Ulysses Radio and Plasma Wave Observations at High Southern Heliographic Latitudes

R. G. Stone, R. J. MacDowall,* J. Fainberg, S. Hoang, M. L. Kaiser, P. J. Kellogg, N. Lin, V. A. Osherovich, J. L. Bougeret, P. Canu, N. Cornilleau-Wehrlin, M. D. Desch, K. Goetz, M. L. Goldstein, C. C. Harvey, D. Lengyel-Frey, R. Manning, M. J. Reiner, J. L. Steinberg, G. Thejappa

Ulysses spacecraft radio and plasma wave observations indicate that some variations in the intensity and occurrence rate of electric and magnetic wave events are functions of heliographic latitude, distance from the sun, and phase of the solar cycle. At high heliographic latitudes, solar type III radio emissions did not descend to the local plasma frequency, in contrast to the emission frequencies of some bursts observed in the ecliptic. Short-duration bursts of electrostatic and electromagnetic waves were often found in association with depressions in magnetic field amplitude, known as magnetic holes. Extensive wave activity observed in magnetic clouds may exist because of unusually large electron-ion temperature ratios. The lower number of intense in situ wave events at high latitudes was likely due to the decreased variability of the high-latitude solar wind.

Radio and plasma wave observations, such as those made by the Unified Radio and Plasma Wave Investigation (URAP) on Ulysses, provide remote diagnostics of solar and planetary radio emissions and the particle acceleration that produces them. In situ wave events, which result from particle anisotropies in the solar wind, are also detected. The URAP instruments (*1*) measure electric fields in the frequency range from 0 to 1 MHz and magnetic fields from 0.22 to 450 Hz. They have been designed to determine the complete polarization state and source direction of emissions from remote radio sources, as well as the intensity and orientation of in situ waves.

Here we examine the variability of wave phenomena that is related to the changing heliographic position of Ulysses along its trajectory from the ecliptic to high southern heliographic latitudes. For several months surrounding the closest approach to Jupiter, which occurred on day 39 of 1992, the radio receiver data (>1 kHz) (Fig. 1) were dominated by low-frequency jovian radio emissions (*2*), whose intensities are partially controlled by solar wind conditions at Jupiter. Before mid-1991 and after 1992, solar radio emissions (*3*) and in situ electron quasithermal noise (QTN) (*4*) predominated. A clear example of QTN can be seen in 1994, where the electron plasma frequency f_{pe} (*4*) began the year at approximately 2 to 3 kHz and gradually rose to ~10 kHz by the end of the year. Because the frequencies of the QTN cutoff and spectral peak depend directly on plasma density, they are functions of distance from the sun, heliographic latitude, and the level of solar activity, which determines the number of transients in the solar wind. In 1994, the QTN spectrum exhibited little fluctuation on a time scale of days because the spacecraft was continuously in high-speed solar wind that has less variability than the wind at lower latitudes (*5*). The greater variability in the QTN spectrum in late 1991, when the Ulysses-sun distances were the same as in early 1994, resulted from the larger number of shocks, coronal mass ejections, and other transients in the solar wind. In late 1992 and early 1993, Ulysses was alternately located in fast- or slow-speed solar wind as a corotating high-speed solar wind stream repeatedly passed the spacecraft (*5*). This quasiperiodic (~25-day) variation in density

