GEOPHYSICAL RESEARCH LETTERS, VOL. 21, NO. 15, PAGES 1571-1574, JULY 15, 1994

Evidence that Jupiter is not the source of the 2-3 kHz heliospheric radiation

D. A. Gurnett and W. S. Kurth

Department of Physics and Astronomy, The University of Iowa

Abstract. It has been suggested that continuum radiation from Jupiter could provide the source for the 2- to 3-kHz radio emissions detected by Voyagers 1 and 2 in the outer heliosphere. By a fortuitous set of circumstances the Ulysses flyby of Jupiter in early 1992 provided an opportunity to compare the intensity of a strong, new heliospheric radio emission event with the intensity of continuum radiation from Jupiter. These comparisons show no evidence that Jupiter is the source of the heliospheric radio emissions.

Introduction

For nearly ten years the Voyager 1 and 2 spacecraft have been detecting unusual radio emissions in the outer heliosphere at frequencies from about 2 to 3 kHz. Two particularly strong events have occurred, the first in 1983-84 [Kurth et al., 1984] and the second in 1992-93 [Gurnett et al., 1993]. The source of these radio emissions has been controversial. In the initial report on these radio emissions, Kurth et al. [1984] considered three possible sources: (1) planetary, (2) heliospheric, and (3) extraheliospheric (pulsars, in particular). Of these, a heliospheric source was considered the most likely. Despite the early evidence that the 2 to 3 kHz radio emission was generated in the outer heliosphere, doubts about the origin persisted. As recently as 1992, Kaiser et al. [1992a] argued that the radio emission originated from Jupiter. In order to test this hypothesis, Kurth [1993] suggested that data from the Ulysses spacecraft, which flew by Jupiter on February 8, 1992, could be used to evaluate Jupiter as the source. By a fortuitous set of circumstances, a strong, new heliospheric radio emission event started only a few months after the Ulysses flyby [Gurnett et al., 1993], while Ulysses was still close to Jupiter, thereby providing a test of the Jovian source hypothesis. The purpose of this paper is to report the results of this test. For a description of the plasma wave instruments on Voyagers 1 and 2, see Scarf and Gurnett [1977]; and for a description of the radio and plasma wave instrument on Ulysses, see Stone et al. [1992a].

Description of the 1992-93 Event

Figure 1 shows the radio emission intensities in the 1.78- and 3.11-kHz channels of the Voyager 1 16-channel plasma wave spectrum analyzer. The new event, hereafter referred to as the 1992-93 heliospheric radio emission event, was first detected in the 1.78-kHz channel of Voyager 1 on day 188 (July 6), 1992, reached a peak intensity of 4.2×10^{-17} W m^{-2} Hz^{-1} (1.8×10^{-17} W m^{-2} Hz^{-1} after subtracting the receiver noise level) in the 1.78-kHz channel on day 327 (November 22), 1992, and was back down to near the receiver noise level by early August 1993. High resolution wideband receiver data show that very similar spectrums were observed at both Voyagers 1 and 2, even though the spacecraft are separated by a distance of 44.6 AU (astronomical unit, 1.50×10^8 km). As of January 1, 1993, Voyager 1 was located at a heliospheric radial distance of R = 50.8 AU, a solar ecliptic latitude of β = 33.6°, and a solar ecliptic longitude of λ = 245°, and Voyager 2 was located at R = 39.0 AU, β = -11.7°, and λ = 283°. The radio emission extended over a bandwidth of about 2 kHz, from approximately 1.8 to 3.6 kHz.

Paper number 94GL01361
0094-8534/94/94GL-01361$03.00

The Jovian Source Hypothesis

Jupiter is a known source of radio emissions in the frequency range around 2 to 3 kHz. This emission is called continuum radiation [Scarf et al., 1979], and occurs over a frequency range from about ten Hz to a few tens of kHz. A typical spectrum of Jovian continuum radiation is shown in Figure 2. This spectrum was obtained in the Jovian magnetospheric cavity by Voyager 1 [Gurnett et al., 1980]. As can be seen, the continuum radiation becomes extremely intense at low frequencies. Since the solar wind electron

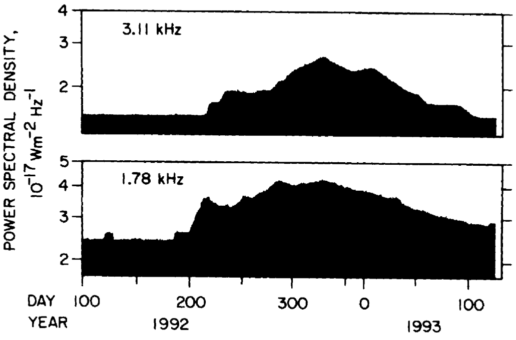

Figure 1. The spectral power flux observed by Voyager 1 at R ≃ 51 AU during the 1992-93 heliospheric radio emission event. These data are from adjacent channels (1.78 and 3.11 kHz) of the 16-channel plasma wave spectrum analyzer. The event started on day 188 (July 6), 1992, reached peak intensity on about day 327 (November 22), 1992, and declined to near the receiver noise level by mid-1993.

