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The return of the heliospheric 2–3 kHz radio emission during solar cycle 23

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[1] In this paper we report the detection of a new heliospheric 2–3 kHz radio emission event by the Voyager 1 spacecraft, the first to be observed during solar cycle 23. The new event started on Nov. 1, 2002, and is believed to be associated with a strong interplanetary shock that originated from a period of intense solar activity in early April 2001. Following previous interpretations of events of this type, we assume that the radio emission is produced when the interplanetary shock interacted with the heliopause, which is the boundary between the solar wind and the interplanetary medium. From the onset time of the radio emission and a simple model for the propagation speed of the interplanetary shock, the heliocentric radial distance to the nose of the heliopause can be calculated, and is about 153 to 158 AU, depending on the parameters used. From computer simulations that give the ratio of the radial distance to the termination shock to the radial distance to the heliopause, the distance to the termination shock can also be calculated and is estimated to be about 101 to 108 AU. *INDEX TERMS:* 2124 Interplanetary Physics: Heliopause and solar wind termination; 2139 Interplanetary Physics: Interplanetary shocks; 2159 Interplanetary Physics: Plasma waves and turbulence. **Citation:** Gurnett, D. A., W. S. Kurth, and E. C. Stone, The return of the heliospheric 2–3 kHz radio emission during solar cycle 23, *Geophys. Res. Lett.*, *30*(23), 2209, doi:10.1029/2003GL018514, 2003.

1. Introduction

[2] For nearly twenty years 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, during solar cycle 21 [*Kurth et al.*, 1984], and the second in 1992–94, during solar cycle 22 [*Gurnett et al.*, 1993]. In addition several much weaker events have been reported, one in late 1985, one in 1989, and three in 1990–91 [*Kurth et al.*, 1987; *Kurth and Gurnett*, 1991]. A strong case can now be made that these radio emissions are generated when a strong interplanetary shock, produced by a period of intense solar activity, interacts with the heliopause [*Gurnett et al.*, 1993; *Gurnett et al.*, 1995], which is the boundary between the solar wind and the interstellar medium [*Axford*, 1990]. Here we report observations of a new heliospheric radio emission event, the first to be detected during solar cycle 23. The new event started on Nov. 1, 2002, and is believed to be associated with a strong interplanetary shock that originated from a period of intense solar activity in early April 2001. In section 2 we describe the observations of this event, in section 3 we identify the causative solar event, and in section 4 we use a simple shock propagation model to estimate the heliocentric radial distance to the heliopause and to the termination shock.

2. Observations

[3] The bottom panel of Figure 1 shows a frequency-time spectrogram of the radio emission intensities detected by Voyager 1 over a twenty-two year period, starting in 1982 and continuing to the most recent data received (August 15, 2003). The radio emission intensities were obtained from the Voyager 1 plasma wave instrument [*Scarf and Gurnett*, 1977], which uses a 14-meter tip-to-tip electric dipole antenna to detect the electric field of plasma waves and radio waves. The top panel of Figure 1 shows the corresponding cosmic ray counting rate at Earth as detected by the Climax neutron monitor. Also shown at the top of the panel is the solar cycle number, which labels the intervals between successive minimums in the sunspot number [*Van Allen*, 2000]. The intense heliospheric radio emission events detected in 1983–84 and 1992–1994 are clearly evident in the bottom panel. These two events each follow a sharp decrease in the cosmic ray counting rate, labeled A and B in the top panel, by about 400 days. Sharp decreases of this type in the cosmic ray counting rates are called Forbush decreases [*Forbush*, 1937], and are caused by strong interplanetary shocks and associated disturbance propagating outward from the Sun in response to energetic solar events. The close correspondence between the occurrence of the large Forbush decreases in 1982 and 1991 and the onsets of the intense 1983–84 and 1992–94 heliospheric radio emission events, each with a delay time of about 400 days, provides strong evidence that the radio emission is triggered by the interaction of the outward propagating shock with one of the boundaries in the outer heliosphere, either the termination shock or the heliopause. That the radio emission is generated at the heliosphere and not the termination shock comes from the radio emission frequency. The only known mechanism for generating the heliospheric radio emissions is via mode

