Adv. Space Res. Vol. 6, No. 1, pp. 379–383, 1986
Printed in Great Britain. All rights reserved.

0273–1177/86 $0.00 + .50

RECENT OBSERVATIONS OF THE VERY LOW FREQUENCY INTERPLANETARY RADIO EMISSION

W. S. Kurth,* D. A. Gurnett* and F. L. Scarf**

**Department of Physics and Astronomy, The University of Iowa, Iowa City, IA 52242, U.S.A.*
***TRW Space and Technology Group, Redondo Beach, CA 90278, U.S.A.*

ABSTRACT

Observations of radio emissions in the frequency range of 2 to 3 kHz have been made in the distant heliosphere by the Voyager 1 and 2 plasma wave instruments. Based primarily on wideband observations made periodically throughout the cruise phases of the missions the radio emission, first observed in 1982, appears to have been present almost continuously since 1983. The spectrum is complex, usually showing two peaks, one near 2 and another near 3 kHz. Occasionally, only one of the peaks is observed. A possible source for the radio emissions is the terminal shock in the outer heliosphere.

INTRODUCTION

Beginning in 1982 the Voyager 1 and 2 plasma wave instruments began detecting a very weak radio emission in the frequency range of a few kHz /1,2/. The emission has been detected fairly regularly since 1983, however, the most intense event was the one reported by Kurth et al. /1/ which began in late 1983 and continued through the first third of 1984. The maximum power flux detected during that event was about 3 x 10^{-17} W/m^{2}Hz, only a factor of two above the Voyager 1 spectrum analyzer channel threshold. The frequency of the strongest component of the 1983 event was about 3 kHz, however, the spectrum appeared to be complex, having at least one other component at about 2 kHz. The Voyager 2 instrument also detected the emission in a wideband waveform capture mode /3/ and the onset of the 1983 event was coincident with the Voyager 1 onset to within the two week resolution afforded by the sparsely obtained waveform samples.

Kurth et al. /1,2/ used a process of elimination to come to a somewhat speculative suggestion that a possible mechanism was that of $2f_p$ generation at the terminal or inner heliospheric shock and, hence, may represent our first observations of that boundary. Compact sources such as planetary magnetospheres were ruled out on the basis that the two spacecraft which were separated by about 10 AU observed signals of about the same intensity. Local solar wind sources seemed to be ruled out by the near coincidence of onset times at the two spacecraft and the nearly fixed frequency of the emission. Obviously such low frequency emissions can not be generated much closer to the sun than about 10 AU due to the increase in the solar wind plasma frequencies at smaller heliocentric distances above the emission frequencies. The only viable sources seemed to be those which might exist at distances further from the sun than the Voyager spacecraft. The $2f_p$ emission mechanism is known to be operative at planetary bow shocks and interplanetary shocks, hence, it was deemed possible that similar waves might be generated at the terminal shock. In spite of the speculative nature of the proposed source, we have found only one alternative explanation proposed in the literature. In a recent review Fahr et al. /4/ suggested the 3-kHz emission might be generated at the heliopause, itself, rather than at the terminal shock. We will address this possibility in the last section of this paper. The purpose of this paper is to update the Voyager observations of the emission, and in the process, perhaps shed additional light on possible generation mechanisms. The observations presented herein are all obtained by the Voyager plasma wave receivers described by Scarf and Gurnett /3/.

OBSERVATIONS

The detection of the low frequency interplanetary radio emission is a challenge in view of the short (7.07m effective length) Voyager antennas and the extremely weak signal. Because of the gain in signal-to-noise ratio which can be achieved by averaging many measurements, the waveform capture mode of the instruments is the most sensitive to the emission. However, as pointed out above, the waveform capture mode is utilized for only a minute or two once every several weeks during the cruise phase because of the high (115.2 kbps) data rate generated by the instrument in this mode. The more continuous spectrum analyzer