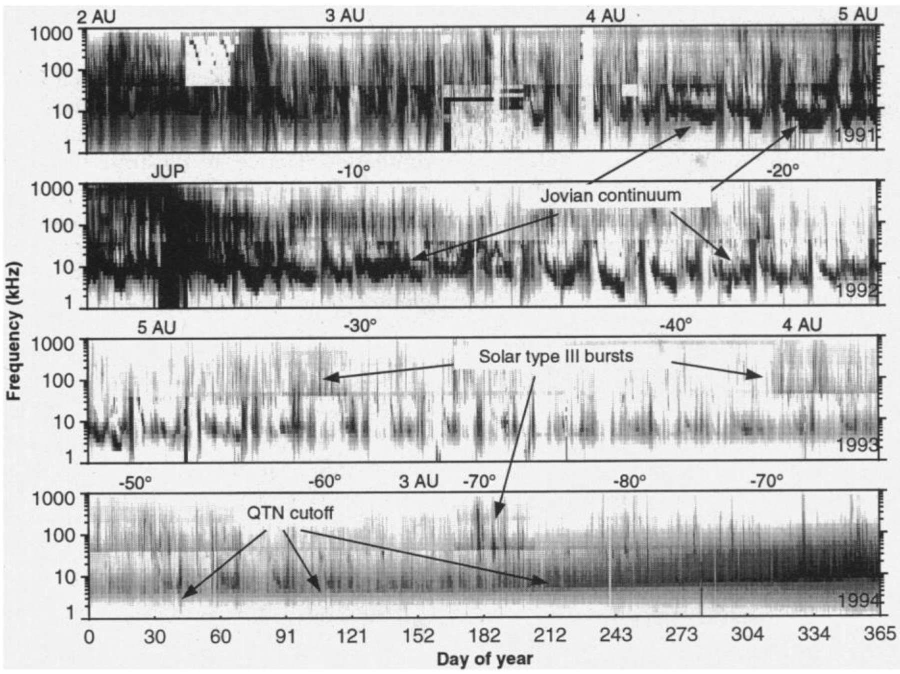


Fig. 1. Data from the URAP radio receivers for the years 1991 to 1994. Four-hour average data are displayed in dynamic spectrum format (frequency versus time) with relative intensity above a frequency-dependent background shown by the gray scale. [The background level used is independent of time and corresponds to the minimum quasithermal noise (QTN) and galactic background detected.] Selected distances from the sun (in astronomical units) and heliographic latitudes are indicated. During the entire year 1992, Ulysses was just beyond 5 AU. The discontinuity at 50 kHz is the boundary between the high and low band radio receivers. Rectangular structures in the 1991 data are artifacts produced by special modes of the instrument. Examples of intense type III bursts may be seen on days 0 to 60, 180 to 190, and 330 to 331 of 1994; type III burst activity does not appear to be intense at the highest frequencies because of the 4-hour averaging. Examples of jovian nonthermal radio continuum and QTN low-frequency cutoffs are also indicated. JUP indicates the jovian flyby.

R. G. Stone, R. J. MacDowall, J. Fainberg, M. L. Kaiser, M. D. Desch, M. L. Goldstein, National Aeronautics and Space Administration (NASA), Goddard Space Flight Center, Greenbelt, MD 20771, USA.
S. Hoang, J. L. Bougeret, C. C. Harvey, R. Manning, J. L. Steinberg, Observatoire de Paris-Meudon, 92195 Meudon Principal Cedex, France.
P. J. Kellogg, N. Lin, K. Goetz, School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA.
V. A. Osherovich and M. J. Reiner, Hughes STX, Lanham, MD 20706, USA.
P. Canu and N. Cornilleau-Wehrlin, Centre des Etudes Terrestres et Planetaires, 78140 Velizy, France.
D. Lengyel-Frey and G. Thejappa, Department of Astronomy, University of Maryland, College Park, MD 20742, USA.

*To whom correspondence should be addressed.

caused an associated variation in the QTN spectrum as well as a modulation of the level of jovian nonthermal radio continuum reaching the spacecraft (*2*).

The level of radio activity diminished as the solar cycle approached its minimum. For example, intense radio activity (above 100 kHz) observed from mid-March through June 1991 was associated with a very high level of solar activity, including a 3B/X9.4 flare occurring on 22 March 1991 (day 81). In 1994, at a similar distance from the sun, but well into the declining phase of the solar cycle, the levels of all types of solar radio activity were greatly reduced. The extent to which this reduction appears to occur because of the high latitude perspective of Ulysses in 1994 remains to be determined.

