prehensible form; and J. Belcher, S. Krimigis, N. Ness, and J. Warwick for helpful discussions concerning the interpretation of the data. Finally, we remember and acknowledge the vital contribution of the late F. L. Scarf, who was principal investigator of the plasma wave team until his death in July 1988. Research at the University of Iowa was supported by NASA through contract 957723 with JPL, and by the state of Iowa through a faculty developmental assignment for one of the authors (D.A.G.). Research at TRW was supported by NASA through contract 957805 with JPL.

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Voyager Planetary Radio Astronomy at Neptune

James W. Warwick, David R. Evans, Gerard R. Peltzer, Robert G. Peltzer, Joseph H. Romig, Constance B. Sawyer, Anthony C. Riddle, Andrea E. Schweitzer, Michael D. Desch, Michael L. Kaiser, William M. Farrell, Thomas D. Carr, Imke de Pater, David H. Staelin, Samuel Gulkis, Robert L. Poynter, André Boischot, Françoise Genova, Yolande Leblanc, Alain Lecacheux, Bent M. Pedersen, Philippe Zarka

Detection of very intense short radio bursts from Neptune was possible as early as 30 days before closest approach and at least 22 days after closest approach. The bursts lay at frequencies in the range 100 to 1300 kilohertz, were narrowband and strongly polarized, and presumably originated in southern polar regions of the planet. Episodes of smooth emissions in the frequency range from 20 to 865 kilohertz were detected during an interval of at least 10 days around closest approach. The bursts and the smooth emissions can be described in terms of rotation in a period of 16.11 ± 0.05 hours. The bursts came at regular intervals throughout the encounter, including episodes both before and after closest approach. The smooth emissions showed a half-cycle phase shift between the five episodes before and after closest approach. This experiment detected the foreshock of Neptune's magnetosphere and the impacts of dust at the times of ring-plane crossings and also near the time of closest approach. Finally, there is no evidence for Neptunian electrostatic discharges.

We first detected Neptune radio bursts on the 229th day of the year 1989 (DOY 229), in the frequency range 700 to 850 kHz. When we reexamined earlier data, we could trace bursts back as far as DOY 207 and as recently as DOY 259 in data complete through DOY 264. The radiation was very intense, narrowband, bursty, and strongly polarized. It was immediately obvious that the bursts were recurring at intervals of 16 hours with some missing episodes. Figure 1 shows the most intense episode of these bursts. They were eventually seen throughout the low-band spectrum, from 100 kHz to its upper limit at 1326 kHz. The intensity of the bursts did not vary as the inverse square of the distance to Neptune. No bursts appeared at higher frequencies than 1326 kHz, which, however, does not necessarily imply that the bursts have a natural cutoff frequency of 1.3 MHz. The threshold detection level for bursts at higher frequencies is nominally 23 dB higher than at lower frequencies.

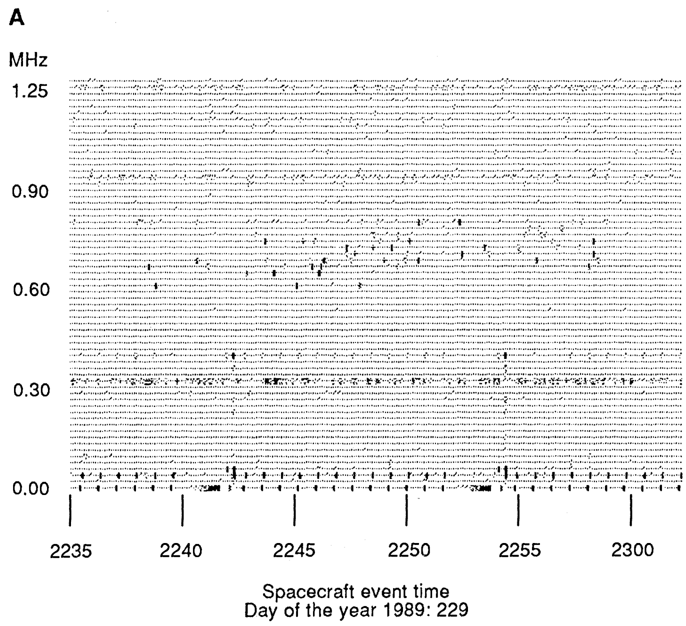
Much interference, often of a rather subtle nature, occurs in this frequency range, and at periods commensurable with Earth's day, 24 hours. It was therefore important to confirm by independent means, as far as possible, that these bursts were produced by Neptune.