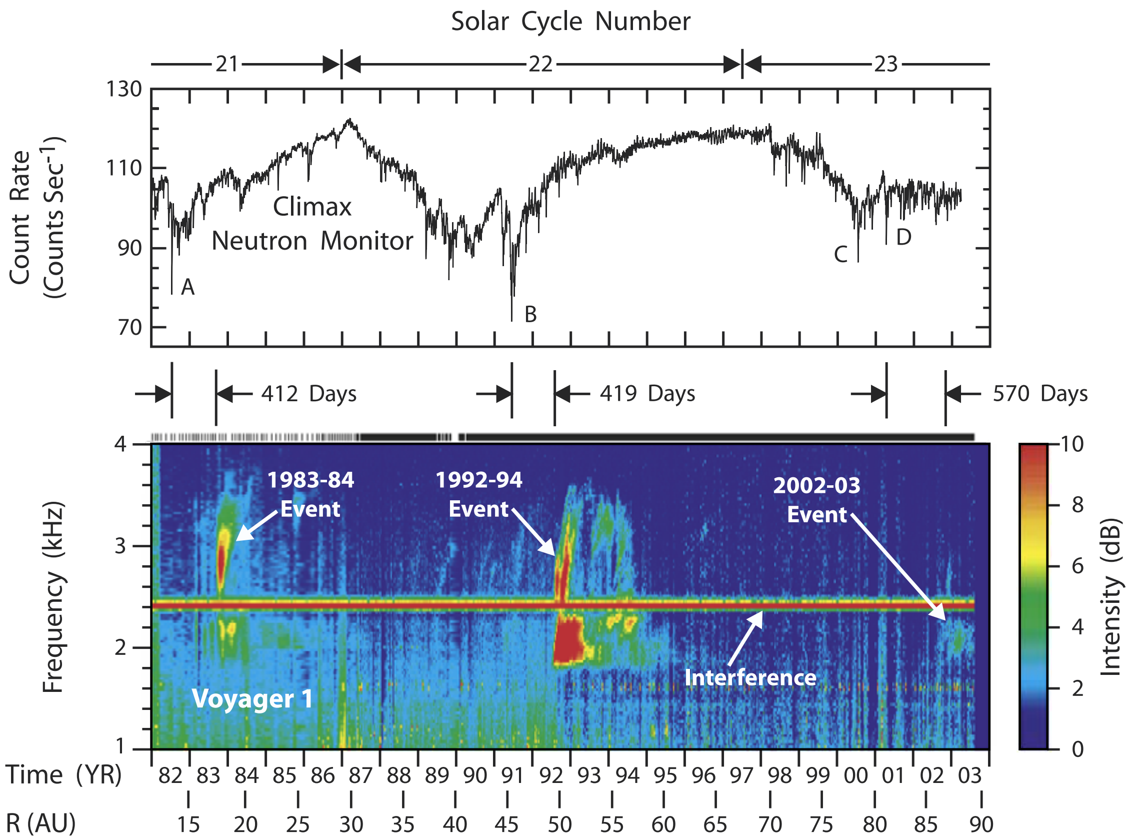

Figure 1. The bottom panel shows a frequency-time spectrogram of the electric field intensities detected by Voyager 1 over a period of twenty-two years, and the top panel shows the corresponding cosmic ray counting rate detected at Earth from the Climax neutron monitor. The electric field intensities, which are in dB above a fixed background, are color coded according to the scale given to the right of the spectrogram. The sharp decreases in the cosmic ray intensities labelled A, B, C, and D are Forbush decreases. These decreases signal the passage of an interplanetary shock and associated plasma disturbances outward though the heliosphere.

conversion from electrostatic oscillations at the electron plasma frequency, given by $f_p = 8990\sqrt{N_e}$ Hz, where N_e is the electron density in cm^{-3}, or its harmonic [*Cairns and Gurnett*, 1992]. At the termination shock the electron plasma frequency, which is about 200 Hz, is much too small to account for the observed radio emission frequencies. However, at the heliopause, where the electron density is about 0.06 to 0.1 cm^{-3} [*Lallement et al.*, 1993], the electron plasma frequency is in a suitable range (2.2 to 2.8 kHz) for generating the radio emission.

[4] Although solar cycles 21 and 22 each produced a very intense heliospheric radio emission event the present solar cycle, #23, has until recently been characterized by an absence of detectable heliospheric radio emissions. However, a new event has now been detected. This event can be seen in the bottom panel of Figure 1, and is labeled the 2002–03 event. Although the event is quite weak, the identification as a heliospheric radio emission is unambiguous. The spectrum of the new event has an upward-drifting feature extending up to about 3 kHz at the onset of the event, followed by a well-defined emission band around 2 kHz, features that are similar to the 1983–84 and 1992–94 events. Figure 2 shows a comparison of the spectrums of the 1983–84, 1992–94 and 2002–03 events near the times of peak intensity. As can be seen the intensity of the 2002–03 event is much weaker than the 1983–84 and 1992–94 events. The absence of detectable heliospheric radio emissions during the early phase of