Solar type III radio bursts are the most frequently observed solar radio emission at frequencies less than 1 MHz (*6*). They have been observed by Ulysses in the ecliptic plane at heliocentric distances from 1 to 5 astronomical units (AU), at frequencies from the high-frequency limit of the radio receiver (1 MHz) extending to low frequencies. The frequency of the emission sometimes descends to the local value of f_{pe}. This usually occurs when type III electrons intercept the spacecraft, where the Langmuir waves they produce are detected (*7*, *8*). In these cases, the source regions of the type III bursts lie along the approximately Archimedean spiral magnetic field lines connecting the sun to the spacecraft. Type III bursts were observed less frequently when Ulysses was at high latitudes; these events had relatively low intensities at low frequencies, compared with bursts observed at low latitudes. No type III burst observed at heliographic latitudes southward of −40° showed radio emission extending as low as f_{pe}, and the emission was

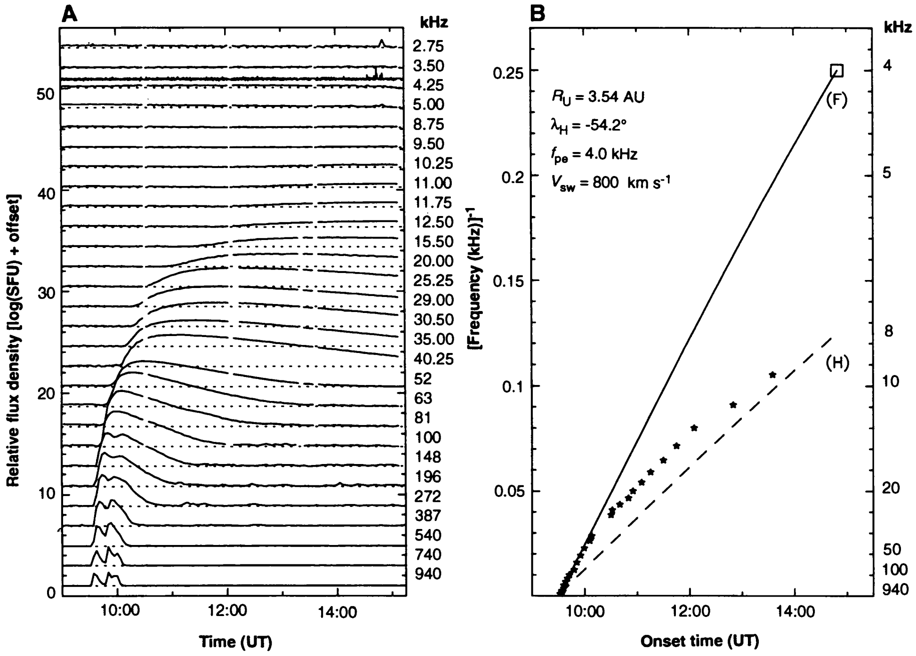
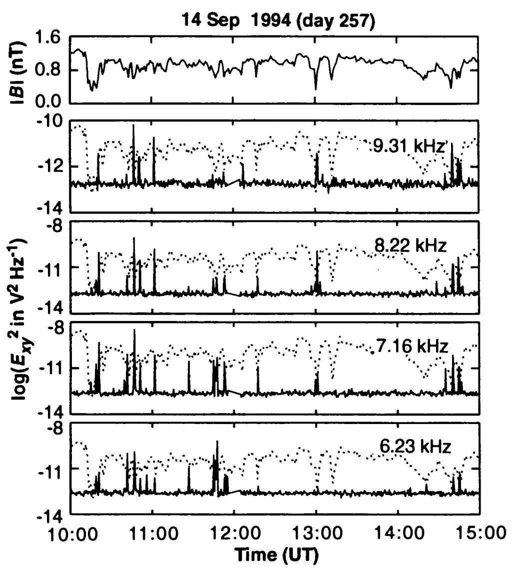