We found such evidence in two ways: starting on DOY 229, we also detected smooth emissions at lower frequencies. Their recurrence period was also close to 16 hours. Second, episodes of bursty emission immediately after closest approach were observed to have different apparent polarization (before correction for the effects of the instrument) but, after correction for instrumental characteristics, the same true polarization as before closest approach. When the planetary radio astronomy (PRA) antennas are oriented so that the source direction lies along the positive direction normal to their electrical plane (close to the physical plane of the two monopoles), the PRA instrument measures apparent polarization nearly equal to the true polarization of the incident wave ("true" polarization). The positive direction is on the side of the spacecraft away from the direction in which the telemetry dish beams its radiation; as Voyager approached Neptune, Neptune lay nominally in the hemisphere containing the positive direction. For a source in the opposite direction, along the negative direction, the opposite sign of polarization is measured ("false" polarization). When the source is closer to the electrical plane, the measured polarization depends on the characteristics of the incoming wave. Strongly circularly polarized radiation will in most cases appear to have weaker polarization. These factors exclude the possibility that the bursts were an artifact.

The bursts were strongly polarized in the true left-hand sense both before and after closest approach. Because the spacecraft approached Neptune at a latitude of about 30°S, and because burst polarization has at other planets usually indicated that the burst mode was extraordinary, in the magnetoionic sense of the word, we suggested that the magnetic fields in the burst sources lying close to Neptune's surface in polar regions of the southern hemisphere point toward the surface. The reason that we assumed the burst emission source is close to the surface was that the 1.3-MHz emission gives us a field strength of 0.46 G in the source; if the source were as high as one planetary radius (R_N) above the planet's surface, the resulting planetary dipole strength would have been much greater than any prior estimates (3.7 G-R_N^3). If the field of Neptune has a strong dipole component, then we may conclude that the dipole lies in the same relation to the planetary rotation axis as do the dipole fields of Jupiter, Saturn, and Uranus, but opposite that relation for Earth. This is the orientation of Neptune's dipole found by Voyager's magnetometry (MAG) team (*4*) from field measurements taken outside of a sphere of four Neptune radii centered on the planet. These two determinations therefore suggest that the dipole field is larger than the higher order fields even close to Neptune's surface.

The periodicity of the bursts can be inter-

J. W. Warwick, D. R. Evans, G. R. Peltzer, R. G. Peltzer, J. H. Romig, C. B. Sawyer, Radiophysics, Inc., Boulder, CO 80301.
A. C. Riddle, Cooperative Institute for Research in the Environmental Sciences, Boulder, CO 80309.
A. E. Schweitzer, Department of Physics, Pomona College, Pomona, CA 91711.
M. D. Desch, M. L. Kaiser, W. M. Farrell, Laboratory for Extraterrestrial Physics, Goddard Space Flight Center, Greenbelt, MD 20771.
T. D. Carr, Department of Astronomy, University of Florida, Gainesville, FL 32611.
I. de Pater, Astronomy Department, University of California, Berkeley, CA 94720.
D. H. Staelin, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02319.
S. Gulkis, R. L. Poynter, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109.
A. Boischot, F. Genova, Y. Leblanc, A. Lecacheux, B. M. Pedersen, P. Zarka, Observatoire de Paris, Section d'Astrophysique, 92190 Meudon, France.



