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HELIOSPHERIC 2–3 kHz RADIO EMISSIONS AND THEIR RELATIONSHIP TO LARGE FORBUSH DECREASES

D. A. Gurnett and W. S. Kurth

Department of Physics and Astronomy, The University of Iowa, Iowa City, IA 52242, U.S.A.

ABSTRACT

Two intense heliospheric 2-3 kHz radio emission events have been observed by Voyagers 1 and 2, the first in 1983-84 and the second in 1992-93. These radio emission events occurred about 400 days after large Forbush decreases in mid-1982 and mid-1991. Since Forbush decreases are indicative of a strong interplanetary shock propagating outward through the heliosphere, this temporal relationship provides strong evidence that the radio emissions are triggered by the interaction of a shock with one of the outer boundaries of the heliosphere. From the travel time and the known speed of the shock, the distance to the interaction region can be estimated and is well beyond 100 AU. At this great distance the plasma frequency at the terminal shock (100 to 200 Hz) is believed to be too small to explain the observed emission frequencies, which extend up to 3.6 kHz. For this reason, we have proposed that the interaction takes place at or near the heliopause, where remote sensing measurements show that the plasma frequency is in a suitable range (~3 kHz) for explaining the radio emission. From the travel time and shock propagation speed, the radial distance to the heliopause has been calculated for various candidate solar events. After taking into account the likely deceleration of the shock, the heliopause is estimated to be in the range from about 110 to 160 AU.

INTRODUCTION

For over ten years the plasma wave instruments on the Voyager 1 and 2 spacecraft have been detecting radio emissions in the outer heliosphere at frequencies from about 2 to 3 kHz. Two unusually intense events have been observed, the first in 1983-84 /1/, and the second in 1992-93 /2/. In addition five much weaker events have been reported, one in late 1985, one in 1989, and three in 1990-91 /3,4/. Various possible sources have been considered, including (1) planetary, (2) heliospheric, and (3) extraheliospheric. Of these, a strong case can now be made that the source is located in the outer regions of the heliosphere. For a discussion of possible source locations, see Kurth et al. /1/, Kurth /5/, and Gurnett and Kurth /6/, and for a review of the various boundaries of the heliosphere, such as the terminal shock and the heliopause, see Axford /7/. A description of the Voyager plasma wave instrument is given by Scarf and Gurnett /8/.

One of the most important issues regarding the 2-3 kHz heliospheric radio emissions is the question of what "triggers" these emissions. McNutt /9/ was the first to suggest that the emission could be triggered by the interaction of a transient high-speed solar wind stream with the terminal shock. This idea was further explored by Grzedzielski and Lazarus /10/, who identified a series of dynamic pressure increases in the solar wind that were believed to be responsible for the 1983-84, 1985, and 1989 events, again assuming an interaction with the terminal shock. Later, in the process of analyzing the 1992-93 event, Gurnett et al. /2/ proposed that the radio emission was triggered by the interaction of an interplanetary shock with the heliopause. Also, see Whang and Burlaga /11/. A key element in their interpretation was the observation that the 1992-93 radio emission event was preceded by an unusually large (~30%) transient cosmic ray intensity decrease in mid-1991, approximately 400 days before the onset of the radio emission. Transient cosmic ray intensity decreases, called Forbush decreases, after Forbush /12/, are indicative of a strong interplanetary shock and associated disturbances propagating outward through the heliosphere. From the time delay and speed of propagation, the distance to the source was determined to be well beyond 100 AU. At this great distance, the plasma frequency at the terminal shock is believed to be too small (100 to 200 Hz) to explain the radio emission frequencies, which extend up to 3.6 kHz. To overcome this difficulty, Gurnett et al. proposed that the radio emission was generated by an interaction with the heliopause, where the plasma frequency is more nearly comparable to the emission frequency, about 3 kHz according to the plasma density estimates of Lallement et al. /13/.

Although the temporal relationship between the large Forbush decrease of 1991 and the intense heliospheric radio emission event of 1992-93 provides a strong case that the radio emission was triggered by the interaction of an interplanetary shock with the heliopause, one event does not prove a cause-effect relationship. Upon re-examining the 1983-84 heliospheric radio emission event, a large (~21%) Forbush decrease was found in 1982, again about 400 days before the onset of the radio emission. The purpose of this paper is to describe and compare these two extraordinary events, and to discuss their interpretation.

RADIO EMISSION SPECTRUM

A spectrogram showing the radio emission intensities detected by the wideband plasma wave receiver on Voyager 1 is given in Figure 1. This spectrogram covers a twelve-year period from January 1, 1982, to December 31, 1993, and a frequency range from 1 to 4 kHz. A nearly identical spectrogram was also obtained from Voyager 2 (not shown). The frequency resolution is approximately 28 Hz. The time resolution is determined by the ground receiving capability and varies from as low as one spectrum per month to as high as two spectrums per week. The short vertical bars at the top of the spectrogram