Fig. 2. (**A**) Intensity-time profiles at different radio receiver frequencies for a type III burst occurring on 27 February 1994 when Ulysses was at 3.54 AU and −54.2° latitude. The intensity is given in solar flux units (1 SFU = 10^{-22} W m^{-2} Hz^{-1}). [The data plotted between 3.50 and 4.25 kHz are from the plasma frequency receiver, whose higher time resolution shows the bursty Langmuir waves (at about 14:50 UT) more clearly.] (**B**) Burst onset times (indicated by stars) at various radio frequencies and Langmuir wave onset time (square) on 27 February 1994, day 58. The ordinate scale in inverse frequency is proportional to the distance from the sun. The solid line (F) is the trace of type III electrons traveling along an Archimedean spiral field line from the sun to Ulysses with a speed of 0.09 *c* and producing fundamental radiation. The dashed line (H) would be the trace if the type III electrons produced harmonic radiation. R_U, distance from the sun to Ulysses; λ_H, heliographic latitude; V_{SW}, velocity of the solar wind.



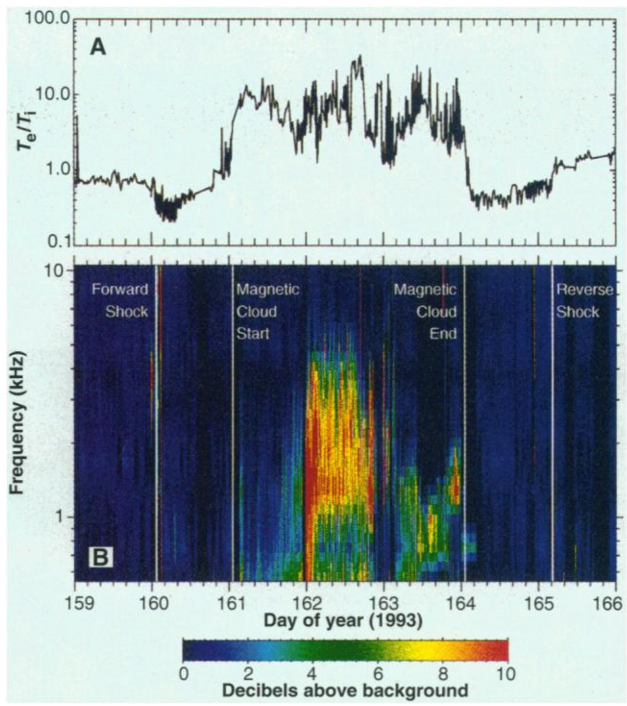


Fig. 3 (left). Five-hour interval of electric field data E_{xy}^2 (16-s resolution measured in the *x*-*y* plane) from 14 September 1994 showing short-duration electrostatic wave bursts for four channels in the frequency range of ~6 to 9 kHz. Magnetic holes are observed in the ambient magnetic field amplitude, *B*, which is plotted in the top panel and overplotted in the other panels [64-s averages, provided by the Ulysses magnetometer (*13*)]. **Fig. 4 (right).** (**A**) Electron-ion temperature ratio (T_e/T_i) during the interval 8 to 14 June 1993 (day 159 to 165), provided by the Ulysses solar wind plasma instrument (*5*). (**B**) Dynamic spectrum of electric field data from 0.5 to 10 kHz during the same interval showing intense wave activity occurring throughout the interval that the spacecraft was inside the magnetic cloud. The magnetic boundaries of the cloud and the arrival times of the associated forward and reverse shocks are indicated by vertical bars.

weak even at several times f_{pe}.