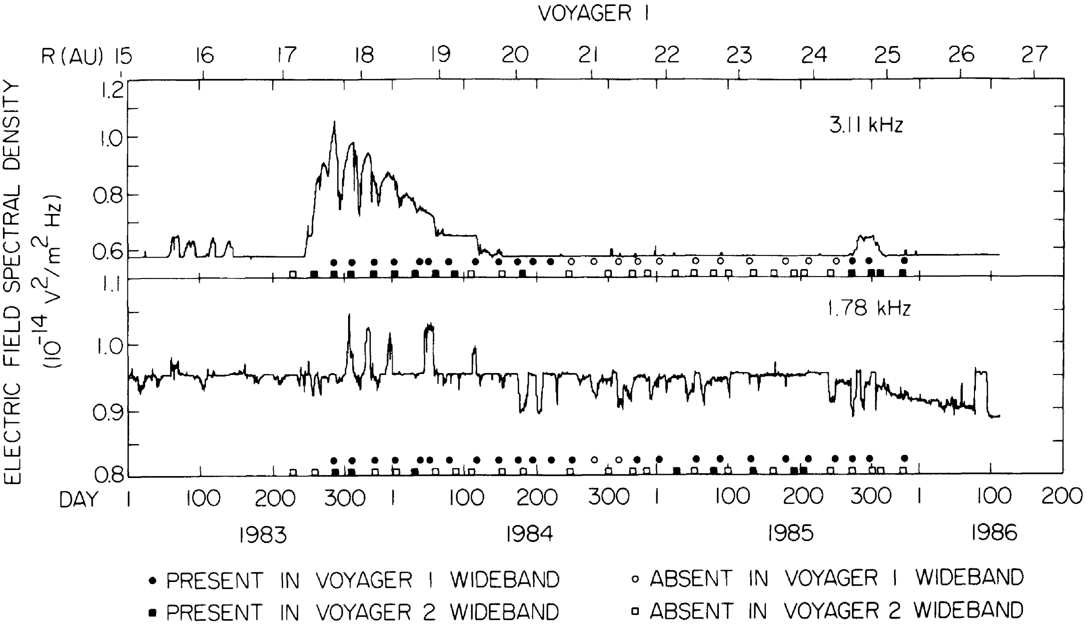

Fig. 1. A summary of observations of the low frequency interplanetary radio emission using the Voyager 1 3.11- and 1.78-kHz spectrum analyzer channels. Plotted values are 8.67 hour averages. The filled symbols indicate evidence for the emission at the respective frequency in short wideband samples taken at the indicated times. The squares represent Voyager 2 wideband samples. The distance scale is for Voyager 1; during the same interval Voyager 2 traversed a radial distance range of from 11 to 19 AU.

measurements are sufficient to record the existence of the emission above certain intensities, but finite-sized resolution steps in the analog-to-digital converter effectively limit the threshold of sensitivity. Also, a failure shortly after launch in the Voyager 2 Flight Data System has degraded the output of the Voyager 2 spectrum analyzer at frequencies of 1 kHz and above so that the emission is virtually impossible to observe in the Voyager 2 spectrum analyzer. Therefore, direct comparisons between Voyagers 1 and 2 are quite difficult. Fortunately, the very long time constant of the emission (of the order of a week or more) allows some progress to be made even with the above limitations.

Figure 1 shows the temporal evolution of the intensity of the signal at 1.78 and 3.11 kHz from the beginning of 1983 through April 1986. The data plotted are obtained from the Voyager 1 spectrum analyzer channels which are sampled at a rate of once per 4 s to once per 96 s depending on the data mode and rate of the spacecraft. Each point in Figure 1 represents an average over 8.67 hours. Note that the amplitude scale is linear and represents a range extending only a factor of two above the threshold of detectability at 3.11 kHz. The rather constant level seen in the 3.11-kHz channel near day 100 of 1984 is one digitizing level above the threshold.

The circles at the bottom of each channel represent times when wideband frames were available from Voyager 1; the filled circles indicate the radio emission was detectable in the wideband data in a frequency range approximately equal to the bandpass of each of the channels shown. The lower row of squares represents the wideband data from Voyager 2. Again, the filled symbols indicate that evidence for the radio emission was found in a frequency range similar to the channel's bandpass. The response in the Voyager 1 3.11-kHz channel is reasonably well behaved showing three basic periods of emission, the last one having a duration of some 50 days and ending late in 1985. Judging from the solid circles in late 1984 and early 1985, however, it is clear that emission exists during times when there is no evidence for it in the spectrum analyzer channel. The reason the wideband measurements are more sensitive to the emission is that we are able to average over 15 or more seconds (more than 250 spectral scans) which effectively increases the signal-to-noise ratio for a signal with a spectrum which is constant over the averaging interval. The shortcomings of the method are that the wideband data are obtained by an automatic gain controlled receiver, making absolute calibrations an indirect, hence, somewhat uncertain process. The most difficult problem, however, is that usually the wideband observations are obtained only once per 4 weeks or so. We are left with very sensitive and high resolution measurements which are made with an extremely low duty cycle of about 5 X 10^{-5}. The average data rate is about 5 bps.