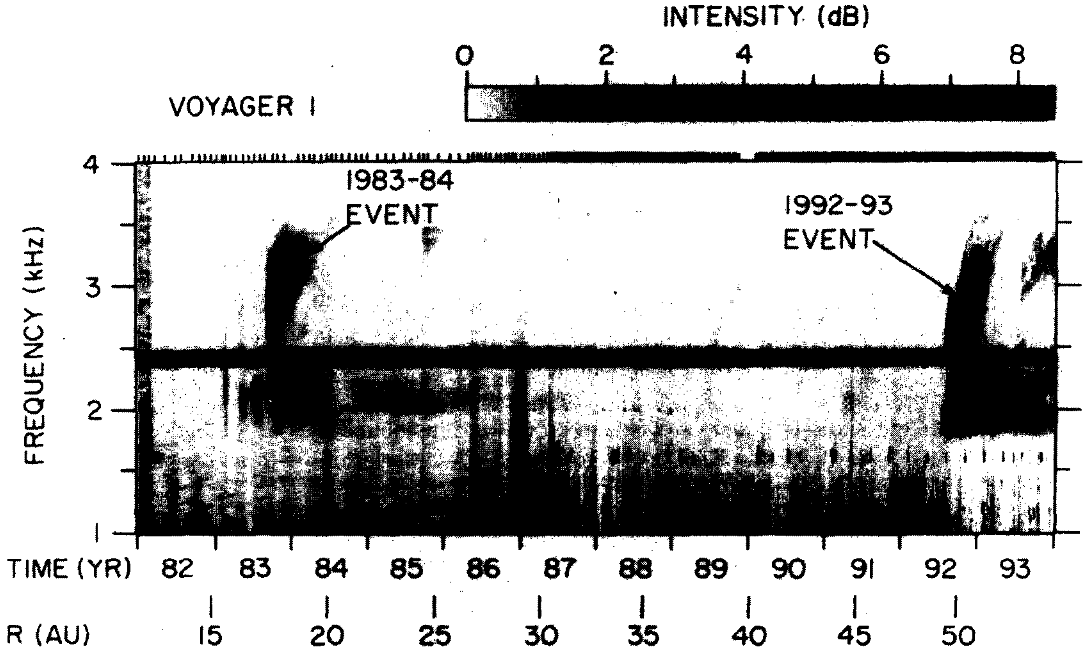

Fig. 1. A twelve-year spectrogram from Voyager 1 showing the 1983-84 and 1992-93 heliospheric radio emission events. In both cases the spectrum consists of a nearly constant frequency band around 2 kHz, and a series of bands drifting upward in frequency to about 3.6 kHz.

indicates the times at which the individual spectrums were obtained. Each spectrum represents an average of about 15 seconds of data. The dynamic range from the lowest intensity (white) to the highest intensity (black) is about 8 dB. The horizontal line across the spectrogram at 2.4 kHz is interference from the spacecraft power system.

The 1983-84 and 1992-93 radio emission events are clearly evident in Figure 1. As can be seen, these two events are by far the most intense heliospheric radio emission events that have been observed during the approximately twelve years for which wideband spectrum measurements of this type are available. (Prior to January 1982, wideband spectrum measurements were generally not available on a regular basis.) For both events the radio emission consists of two components: (1) a nearly constant frequency band around 2 kHz, and (2) a series of bands drifting upward in frequency to about 3.6 kHz at rates ranging from 1 to 3 kHz/y. The 2-kHz band is very strong during the 1992-93 event, but is nearly undetectable during the 1983-84 event. For the 1992-93 event the radiation remains weakly detectable into 1994. However, since the highest intensities occurred in 1992-93 we continue to refer to this event as the 1992-93 event.

The low intensity of the 2-kHz band during 1983-84 is believed to be due to the fact that during this period the local plasma frequency ($f_p = 9\sqrt{n}$ kHz, where n is the electron density in cm-3) was too high to allow direct access to the spacecraft in this frequency range. Since the electron density in the solar wind varies approximately as $1/R^2$, the solar wind plasma frequency is expected to vary approximately as 1/R, where R is the distance from the Sun. Based on the plasma density measurements of Belcher et al. /14/, the plasma frequency at Voyager 1 during 1983-84 ($R \simeq 18$ AU) is believed to have an average value of about 1.1 kHz, with peaks of about 2.5 kHz. Since the plasma frequency is the low frequency limit of free-space electromagnetic propagation, these peaks effectively prevent the radiation from reaching the spacecraft at frequencies below about 2.5 kHz. By the time of the 1992-93 event, the spacecraft was much farther from the Sun ($R \simeq 51$ AU), so the plasma frequency was considerably lower. At this radial distance the plasma density profile of Belcher et al. /14/ shows that the plasma frequency should have an average value of about 0.37 kHz, with peaks of only 0.75 kHz, which explains why the 2-kHz component was able to reach the spacecraft during the 1992-93 event.

A remarkable feature of the spectrum of the 1992-93 event is the extremely sharp, almost completely constant, low-frequency cutoff at 1.8 kHz /2/. This cutoff is almost certainly not a local effect and must be due to either the emission spectrum of the source, or a propagation cutoff at some remote point between the source and the spacecraft.

COMPARISON WITH THE LARGE FORBUSH DECREASES OF 1982 AND 1991

Figure 2 illustrates the relationship between the large Forbush decreases in 1982 and 1991, and the 1983-84 and 1992-93 radio emission events. The top panel shows the cosmic ray intensities from the Deep River neutron monitor, and the bottom panel shows a twelve-year plot of the radio emission intensity at 3.11 kHz from the Voyager 1 16-channel spectrum analyzer. The Deep River neutron monitor responds to cosmic rays with rigidities greater than about 1 GV. Two deep depressions can be seen in the cosmic ray intensity, the first in 1982 and the second in 1991. These two events, marked A and B, are the two largest Forbush decreases observed in the over thirty years for which neutron monitor data are available. Event A, which was a 21% decrease /15/, reached minimum intensity on day 195 (July 14), 1982, and event B, which was a 30% decrease /16/, reached minimum intensity on day 164 (June 13), 1991. The two intense heliospheric radio emission events are marked event A′ and event B′. The onset time of event A′ (at 3.11 kHz) was day 242 (August 30), 1983, and the onset time of event B′ (at 3.11 kHz) was day 218 (August 6), 1992. The delay time from event A to event A′ was 412 days, and the delay time from event B to event B′ was 419 days.