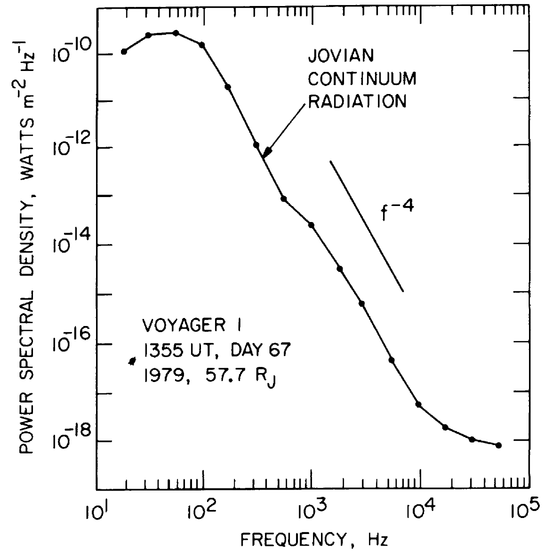

Figure 2. A continuum radiation spectrum obtained by Voyager 1 in the Jovian magnetotail [from Gurnett et al., 1980]. Note that in the range around a few kHz, the spectrum varies as $1/f^4$.

plasma frequency at Jupiter is about 5 kHz, it was originally thought that the low-frequency continuum radiation could not escape from the low-density cavity of Jupiter's magnetosphere. However, because the tail of Jupiter's magnetosphere extends at least to the orbit of Saturn [Scarf et al., 1983], where the solar wind electron plasma frequency is often below 2 kHz, it is possible that continuum radiation could escape from the distant tail at frequencies as low as 2 kHz. The escape scenario is illustrated in Figure 3. In this model, the Jovian magnetotail acts like a waveguide, with the radiation repeatedly reflecting from the walls of the cavity as it propagates down the tail. Once the radiation reaches the point where the solar wind plasma frequency is below the wave frequency, the radiation can in principle escape. The exact escape condition depends on the angle of incidence and various other details.

The possibility that Jupiter could be the source of the heliospheric radio emission was considered in the initial paper by Kurth et al. [1984]. Three arguments were given supporting the view that Jupiter was not the source: (1) the spectrums of the Jovian continuum radiation and the heliospheric radio emissions were quite different; (2) the heliospheric radio emission did not display a 10-hour rotational modulation characteristic of a Jovian source; and (3) the intensity did not follow the expected $1/r^2$ scaling law for a source at Jupiter. Despite the strength of these arguments, the case against a Jovian source was not completely convincing. One unknown factor was the effect the interstellar plasma may have on the propagation. For example, Czechowski and Grzedzielski [1990], Farrell [1993], and others have suggested that the radiation could be trapped in the heliospheric cavity. Repeated reflections from the walls of the cavity would invalidate the $1/r^2$ scaling law and cause various other effects. For a review of these and other considerations, see Kurth [1993].

Voyager-Ulysses Comparisons

The Ulysses flyby of Jupiter occurred on day 39 (February 8), 1992, approximately five months before the onset of the 1992-93 heliospheric radio emission event. After the flyby, Ulysses departed southward on an orbit over the poles of the Sun [Smith et al., 1992]. At the onset of the 1992-93 heliocentric radio emission event (day 188, 1992), Ulysses was located 1.18 AU from Jupiter at a Joviocentric latitude of -38.4° and a local time of 17.5 hr. Starting about one year before closest approach, the Ulysses radio and plasma wave instrument began to detect continuum radiation escaping from Jupiter. The escaping continuum radiation continued to be observed for more than two years after closest approach. For an initial report on the radio and plasma wave observations near Jupiter, see Stone et al. [1992b], and for a description of the continuum radiation observations, see Kaiser et al. [1992b].

