A Coincidence in Time Between Two Large Interplanetary Shocks Reaching Voyagers 1 and 2 Near the Heliospheric Termination Shock and the Onset of Two Recent kHz Heliospheric Radio Events at About 2004.64 and 2006.39

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Abstract. Two of the most recent outer heliospheric kHz emissions detected by the University of Iowa plasma wave detector on Voyager 1 started at about 2004.64 and 2006.39, respectively. Large interplanetary shocks reached V1 and V2, which are near the heliospheric termination shock, at almost the same time that the two kHz radio emissions turned-on. So, in fact, the arrivals of these large shocks near the heliospheric termination shock were coincident with the onset of these kHz emissions. These two large shocks were unusual in that they were the two strongest shocks in solar cycle 23 seen in the outer heliosphere at V2. They had developed maximum dynamic pressures ~4-6 times the average solar wind dynamic pressure for periods >26 days by the time they reached V2.

Keywords: Heliospheric kHz Radio Emissions, Solar Wind Termination Shock, Voyager
PACS: 96.50 EK, 96.50 Fm, 96.50 Sh, 96.50 Vg

INTRODUCTION

The kHz radio emissions detected by the University of Iowa plasma wave detectors on the Voyager spacecraft have provided a remarkable insight into conditions in the outermost heliosphere. The present paradigm is that these emissions originate when a large shock reaches the outermost boundary of the heliosphere, the heliopause (HP). This interaction then triggers plasma waves in the local interstellar medium (LISM) at frequencies just above the local plasma frequency [1]. To date perhaps 10-12 of these radio events have been observed over three solar 11-year cycles, cycles 21, 22 and 23. The first kHz emission starting at 1983.84 in solar cycle 21 and another starting at 1992.75 in solar cycle 22 are by far the largest and best documented. The particular shocks and interplanetary disturbances that are believed to be the source of these kHz emissions have their origin near the Sun. For the two kHz emissions noted above, using an identification near the Sun based on large cosmic ray decreases at the Earth, the travel times to the onset of the kHz emission have been determined to be ~415±5 days. These times along with estimates of the speed profile of the shocks with distance from the Sun have allowed estimates of the HP distance in the range 120-160 AU and have served to define the scale size of the heliosphere [2].

In the most recent solar cycle 23 starting at about 1997.5, there have been no really large kHz radio emissions like those in cycles 21 and 22, but there have been 3 smaller ones seen in the V1 plasma wave data. The first of these starting at about 2002.84 has

CP1302, *Pickup Ions throughout the Heliosphere and Beyond: Proceedings of the 9th Annual International Astrophysics Conference,*
edited by J. A. le Roux, V. Florinski, G. P. Zank, and A. J. Coates

been discussed by [3]. The most recent two kHz events, starting at about 2004.64 and 2006.39, have been noted by [4], but have not been discussed in detail.

Voyagers 1 and 2 (V1 and V2) are at much larger distances from the Sun during the current solar cycle. At 2004.95 V1 crossed the termination shock at a distance of ~94 AU [5]. At 2007.66 V2 crossed the termination shock at ~84 AU [6].

In this paper we consider the two most recent kHz emissions. As we describe below the onset times of these events are coincident with the arrival times at V1 and V2 of two of the largest interplanetary shocks seen in solar cycle 23. These spacecraft are just outside and just inside the heliospheric termination shock (HTS) at these two times.

The plasma observations (solar wind speed and solar wind pressure) and cosmic ray observations >70 MeV related to these kHz events are shown in Figure 1 for the time period from 2003 to when V2 crossed the termination shock in 2007 at 83.7 AU, with the important times noted by the vertical lines A, 1 and 2.