Nevertheless, we can make some gross observations with the data in hand which serve to increase the information content beyond the output of the spectrum analyzer channel. The most important of which is that the radio signal is present a majority of the time. If one includes observations over the entire frequency range from 2 to 3 kHz and assumes that the time constant for amplitude changes is on the order of a week or more, then there has been almost continuous observation of the emission since mid-1983. The other important datum is that the frequency spectrum seems to be bimodal. The emission is virtually always present in one or both of the bands near 2 and 3 kHz. Some brief comments on the importance of this observation will be given below.

The squares shown at the bottom of each panel represent wideband observations available from Voyager 2 to show the correspondence between the two observing vantages. Unfortunately, the Flight Data System failure makes it virtually impossible to make one-to-one comparisons using the spectrum analyzer data which would be more meaningful in light of the more continuous nature of the spectrum analyzer measurements. It is possible to say, however, that there is reasonably good agreement between the two spacecraft if one assumes (as was shown in Kurth et al. /2/ that the Voyager 2 wideband receiver is slightly less sensitive than the Voyager 1 instrument. In virtually no case within the gross timing mismatches that samples once per few weeks provide is an emission detected at Voyager 2 that is not also detected at Voyager 1. The converse is not true due to the lower sensitivity of the Voyager 2 instrument.

The 1.78-kHz trace shown in Figure 1 is characteristically different than the 3.11-kHz trace. We believe the basis for this difference is primarily that the zero-input level of the 1.78-kHz channel is very close to a transition between two digitizing levels whereas at 3.11 kHz a much stronger signal is required to go to the next higher level above the threshold value. There are some worrisome aspects about the 1.78-kHz trace which may be attributable to this difference, but which may also cast some doubt on the validity of the variations shown in the lower panel of Figure 1. For example, there seem to many examples of the trace jumping from one digitization level to the next without smooth transitions which might be expected from the averaging process. The addition of the filled symbols at the bottom of the panel lends some validity to the gross trends--higher amplitudes in late 1983, weaker signals in late 1984, and a recurrence of emission in mid-1985.

As mentioned above, there does seem to be reasonable correspondence between the signals observed on the two spacecraft. That was demonstrated in part by the general agreement of the results of the wideband analyses shown by the use of symbols in Figure 1 with the assumption that the Voyager sensitivity is perhap a couple dB poorer than Voyager 1. Figure 2 reinforces the conclusion that the Voyager 1 and 2 observations are correlated. Plotted are spectra taken from the two spacecraft utilizing 15-second averages of the wideband data for four selected times when wideband data were obtained on the two spacecraft within a few days of each other. While differing somewhat in detail, the general features of the emissions are quite similar. The dark areas in the spectra are the difference between the measured spectrum and a straight line estimate of the noise threshold. In some cases it may be questionable whether the indicated noise is significant or statistical fluctuations, but we believe in most cases the gross characteristics stand out clearly above the random fluctuations.

Finally, we would like to take advantage of the Voyager 2 Uranus Observatory Phase during which wideband data were available on virtually a daily basis to examine temporal variations on time scales of several weeks. (In reference to Figure 2 we should point out that an unusually large gap of about 5 days occurred in the Voyager 2 wideband samples when a Voyager 1 sample occurred on day 343, hence, we did not choose to show comparative spectra for this day in Figure 2.) This analysis will serve in particular, to reinforce the premise that the high resolution samples taken on a monthly basis is sufficient to observe major trends in the emission amplitude. Figure 3 is a spectrogram made up of 15-second averages obtained approximately once per day. In superposing these short, high resolution samples with gaps of a day in between we are assuming the variation on time scales of a day or less are unimportant and, in fact, we believe the data support that conclusion. The feature of interest in Figure 3 is the emission appearing at the beginning of the plotted interval at about 3.4 kHz which fades out by about day 350. It would seem that this is the trailing edge of the event which could be seen prominently at 3.11 kHz in Figure 1 late in 1985. There is also sporadic evidence for the 2-kHz component just below the power supply interference line at 2.4 kHz. On the basis of the data shown in Figure 3 we conclude that at least during some intervals the two bands are relatively independent of each other.