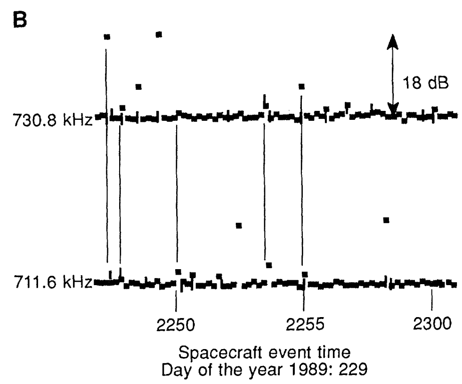


Fig. 1. (**A**) The most intense episode of Neptune bursts. The bursts lie in channels from 157 to 169 (826.8 to 596.2 kHz, inclusive). Even when these bursts are averaged over eight scans, they remain easily visible; this is the modality in which they were first recognized. (**B**) Two channels selected from the middle of those shown in the upper panel. The heavy squares represent 30-ms samples observed at intervals of 12 s in the true left-hand polarized state; vertical bars, the same, in true right-hand polarized state. Note that one burst is observed first in the right-hand and then in the left-hand polarization state. It therefore lasted at least 6 s. During a few of the bursts, corresponding times on the two traces are indicated by vertical bars.

preted in terms of a radio rotation period for the planet. The period is well-defined, 16.11 ± 0.02 hours. There is no time delay or phase shift at closest approach. The bursts before and after closest approach occur with a regular clock period. It may help to think of the burst source as blinking rapidly (as though someone were flicking a light switch on and off) many times during an episode lasting an hour or so. The source emits radiation simultaneously in all directions accessible to the spacecraft.

From DOY 233 until DOY 241, excluding the day of closest approach, DOY 237, we observed about 12 episodes of smooth continuum, at substantially lower frequencies than those of the bursts (Fig. 2). In each episode, the polarization variation repeated itself: mostly in the right-hand polarization sense, preceded and followed by emission in the left-hand sense. The variation of true polarization followed the same pattern throughout the encounter.

It is possible to identify stable features in the polarization variation, for example, the characteristic switch from smooth right-hand polarized emission to smooth left-hand polarized emission late in the episode at higher frequencies. These features permit us to measure the rotation phase more accurately than would otherwise be the case. At 154.8 kHz, the measurements imply a rotation period of 16.10 ± 0.08 hours.

In contrast to the bursty emissions, the smooth emissions showed a phase jump of 8 hours at closest approach. This jump corresponds, as accurately as the measurements can establish it, to the change in longitude of Voyager that occurred virtually discontinuously as the spacecraft flew over the north pole of Neptune. In other words, the smooth emissions occur repetitively at particular subspacecraft longitudes in the Neptune system rotating in the sidereal period of 16 hours.

The times when there was no continuum emission (Fig. 2) correspond to times when Voyager was nearly above the southern hemisphere's dipolar magnetic pole [as established by the MAG team (*4*)]. As Voyager approached Neptune, we observed the bursts during the trailing edge of smooth emissions, when the rotation of Neptune was carrying the magnetic dipole equator across Voyager from southerly to northerly magnetic latitudes. Both of these emissions would originate, if we identify them with radiation near the electron cyclotron frequency, close to Neptune where the field strength lies in the range 0.05 to 0.5 G.

A more detailed interpretation of the Neptunian emissions poses great challenges. The sense of the polarization reversal in the smooth emissions near 00 kHz and its abruptness suggest beamed emission from conjugate sources. But the episodic nature of the high-frequency bursts and the asymmetry of the variations in polarization of the 100-kHz smooth emission require dependence on factors other than the offset-tilted-dipole latitude of Voyager. Possible factors to include might be: the offset between dipole center and planet center, complex magnetic field irregularities described by a multipole model, and asymmetries introduced by solar radiation in the planetary ionosphere or by the interaction of the rotating Neptune magnetosphere with the interplanetary magnetic field.