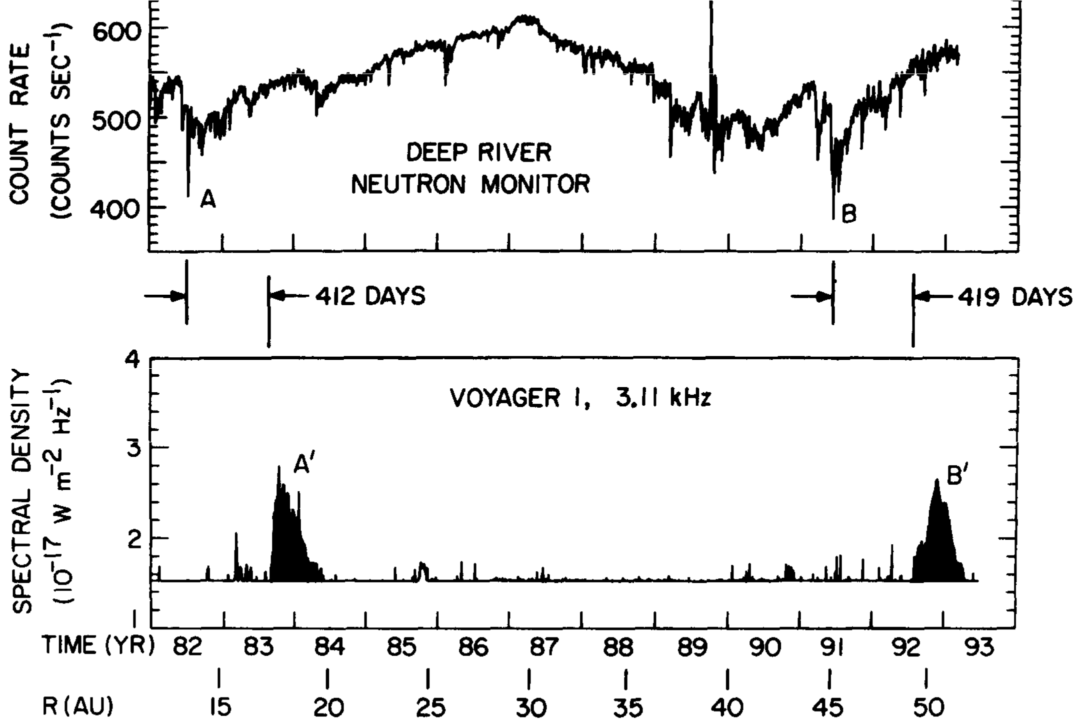

Fig. 2. A twelve-year plot showing the radio emission intensity at 3.11 kHz from Voyager 1, and the corresponding cosmic ray intensity from the Deep River neutron monitor. The Forbush decreases marked A and B are the two deepest depressions in the cosmic ray intensity observed in the over thirty years for which such data are available. These events are indicative of strong shocks and associated disturbances propagating outward through the heliosphere. The two strong heliospheric radio emission events, marked A′ and B′, occurred a little over 400 days after these large Forbush decreases.

In order to provide a better overview of the temporal evolution of each event, expanded time scale plots are shown in Figures 3 and 4. These plots show the cosmic ray intensities from the Deep River neutron monitor and the corresponding radio emission intensities in both the 1.78- and 3.11-kHz channels of the 16-channel spectrum analyzer. For event B′, the onset time in the 1.78-kHz channel was day 188, 1992, 30 days earlier than the onset time in the 3.11-kHz channel. This time difference arises because the 3.11-kHz channel responds to the upward drifting bands, whereas the 1.78-kHz channel responds to the 2-kHz component. For event A′ no response occurred in the 1.78-kHz channel. The absence of a response in the 1.78-kHz channel is due to the fact that during 1983-84 the local plasma frequency was too high to allow the radiation to reach the spacecraft at 1.78 kHz. Evidence of the high plasma frequency during the 1983-84 event can be seen from the periodic depressions in the intensity at 3.11 kHz with a period of about 26 days. As discussed by Kurth et al. /3/, the 26-day modulation is believed to be caused by local variations in the solar wind plasma frequency imposed by the solar rotation. If one assumes that the spectrums of the two events are similar, the 30-day delay in the response of the 3.11-kHz channel during event B′ suggests that the onset time of event A′ at 1.78 kHz should have been on or about day 213, 1983. In all subsequent calculations, day 213, 1983, will be used as the onset time of event A′.

Deep depressions in the cosmic ray intensity, such as in Figure 2, are usually associated with a complex series of solar events. For example, event A in Figure 3 was preceded by a period of intense solar activity from May 20 to June 10, 1982. This period of intense activity, labeled the May-June events at the top of Figure 3, resulted in a substantial decrease in the Deep River neutron monitor intensity,

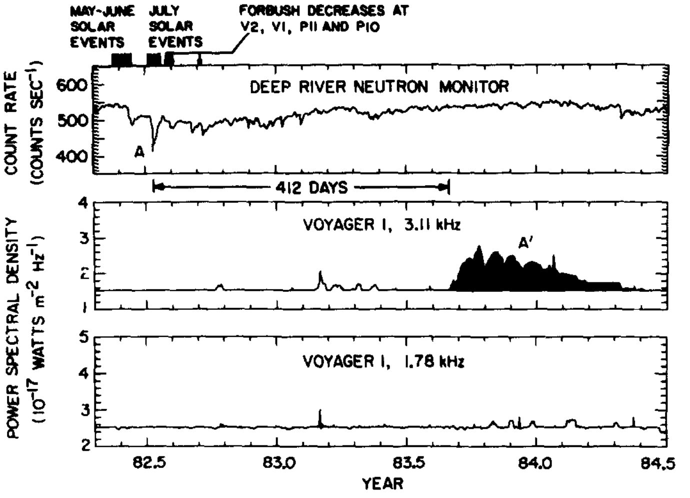

Fig. 3. An expanded time scale plot showing further details of events A and A′. The large 1982 Forbush decrease was caused by two periods of intense solar activity, the first in May-June, and the second in July. The deep Forbush decrease associated with the July activity was subsequently detected by Voyager 1 (V1), Voyager 2 (V2), Pioneer 11 (P11), and Pioneer 10 (P10) as indicated by the arrows at the top of the plot. The 1983-84 heliospheric radio emission event occurred a little over one year later.

