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Voyager 1,2 Plasma Wave Observations for the September 1977 Storm Period

by

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Introduction

The significant interplanetary disturbances of September 1977 occurred soon after the launches of Voyager 1 and Voyager 2, and both spacecraft were still sufficiently close to Earth that the available information is relevant for many solar-terrestrial studies. Recently Bridge et al. [1978] and Acuna et al. [1978] summarized the Voyager 1 and 2 plasma and magnetic field observations for the period September 20-23, 1977. In this brief report, we present a preliminary description of the corresponding plasma wave observations for September 20 (Voyager 2) and for September 21 (Voyager 1 and 2). A more detailed analysis of the wave observations for the entire period, along with plasma and field correlations, will be presented elsewhere.

Background

Each of the Voyager plasma wave instruments utilizes a balanced electric dipole with 7-meter effective length. In cruise, the sensor output is processed with a 16-channel spectrum analyzer covering the range 10 Hz to 56 kHz. The time for a single 16-channel spectral scan ranges from a minimum of 4 sec to a maximum of 96 sec. The Voyager spectrum analyzers do not sample continuously, however, since only two log compressors are used for the full spectral coverage, and there is no peak detection or sample and hold capability. Details of the instrumentation and a full description of the planetary science objectives are given in a recent report by Scarf and Gurnett [1977].

The near-Earth spacecraft trajectories and some aspects of the in-flight plasma wave sensitivity are summarized in Figure 1. Both spacecraft were launched toward the dawn terminator, and for many days in this region the low-energy charged particle instruments and the magnetometers detected intermittent burst of ions and upstream MHD waves from the Earth's magnetosphere [Krimigis et al., 1978]. It appears that these burst events were also associated with detection of upstream ion acoustic waves [Kurth, Gurnett and Scarf, 1978], but in this near-Earth region there were many quiescent intervals that allowed us to evaluate the in-flight sensitivity. We found that the Voyagers are exceptionally quiet spacecraft in the frequency range of interest, and this yields unprecedented sensitivity for short wavelength electric field measurements having $f \lesssim 56$ kHz.

A comparison of the Voyager in-flight threshold levels with corresponding data from Helios-2, IMP-8 and ISEE-1 is contained on the right side of Figure 1. These threshold electric field curves are computed assuming that in all cases the sensor effective length, ℓ(eff) [7 m for Voyager, 15 m for Helios-2, 61 m for IMP-8 and 100 m for ISEE-1] is small compared to a half wavelength, so that $E(\min) = \phi(\min)/\ell(\mathrm{eff})$ is the measured minimum voltage amplitude on the sensor. This means that the comparison of Figure 1 is valid as plotted only for those waves having $\lambda \gg 200$ m.

Even for these longer wavelength oscillations it can be seen that the Voyager sensitivity is exceptional. For instance, in the 30-50 Hz frequency range, the Voyager threshold is approximately 1,000 times lower than that for Helios-2, almost two orders of magnitude lower than the IMP-8 threshold, and approximately equal to the measured threshold for ISEE-1 [Gurnett et al., 1978]. This result could never have been attained if the various in-flight thresholds were associated with detection of the same voltage noise signal from each of the spacecraft or from the essentially identical plasma wave preamplifier systems. In these cases, we would expect to find $E(\min) \times \ell(\mathrm{eff}) \sim$ constant, a result which is actually satisfied fairly well only in the narrow spectral range near 10 kHz.

Of course the relation $E(\min) \times \ell(\mathrm{eff}) \approx$ constant is roughly applicable for all frequencies above about 1 kHz, and we conclude that the truly exceptional aspect of the Voyager sensitivity develops only in the $f \lesssim 1$ kHz region. For instance, when we consider the differences in sensor effective length, we find that $\phi(\min, \mathrm{Voyager}) \approx \phi(\min, \mathrm{Helios\text{-}2})/2000$ at $f = 30$ Hz, and $\phi(\min, \mathrm{Voyager}) \approx \phi(\min, \mathrm{ISEE\text{-}1})/14$ at $f = 10$ Hz. These low noise levels on Voyager are undoubtedly associated with the imposition of an electrostatic cleanliness specification leading to a Faraday shield around the spacecraft, and to the absence of solar arrays which frequently couple noise to the plasma; even before the launch of Voyager, Scarf and Gurnett [1977] discussed the good prospects for a quiet in-flight environment based on the unique characteristics of these RTG-powered spacecraft.