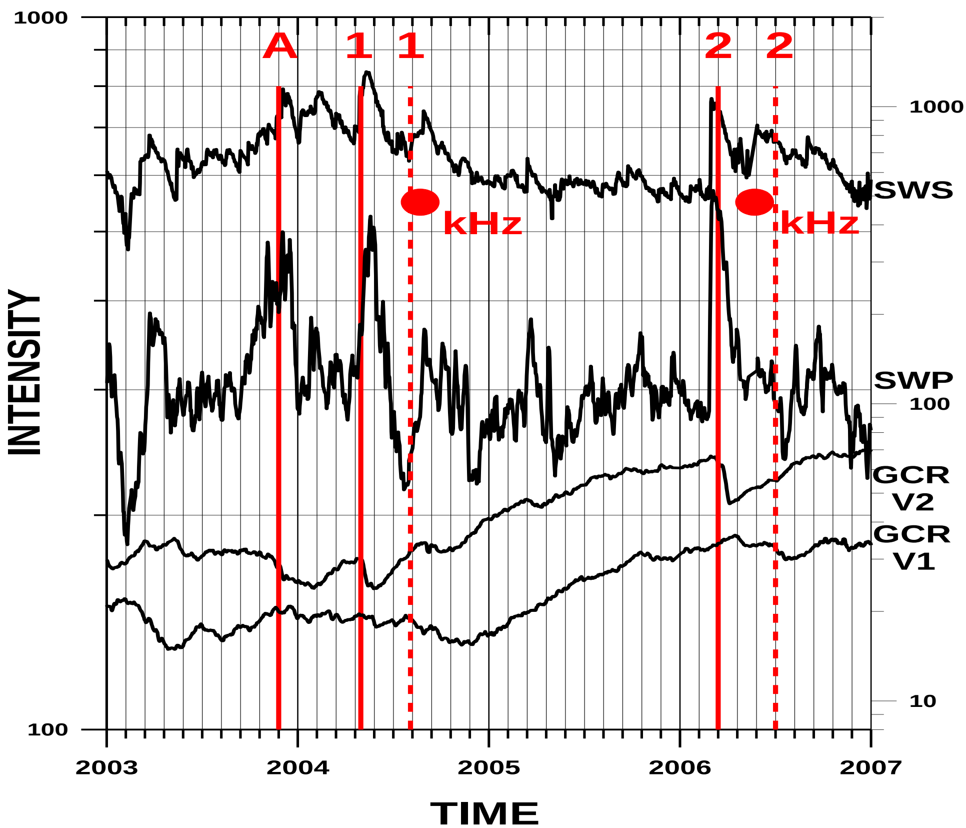

FIGURE 1. 5 day running averages. Top: Solar wind speed at V2 (x 6.5 for LHS in km s^{-1}); Middle: Solar wind dynamic pressure at V2 (x 2.5 x 10^{-6} for RHS, in n Pa); Bottom: >70 MeV galactic cosmic rays (GCR's) at V1 and V2 (x 5 x 10^{-3} for V2, x 7.5 x 10^{-3} for V1 for LHS in cts s^{-1}). Vertical red lines show times of shock arrivals at V2 (solid) and V1 (dashed).

THE HELIOSPHERIC kHz EMISSIONS WITH AN ONSET AT 2004.64 AND RELATED PLASMA AND COSMIC RAY OBSERVATIONS AT V1 AND V2

At V2, then at 73.4 AU, a solar wind speed jump of ~100 $km \cdot s^{-1}$ to ~560 $km \cdot s^{-1}$ was observed in the MIT plasma detector at 2004.33 (event #1 in Figure 1). This large speed jump was considered to be due to the passage at V2 of the so called Halloween 2003 event at the Earth [7, 8]. At this time the dynamic solar wind pressure increased by a factor ~4-5, also shown in Figure 1. An increase of a factor ~4 was seen in 2-3 MeV protons, peaking at 2004.31, and a decrease of >70 MeV cosmic rays ≥ 10% was observed by CRS detectors on V2 as shown in Figure 1. These cosmic ray intensity changes have also been attributed to the arrival of the Halloween event at V2 [8, 9]. This event was one of the largest in solar cycle 23 by all measures [8] both at the Earth and at V2.

At V1, then at 92.3 AU and just inside the HTS at ~94 AU, there is a decrease in the >70 MeV rate ~6% at 2004.59, followed by a further decrease ~5% starting at 2004.71 observed by the CRS detectors. Collectively these decreases mark the arrival of this same shock at V1 [9, 10]. This time (2004.59) is shown as the dashed vertical line #1 in Figure 1.

