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THE OUTER HELIOSPHERE: THE NEXT FRONTIERS

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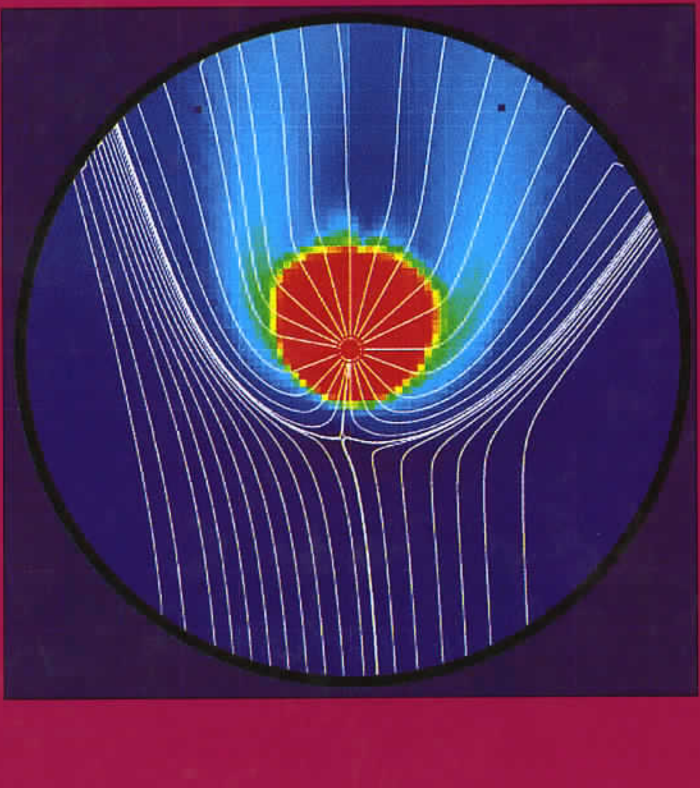

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Dual spacecraft measurements as a tool for determining the source of low-frequency heliospheric radio emissions

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Individual spectral elements of the low frequency heliospheric radio emissions are often observed to have different intensities as determined by the two widely-spaced Voyager spacecraft. In principle, these intensity differences allow the determination of a locus of possible source locations, assuming the source emits uniformly in all directions. We take into account the dipole antenna patterns of the plasma wave antenna system on each spacecraft. The results of this relative intensity analysis are then coupled with the results of direction-finding measurements using the rotating dipole technique with Voyager 1. Near the beginning of the major radio emission event observed from mid-1992 through 1994, the results of this analysis are consistent with a source near the nose of the heliosphere.

1. INTRODUCTION

Kurth et al. (1) reported the discovery of low-frequency radio waves observed by the two Voyager spacecraft in the outer heliosphere. Gurnett et al. (2) reported a second major radio emission event and suggested that the emissions were generated as a result of a global merged interaction region and associated shock interacting with the interstellar medium just beyond the heliopause. See Kurth and Gurnett (3) for a review of the low-frequency heliospheric radio emissions. Gurnett et al. (4) used the rotation of the Voyager plasma wave antennas performed a few times per year for calibration purposes to determine the plane containing the source of the radio emission at several times during the most recent radio event (1992 - 1994) and concluded that the source direction was consistent with the direction to the nose of the heliosphere early in the event, but moved away from the nose at later times.

In this paper we take advantage of the fact that the two Voyager plasma wave receivers observe components of the low-frequency emissions at slightly different intensities, differing by up to a few dB. This difference in received power is most likely due to differences in the distances between the source and the two spacecraft, which are separated by more than 40 AU during this time interval. Another source of differing received powers, however, is the likelihood that the antennas on the two spacecraft present substantially different aspects with respect to the source direction. Since the dipole antenna response

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is not omnidirectional, differences due to the different antenna orientations must be taken into account.

The instruments used for the measurements presented herein are identical plasma wave receivers on the two Voyager spacecraft described in detail by Scarf and Gurnett (5). Because of a failure in the Voyager 2 flight data system, signals from the upper eight frequency channels of the Voyager 2 spectrum analyzer covering the frequency range from 1 to 56 kHz are degraded. As a result, we must rely on wideband measurements from the two spacecraft. The wideband receivers utilize an automatic gain control circuit; hence, there is no absolute calibration. We will discuss methods for obtaining cross-calibrated measurements below.