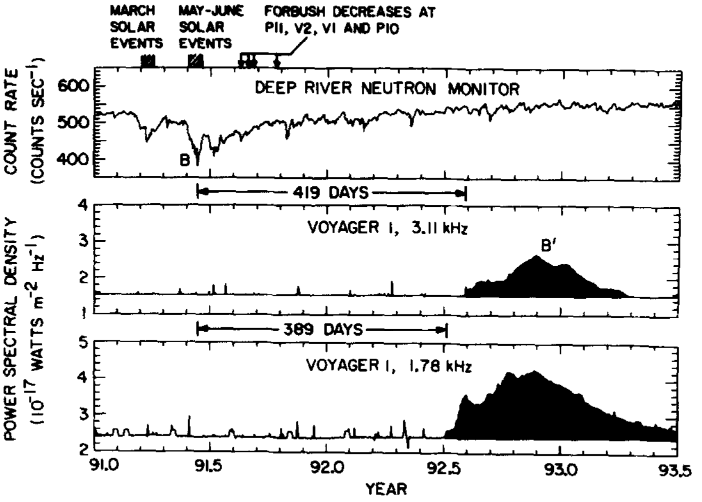

Fig. 4. An expanded time scale plot showing further details of events B and B′. The deep 1991 Forbush decrease was again caused by two periods of intense solar activity, the first in March, and the second in May-June. The deep Forbush decrease associated with the May-June activity was subsequently detected by P11, V2, V1, and P10 as indicated by the arrows at the top of the plot. The 1992-93 heliospheric radio emission event occurred about nine months later.

with a well-defined Forbush decrease on day 165/166 (June 14/15), 1982, followed by a partial recovery /15/. This recovery was followed by an even more intense period of solar activity about three weeks later, from July 8 to 22, that produced 67 M-class and 5 X-class solar flares /17/. This activity is labeled the July solar events at the top of Figure 3. The July solar events caused a sharp drop in the Deep River neutron monitor intensities, leading to the deep Forbush decrease labeled event A in Figure 3. Event B in Figure 4 has a remarkably similar chronology. This event was preceded by a period of intense solar activity in March 1991, labeled the March solar events at the top of Figure 4. During this period, three active regions in the southern hemisphere of the Sun produced 35 solar flares of classification M-5, or higher. These events caused a well-defined Forbush decrease on day 83 (March 24), 1991, followed by a partial recovery /18/. This recovery was followed by an even more intense period of solar activity in the northern hemisphere about six weeks later, from May 25 to June 15, that produced 70 M-class and 6 X-class solar flares /19/. This activity is labeled the May-June solar events at the top of Figure 4. The May-June solar events produced a sharp decline in the Deep River neutron monitor intensity, eventually causing the deep Forbush decrease labeled event B in Figure 4.

The current view is that large Forbush decreases, such as events A and B, are caused by a series of solar events lasting days, or even weeks /20/. As the interplanetary shocks and associated disturbances produced by these solar events propagate outward from the Sun, they are believed to merge into a shelllike region of compressed plasma and magnetic field called a Global Merged Interaction Region (GMIR). For a discussion of GMIRs, see Burlaga et al. /21,22/ and McDonald and Burlaga /23/. A GMIR is usually preceded by a strong shock that is formed by the coalescence of several shocks. The strong leading shock is typically followed by a region of turbulence plasma with numerous MHD discontinuities. Other shocks may also be imbedded within the GMIR. The turbulent magnetic fields in the GMIR scatter and impede the transmission of cosmic rays, thereby causing the transient intensity decrease known as a Forbush decrease.

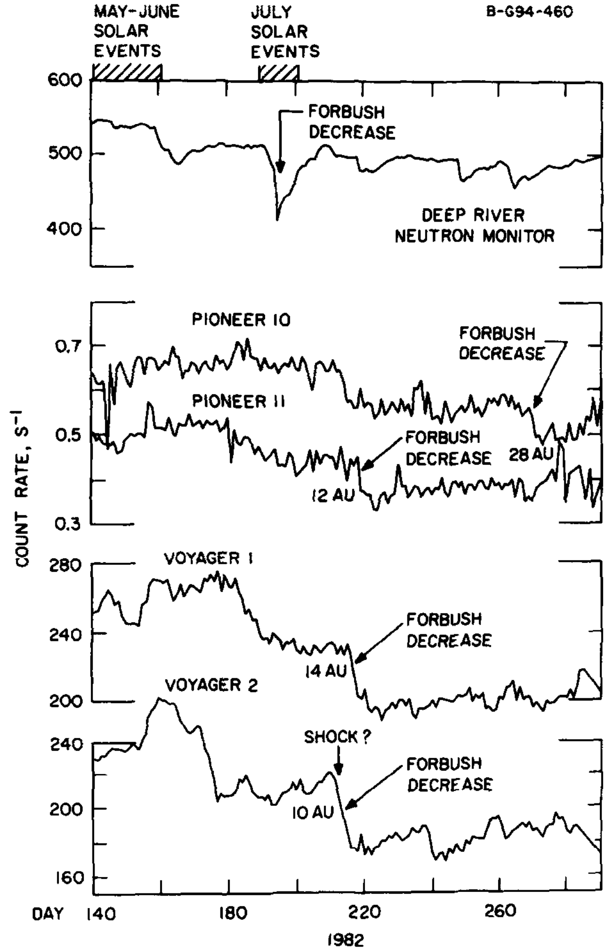

Fig. 5. The cosmic ray intensities from Pioneers 10 and 11, and Voyagers 1 and 2, showing the large Forbush decrease produced by the July 1982 solar event. Illustration adapted from Van Allen and Randall /15/ and Webber et al. /24/.