DISCUSSION AND CONCLUSIONS

We have shown evidence that although the low frequency interplanetary radio emission has not returned to the intensities first recorded in 1983, the radio waves were detectable near either 3 or 2 kHz for virtually the entire period since late 1983 based on infrequent samples of the wideband data. Further, we continue to see evidence that the emission is

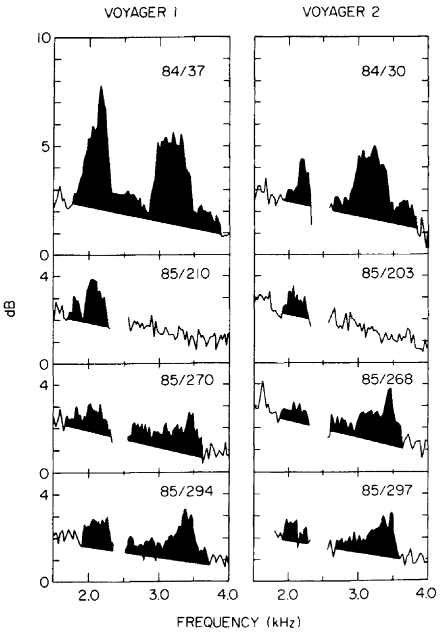

Fig. 2. Comparison of 15-s average spectra taken during selected times from the two Voyagers. Despite the large (> 10 AU) separation of the two spacecraft, the spectra are very similar. Although these spectra should not be compared to absolute amplitudes, it is generally true that the amplitudes are similar at the two spacecraft.

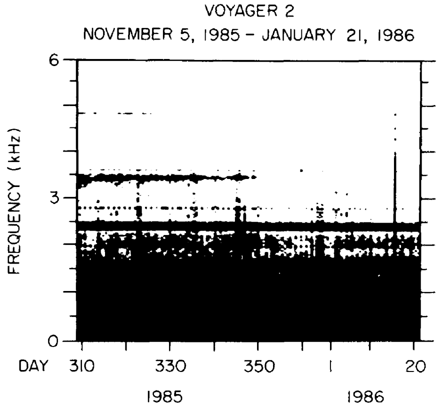

Fig. 3. A frequency-time spectrogram comprised of 15-s average spectra taken at approximately daily intervals from Voyager 2 as it approached Uranus. (Uranus closest approach occured on day 24 of 1986.) Notice the emission at 3.4 kHz decreases smoothly in amplitude and has become undetectable by about day 350 1985. Evidence of the 2-kHz component (between the interference lines at 1.7 and 2.4 kHz) is also visible. The 2-kHz emission does not correlate well with the 3.4-kHz component in this interval and seems to be more sporadic.

very similar as seen by both Voyagers even though the spacecraft are separated by large distances. Finally, the Uranus encounter provided an opportunity to track the emission through a decay phase of a 3-kHz event on a nearly daily basis and the data support the claim that the emission's spectrum changes smoothly on time scales of a week or longer.

While it may seem bothersome that the most intense burst occurred in 1983 while both spacecraft were much closer to the sun than they currently are, we must point out that even that early peak was only a factor of two above our detection threshold. Most radio emission we know of display variations over several orders of magnitude, hence, statistical variations in intensity may only infrequently result in similar amplitudes. In view of the time scale for variation shown herein of the order of a month, it is possible that we simply need to be patient in waiting for a recurrence of the 1983 amplitudes.

While we have not dwelt on the interpretation of the emission at length in this paper, we have referred to our previous model of generation from the terminal shock. The continuing observations of the radio waves certainly do not detract from that model, however, the persistence of one or the other of the two components near 2 and 3 kHz implies a more complex model than simply emission at $2f_p$ in the vicinity of the shock. Were the frequencies of the two components in the ratio of 2:1 it would be tempting to suggest emission at both f_p as well as the second harmonic. These two mechanisms may operate independently, even though the underlying Langmuir waves are required in either case, hence, the lack of correlation shown herein between the two components is not a severe problem. The ratio of the two frequencies is less than 2:1, however. Comparing the high and low frequency peaks in Figure 2 gives an average ratio of about 1.6:1. Hence, it does not seem reasonable to consider emission at f_p and $2f_p$ from the same location.