2. SOURCE DETERMINATION USING RELATIVE POWER DETECTED BY TWO OBSERVERS

In principle, we can use the relative power detected by two widely separated observers such as the two Voyager spacecraft to determine a locus of possible source locations of a radio emission source. If we assume omnidirectional sensors, then the basic equation is

$$(\frac{\mathbf{r}_2}{\mathbf{r}_1})^2 = \frac{P_1}{P_2} \qquad (1)$$

where $\mathbf{r}_1$ and $\mathbf{r}_2$ are the vectors to the source from Voyager 1 and 2, respectively, and P_1 and P_2 are the observed power fluxes at the two spacecraft. The geometry is illustrated in Figure 1 and detailed information is given in Table 1 in heliocentric distance, ecliptic latitude β, and longitude λ. For any given ratio of received power, one can determine a surface upon which the source must lie. In three dimensions, each of these surfaces is a sphere surrounding the spacecraft receiving the most power except for the limiting case of no difference (0 dB) which gives a plane orthogonal to and bisecting the line segment between the two spacecraft.

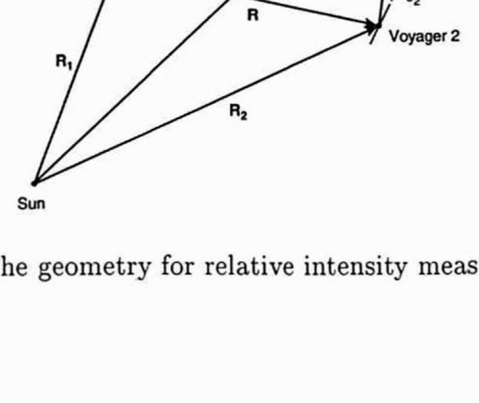

Figure 1. The geometry for relative intensity measurements.

Table 1
Geometry for August 7, Day 220, 1992

Vector	R (AU)	β(deg)	λ(deg)
$\mathbf{R}_1$ Voyager 1 Position	49.4	33.5	245.0
$\mathbf{R}_2$ Voyager 2 Position	37.9	−10.5	283.0
$\mathbf{X}_1$ V1 Antenna Orientation		−31.3	309.7
$\mathbf{X}_2$ V2 Antenna Orietation		−34.8	19.7
Nose Direction*		5	254
Solution 1	136	8	249
Solution 2	138	75	219

*Ajello et al. (6)

In reality, the two Voyager plasma wave instruments use electric dipole antennas which are not omnidirectional, but which have a response of the form $a(\theta) = \sin^2\theta$ where θ is the angle between the antenna axis and the direction to the source $\mathbf{r}$. When the source is collinear with the antenna axis, the response is zero for a point source; when the source is in a direction perpendicular to the antenna axis, the response is 1. Hence, Equation 1 must be modified in the following way to account for the dipole antenna patterns of the two spacecraft:

$$\frac{a_1(\theta_1)}{a_2(\theta_2)}\left(\frac{\mathbf{r}_2}{\mathbf{r}_1}\right)^2 = \frac{P_1}{P_2} \tag{2}$$

The shape of a surface defined by a constant ratio of received power becomes considerably distorted and is no longer a sphere. It should be noted that even though the Voyager antenna system consists of two physical elements extended at right angles to each other, their response is the same as a linear dipole much shorter than the wavelength of the received wave. The effective antenna axis is parallel to a line connecting the midpoints of the two elements. For the Voyager antennas, this direction is parallel to the spacecraft x axis, i.e., perpendicular to both the high gain antenna axis and the magnetometer boom.

3. COMPARISON OF VOYAGER 1 AND VOYAGER 2 AMPLITUDES

The wideband receivers employed in this analysis utilize automatic gain control circuitry and gain information is not returned with the wideband data, hence, there is no absolute calibration for these data. We utilize the fact that the 2-kHz component of the emission shows no roll modulation (4) to suggest that this low-frequency source is nearly isotropic and, hence, both spacecraft should observe approximately the same amplitude. Using the 2-kHz component for calibration, then, we can compare the intensities of the more transient higher frequency components. We recognize that this assumption is suspect, however, and generally evaluate surfaces using a range of power ratios to understand the sensitivity to a specific value.