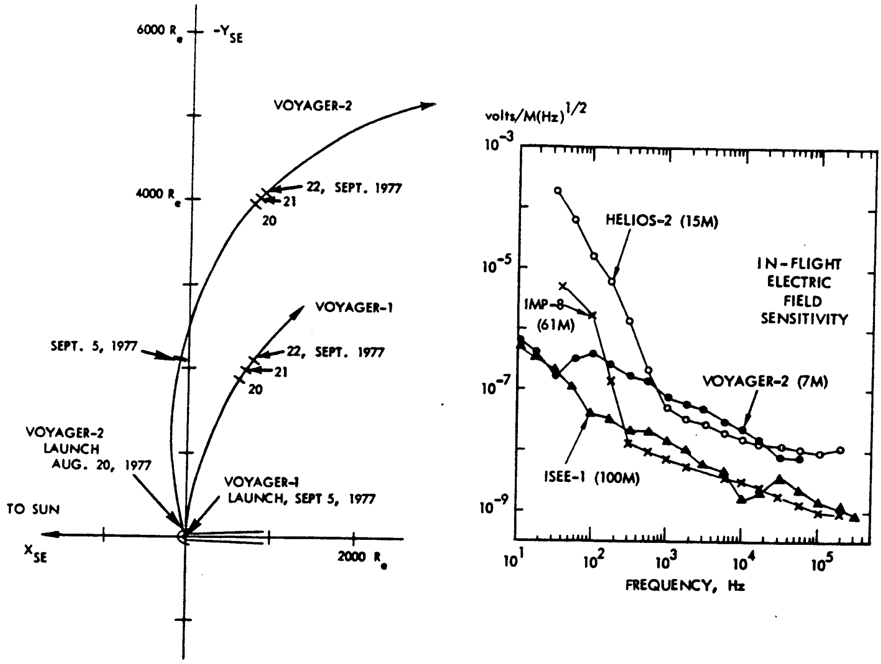

Fig. 1. Left-hand panel: Near-Earth trajectories for Voyager 1, 2: Right-hand panel: Comparison of in-flight threshold levels for several recent investigations utilizing balanced electric dipoles. These levels are computed using $E = \phi/\ell(\text{eff})$, where ϕ is the measured antenna voltage and $\ell(\text{eff})$ is the effective length (given in parentheses). This comparison is strictly valid only for waves having $(\lambda/2)$ large compared to 100m, the ISEE-1 effective antenna length.

The Voyager-2 Plasma Wave Observations

Changes in interplanetary plasma conditions associated with the September storms were first detected on Voyager 2 at 0506 UT on September 20, and Figure 2 shows all of the related plasma wave measurements for the first 12 hours of September 20 and for another interesting 12-h period on September 21. Throughout these intervals both Voyagers were transmitting at their lowest data rates, leading to completion of one spectral scan every 96 sec.

Acuna et al. [1978] identified the initial discontinuity [0506 UT September 20] as a fast forward shock, with a jump in B from 3.6γ to 7.8γ. Thus after 0506 UT, the electron cyclotron frequency was 218 Hz, and we identify the enhanced post-shock noise in all channels up to and including the 178-Hz one as whistler mode turbulence [the few isolated very intense noise bursts in the 10-Hz and 17.8-Hz channels (such as those near 0710, 0800, 1010, 1215 UT on September 20, and 1655 UT on September 21) are thought to be associated with plasma sheath noise impulses as bursts of hydrazine gas are emitted from the attitude control system and then ionized]. On September 21, the discontinuity at 1625 UT yielded an abrupt increase in B to more than 35γ [Acuna et al., 1978], so that the electron cyclotron frequency rose to 980 Hz, just as the enhanced noise appeared in the 311-, 562-, and 1-kHz channels. Once again, the observations are consistent with detection of whistler mode waves in all channels having $f < f_c^-$ for an extremely long period (many hours and days) following the passage of the discontinuity. However, Figure 2 shows also that the onset of turbulence can be quite gradual (as on the 20th) or extremely abrupt (as on the 21st).