One such type III burst (Fig. 2) was associated with a solar flare at about 9:00 UT in active region 7671. The observed radio emission drifted from high to low frequencies, starting at 940 kHz and disappearing below background levels by 9.50 kHz, approximately twice the local f_{pe}. The radio emission is likely to have occurred on field lines that passed near the spacecraft. On the same day, the Ulysses HISCALE (heliosphere instrument for spectra, composition, and anisotropy at low energies) investigation detected solar electrons of energies ~50 to 400 keV, which were channeled in selected magnetic structures from the solar flare site near the equator to Ulysses at high southern latitude (9). It is reasonable that lower energy, type III–producing electrons originating from the same site could have traveled in the same magnetic structures and intercepted Ulysses. Furthermore, Langmuir waves were detected by the URAP radio and plasma frequency receivers around the local f_{pe} (~4 kHz) at about 14:50 UT. Because these Langmuir waves occurred in magnetic holes, it is possible that they were not associated with the electrons that produced this type III burst. Nevertheless, the URAP radio direction determinations for this type III burst show that the radio sources drifted to the west and south of the sun from high to low frequencies, as expected for electron streams traveling along Archimedean spiral field lines toward Ulysses. The Archimedean spiral connecting the spacecraft to the sun, with curvature set by the measured average solar wind speed of 800 km s^{-1}, intersected the sun within 18° of the active region's center. The speed for electrons traveling along this path is calculated to be 0.09 *c* (*c*, speed of light), in reasonable agreement with values measured in the ecliptic plane by Ulysses (8) and ISEE-3 (*10*).

Assuming that the solar wind density decreases as a function of R^{-2} (*R*, distance from the sun), it is possible to predict the onset times of the radio emission at the fundamental (F) and harmonic (H) of f_{pe} along the path traveled by the type III electrons (Fig. 2B). The burst appears to start at high frequencies as fundamental emission and to change to harmonic emission at lower frequencies (at approximately 0.5 AU from the sun). Except for the low intensity at low frequency, this behavior is similar to observations of many bursts made in the ecliptic. This similar behavior will facilitate triangulating burst positions by using URAP data in conjunction with observations from the recently launched Wind spacecraft.

Depressions in the magnetic field, known as magnetic holes, have been reported (*11*, *12*). The URAP instruments detected short-duration bursts of waves occurring at frequencies near the ambient f_{pe} in association with the magnetic holes (Fig. 3). These waves are likely to be Langmuir waves, which are usually excited by electron streams. It is not clear whether the magnetic holes are remnants of coronal structures or result from random fluctuations in solar wind parameters. The URAP observations indicate that the bursts of Langmuir waves occurred much more frequently at high heliographic latitudes than in the ecliptic, as was the case for magnetic holes (*13*).

Low-frequency electromagnetic waves (*14*) with frequencies of a fraction of the local electron cyclotron frequency, f_{ce}, sometimes accompanied the Langmuir waves observed in magnetic holes. Waves