Figure 2 shows wideband spectrograms for both Voyager 1 and 2. In these displays the power relative to background is plotted as a function of frequency and time using a false color scheme defined by the color bar on the right. Note that particularly above the

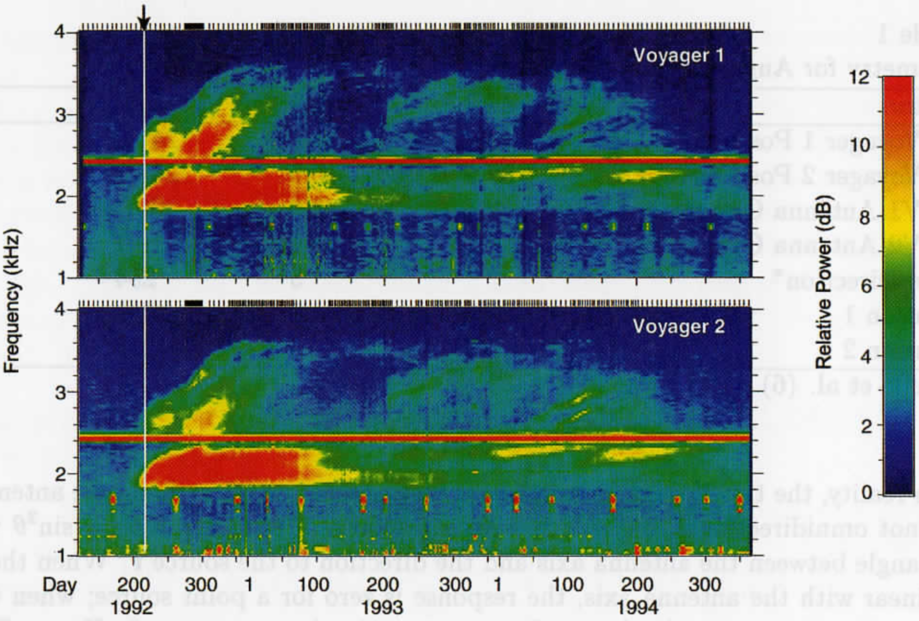

Figure 2. Frequency-time spectrograms for Voyager 1 and 2 showing the subtle differences in the intensities of the low frequency heliospheric emissions, especially above 2.4 kHz. The arrows indicate the time for the source location determination presented herein.

narrow line at 2.4 kHz (a power supply interference tone) there are subtle but definite differences in the received power for some of the components of the radio emission. Figure 3 shows a detailed spectral comparison for wideband data obtained on day 224 of 1992. The amplitude scale is proportional to power flux but the absolute value is arbitrary. Note that the 2-kHz emission is observed to be nearly identical in amplitude at the two spacecraft. However, Voyager 1 observes a signal centered near 2.7 kHz which is approximately 3 dB larger than that observed by Voyager 2.

In principle, the use of Equation 2 and the observed power ratio defines a surface upon which the source must lie. Rather than perform a search in three dimensional space for this surface, we have chosen to make use of the results of the rotating dipole direction-finding measurements (4) to limit our search to the plane of the source as determined by that method. By performing a coordinate transformation from the solar ecliptic frame into one based on the plane defined by the roll axis of Voyager 1 and the direction to the source (from the rotating dipole technique), we can then compute the intersection of the appropriate relative power contour in the plane of the source. This is shown in Figure 4 for the rotating dipole determination of day 220 of 1992, just a few days before the spectral comparison in Figure 3 was obtained. Earth (and, to a good approximation, the Sun) is at (0,0) in these coordinates and Voyager 1 is at the vertex of the two cross-hatched regions that are explained below. Since we believe there are errors of the order of a dB or so in determining the relative power at the two spacecraft, we have included contours for not only the stated 3 dB difference, but also contours for 2 and 4 dB differences, as well. The 2 and 4 dB contours show the sensitivity of the determination to uncertainties in the