The intense solar activity of May-July 1982 and March-June 1991 both produced interplanetary disturbances that were observed by several interplanetary spacecraft. Well-defined Forbush decreases were observed for both the May-June and July 1982 solar events. Of these we will focus on the July solar events, since these events produced the deepest minimum in the Deep River neutron monitor count rate. As the GMIR associated with the July solar activity propagated outward from the Sun, large Forbush decreases were observed by Voyager 2 on day 211 at 10.3 AU, by Voyager 1 on day 216 at 13.8 AU, by Pioneer 11 on day 219 at 12.1 AU, and by Pioneer 10 on day 271 at 28.3 AU. The cosmic ray intensities from these spacecraft are shown in Figure 5, and the approximate times of these Forbush decreases are indicated at the top of Figure 3. For a discussion of these events, see Van Allen and Randall /15/, Webber et al. /24/, and Cliver et al. /17/. Observations of the leading shock associated with this GMIR are quite limited. Burlaga et al. /21/ note the existence of a shock in the Voyager 2 plasma measurements during a data gap on day 213 that corresponds closely to the onset of the cosmic ray intensity decrease at this spacecraft. The 1983-84 heliospheric radio emission event occurred approximately one year after this shock passed Voyager 2 (see Figure 3).

Very similar effects were also observed in the outer heliosphere in response to March-June 1991 solar activity, except the spacecraft involved were considerably farther from the Sun. As the disturbances associated with the 1991 activity propagated outward from the Sun, large Forbush decreases were observed by Pioneer 11 on day 233 at 34 AU, Voyager 2 on day 250 at 35 AU, Voyager 1 on day 257 at 46 AU, and Pioneer 10 on day 273 at 53 AU. The cosmic ray intensities from these spacecraft are shown in Figure 6, and the approximate times of these Forbush decreases are indicated at the top of Figure 4. For a discussion of these events, see Van Allen and Fillius /25/, Webber and Lockwood /16/, and McDonald et al. /19/. A strong shock was also observed essentially coincident with these Forbush decreases by the Pioneer 11 magnetometer on day 232 /26/, by the Voyager 2 plasma instrument on day 251 /27, 28/, and by the Voyager 1 plasma wave instrument on day 257 /29/. It was this shock that Gurnett et al. /2/ identified as the trigger for the 1992-93 heliospheric radio emission event. The 1992-93 heliospheric radio emission event started about nine months after the shock passed Voyager 1 (see Figure 4).

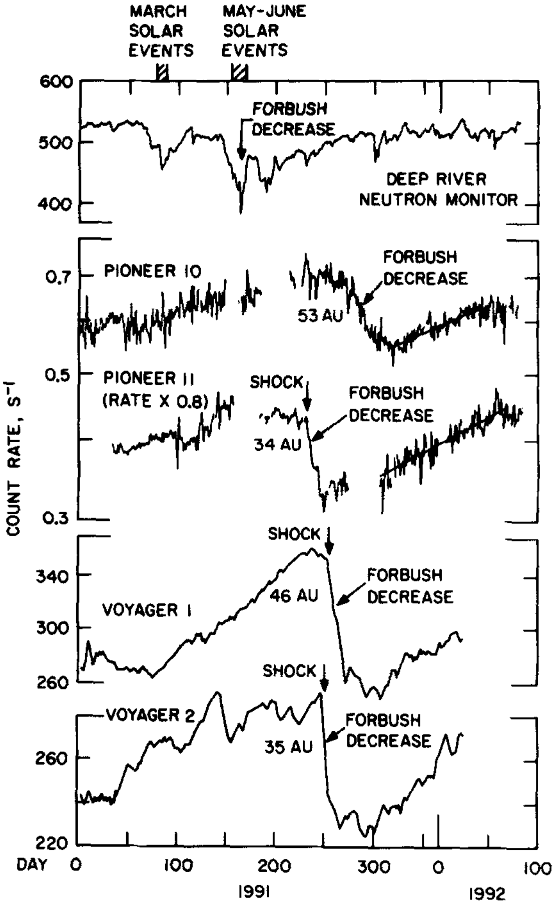

Fig. 6. The cosmic ray intensities from Pioneers 10 and 11, and Voyagers 1 and 2, showing the large Forbush decreases produced by the May-June 1991 solar events. Illustrations adapted from Van Allen and Fillius /25/ and Webber and Lockwood /16/.