Figure 2 shows that very intense and impulsive higher frequency waves were also detected in association with all three discontinuities. These waves are thought to be short wavelength ($\lambda \gtrsim 2\pi\lambda_D$, where λ_D is the Debye length) Doppler shifted ion sound waves (of the type discussed by Gurnett and Anderson [1977], Kurth et al. [1978] and others), and a preliminary analysis supports this interpretation. For instance, just after 0506 UT on September 20, the MIT plasma probe data yielded $V \approx 380$ km/sec, $N \approx 20$ cm^{-3}, $T_+ \approx 2.5 \times 10^4$ °K (J. Sullivan and H. Bridge, private communication) so that f_p^+ (the rest frame ion plasma frequency) was 935 Hz and the proton Debye length was 2.5 m. However, for $T_- \approx 10^5$ °K, the electron Debye length is near 5 m and in this case the Doppler shift, $\Delta f = kV \cos(k,V)$, has a peak value $[\Delta f(\max)]$ of $V/(2\pi\lambda_D) \approx 12$ kHz, thus it is easy to explain the observed signals in all the channels up to and including the 17.8-kHz one, in terms of ion sound wave detection.

Note that $\lambda/2 \approx 15M > \ell(\text{eff})$ for Voyager, so that the amplitude determination made with this short antenna is not in question. However, for $\ell(\text{eff}) \gtrsim 15M$, as it would be for the other sensors discussed above, it is clear that one would have to use $E \approx 2\phi/\lambda$, rather than $E \approx \phi/\ell(\text{eff})$ for these very short waves.

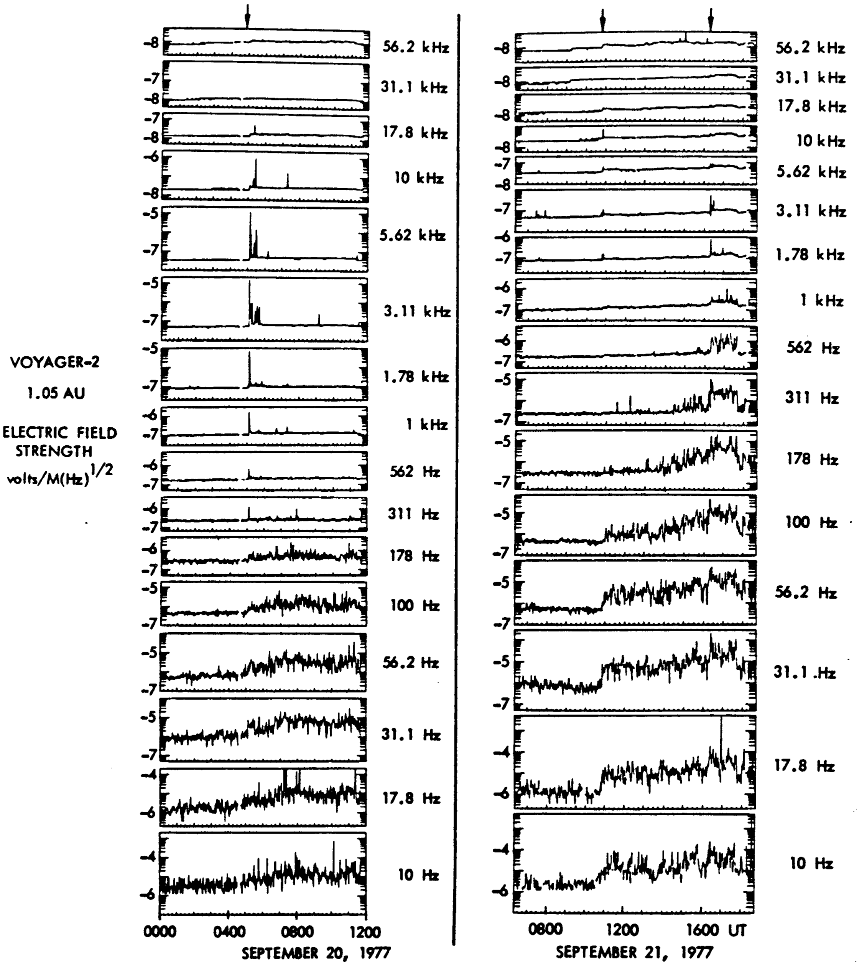

Fig. 2. The Voyager 2 plasma observations for two interesting 12-h intervals, during which three interplanetary discontinuities were detected.