The ratio of 1.6:1 is more reminiscent of the ratio between the frequencies of the first two $(n+1/2)f_g$ or Bernstein modes since $5/2f_g:3/2f_g \approx 1.7$ (f_g is the electron gyrofrequency). It is conceivable that the two bands of electrostatic waves at a density gradient could mode-couple into freely propagating radio waves /5/. The spacing of the bands of about 1.2 kHz implies a magnetic field strength at the source of about 45 nT since $f_g[\mathrm{Hz}] = 28B[\mathrm{nT}]$ where B is the field strength. Hence, emission from the first two Bernstein bands is untenable since field strengths in the outer heliosphere and local interstellar medium are thought to be smaller than 1 nT.

It may be necessary to relate the two different frequency components to two different regions altogether (although a more thorough analysis of the correlation between the two components needs to be completed before adopting this model). This brings to mind the suggestion by Fahr et al. /4/ that the source of the 3-kHz emission could be located at the heliopause. We are not opposed, in principle to this idea, however, it would be necessary to assure ourselves that Langmuir waves could be driven unstable at or near the heliopause (or that some other emission mechanism is feasible there) before fully endorsing the suggestion. It could be that the 2-kHz source is located at the terminal shock and the higher frequency source is at the heliopause, thus providing an explanation of the two frequency components. One can not use the method of Kurth et al. /1/ to arrive at a distance of a heliopause source since there is not straightforward way to relate the solar wind density to a model which accounts for the region of shocked plasma between the terminal shock and the heliopause without detailed modeling of the solar wind/interstellar medium interaction. One can use the assumption of $2f_p$ generation at the shock to produce the 2-kHz emission and an R^{-2} density model with $n_e = 5\ \mathrm{cm}^{-3}$ at 1 AU to arrive at a heliocentric distance to the shock of about 40 AU, similar to other values reported using this method /1,2,6/. We emphasize, however, that additional consideration of the implications of a 2-component source is required before a final conclusion is reached.

As additional observations of the low frequency interplanetary radio emission are obtained, it becomes possible to investigate correlations between the reception of the radio signals and solar wind conditions in the outer heliosphere. For example, some evidence has already been shown that the 1983 event was coincident with a marked decrease in the fluxes of solar wind accelerated protons /7,8,9/. Work is currently under way to determine if the correlation stands or if it was only coincidental. It has been conjectured /7/ that the decrease in fluxes implies a quiet solar wind condition which might be more favorable to inward propagation of low frequency radio waves. Consideration of this correlation may serve to limit the possible generation mechanisms or source locations of the very low frequency radio emission.

ACKNOWLEDGEMENTS

The research at the University of Iowa was supported by the National Aeronautics and Space Administration through Contract 954013 with the Jet Propulsion Laboratory and through Grant N00014-K-85-0404 with the Office of Naval Research. The research at TRW was supported by NASA through Contract 954012 with the Jet Propulsion Laboratory.

REFERENCES

1. W.S. Kurth, D.A. Gurnett, F.L. Scarf, and R.L. Poynter, Detection of a radio emission at 3 kHz in the outer heliosphere, Nature, 312, 27 (1984)

2. W.S. Kurth, D.A. Gurnett, F.L. Scarf, and R.L. Poynter, A new radio emission at 3 kHz in the outer heliosphere, in: Proceedings of a Course and Workshop on Plasma Astrophysics (ESA SP-207), Varenna, Italy, August 28-September 7, 285 (1984)

3. F.L. Scarf and D.A. Gurnett, A plasma wave investigation for the Voyager mission, Space Sci. Rev., 21, 289 (1977)

4. H.J. Fahr, W. Neutsch, S. Grzedzielski, W. Macek, and R. Ratkiewicz-Landowska, Plasma transport across the heliopause, Space Sci. Rev., 43, 329 (1986)

5. W.S. Kurth, Detailed observations of the source of terrestrial narrowband electromagnetic radiation, Geophys. Res. Lett., 9, 1341 (1982)

6. S.T. Suess and A.J. Dessler, Probing the local interstellar medium, Nature, 317, 702 (1985)

7. L.J. Lanzerotti, C.G. Maclennan, and R.E. Gold, Interplanetary conditions during 3-kHz radio-wave detections in the outer heliosphere, Nature, 316, 243 (1985)

8. S.P. Christon and E.C. Stone, Latitude variation of recurrent MeV-energy proton flux enhancements in the heliocentric radial range 11 to 20 AU and possible correlation with solar coronal hole dynamics, Geophys. Res. Lett., 12, 109 (1985)

9. J. A. Van Allen, private communication (1984)