PROPAGATION SPEED AND DISTANCE TO THE HELIOPAUSE

The temporal relationship illustrated in Figure 2 provides strong evidence that the solar wind disturbance associated with the large 1982 and 1991 Forbush decreases provided the "trigger" for the intense 1983-84 and 1992-93 heliospheric radio emission events. If the interaction takes place at the heliopause, as suggested by Gurnett et al. /2/, then the distance to the heliopause can be computed from the known time delay and speed of the shock. To compute the distance to the heliopause, a model must be used to extrapolate the shock speed beyond the point where direct in situ measurements are available. As a simple model we assume a constant initial propagation speed V_1, from the Sun to the terminal shock, and a second constant propagation speed V_2, from the terminal shock to the heliopause. The distance to the heliopause is then given by

$$R_H = V_1 T \frac{\alpha}{1-(1-\alpha)\delta} \quad , \qquad (1)$$

where T is the total travel time, $\alpha = V_2/V_1$ is the ratio of the two shock speeds, and $\delta = R_T/R_H$ is the ratio of the distance to the terminal shock R_T to the distance to the heliopause R_H. From numerical simulations such as performed by Baranov and Malama /30/, Washimi and Sakurai /31/, Steinolfson et al. /32/, and others, a reasonably well-constrained value for the parameter δ can be determined. A representative value is $\delta = 0.73$. By numerically following an interplanetary shock outward through the heliosphere, such as has recently been done by Steinolfson and Gurnett /33/, an average value for α can also be determined. A representative value is $\alpha = 0.6$.

Although some uncertainty exists in the parameters α and δ, the largest uncertainty in calculating the distance to the heliopause comes from the uncertainty in determining the initial shock propagation speed V_1. Two techniques can be used for estimating the speed of an interplanetary shock: (1) travel time measurements, and (2) in situ measurements. Travel time measurements involve timing the arrival of the shock at two or more points and computing the radial component of the velocity using $V = \Delta R/\Delta T$. Although simple in principle, this approach is often difficult to apply in practice. Usually, the observing points are not radially aligned, so variations in the shock speed with direction from the Sun introduce uncertainties. Also, if the radial separation is large and a series of shocks is involved, it may not be possible to uniquely identify the same shock at widely separated locations. In situ measurements involve the use of local measurements of the plasma velocity, density and magnetic field, together with the MHD jump conditions, to compute the shock speed. Although in situ measurements can give a very accurate determination of the shock speed, the measurements are local, and may not be representative of the average shock speed over long distances. Also, the in situ technique requires simultaneous measurements of both the plasma and magnetic field. Unfortunately, several of the required instruments on Pioneer and Voyager are no longer operating, so relatively few measurements of this type are available.

To illustrate the range of speeds involved, a listing of all the published propagation speeds obtained using measurements from Pioneers 10 and 11 (P10 and P11) and Voyagers 1 and 2 (V1 and V2) is given in Table 1 for the 1982 event and in Table 2 for the 1991 event. In addition, for each case we have computed the travel time, T, from the event on the Sun to the onset of the radio emission, and the corresponding distance to the heliopause, R_H, using Equation 1. These distances are intended to give the range of source distances compatible with the existing observations. For the 1983-84 radio emission event, which was not detected in the 1.78-kHz channel, the onset time at 3.11-kHz was used, minus 30 days. The 30-day offset corrects for the fact that the radio emission almost certainly would have been detected earlier had the radiation been able to reach the spacecraft at 1.78 kHz. In cases where the event time at the Sun is not known, the onset time at Earth was used and 1 AU was added to the distance computed using Equation 1. Similarly, for the in situ measurements the travel time is from the time at the observing point to the onset of the radio emission, and the distance from the Sun to the observing point has been added to the distance computed using Equation 1.

DISCUSSION

Tables 1 and 2 give heliopause radial distances that are compatible with the measured propagation speeds and travel times. As one would expect, the smallest radial distances tend to be associated with the lowest propagation speeds, and the largest radial distances tend to be associated with the highest propagation speeds. For example, for event A the smallest heliopause distance, $R_H = 117$ AU, was obtained for the day 195, 1982 solar event. Van Allen and Randall /15/ have estimated the propagation speed of the Forbush decrease associated with this event to be 620 km/s, based on the travel time from Earth to Pioneer 10. This is the slowest propagation speed reported for event A. The largest heliopause distance for event A, $R_H = 196$ AU, was obtained for the Forbush decrease associated with the day 157, 1982 solar event, which Webber et al. /24/ estimated to have a propagation speed of 950 km/s. This is one of the highest propagation speeds reported. For event B, the smallest heliopause distance, $R_H = 117$ AU, was obtained for the day 145, 1991 solar event. Webber and Lockwood /16/ have estimated the propagation speed of the Forbush decrease associated with this event to be 580 km/s, based on the travel time from Earth to Voyager 2. The largest radial distance for event B, $R_H = 166$ AU, was obtained for the day 162, 1992 solar event. Van Allen /18/ estimated the propagation speed of this event to be 865 km/s, based on a best-fit arrival time of the Forbush decrease at six spacecraft. From the above comparisons one would conclude that the observations are consistent with a heliopause radial distance in the range from 116 to 196 AU for event A, and from 116 to 166 AU for event B. It is evident that the range of allowed heliopause radial distances is very similar for the two events.

TABLE 1. Event A (May-July 1982)

Reference	Method	Event Time Day 1982	Observing Points	Speed km/s	T d	R_H AU
Van Allen and Randall, 1985	Travel time	161 (at E)	E, P11	740	416	152
Van Allen and Randall, 1985	Travel time	161 (at E)	E, P10	860	416	177
Van Allen and Randall, 1985	Travel time	195 (at E)	E, P11	810	382	153
Van Allen and Randall, 1985	Travel time	195 (at E)	E, P10	620	382	117
Webber et al., 1986	Travel time	157 (at Sun)	E, V2	950	420	196
Webber et al., 1986	Travel time	157 (at Sun)	E, V1	950	420	196
Webber et al., 1986	Travel time	157 (at Sun)	E, P10	850	420	175
Webber et al., 1986	Travel time	192 (at Sun)	E, V2	850	385	161
Webber et al., 1986	Travel time	192 (at Sun)	E, V1	900	385	170
Webber et al., 1986	Travel time	192 (at Sun)	E, P10	650	385	123
Cliver et al., 1982	Travel time	154 (at PVO)	PVO, P10	850	423	177
Cliver et al., 1982	In situ	210 (at P10)	P10	840	397	192
Cliver et al., 1982	Travel time	154 (at PVO)	E, P11	730	423	152
Cliver et al., 1982	Travel time	160 (at E)	E, P11	670	417	138
Cliver et al., 1982	Travel time	194 (at E)	E, V2	890	383	168
Cliver et al., 1982	Travel time	194 (at E)	E, P11	990	383	187