The smooth emissions and bursts during DOY 237, the day of closest approach, offer particularly difficult challenges for interpretation. It will undoubtedly emphasize not only the complexities of the field but also the complicated relation between PRA apparent polarization and true polarization. In addition, the close-in flyby requires careful attention to source occultations by the planet and its ionosphere. We therefore will not attempt to interpret the bursts and continuum seen on DOY 237 near closest approach.

Data obtained during the outbound ring-plane crossing are shown in Fig. 3. During both ring-plane crossings the PRA instrument detected many particle impacts, as indeed it also did at both Saturn and Uranus. However, the latter two planets produced ring signatures that were minor in comparison with the two Neptune events.

The PRA experiment can operate in many modes, including one in which the instrument observes simultaneously signals in two channels separated by 307.2 kHz each with a bandwidth of 200 kHz and in conjugate states of polarization. The resolution of the data in this mode, called PHIEX, is 140 μs. When the experiment was designed, it was expected that this mode would be used for the detection of planetary lightnings through their associated radio emissions [see (*1*) for details]. During the Neptune encounter, PHIEX was activated periodically, on a daily basis, until the near-encounter phase of the mission when five separate "frames" [corresponding precisely to imaging system (ISS) pictures in the sense that they required 48 s for their acquisition and were stored on the Voyager tape recorder for later playback] were taken.

PHIEX data were acquired near both ring-plane crossings; a characteristic impact is shown in the insert panel of Fig. 3. The rest (POLLO scans) of the outbound ring-plane crossing data, shown in Fig. 3, demonstrate many particle impacts on the spacecraft at this time. We obtained two PHIEX frames near the first ring-plane crossing, which was even more intense. We acquired

