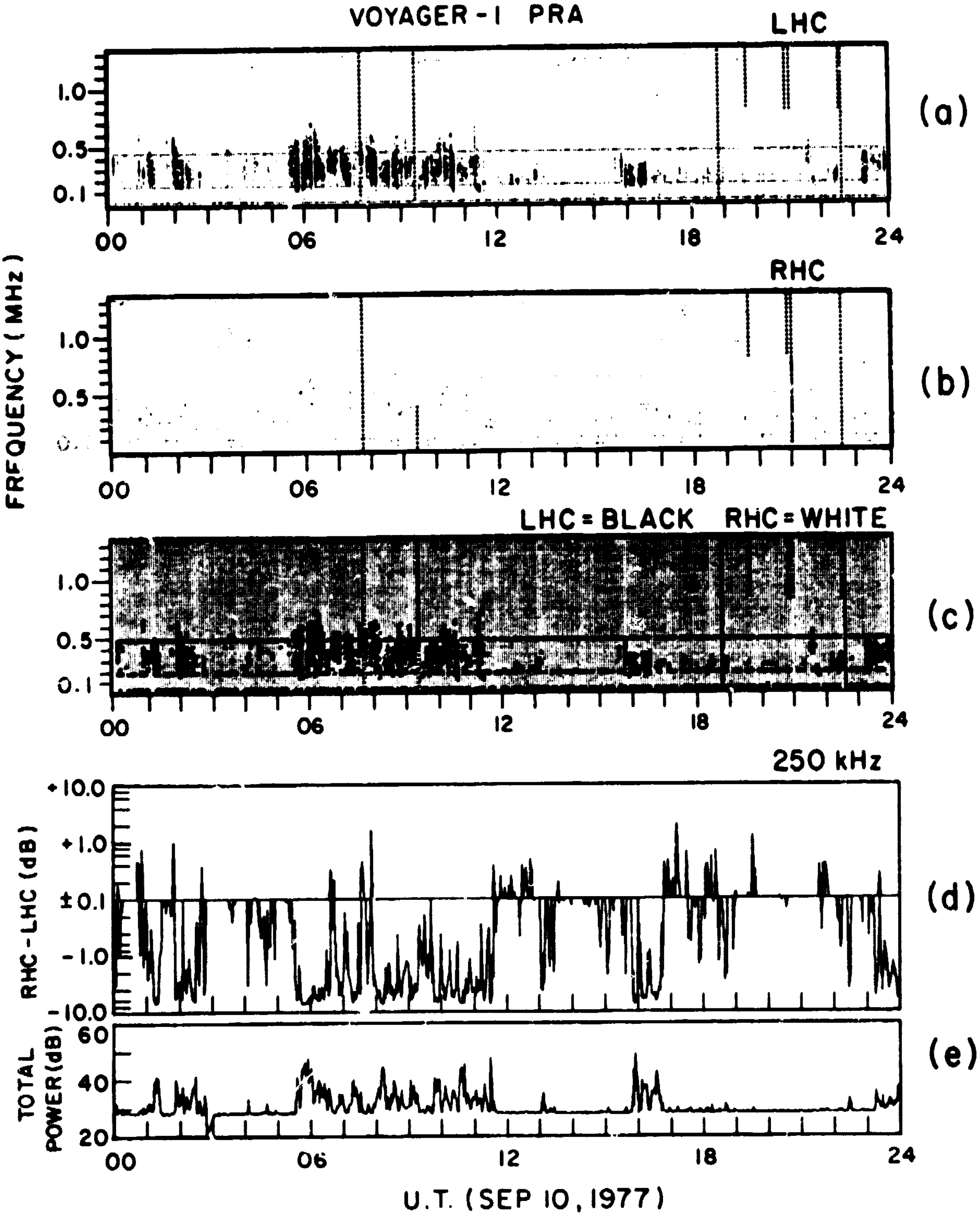
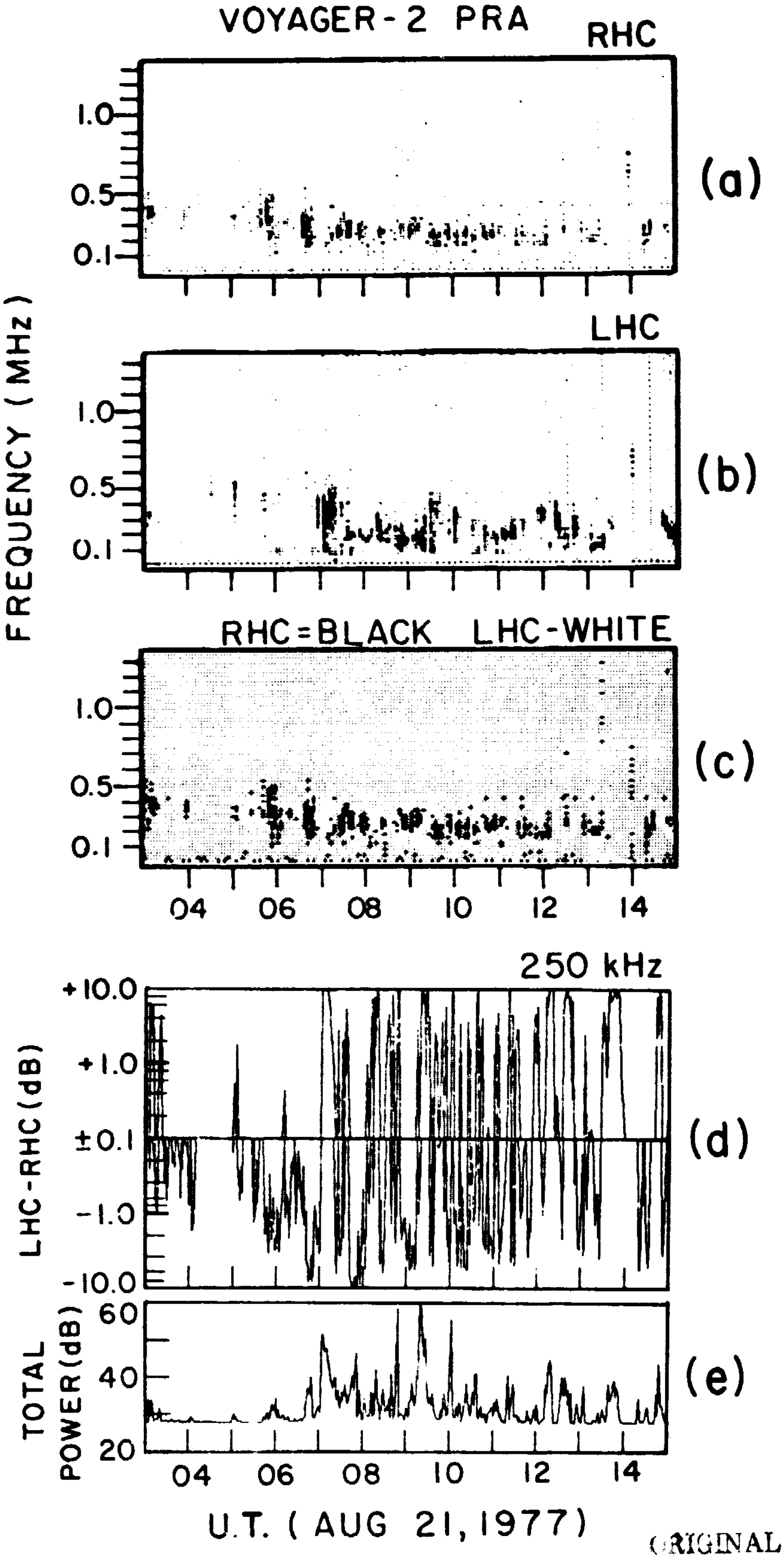
FIGURE CAPTIONS