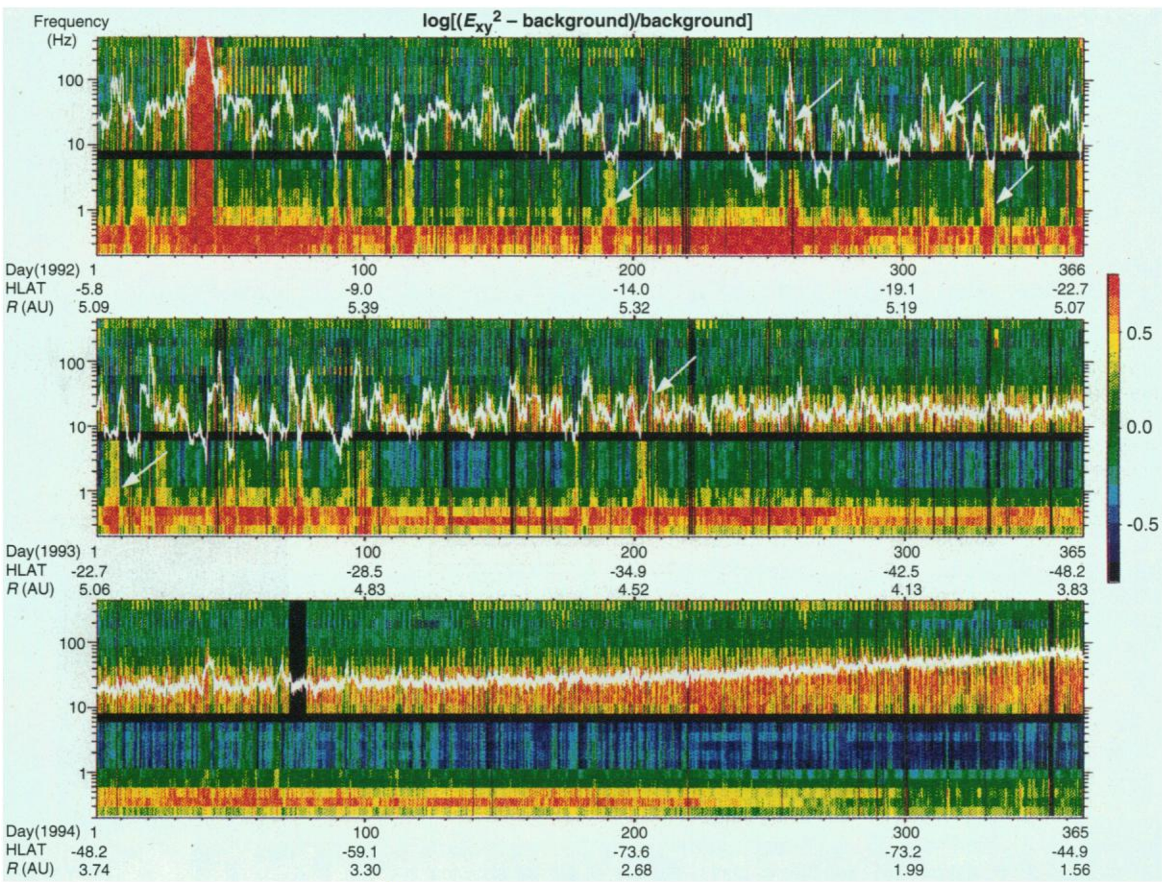


Fig. 5. Dynamic spectra of 1-hour averaged electric wave power measured in the spacecraft spin plane in the frequency range 0.2 to 450 Hz for the years 1992 to 1994. The horizontal black strip near the middle of each panel is a frequency gap between low (0.2 to 5.3 Hz) and high (9.3 to 448 Hz) band channels of the instrument; the high band has significantly greater sensitivity (*21*). The local electron cyclotron frequency, f_{ce}, determined from magnetic field amplitude provided by the Ulysses magnetometer (*13*), is overplotted as a white line in each panel. Day of year, heliographic latitude (HLAT), and distance from the sun (*R*, in astronomical units) are indicated. The strong signals around day 39 of 1992 occurred during the Jupiter flyby. The color scale to the right indicates relative wave power as log[(E_{xy}^2 – background)/background].

excited in this frequency range are likely to be whistler-mode waves (*15*). They may have been excited by an anisotropy in electron temperature, which has been observed in the vicinity of the magnetic holes (*11*), or they may have been generated through the decay of Langmuir waves (*16*) or by current instabilities associated with the magnetic discontinuities.

Two intervals of extended wave activity near and below f_{pe} were observed in June and July 1993, each lasting for several days. These intervals occurred in association with coronal mass ejections, identified by the solar wind plasma experiment (*17*). Both intervals exhibited the characteristics of magnetic clouds, defined as large structures in the solar wind characterized by a magnetic field enhancement with a smooth rotation of the magnetic field vector and by low-density plasma and low ion temperature T_i (*18*). Recently, it has been shown that the electron temperature T_e, in contrast to that of the ions, is anticorrelated with density ρ, and T_e reaches a maximum in a cloud (*19*). For one magnetic cloud observed at 1 AU, the ratio of temperatures T_e/T_i was 6 to 7 (*19*).

In the magnetic cloud observed by Ulysses (*17*) during the period 10 to 13 June 1993 (days 161 to 164) at –32.6° heliographic latitude and 4.7 AU, the temperature ratio reached values of $T_e/T_i \sim 10$ to 20 (Fig. 4A). Furthermore, we find $\gamma_i > 1$ and $\gamma_e < 1$ in this cloud (*20*), where γ is the polytropic index for the species. (For an ideal polytropic gas, $T \sim \rho^{\gamma - 1}$.) Therefore, as the cloud expands, T_i decreases and T_e increases. Because Landau damping of ion-acoustic waves is not effective when $T_e/T_i >> 1$, it has been suggested (*19*) that the ion-acoustic wave activity in magnetic clouds should be enhanced, compared with levels observed in the solar wind. This is consistent with the sharp rise in wave activity at frequencies corresponding to Doppler-shifted ion-acoustic waves (Fig. 4B) inside the 10 to 13 June 1993 magnetic cloud.