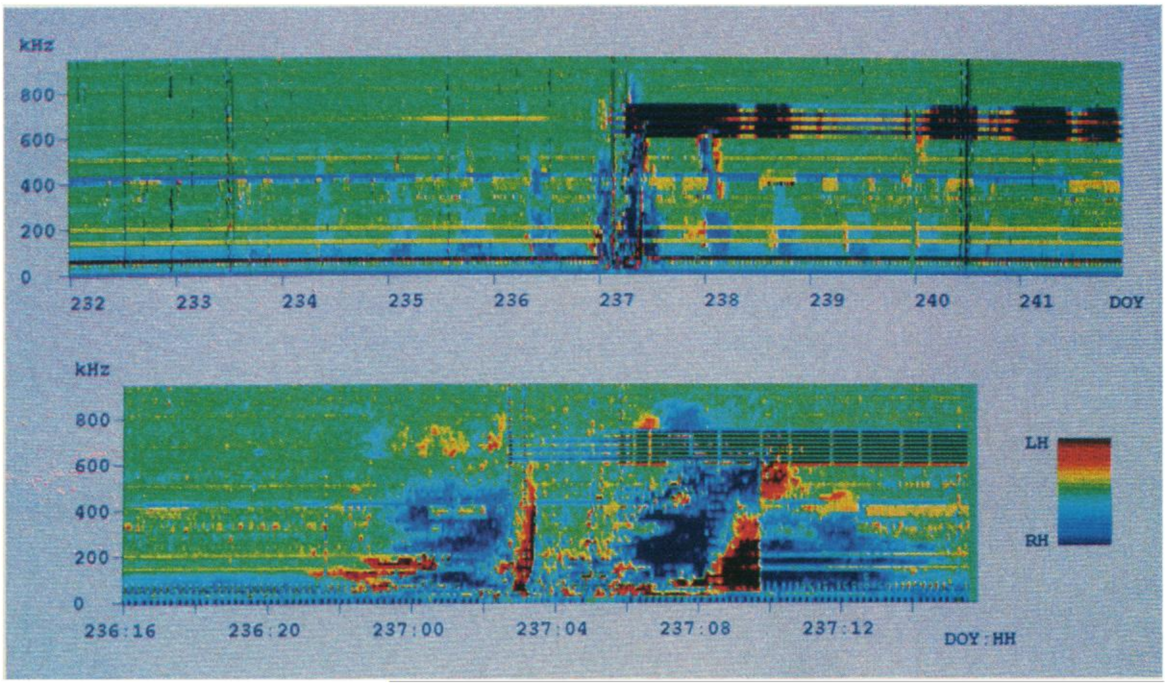


Fig. 2. The episodes of smooth, broadband Neptune emission. The upper panel is a panaromic view of the entire encounter. The timing of the episodes of smooth emission jumps by one-half a cycle immediately at closest approach. The lower panel is an expanded-time version of the emission near closest approach.

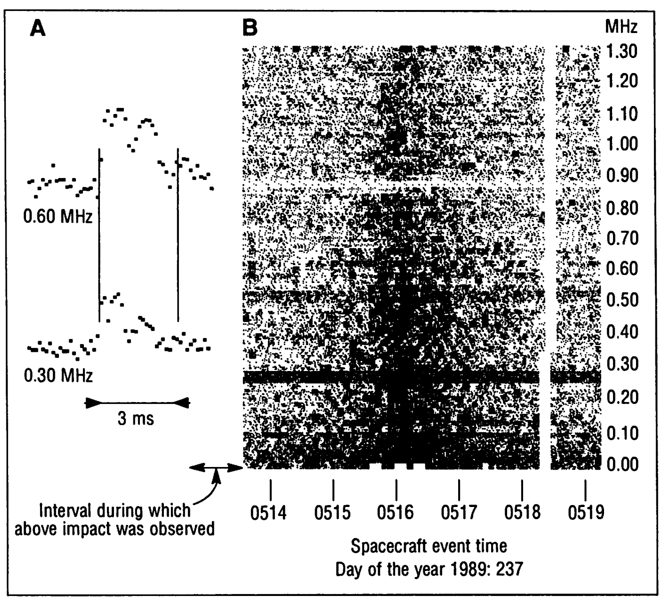


Fig. 3. The outbound ring-plane crossing as seen by PRA. (**A**) The shape of an impact recorded by PRA in its high-rate mode (PHIEX). (**B**) Outbound ring-plane crossing: all impacts. The POLLO data in the frequency range from 1.2 to 1326 kHz.

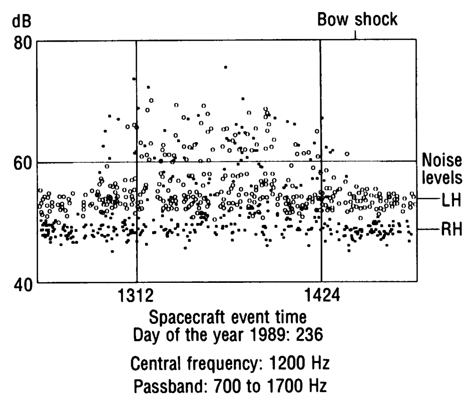


Fig. 4. The inbound foreshock of Neptune as observed by the PRA instrument. These data are from channel 200 (1.2 kHz) on DOY 236 at spacecraft event times shown on the horizontal scale. The time of the bowshock crossing as identified by the MAG team (*4*) is indicated. ■, Right-hand; ○, left-hand.

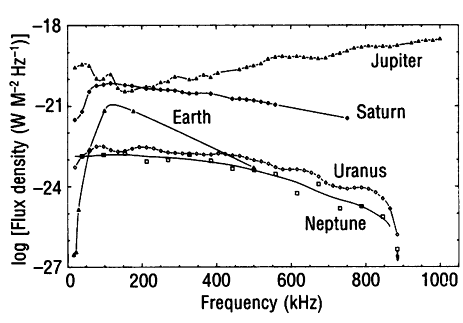


Fig. 5. Peak-flux-density spectrum of the continuum component of the emission from Neptune, the other giant planets, and Earth. These data are adjusted to a distance of 4 A.U. Each of the points (indicated by a square) is the mean of the measured values for three adjacent frequency channels. References for the curves from Jupiter, Saturn, and Uranus are given in (*7*).

two other PHIEX frames during the near-encounter phase, one only 10 min after the time of Voyager's closest approach to Neptune. Both show impacts. No other PHIEX frames, before or after the near-encounter mission phase, show any impacts.