At the time of the arrival of this shock at V1 (between 2004.59-2004.71), this spacecraft was just 1-2 AU inside the HTS. This time period brackets the time of onset of the kHz radio emission at 2004.64, shown as a large red dot in Figure 1. So, in effect, the onset of the kHz radio emission for this event coincides very closely with the arrival of the "Halloween" shock at V1, just inside the HTS (see Appendix for a possible alternate scenario for this kHz event due to an earlier shock, labeled A in Figure 1).

THE HELIOSPHERIC kHz RADIO EMISSION WITH AN ONSET AT 2006.39 AND RELATED PLASMA AND COSMIC RAY OBSERVATIONS AT V1 AND V2

At V2, then at 79.0 AU, the largest solar wind speed jump yet observed in the outer heliosphere in solar cycle #23 (~140 $km \cdot s^{-1}$ up to a maximum solar wind speed of ~520 $km \cdot s^{-1}$) was observed at 2006.17 [11] (event #2 in Figure 1). At this time the dynamic solar wind pressure increased by a factor ~6, also shown in Figure 1. The >70 MeV cosmic ray rate also decreased by ~14% at 2006.21 [9].

At V1 at 99.7 AU, and now beyond the HTS, a decrease ~5-6% was seen in the >70 MeV rate by the CRS experiment at 2006.51 [9] and is believed to mark the arrival of this event at V1. This time is noted as the dashed vertical line #2 in Figure 1.

The onset of the kHz radio emission at 2006.39, shown in Figure 1 by the large red dot, thus occurs between the time of arrival of this large IP shock at V2 at 79 AU inside the HTS and its arrival at V1 at 99.7 AU outside the HTS, which is estimated to be at ~92 AU at the latitude of V1 at that time [12].

DISCUSSION

The coincidences in the arrival of the two large IP shocks discussed above at the vicinity of HTS and the onset of the two heliospheric radio emissions is striking. We would also like to note the possible significance of the large pressure waves that accompany these two shocks. These pressure waves appear to develop during the propagation of these IP shocks through the heliosphere inside the HTS. Figure 1 shows the daily average solar wind ram pressures measured at V2 between 2003 and the time it crossed the HTS at 83.7 AU at 2007.66. The two largest pressure waves seen at V2 in solar cycle 23 are coincident with the two shocks described above as they pass V2 at 73 and 79 AU, respectively. These pressure waves, with peak pressures ~4-6 times the average solar wind pressure and extending for more than one 26 day solar rotation period, are known to directly and immediately influence the HTS, its location and the structure of the heliosheath beyond the HTS [12, 13], see also [14], for a description of the effects of a pressure wave with ~1.5 times the average solar wind pressure impacting the HTS. Such large pressure waves with peak pressures greater than several times the average solar wind pressure for extended periods of time are not apparent in the records of Earth based plasma measurements (e.g., from SWEPAM) during this time period.

These large over pressures seen at V2 may be examples of the development of a shock or series of shocks in the heliosphere as described by [15, 16, 7, 17]. These over pressures may form from multiple interplanetary coronal mass ejections and the merger of the leading forward shocks from each ejection as they propagate outward, analogous to the merged interaction regions that develop in the magnetic field as described by [18].

It is possible that as the largest of these pressure waves interact with the HTS and the resulting compression waves pass through the heliosheath [14] the plasma density in these compressed regions may be high enough to produce the kHz emissions.

SUMMARY AND CONCLUSIONS

In this study we utilize plasma and cosmic ray observations related to large IP shocks as they pass V2 and V1 in the outer heliosphere between ~72 and 99 AU, just inside and just outside the HTS which is between about ~83-94 AU at these times as determined by the V1 and V2 HTS crossings. We find that two of these IP shocks arrive coincidently near the HTS near the times of two of the most recent outer heliospheric kHz radio emissions that were found to begin on 2004.64 and 2006.39 as observed by the Iowa plasma wave detector [4].