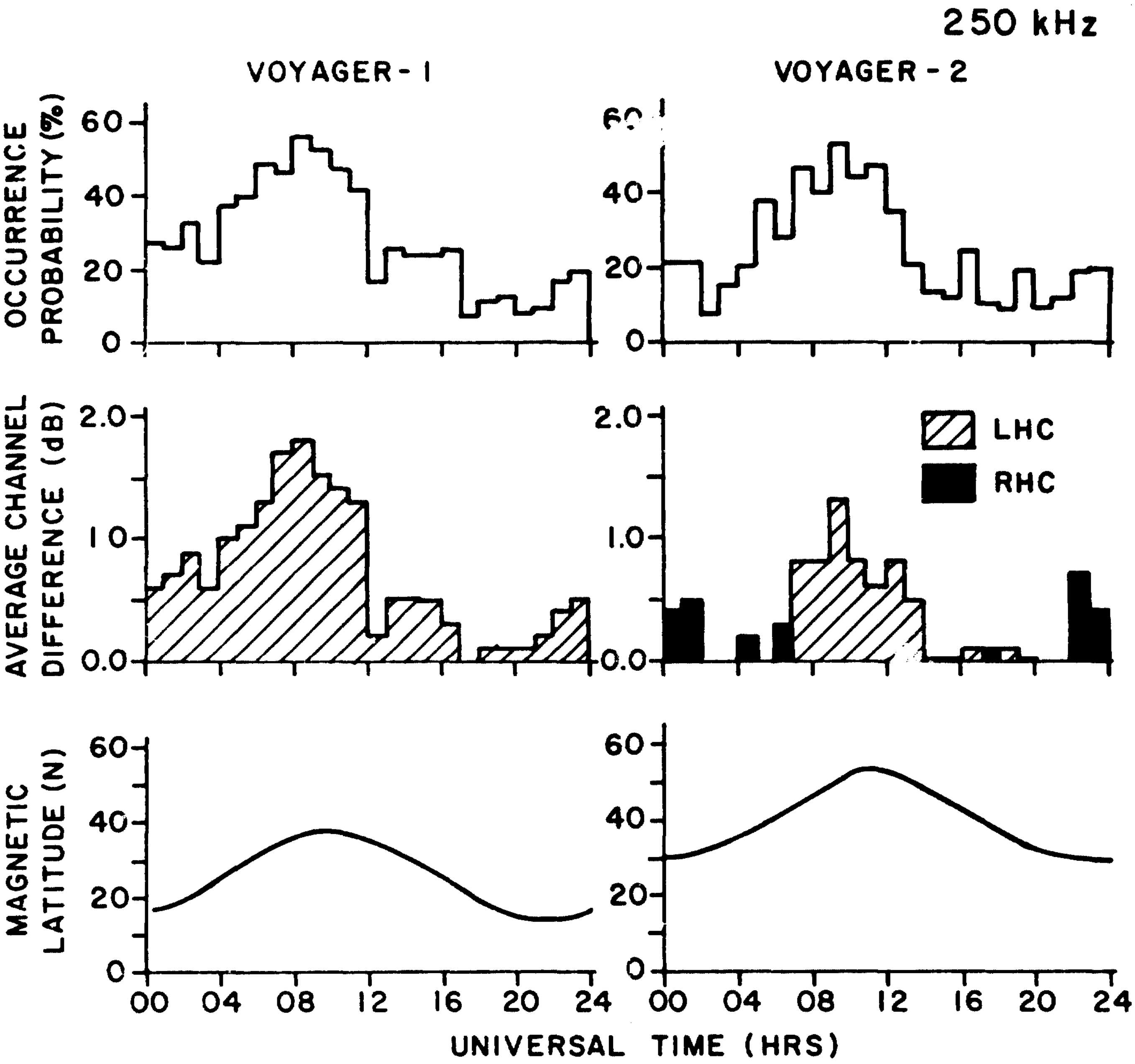
Figure 1. Examples of polarized terrestrial kilometric radiation observed by Voyager-1. Panels (a) and (b) show the Left Hand Circular (LHC) and Right Hand Circular (RHC) "excess" signals in the Voyager-1 low frequency band for September 10, 1977. When LHC and RHC signals are equal, only the white background is displayed. As the signal in one polarization sense begins to exceed the signal in the opposite sense a pixel with darkness proportional to the signal difference is displayed in panel (a) for LHC > RHC or panel (b) for RHC > LHC. Panel (c) is a "false color" combination of panels (a) and (b) coded such that black is displayed when LHC signal exceeds RHC signal, white for the reverse situation, and gray when LHC = RHC. Panels (d) and (e) show the detail of panels (a) and (b) for a single frequency channel (250 kHz). Panel (d) is again the "excess" signal between LHC and RHC displayed on a semilog scale to enhance the weaker signals. If the LHC signal exceeds RHC by more than 0.1 dB, the value of this difference in dB is shown as a negative number. For the cases of RHC > LHC the difference appears as a positive number. Panel (e) is the total received power (LHC + RHC) in decibels above the receiver threshold.