The Plasma Wave Subsystem (PWS), operating in its wave-form mode, also reports dramatic records of particle impacts on Voyager (*5*). Their data represent electrical signatures of impacts on a time scale less rapid than 12 kHz. In distinction to their data, and to complement it, we note that the PRA data concerning particle impacts represent electrical signatures of impacts on time scales in the range 200 to 1000 kHz. The impacts produce PRA patterns that last typically for several milliseconds, as do the PWS impact patterns. However, the electrical fields seen by the PRA instrument are evidently not simply the components at high frequency of a Fourier transform of the PWS signature. In other words, the PRA signature represents the continual presence in the charge-cloud in process of being attached to the antennas of variations on a time scale of no more than 1 μs.

None of the high-rate frames or POLLO scans (low data rate mode) show evidence for lightning discharges.

The Voyager PRA instrument also detected foreshock emissions immediately preceding the inbound bow shock crossing in the instrument's lowest channel, 1.2 kHz (Fig. 4). These "emissions," often called electrostatic noise, as observed at Earth, lie typically within a few tens of percent of the local plasma frequency. During the period when PRA observed electrostatic noise, the Voyager Plasma Subsystem (PLS) recorded electron plasma densities of the order of 0.004 to 0.006 cm^{-3} (*6*). The PRA instrument operates with a passband of 1 kHz, sharply bounded between a lower frequency of 700 Hz and an upper frequency of 1700 Hz. The PLS density values correspond to plasma frequencies from 570 to 697 Hz, slightly less than the lower bound of the PRA band at 1.2 kHz. Figure 4 also suggests that the noise may be somewhat polarized, insofar as there are more strong peaks in the right-hand channel than in the left-hand channel. To draw this conclusion is difficult with the available data, since strong spacecraft interference must first be removed.

Finally, we can now compare the peak intensity of the radio emissions from all the giant planets and from Earth (Fig. 5). Jupiter remains the chief among these, with Saturn in second place, then Uranus, with Neptune close behind. Earth remains the weakest source at frequencies above 500 kHz but is stronger than Uranus and Neptune below.

Both the rotating planetary field and the position of the giant satellite Io time Jupiter's radio emissions. This phenomenon remains unique among the planets. Saturn's kilometric emissions are timed by its rotating magnetic field at phases controlled by an external inertial mechanism, as are Earth's kilometric radiations and Neptune's bursty emissions. Uranus's emissions are timed essentially completely by the rotating planetary magnetic field, as are Neptune's smooth emissions. Neptune appears to be unique insofar as the two types of control both seem to be equally important there. Perhaps a similar pattern of control at Uranus is concealed by its great day-night asymmetry.

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8. This paper represents PRA results at the sixth, and last, Voyager planetary encounter. This accomplishment would have been impossible without the total dedication and competence of Jet Propulsion Laboratory's Voyager personnel working for more than 18 years. It is customary for a team in its encounter report to thank the personnel who made its work possible, but who are not formally team members. The singling out of names must inevitably omit a great many or all of whom were necessary to our success. Nevertheless, we wish particularly to mention P. Liggett and her colleagues of the Voyager Neptune Encounter Science Support Activity (VNESSA) for the extraordinary difference they made at this encounter to our ability to understand the encounter data in near real time. Our work will be published on a schedule that is almost twice as fast than that of any previous encounter; we thank VNESSA for making this possible.

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"—Times the speed of light, squared."