We, therefore, suggest that for these two most recent kHz emissions, strong arguments, from both the timing and shock strength point of view can be made for the onset of the radio emission to be coincident with the arrival of the instigating interplanetary disturbances near the HTS. Earlier theories for the origin of kHz radiation in the Heliosheath just beyond the HTS [19] need to be re-examined utilizing the much better current understanding of conditions there, following the latest V2 observations at the HTS and beyond [14, 20].

We note that [21], originally suggested that the onset of the heliospheric radio emissions might be due to the arrival of solar wind disturbances at a hypothesized heliospheric termination shock. Subsequent attempts to explain the radio emissions in terms of the electron density either in the foreshock region or in the region just beyond the HTS have had difficulties in explaining the radio emission at frequencies ≥ 2 kHz (e.g., [22]) leading eventually to the current paradigm developed earlier by [1] involving the heliopause and the presumed higher (electron) densities present there.

We should also note that there appear to be at least two types of radio emissions in the 2-4 kHz range [1]. One type drifts significantly to higher frequency as a function of time, the other remains at a nearly constant frequency of 2.0-2.4 kHz. The two events discussed here appear to be of the 1st type. The two earlier giant kHz events in 1983 and 1992, upon which the earlier theories were based, contain a strong 2.2 kHz component as well as a weaker higher frequency drifting component. It could be, for example, that the different frequency intervals involved in the kHz emission could represent interactions of the outward moving solar disturbance just beyond the HTS in one case and beyond the HP in the other and that these effects combine to give the different types of kHz emissions.

APPENDIX

Here we consider an alternative more conventional scenario for the onset of the Heliospheric kHz event occurring at 2004.64. In this case the origin is related to the large IP shock, labeled A is Figure 1, that reached V2 at a distance of 72.2 AU at approximately 2003.92, roughly 0.40 year earlier than the Halloween event. This event A had its origin near the Sun earlier in 2003. The solar wind speed jump for this event at V2 was ~70 $km{\cdot}s^{-1}$ to a speed ~520 $km{\cdot}s^{-1}$ and the dynamic solar wind pressure increased to ~4 times the normal pressure at that time [7]. A decrease ~8% was also seen in >70 MeV cosmic rays at V2. These values are almost as large as those associated with the 2003 Halloween event at V2, although at the Earth this earlier event is considerably weaker and produced less well defined effects than the Halloween event.

No clear signal for the arrival of this event at V1 is observed. According to calculations by [20], this event, which reached V2 at 2003.92, would be expected to reach ~120 AU in the vicinity of the HP (in the direction of V2) at about 2004.60, just about the time the kHz emission turns on.

So for the kHz emission event at 2004.64 there appear to be two almost equally probable instigating events, the one described above, reaching the HP at about the time of the onset and originating near the Sun about 440 days earlier, and the other (the 2003 Halloween event labeled 1 in Figure 1) reaching the HTS also at about 2004.64. We believe the coincidence of the arrival of the Halloween 2003 event at V1 and the onset of the kHz radiation appears more compelling and thus, favor this association.

This uncertainty regarding the possible originating events reflects our lack of understanding of just what features of these large IP shocks are indeed responsible for instigating a kHz radio event in the first place (e.g., why aren't all large shocks followed by kHz event, which appear to be much rarer). It also could suggest the possibility that the encounters of this shock with both the HTS and HP are responsible for certain features of each of the kHz events. A re-examination of the details of earlier kHz events, making use of V1 and V2 plasma, magnetic field and cosmic ray data as the various proposed instigating events pass these spacecraft, may be helpful in examining these effects.

It should be noted that for the 2006.39 kHz event there is no reasonable alternate shock to the one that reaches V2 (79 AU) at 2006.19 and V1 (99.7 AU) at 2006.51 that we have discussed in this paper.

ACKNOWLEDGMENTS

The authors express their appreciation to the MIT plasma experimenters (J. Richardson, P.I.) and the Iowa plasma wave experimenters (D. Gurnett, P.I.) on Voyager for making their data available on their web-sites and for valuable discussions. The work at the Carmel Research Center was supported by NASA grant NNX08AE40G and by the Carmel Research Center.

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