Enhanced electric field wave events were observed at heliographic latitudes equatorward of approximately −40°. During this period, the spacecraft regularly encountered solar wind turbulence and interplanetary shocks associated with corotating interaction regions. The spectra (Fig. 5) show that the maximum frequency of enhanced wave power was approximately f_{ce}. Southward of $\sim -40°$, the wave spectra became less variable, presumably because the solar wind had a relatively constant speed ($\sim$700 to 800 km s^{-1}), and the solar wind magnetic field became relatively stable (*5*, *13*). In late 1993 and in 1994, when Ulysses was in fast solar wind, nearly continuous activity was observed extending from lower frequencies up to $\sim f_{ce}$ (*21*).

Most spectra (*14*) of magnetic wave power for the same period and the same frequency range were relatively quiet. Near interplanetary shocks, however, electromagnetic waves extending up to a few tens of hertz were often observed, for example, in 1992 on days 256 to 259 and 313 and in 1993 on day 207 (Fig. 5, arrows). These waves are thought to be whistler-mode waves and have been observed previously near interplanetary shocks (*22*). The temperature anisotropy of electrons of a few tens to several hundreds of electron volts in regions near the shocks may provide the free energy for the instability. At high latitudes, such enhancements in wave activity were rarely observed because of the lack of interplanetary shocks.

Low-frequency electrostatic waves were also frequently observed during intervals when no shocks occurred, for example, the intense wave bursts (extending below 5 Hz) in 1992 near days 190 and 330 and in 1993 on day 006 (Fig. 5, arrows). The frequencies of these waves were below f_{ce} and extended to the lowest frequency channel of the instrument. These waves may be whistler-mode waves propagating at large wave angles (near the resonance cone), which causes them to appear as electrostatic noise; however, an alternative source is the lower hybrid mode (*23*). The low-frequency cutoff of these waves may occur at the lower hybrid frequency (about 0.1 to 1 Hz), which is close to the lower limit of the URAP observations. This mode can be driven by the anisotropic halos of electron distributions; however, the detailed source requirements are not understood. Apparently, the appropriate conditions did not exist at high heliographic latitudes, where such bursts were not observed.

Although considerable progress has been made in separating the respective contributions of latitude, distance, and phase in the solar cycle to the variability of electric and magnetic wave events, the decisive observations will be obtained during a second Ulysses orbit over the poles of the sun in 2000 and 2001, when solar activity will be near a maximum. At that time, a significantly larger number of radio bursts and in situ events will be observed, facilitating comparison with the 1991–1992 in-ecliptic data.