The top two or three panels in Figure 2 show another interesting phenomenon: enhanced levels of high frequency waves (thought to be electron plasma oscillations) were detected for periods extending many hours after passage of the initial shocks. This suggests that the post-shock electron distributions were significantly non-Maxwellian.

Voyager 1 Plasma Wave Observations

On September 20, the Voyager 1 tracking was incomplete and the discontinuity corresponding to the initial 0506 UT Voyager 2 shock was detected near a tracking gap. Therefore, we concentrate on the September 21 discontinuities near 0530 and 1625 UT (another discontinuity was detected at 2220 UT on the 21st). Figure 3 can be used to contrast responses in four Voyager 1 channels with the corresponding channel responses on Voyager 2, and it can be seen that the two instruments measured extremely different wave phenomena on these days. For example:

a) There is no evidence on Voyager 1 for the intense whistler mode noise enhancement detected in the 311-Hz channel on Voyager 2 following the 1625 UT discontinuity.

b) The Voyager 1 discontinuity at 1630 UT appears to signal onset of a quiet period in the 3.1-kHz channel, rather than onset of an interval with enhanced turbulence.

c) The initial Voyager-1 noise increase at 31 Hz (0530 UT) is smooth and gradual in contrast to the abrupt rise in turbulence detected before 1100 UT on Voyager 2.

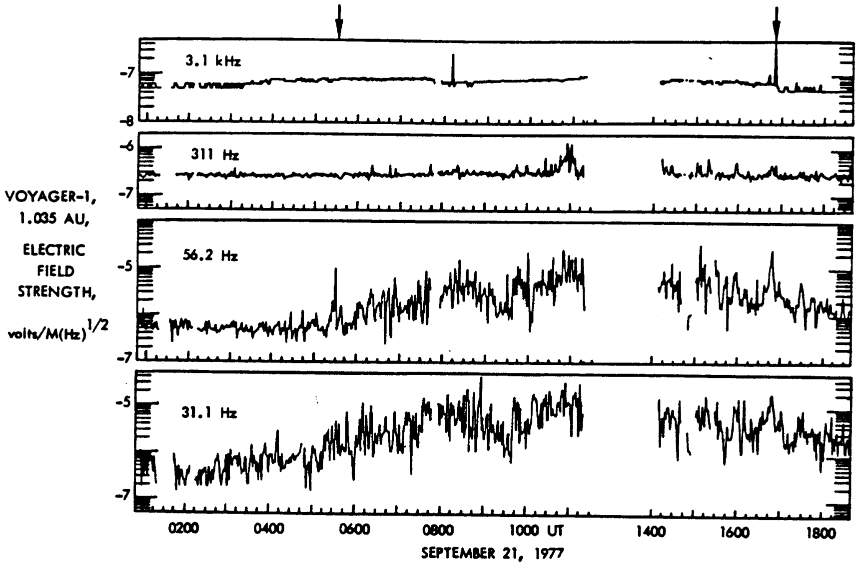

Fig. 3. Some Voyager 1 wave observations for comparison with corresponding plots in Figure 2.

Summary

The September 1977 events provided the first direct information on the response of the Voyager plasma wave instruments to changing interplanetary conditions. We find the first direct confirmation that the intense low frequency electric field turbulence represents detection of whistler mode noise, with f ranging up almost to f_c^-. This Voyager identification is made by noting how the upper frequency of the broadbanded turbulence varies with variations in f_c^-. In fact, the electric field amplitudes can also be related to the earlier Helios 1, 2 measurements of magnetic amplitudes for whistler mode waves [Neubauer et al., 1977] using $E = cB/n$, where n is the computed index of refraction for whistlers. Although we have no direct simultaneous comparisons, the range of Voyager E-field levels does appear to be quite compatible with levels expected using the Helios measurements of magnetic components.

We also find evidence that the impulsive noise burst with $f_p^+ < f < f_p^-$ are indeed Doppler-shifted ion sound waves, and that enhanced levels of electron plasma oscillations are detected for long periods after passage of the shock. These wave measurements also suggest that the local conditions at Voyager 1 and 2 differed greatly during this time period, although the spacecraft-to-spacecraft separation was relatively small (less than 0.1 AU) at this time.

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