TABLE 2 Event B (March-June 1991)

Reference	Method	Event Time Day 1991	Observing Points	Speed km/s	T d	R_H AU
Van Allen and Fillius, 1992	Travel time	162 (at Sun)	E, P10, P11, V1	820	391	157
Webber and Lockwood, 1993	Travel time	145 (at Sun)	E, V2	580	408	116
Webber and Lockwood, 1993	Travel time	145 (at Sun)	E, P10	740	408	148
Van Allen, 1993	Travel time	162 (at Sun)	IMP-8, P10, P11, V1, V2, Ulysses	865	391	166
Belcher et al., 1993	In situ	251 (at V2)	V2	550	302	128
McDonald et al., 1994	Travel time	71 (at Sun)	PVO, P10	572	482	135
McDonald et al., 1994	Travel time	157 (at Sun)	V2	650	396	126
McDonald et al., 1994	Travel time	157 (at Sun)	V1	774	396	151

This is a consequence of the generally comparable travel times for the two events (roughly 400 days), and the similar propagation speeds, which are typically in the range from 550 to 900 km/s.

The calculations in Tables 1 and 2 also allow us to evaluate certain special cases. For example, McDonald et al. /19/ suggested that the 1992-93 radio emission event was triggered by the GMIR produced by the March 1991 solar activity. Assuming that the event was caused by the day 71 (March 12), 1991 solar event, as suggested by McDonald et al., the travel time is increased somewhat, to 482 days (see Table 2). However, the propagation speed for this event is relatively slow, 572 km/s, so the heliopause distance is still only 135 AU. Another comparison of interest is the in situ measurement of Belcher et al. /27/ which gave a speed of 550 km/s for the interplanetary shock observed by Voyager 2 on day 251, 1991. As discussed earlier, this shock is believed to be the most likely candidate for the event that triggered the 1992-93 radio emission event. The heliospheric distance calculated from this shock speed is 128 AU (see Table 2).

The above calculations all involve extrapolations into regions for which no measurements are available. Although numerical simulations by Steinolfson and Gurnett /33/ and others show nearly constant shock propagation speeds inside of the terminal shock for R ≥ 30 AU, various processes not included in the simulations, such as charge exchange, could lead to significant levels of deceleration. Probably the best event for evaluating such deceleration effects is the shock detected by Voyager 2 on day 251, 1991. For this event the in situ analysis of Belcher et al. /27/ gave a speed of 550 km/s. The Forbush decrease associated with this shock has been analyzed by Van Allen /18/, who identified the solar flare on day 162, 1991, as the most likely origin of this event. Assuming that the shock originated from the day 162 solar flare, the average propagation speed from the Sun to Voyager 2 is 685 km/s. The approximately 20% difference between the average propagation speed and the in situ speed indicates that a significant deceleration has occurred as the shock traveled from the Sun to the spacecraft. This comparison suggests that the heliopause distances listed in Tables 1 and 2 are probably too large, since in most cases they are based on average propagation speeds. Since the solar wind speed (~400 km/s) sets a lower limit to the shock propagation speed, the distances computed from the higher propagation speeds are probably overestimated by the largest factor. Therefore, the lower values of R_H given in Tables 1 and 2 are probably reasonably accurate, but the higher values should be reduced by on the order of 20%. From these considerations, it would appear that the radial distance to the heliopause is most likely in the range from about 110 to 160 AU.

Once the distance to the heliopause has been determined, the distance to the terminal shock can then be estimated. Using the nominal value (0.73) for $\delta = R_T/R_H$ the distance to the terminal shock works out to be about 80 to 115 AU. Note that in our interpretation the heliospheric radio emissions do not give a "direct" determination of the terminal shock location, since the radio emissions are not believed to be generated at the terminal shock. Therefore, uncertainties in δ have a direct influence on the distance to the terminal shock. For example, the nominal value for δ used above implicitly assumes that the plasma is allowed to "slip" at the heliopause /32/. Should a "no-slip" condition be imposed by large-scale turbulent mixing across the heliopause, it can be shown that δ decreases /34/, which would have the effect of reducing the distance to the terminal shock, possibly by a significant factor.

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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 emission of 3 kHz in the outer heliosphere, *Nature* 312, 27 (1984).

2. D.A. Gurnett, W.S. Kurth, S.C. Allendorf and R.L. Poynter, Radio emission from the heliopause triggered by an interplanetary shock, *Science* 262, 199 (1993).

3. W.S. Kurth, D.A. Gurnett, F.L. Scarf and R.L. Poynter, Long-period dynamic spectrograms of low-frequency interplanetary radio emissions, *Geophys. Res. Lett.* 14, 49 (1987).

4. W.S. Kurth and D A. Gurnett, New observations of the low frequency interplanetary radio emissions, *Geophys. Res. Lett.* 18, 1801 (1991).

5. W.S. Kurth, The low-frequency interplanetary radiation, *Adv. Space Res.* 13, (6)209 (1993).

6. D.A. Gurnett and W.S. Kurth, Evidence that Jupiter is not the source of the 2-3 kHz heliospheric radio emission, *Geophys. Res. Lett.* 21, 1571 (1994).