Continuum radiation is typically observed escaping from Jupiter over a frequency range from a few kHz to several tens of kHz. The low-frequency limit of the escaping continuum radiation is determined by the propagation cutoff at the solar wind electron plasma frequency, which is typically about 5 kHz in the vicinity of Jupiter. Since the propagation cutoff in the solar wind prevents radio emissions from reaching Ulysses at frequencies below about 5 kHz, it is not possible to directly monitor the Jovian continuum radiation in the frequency range from 2 to 3 kHz. However, from previous observations in the Jovian magnetospheric cavity by Voyager [Gurnett et al., 1980] and Ulysses [Kaiser et al., 1992b], it is known that the continuum radiation has a power law spectrum with exponent of minus four (i.e., $1/f^4$, see Figure 2). Since the shape of the spectrum is known, the intensity can be extrapolated from frequencies above 5 kHz, where it can be measured by Ulysses, to the frequency range around 2 to 3 kHz. The bottom plot in Figure 4 shows such an extrapolation. In this plot, the intensity was measured at a frequency of 10 kHz and extrapolated to a frequency of 1.78 kHz, where the intensity is the strongest in the Voyager data. The extrapolation consists of simply multiplying the observed power spectral density (in W m^{-2}

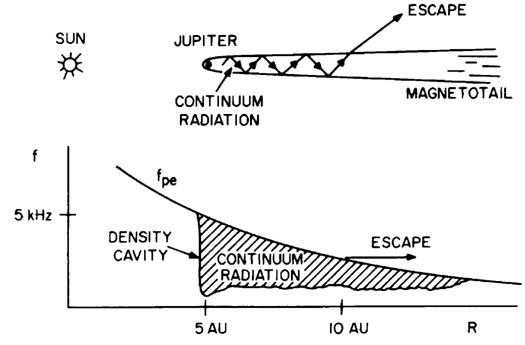

Figure 3. Continuum radiation escaping down the Jovian magnetotail has been suggested as a possible source for the 2- to 3-kHz radio emissions detected by Voyagers 1 and 2. The Jovian magnetosphere forms a low-density cavity in the solar wind. Radiation propagating down the tail can escape as soon as the electron plasma frequency, f_{pe}, in the solar wind drops below the wave frequency.

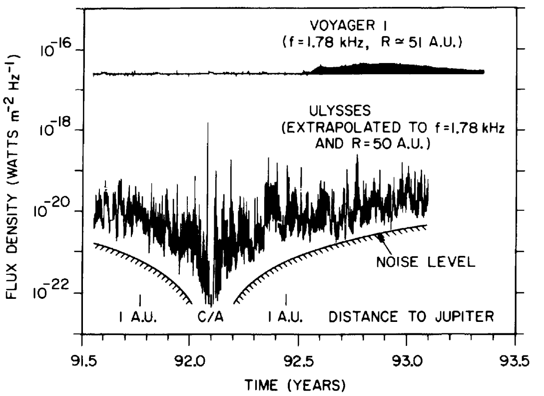

Figure 4. A comparison of Jovian continuum radiation intensities detected by Ulysses in the vicinity of Jupiter with the intensity of the 1992-93 heliospheric radio emission event detected by Voyager 1 at a frequency of 1.78 kHz. The Ulysses measurements have been extrapolated from a measured frequency of 10 kHz to 1.78 kHz using a $1/f^4$ scaling law (see Figure 3), and to a distance of 50 AU using a $1/r^2$ scaling law.

Hz^{-1}) at 10 kHz by a factor of $(10/1.78)^4 = 10^3$. To facilitate a more direct comparison with the Voyager 1 measurements at R = 51 AU, the spectral density has also been corrected to a distance of 50 AU using a $1/r^2$ scaling law, where r is the distance from Jupiter. This $1/r^2$ correction effectively assumes that the radiation is being emitted isotropically from Jupiter. No attempt has been made to account for the fact that the radiation would actually escape about 5 AU downstream of Jupiter. Since 5 AU is only a small fraction of the distance from Jupiter to Voyager 1, the error introduced by this assumption is negligible.

The top plot in Figure 4 shows the radio emission intensity at 1.78 kHz as detected by Voyager 1 at R = 51 AU. The 1992-93 heliospheric radio emission event can be clearly seen starting at about t = 92.5 years. Three points are immediately obvious from the Ulysses-Voyager comparison. First, the radio emission intensities observed by Voyager 1 are much higher than the intensities observed by Ulysses, by roughly a factor of three hundred. Second, the intensity variations are quite different. The escaping Jovian continuum radiation is very spiky and irregular, whereas the heliospheric radio emission is very smooth and continuous. Third, there is no obvious increase in the intensity of the escaping Jovian continuum radiation at the onset of the heliospheric radio emission event. Except for a symmetrical decrease in the intensity near closest approach (C/A), which is probably indicative of a breakdown in the $1/r^2$ scaling law in the near vicinity of the planet, there is no significant overall change in the continuum radiation intensity. These comparisons all give the strong impression that the signals being detected by Ulysses and Voyager are of entirely different origin.