REFERENCES AND NOTES

1. R. G. Stone *et al.*, *Astron. Astrophys. Suppl. Ser.* **92**, 291 (1992).
2. R. G. Stone *et al.*, *Science* **257**, 1524 (1992); R. J. MacDowall *et al.*, *Space Sci. Rev.* **72**, 125 (1995).
3. See G. A. Dulk, *Annu. Rev. Astron. Astrophys.* **23**, 169 (1985); and D. B. Melrose, *ibid.* **29**, 31 (1991), and references therein.
4. QTN, generated by thermal fluctuations in the plasma surrounding the antenna, is most intense at a frequency just above the local f_{pe} (kHz) $\approx 9\sqrt{N_e}$, where the electron plasma density N_e is in electrons/cm^3, and extends to higher frequencies [N. Meyer-Vernet and C. Perche, *J. Geophys. Res.* **94**, 2405 (1989), and references therein].
5. J. L. Phillips *et al.*, *Science* **268**, 1030 (1995).
6. Type III radio bursts are generated when suprathermal electrons (velocity ~0.05 to 0.3 *c*, where *c* is the speed of light) are ejected from solar active regions and then travel outward along open magnetic field lines through the corona and interplanetary medium. Along their paths, these electrons excite plasma oscillations (Langmuir waves) at f_{pe}; these electrostatic waves are then partially converted into radio waves at f_{pe}, $2f_{pe}$, or both. Thus, the progress of the electrons into regions of decreasing density produces radio waves progressing to successively lower frequencies. The low-frequency limit of the radio waves is imposed by the local f_{pe}, below which the waves cannot propagate.
7. D. A. Gurnett and R. R. Anderson, *Science* **194**, 1159 (1976); P. J. Kellogg, *Astrophys. J.* **236**, 696 (1980); R. P. Lin, D. W. Potter, D. A. Gurnett, F. L. Scarf, *ibid.* **251**, 364 (1981); M. J. Reiner, J. Fainberg, R. G. Stone, *ibid.* **394**, 340 (1992).
8. S. Hoang, G. A. Dulk, Y. Leblanc, *Astron. Astrophys.* **289**, 957 (1994).
9. M. Pick *et al.*, in preparation.
10. G. A. Dulk, J. L. Steinberg, S. Hoang, M. V. Goldman, *Astron. Astrophys.* **173**, 366 (1987); R. P. Lin *et al.*, *Astrophys. J.* **308**, 954 (1986).
11. J. M. Turner, L. F. Burlaga, N. F. Ness, J. F. Lemaire, *J. Geophys. Res.* **82**, 1921 (1977).
12. D. Winterhalter *et al.*, *ibid.* **99**, 23371 (1994).
13. A. Balogh *et al.*, *Science* **268**, 1016 (1995).
14. R. G. Stone *et al.*, data not shown.
15. F. M. Neubauer, G. Musman, G. Dehmel, *J. Geophys. Res.* **82**, 3201 (1977).
16. P. J. Kellogg *et al.*, *Geophys. Res. Lett.* **19**, 1299 (1992).
17. J. T. Gosling *et al.*, *ibid.* **21**, 237 (1994).
18. L. F. Burlaga, E. Sittler, F. Mariani, R. Schwenn, *J. Geophys. Res.* **86**, 6673 (1981).
19. V. A. Osherovich *et al.*, *ibid.* **98**, 15331 (1993).
20. V. A. Osherovich *et al.*, in preparation.
21. Slowly varying, time-dependent backgrounds have been subtracted, primarily to reduce the effects of changing solar aspect angle, which produces large changes in the low band backgrounds. This effect may be due to contributions from harmonics of the spin-modulated photoelectron background. It does not affect the high band of the instrument, which is isolated from lower frequencies by a high-pass filter. In the low band, however, the high level of the solar aspect angle–dependent background level, which is a maximum in 1994, would make it difficult to detect weaker activity.
22. F. V. Coroniti, C. F. Kennel, F. L. Scarf, E. J. Smith, *J. Geophys. Res.* **87**, 6029 (1982); D. A. Gurnett, in *Physics of the Heliosphere II*, R. Schwenn and E. Marsch, Eds. (Springer-Verlag, Berlin, 1991), vol. 21, p. 135; D. Lengyel-Frey *et al.*, *J. Geophys. Res.* **99**, 13325 (1994).
23. E. Marsch and T. Chang, *Geophys. Res. Lett.* **9**, 1155 (1982).

24. URAP is a collaboration of the National Aeronautics and Space Administration's Goddard Space Flight Center, the University of Minnesota, the Observatoire de Paris-Meudon, and the Centre des Etudes Terrestres et Planetaires, Velizy, France. We thank the many people at these institutions who are involved with URAP data analysis, as well as the project, mission operations, and data systems teams at the Jet Propulsion Laboratory and the European Space Agency. The French contributions to this experiment have been funded by the Centre National des Etudes Spatiales and the Centre National de la Recherche Scientifique. We thank A. Balogh and J. L. Phillips for permission to publish the solar wind and magnetic field data presented in Figs. 3, 4, and 5.

2 February 1995; accepted 20 April 1995