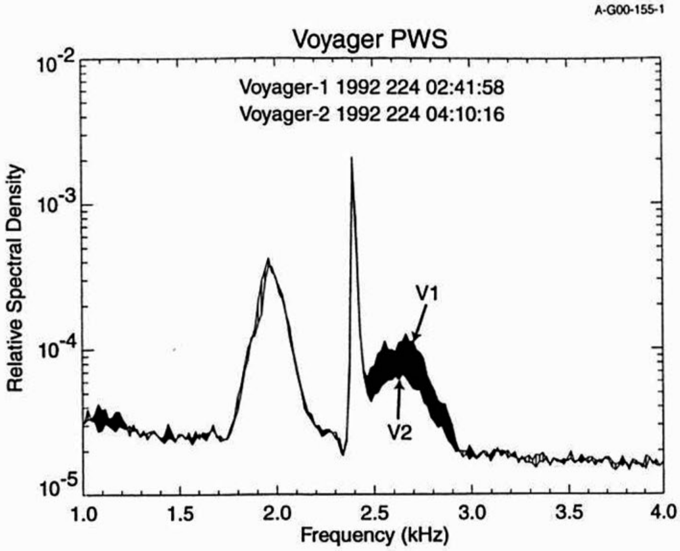

Figure 3. A detailed comparison of the spectrum observed at the two spacecraft at nearly the same time. Notice that the 2-kHz component is nearly identical in intensity, but there is a substantial difference in the high-frequency component.

detected power of order 1 dB. A line labeled "nose direction" indicates the projection of the nose of the heliosphere into the plane of analysis, with an assumed distance of 150 AU. Notice that this direction is very close to all three contours for an extended distance. Gurnett et al. (4) found the source to be consistent with the direction to the nose, so it is comforting to see the contours lie close to the nose position, as well. Because the contours extend for a large distance beyond the nose, the relative amplitude source location method does not, in this case, provide a useful restriction in the distance to the source. Note that both the rotating dipole technique and the relative amplitude method have ambiguities; e.g. there is no a priori way of eliminating the 3-dB contour in the upper half of the plane as the true source direction. We note that the feature centered at 2.7 kHz in Figure 3 does not coincide with the frequency channel used by Gurnett et al. for the rotating dipole technique. However, the response of that channel does include the high-frequency wing of the 2.7-kHz line and we assume that the entire band is generated in the same general location. Furthermore, there is no emission apparent at higher frequencies to act as a source of confusion.

The cross-hatched regions in Figure 4 represent locations in the source plane where the source would seem to be ruled out by the modulation index m of 0.29 reported by Gurnett et al. (4). The modulation index is basically the amplitude of modulation observed in the received power as the antennas are rotated. There are three factors which determine the modulation index: (1) the elevation angle of the source out of the spacecraft spin plane (perpendicular to the roll axis), (2) the angular size of the source, and (3) scattering of the radio waves between the source and the spacecraft. In Figure 4, the spin plane is parallel to the Y' axis and perpendicular to the plane of the illustration. If the source were directly in the spacecraft spin plane, was a point source, and there was no scattering,

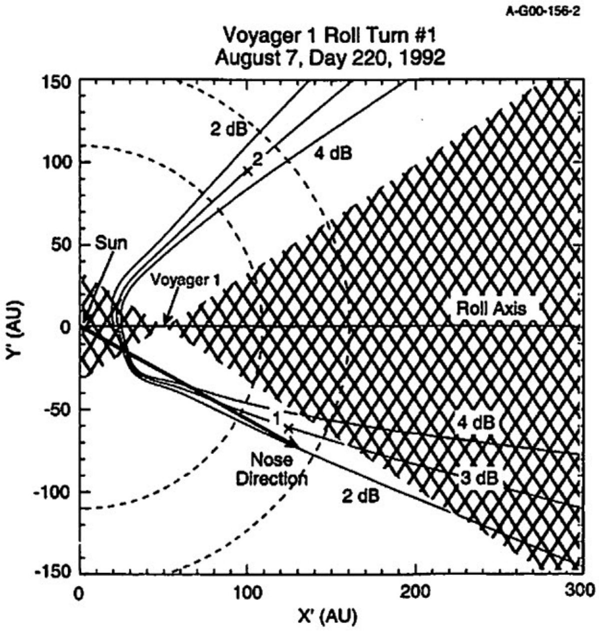

Figure 4. Contours of constant observed relative power in the plane of the source as determined by the rotating dipole technique. Superimposed on these contours is a line representing the projection of the direction to the nose of the heliosphere chosen to be at 150 AU for illustrative purposes. The cross- hatched regions are precluded as source regions by the modulation index measured in the rotating dipole analysis. For a point source with no scattering, the source would lie along one of the edges of the cross-hatched regions. Either scattering or extended source sizes, however, would move the source direction toward the spin plane (away from the cross-hatched regions). The crosses marked by 1 and 2 represent centroids of possible source locations on the 3-dB contours at heliocentric distances of about 135 AU. These positions are transformed back to ecliptic coordinates and represent the solution 1 and 2 entries in Table 1.