Validity of the Scaling Assumptions

Since intensity comparisons are a key element in the test of the Jovian source hypothesis, it is useful to review the validity of the assumptions involved. Two assumptions were made: first, that the frequency spectrum of the Jovian continuum radiation varies as $1/f^4$, and second, that the intensity varies as $1/r^2$. The spectrum of the continuum radiation has been measured only three times in the Jovian magnetospheric cavity, first by Voyager 1 in March 1979, then by Voyager 2 in July 1979, and most recently by Ulysses in February 1992. In all three cases the spectrums were essentially identical, both in intensity and spectral slope. However, since observations of the low-frequency component were limited to the short periods when the spacecraft were actually in the magnetospheric cavity, it could be that something unusual happened to the low-frequency component. For example, if the intensity at 2 to 3 kHz increased by a large factor on day 188, 1992, then the continuum radiation escaping down the tail could account for the signals detected by Voyager, but still remain undetected by Ulysses at frequencies above 5 kHz. Although such a scenario is possible, the generation of such intense radio emissions has serious energy balance problems.

Recently, Gurnett et al. [1993] estimated that the power involved in the 1992-93 heliospheric radio emission event is at least 10^{13} W. At Jupiter the total power available to drive magnetospheric processes from all sources (solar wind and Io) has been estimated by Nishida et al. [1979], Hill et al. [1983], and others, and is in the range from about 10^{13} to 10^{15} W. The overall conversion efficiency required to generate a radio emission of 10^{13} W would then have to be 1% or more. Such high conversion efficiencies are implausible. Desch and Kaiser [1985] have computed the conversion efficiency for various planetary radio sources and find that the efficiencies (radiated power divided by power input) are usually in the range from 10^{-5} to 10^{-6}. Thus, based on everything that is known about planetary radio emission processes, it is unrealistic to expect that the radio emissions detected by Voyager could be produced by direct ($1/r^2$) propagation from a Jovian source.

Trapping in the Heliospheric Cavity

If the electron density in the interstellar medium is sufficiently high, then low-frequency radio emissions can be trapped in the heliospheric cavity. Trapping occurs if the electron plasma frequency in the interstellar medium exceeds the wave frequency, i.e., if $f_{pe} > 1.8$ kHz. If the heliospheric radio emissions are trapped in a high-Q cavity, then multiple reflections within the cavity would invalidate the $1/r^2$ propagation model used in the previous section. For electromagnetic radiation trapped in a cavity of size L, it is straightforward to show that the power P required to maintain an intensity S (in W m^{-2}) is given by

$$P = k\frac{SL^2}{Q} \quad , \qquad (1)$$

where k is a factor of order unity that depends on the detailed geometry of the cavity, and Q is the number of cycles required to damp the radiation by a factor of e^{-1}. Equation 1 shows that the power required to maintain a given radiation intensity can be made quite small if Q is sufficiently large. For example, if the escaping continuum radiation power detected by Ulysses in Figure 4 ($\Delta P/\Delta f \simeq 4\pi(50)^2(1.50 \times 10^{11}\ \mathrm{m})^2 (2 \times 10^{-20}\ \mathrm{W\ m^{-2}\ Hz^{-1}}) =$

1.4×10^7 W Hz^{-1}) is trapped in a cavity with a characteristic dimension of L = 100 AU, then the power spectral density observed by Voyager 1 ($\Delta S/\Delta f \simeq 1.8 \times 10^{-17}$ W m^{-2} Hz^{-1}) could be obtained if $Q \gtrsim 300$.

Two factors lead us to believe that Q is quite small. First, as discussed by Gurnett et al. [1993], during a series of roll maneuvers it was found that the electric field intensity at 3.11 kHz has a substantial anisotropy, ~10% to 20%. Unfortunately, because of the very poor geometry for direction finding (Jupiter is only 6° from the roll axis), the roll modulation cannot be used to rule out Jupiter as a source. Subsequent (unpublished) roll maneuvers have shown anisotropies as high as 50% at 3.11 kHz. No roll modulation has been detectable in the next lowest frequency channel at 1.78 kHz, although spacecraft-related interference somewhat compromises the detection of modulation in this channel. The existence of anisotropies as large as 50% is not consistent with trapping in a high-Q cavity (at least not at 3.11 kHz), since multiple reflections in the cavity should quickly lead to an isotropic electric field distribution. Second, small but significant differences can be seen in the spectrums at Voyagers 1 and 2, sometimes by as much as 3 to 4 db. Such differences indicate that the entire spectrum cannot be trapped in a high-Q cavity, since multiple reflections should lead to a uniform intensity throughout the cavity. Even if the 2.0 kHz component is trapped, the Q-factor cannot be large because the intensity is similar to the 3.0 kHz component.