Figure 2. An example of complex TKR as observed by Voyager-2. The format is the same as Figure 1 except the LHC and RHC labels have been reversed because of differing spacecraft-earth geometry.

Figure 3. The hourly average values at 250 kHz of the occurrence of polarized signals (top panels), the channel difference and sense of polarization (middle panels), and the sub-spacecraft geomagnetic latitude for the first ten days of Voyager-1 and the first eight days of Voyager-2.


VOYAGER-I PRA
LHC
(a)
RHC
(b)
LHC = BLACK RHC = WHITE
(c)
250 kHz
(d)
(e)
FREQUENCY (MHz)
1.0
0.5
0.1
00
06
12
18
24
RHC-LHC (dB)
+10.0
+1.0
±0.1
-1.0
-10.0
TOTAL POWER (dB)
60
40
20
U.T. (SEP 10, 1977)


VOYAGER-2 PRA
RHC
LHC
RHC=BLACK LHC-WHITE
FREQUENCY (MHz)
1.0
0.5
0.1
(a)
(b)
(c)
04
06
08
10
12
14
250 kHz
+10.0
+1.0
±0.1
-1.0
-10.0
LHC-RHC (dB)
(d)
TOTAL POWER (dB)
60
40
20
(e)
U.T. (AUG 21, 1977)


250 kHz
VOYAGER - 1
VOYAGER - 2
OCCURRENCE PROBABILITY (%)
60
40
20
0
AVERAGE CHANNEL DIFFERENCE (dB)
2.0
1.0
0.0
LHC
RHC
MAGNETIC LATITUDE (N)
60
40
20
0
00
04
08
12
16
20
24
UNIVERSAL TIME (HRS)