the modulation index would be 1. If we assume for the moment that the last two of these assertions are true, then the modulation index is entirely determined by the elevation of the source from the spin plane $\alpha = \cos^{-1}\sqrt{\mathrm{m}}$. Hence, the source would lie on one edge of the cross-hatched regions extended from the Voyager 1 position at the vertex of the two cross-hatched regions. Any extension of the source size or scattering (both of which reduce the modulation index) would have the effect of moving the source closer to the spin plane. Cairns (7,8) estimated the scattering would be so great that basically no roll modulation should have been seen by Voyager at all. However, Armstrong et al. (9) have re-estimated the magnitude of scattering and find it consistent with the modulation observed. The combined evidence for the source location in Figure 4, then, is consistent with the direction to the nose and at a distance of order 150 AU. This distance is similar to the source distance gained by time-of-flight arguments (10). To determine a result in ecliptic coordinates, we take positions along the 3-dB contour in Figure 4 approximately centered between the 110 and 160 AU distance derived from the time-of-flight determination of Gurnett and Kurth (10) designated by the crosses in the figure and transform back to the ecliptic coordinate system. Note that this entire distance range along the 3-dB contour falls within the region which is not cross-hatched in Figure 4. Not surprisingly, one of the solutions shown in Table 1 is within a few degrees of the direction to the nose; the other solution is well separated from the nose. Errors from the direction-finding analysis of Gurnett et al. (4) are of order a few degrees and those from the analysis of the intensity differences are at least as large. The uncertainty in the distance determined from time-of-flight considerations (10) is large as mentioned above.

4. CONCLUSIONS

We have developed a technique for defining the locus of possible source locations for heliospheric radio emissions based on the relative power detected at the two Voyager spacecraft. We have combined the relative power technique with the results of the rotating dipole technique by presenting the loci of possible source positions given by the relative power technique in the plane of the source as determined by the rotating dipole technique. We further restrict the source location by excluding a portion of this plane on the basis of the modulation index reported by Gurnett et al. (4). The results are consistent with a source near the nose of the heliosphere early in the 1992-1994 heliospheric radio emission event.

REFERENCES

1. W.S. Kurth, D.A. Gurnett, F.L. Scarf, and R.L. Poynter, *Nature 312,* 27-31 (1984).
2. D.A. Gurnett, W.S. Kurth, S.C. Allendorf, and R.L. Poynter, *Science 262,* 199-203 (1993).
3. W.S. Kurth, and D.A. Gurnett, in *Cosmic Winds and the Heliosphere,* eds. J. R. Jokipii, C. P. Sonett, and M. S. Giampapa, University of Arizona Press, Tucson, pp. 793-832 (1997).
4. D.A. Gurnett, S.C. Allendorf, and W.S. Kurth, *Geophys. Res. Lett. 25,* 4433-4436 (1998).
5. F. L. Scarf and D.A. Gurnett,*Space Sci. Rev. 21,* 289-308 (1977).
6. J.M. Ajello, A.I. Stewart, G.E. Thomas, and A. Garps, *Ap. J. 317,* 964-986 (1987).
7. I.H. Cairns, *Geophys. Res. Lett. 22,* 3433-3436 (1995).
8. I.H. Cairns, in *Solar Wind Eight,* AIP Conf. Proc. 382,ed. by D. Winterhalter et al., pp. 582-585 (1996).
9. J.W. Armstrong, W.A. Coles, and B.J. Rickett, *J. Geophys. Res. 105,* 5149-5156 (2000).
10. D.A. Gurnett, and W.S. Kurth, *Adv. Space Sci. 16,* (9)279 (1995).