Conclusions

In this study we have used measurements from Ulysses to evaluate Jupiter as the source of the 2- to 3-kHz radio emissions detected by Voyagers 1 and 2 in the outer regions of the heliosphere. Using reasonable extrapolations of the spectrum and a $1/r^2$ scaling law we find that the power radiated by Jupiter is too small by a factor of about three hundred. The power involved in the heliospheric radio emissions is also so large, $> 10^{13}$ W, that an unreasonable fraction of the power available in the Jovian magnetosphere (> 1%) would be required to account for the observed intensities. Evidence was also presented that trapping plays a negligible role in altering the intensity of radiation escaping from Jupiter. Based on these arguments, we conclude that Jupiter cannot be the source of the heliospheric radio emissions detected by Voyagers 1 and 2.

Acknowledgements. The research at the University of Iowa was supported by NASA through contract 959193 with the Jet Propulsion Laboratory. The authors would like to thank R. Stone of Goddard Space Flight Center for allowing us to use the data from the Ulysses radio and plasma wave investigation, and M. Kaiser, M. Desch, and W. Farrell for their assistance in processing the Ulysses data and their many other useful comments.

References

Czechowski, A., and S. Grzedzielski, Frequency drift of 3-kHz interplanetary radio emissions: Evidence of Fermi accelerated trapped radiation in a small heliosphere?, *Nature*, **344**, 640-641, 1990.

Desch, M. D., and M. L. Kaiser, Predictions for Uranus from radiometric Bode's law, *Nature*, **310**, 755-767, 1984.

Farrell, W. M., The heliospheric cavity radio emission: Generation of discrete tones by Fermi acceleration via oscillating boundary, *Geophys. Res. Lett.*, **19**, 2011-2014, 1993.

Gurnett, D. A., W. S. Kurth, and F. L. Scarf, The structure of the Jovian magnetotail from plasma wave observations, *Geophys. Res. Lett.*, **7**, 53-56, 1980.

Gurnett, D. A., et al., Radio emission from the heliopause triggered by an interplanetary shock, *Science*, **262**, 199-203, 1993.

Hill, T. W., A. J. Dessler, and C. K. Goertz, Magnetospheric models, *Physics of the Jovian Magnetosphere*, ed. by A. J. Dessler, Cambridge Univ. Press, Cambridge, 353-394, 1983.

Kaiser, M. L., M. D. Desch, and W. M. Farrell, Jupiter as the likely source of the heliospheric "3 kHz" noise, Symposium on the Magnetospheres of the Outer Planets, Univ. of California, Los Angeles, California, June 22-26, 1992a.

Kaiser, M. L., et al., Ulysses observations of escaping VLF emissions from Jupiter, *Geophys. Res. Lett.*, **19**, 649-652, 1992b.

Kurth, W. S., The low-frequency interplanetary radiation, *Adv. in Space Res.*, **13**, (6)209-(6)215, 1993.

Kurth, W. S., et al., Detection of a radio emission at 3 kHz in the outer heliosphere, *Nature*, **312**, 27-31, 1984.

Nishida, A., K. Maezawa, and T. Terasawa, Energetics of Terrestrial and Jovian magnetospheres, *Space Sci. Rev.*, **23**, 345-356, 1979.

Scarf, F. L., and D. A. Gurnett, A plasma wave investigation for the Voyager mission, *Space Sci. Rev.*, **21**, 289-308, 1977.

Scarf, F. L., D. A. Gurnett, and W. S. Kurth, Jupiter plasma wave observations: An initial Voyager 1 overview, *Science*, **204**, 991-995, 1979.

Scarf, F. L., et al., Voyager plasma wave measurements at Saturn, *J. Geophys. Res.*, **88**, 8971-8984, 1983.

Smith, E. J., K.-P. Wenzel, and D. E. Page, Ulysses at Jupiter: An overview of the encounter, *Science*, **257**, 1503-1507, 1992.

Stone, R. G., et al., The unified radio and plasma wave investigation, *Astron. Astrophys. Suppl. Ser.*, **92**, 291-316, 1992a.

Stone, R. G., et al., Ulysses radio and plasma wave observations in the Jupiter environment, *Science*, **257**, 1524-1531, 1992b.

D. A. Gurnett and W. S. Kurth, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242

(Received: January 31, 1994; revised: April 15, 1994; accepted: May 5, 1994.)