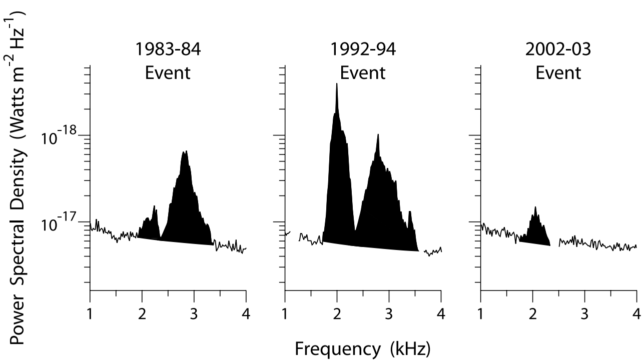

Figure 2. A comparison of the spectrums of the 1983–84, 1992–94, and 2002–03 heliospheric radio emission events near the times of maximum intensity. The 2002–03 event is relatively weak, likely due to the low strength of the shock that caused this radio emission.

solar cycle 23 and the low intensity of the 2002–03 event are consistent with the generally lower level of solar activity during solar cycle 23. Note from the top panel of Figure 1 that both the rate and amplitude of the Forbush decreases during solar cycle 23 are generally lower than during solar cycles 21 and 22.

3. The Causative Solar Event

[5] From inspection of the cosmic ray counting rate at Earth it appears there are only two likely solar events that might have triggered the 2002–03 radio emission event. These are labeled C and D in the top panel of Figure 1. Event C was associated with a powerful solar flare that occurred on July 14, 2000, the so-called Bastille Day event [*Wang et al.*, 2001]. This event resulted in an approximately 10% Forbush decrease at Earth on July 16, 2000. The solar flare activity that led to event D was on the back side of the Sun and was not directly observed at Earth [*Wang and Richardson*, 2002]. Nevertheless, the activity resulted in a large, approximately 18%, Forbush decrease at Earth on April 12, 2001. This activity lasted over a period of a week or more, since the initial decrease in the cosmic ray counting rate appears to have started as early as March 27.

[6] Of the two events described above, we believe that event D is the most likely candidate for triggering the 2002–03 heliospheric radio emission event. Although event C (the Bastille Day event) produced an interplanetary shock that was observed by the Voyager 2 spacecraft [*Wang and Richardson*, 2002] on January 12, 2001, no heliospheric radio emission was observed at the time (October to December 2001) that this shock was predicted to arrive at the heliopause [*Zank et al.*, 2001; *Wang et al.*, 2001]. The reason that the shock did not produce a radio emission is not completely understood, but may be due to the fact that the shock originated from a single solar event rather than from an extended period of solar activity. It is believed that the merging of a series of shocks from an extended period of solar flare activity is more effective in producing a strong global heliospheric shock in the outer heliosphere than a single, exceptionally strong solar event. *McDonald and Burlaga* [1994] have emphasized that the merging of the disturbances from several solar events into an outward propagating shell of disturbed plasma and magnetic field called a Global Merged Interaction Region (GMIR) is an essential factor in controlling cosmic ray modulation in the outer heliosphere. The series of solar events in early April 2001 that led to event D appears to be a good example of just such an effect. Although this solar flare activity did not lead to a detectable shock at Earth, it did lead to a strong shock that was observed in the outer heliosphere by the Voyager 2 spacecraft at 65.3 AU on October 16, 2001 [*Wang and Richardson*, 2002]. This shock had a velocity jump of 105 km/s that was considerably larger than the shock associated with the Bastille Day event, which had a velocity jump of only 55 km/s. Thus, on energetic grounds alone, event D is a much better candidate than event C. Assuming that event D is the causative event, the travel time from the solar event at the Sun, which we assume to be on April 10, 2001 (i.e., 2 days before the deep minimum in the Forbush decrease) to the onset of the heliospheric radio emission event on November 1, 2002, is 570 days.

4. Distance to the Heliopause and the Termination Shock

[7] As was done for the 1983–84 and 1992–94 events it is possible to use the 2002–03 event to estimate the heliocentric radial distance to the heliopause and the termination shock. The basic principle involved is quite simple, since the radial distance to the interaction region is simply the product of the propagation speed of the shock and the travel time. The main difficulty is that the shock slows down somewhat as it crosses the termination shock. To account for this slowdown effect the propagation path is divided into two parts, the first with a constant shock speed V_1 from Voyager 2 to the termination shock, and the second with a constant shock speed V_2 from the termination shock to the heliopause. Assuming that the shock front is approximately spherical, so that the first contact occurs near the nose of the heliopause, it is easy to show that the distance from the Sun to nose of the heliopause is given by