7. W.I. Axford, Introductory lecture--The heliopause, in *Physics of the Outer Heliosphere*, ed. by S. Grzedzielski and D. E. Page, Pergamon Press, Oxford, 1990, p. 7-15.

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

9. R.L. McNutt Jr., A solar-wind "trigger" for the outer heliospheric radio emissions and the distance to the terminal shock, *Geophys. Res. Lett.* 15, 1307 (1988).

10. S. Grzedzielski and A.J. Lazarus, 2- to 3-kHz continuum emissions as possible indications of global heliospheric "breathing," *J. Geophys. Res.* 98, 5551 (1993).

11. Y.C. Whang and L.F. Burlaga, Interaction of GMIR shock with the heliopause and its relation to the 2- and 3-kHz radio emission, *J. Geophys. Res.*, in press (1994).

12. S.E. Forbush, On the effects in cosmic-ray intensity observed during the recent magnetic storm, *Phys. Rev.* 51, 1108 (1937).

13. R. Lallement, J.-L. Bertaux and J.T. Clark, Decelaration of interstellar hydrogen at the heliosphere interface, *Science* 260, 1095 (1993).

14. J.W. Belcher, A.J. Lazarus, R.L. McNutt, Jr. and G.S. Gordon, Jr., Solar wind conditions in the outer heliosphere and the distance to the termination shock, *J. Geophys. Res.* 98, 15,177 (1993).

15. J.A. Van Allen and B.A. Randall, Interplanetary cosmic ray intensity: 1972-1984 and out to 32 AU, *J. Geophys. Res.* 90, 1399 (1985).

16. W.R. Webber and J.A. Lockwood, Giant transient decreases of cosmic rays in the outer heliospheric in September 1991, *J. Geophys. Res.* 98, 7821 (1993).

17. E.W. Cliver, J.D. Mihalov, N.R. Sheeley, Jr., R.A. Howard, M.J. Koomen and R. Schwenn, Solar activity and heliosphere-wide cosmic ray modulation in mid-1982, *J. Geophys. Res.* 92, 8487 (1987).

18. J.A. Van Allen, Recovery of interplanetary cosmic ray intensity following the great Forbush decrease of mid-1991, *Geophys. Res. Lett.* 20, 2797 (1993).

19. F.B. McDonald, A. Barnes, L.F. Burlaga, P. Gazis, J. Mihalov and R.S. Selesnick, Effects of the intense solar activity of March/June 1991 observed in the outer heliosphere, *J. Geophys. Res.* 99, 14,705 (1994).

20. E. Barouch and L.F. Burlaga, Causes of Forbush decreases and other cosmic ray variations, *J. Geophys. Res.* 80, 449 (1975).

21. L.F. Burlaga, F.B. McDonald, M.L. Goldstein and A.J. Lazarus, Cosmic ray modulation and turbulent interaction regions near 11 AU, *J. Geophys. Res.* 90, 12,027 (1985).

22. L.F. Burlaga, F.B. McDonald and N.F. Ness, Cosmic ray modulation and the distant heliospheric magnetic field: Voyager 1 and 2 observations from 1986 through 1989, *J. Geophys. Res.* 98, 1 (1993).

23. F.B. McDonald and L.F. Burlaga, Global merged interaction regions in the outer heliosphere, *Cosmic Winds and the Heliosphere*, ed. by J. R. Jokipii, C. P. Sonnett, and M. S. Giampapa, Univ. of Arizona Press, Tucson, submitted (1994).

24. W.R. Webber, J.A. Lockwood and J.R. Jokipii, Characteristics of large Forbush-type decreases in the cosmic radiation, 2. Observations at different heliocentric radial distances, *J. Geophys. Res.* 91, 4103 (1986).

25. J.A. Van Allen and R.W. Fillius, Propagation of a large Forbush decrease in cosmic-ray intensity past the Earth, Pioneer 11 at 34 AU, and Pioneer 10 at 53 AU, *Geophys. Res. Lett.* 19, 1423 (1992).

26. D. Winterhalter, E.J. Smith and L.W. Klein, The 1991 Pioneer 11 large amplitude solar wind event, abstract, *EOS Trans. AGU* 73(4), 237 (1992).

27. J.W. Belcher, A.J. Lazarus, G.S. Gordon, Jr., A. Szabo and R.L. McNutt, Jr., Voyager 2 observations of the solar wind plasma responsible for the 1992-93 heliospheric radio event, abstract, Conference on Cosmic Winds and the Heliosphere, Tucson (1993).

28. J.W. Belcher, personal communication (1994)

29. W.S. Kurth and D.A. Gurnett, Plasma waves as indicators of the termination shock, *J. Geophys. Res.* 98, 15,129 (1993).

30. V.B. Baranov and Y.G. Malama, The model of the solar wind interaction with the local interstellar medium. Numerical solution of self-consistent problem, *J. Geophys. Res.* 98, 15,157 (1993).

31. H. Washimi and T. Sakurai, A simulation study of the solar wind including the solar rotation effect, *Solar Physics* 143, 173 (1993).

32. R.S. Steinolfson, V.J. Pizzo and T. Holzer, Gasdynamic models of the solar wind/interstellar medium interaction, *Geophys. Res. Lett.* 21, 245 (1994).

33. R.S. Steinolfson and D.A. Gurnett, Distances to the termination shock and heliopause from a simulation analysis of the 1992-93 heliospheric radio emission event, *Geophys. Res. Lett.*, in press (1994).

34. S.T. Suess and S. Nerney, The termination shock and the heliopause, abstract, Conference on Cosmic Winds and the Heliosphere, Tucson (1993).