$$R_H = (R_{V2} + V_1 T_{V2})\left[\frac{\alpha}{1-(1-\alpha)\delta}\right],$$

where R_{V2} = 65.3 Astronomical Units (AU) is the heliocentric radial distance of Voyager 2 at the time of arrival of the shock, V_1 is the shock speed, T_{V2} = 381 days is the time from the arrival of the shock at Voyager 2 to the onset of the radio emission, $\alpha = V_1/V_2$ is the ratio of the two shock propagation speeds, and $\delta = R_T/R_H$ is the ratio of the radial distance to the termination shock to the radial distance to the nose of the heliopause. For the shock speed we use the shock propagation model of *Wang and Richardson* [2002], which interpolating from panels (f) and (g) of their Figure 3 gives V_1 = 498 km/s. This shock speed is in good agreement with the speed of about 495 km/s estimated from the 63-day time delay between the Forbush decreases observed by Voyager 1 at a heliolatitude of 34° and Voyager 2 at a heliolatitude of −24° [see, e.g., Figure 3 in *McDonald et al.*, 2003], which supports the assumption that the shock front is spherical, at least to a first approximation. Note that the shock propagation speed is slower than the speeds estimated for the shocks responsible for the 1983–84 and 1992–94 events, which were typically 600 to 800 km/s [*Gurnett and Kurth*, 1995]. The slower propagation speed accounts for the longer, 570-day travel time, compared to the travel times for the 1983–84 and 1991–94 events, which were only 412 and 419 days (see Figure 1). The parameters α and δ in equation (1) have been previously estimated by *Gurnett et al.* [1993] from computer simulations [*Steinolfson and Gurnett*, 1995], and have nominal values of α = 0.7 and δ = 0.75. Using the above parameters the radial distance to the heliopause given by Equation 1 is R_H = 158 AU. This distance is very comparable to the distances computed using a similar technique for the 1983–84 and 1992–94 events [*Gurnett and Kurth*, 1995], which have an average value of 156 AU.

[8] Of the various parameters in Equation 1, the parameter δ is the least well known, and directly affects the distance to both the heliopause and the termination shock.

Although the nominal value $\delta = 0.75$ is generally consistent with early computer simulations, more recent simulations by *Pauls et al.* [1995], *Zank and Moller* [2003], and Florinski (personal communication, 2003) that include other effects, such as pickup ions and the interstellar magnetic field, yield somewhat smaller δ values. For example, from Table 2 of Pauls et al., the ratio of the radial distance to the termination shock to the radial distance to the heliopause at the nose of the heliosphere is $\delta = 0.66$. This new value for δ changes the distance to the heliopause to $R_H = 153$ AU. Another source of uncertainty arises from the lack of knowledge of the angular distribution of the shock strength. Equation 1 assumes that the first contact of the shock front with the heliopause occurs near the nose of the heliosphere. For the 1992–94 event we were able to show from direction-finding measurements that the onset of the radio emission occurred near the nose of the heliopause [*Gurnett et al.*, 1993; *Kurth and Gurnett*, 2003]. However, because of a recent failure in the Voyager 2 plasma wave receiver it is no longer possible to do a comparable direction-finding analysis for the 2002–03 event. Thus, if the first detectable radio emission occurred at a substantial angle from the nose, then because of the parabolic shape of the heliopause the distances computed from Equation 1 would tend to overestimate the distance to the nose of the heliopause. In fact, there is some evidence that the shock front and its associated GMIR did have a substantial angular dependence. Although a marked Forbush decrease was observed at Voyager 2, which is at a helio–latitude and longitude of $-24°$ and $287°$, only a very modest Forbush decrease was observed at Voyager 1 (see, e.g., Figure 3 in *McDonald et al.* [2003]), which was at a helio-latitude and longitude of $34°$ and $252°$. Unfortunately, because of the very limited amount of information on the angular structure of the shock it is difficult to quantitatively evaluate the possible error due to this effect, other than to note that it would decrease our estimate of the distance to the heliopause. As a rough estimate of the sensitivity to the angle from the nose one can see from the computer simulations of *Pauls et al.* [1995] that the reduction in the radial distance to the heliopause is about 7% for an angle of 30 degrees away from the nose.

[9] It is also possible to compute the radial distance to the termination shock from the above analysis, although this determination is less direct than the determination of the distance to the heliopause, since it relies on computer simulations to give a good estimate of δ, the ratio of the radial distance to the termination shock to the radial distance to the nose of the heliosphere. If we use $\delta = 0.75$ and $R_H = 158$ AU, the termination shock would be located at $R_T = \delta R_H = 118$ AU, and if we use $\delta = 0.66$ and $R_H = 153$ AU the termination shock would be located at 101 AU. Voyager 1 will reach 101 AU in 2006 and 118 AU in 2011. As of the present date, October 20, 2003, there has been no indication in the plasma wave data of upstream waves or electrostatic noise such as might be expected to occur near or at the termination shock [see *Kurth and Gurnett*, 1993].

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