Adv. Space Res. Vol. 8, No. 9–10, pp. (9)437–(9)441, 1988
Printed in Great Britain.

0273–1177/88 $0.00 + .50

MULTI-POINT MEASUREMENTS OF ULF WAVE PHASES USING A MULTI-CHANNEL ENERGETIC ION DETECTOR

N. Lin,* M. G. Kivelson,*,** R. L. McPherron,*,**
D. J. Williams*** and T. A. Fritz†

*Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024, U.S.A.
**Department of Earth and Space Science, University of California, Los Angeles, CA 90024, U.S.A.
***Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20707, U.S.A.
†Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.A.

ABSTRACT

The oscillation of differential fluxes of energetic ions modulated by a ULF wave often shows a phase shift between measurements in back-to-back detectors with look directions perpendicular to the ambient magnetic field. In a plasma of a single ion species, the phase difference is caused by displacement of the effective measurement positions by one ion gyroradius to each side of the detector. As the wave phase is periodic, the observed phase shift can correspond to a family of possible wavelengths. Simultaneous measurements of the flux modulations in different energy channels, which are equivalent to measurements of the wave phase at different positions, may allow one to single out a unique wavelength consistent with all the measurements. Using the MEPE (Medium Energy Particle Experiment) instruments of ISEE-1 and 2, each of which may serve as a back-to-back detector, we have applied the above method to a compressional Pc 5 wave observed near the equatorial plane between $L \sim 7$ and 11, and determined unambiguously the transverse propagation properties of the wave.

INTRODUCTION

The propagation characteristics of a ULF wave in the plasma rest frame differ for different types of theoretically predicted waves. To determine which wave generation mechanisms are significant in the magnetosphere, one must characterize the wave properties fully and compare the measurements with the theoretical predictions. However, wavelengths and phase velocity in the plasma rest frame are hard to determine unambiguously. For example, simultaneous measurements from three spacecraft noncolinear in a plane oblique to the magnetic field vector are needed to determine the direction of wave propagation from the phase delays in magnetic perturbations, and such simultaneous measurements are rarely available. Even multipoint measurements remain ambiguous because phases are uncertain by integral multiples of 2π. Hughes *et al.* /1/, measuring phase differences among magnetic signals recorded by three geostationary satellites, were able to determine the propagation direction and estimate the azimuthal wave number, but no information on radial propagation could be obtained from these measurements. Su *et al.* /2/ attempted to determine both the azimuthal and radial components of the propagation vector for a compressional wave at synchronous orbit, making use of finite Larmor radius effects of energetic particles. but they did not consider the $2n\pi$ ambiguity in evaluating the phase velocity. In this report, we determine the perpendicular phase velocity of a compressional wave by using the finite Larmor radius effects in the signature of a multichannel energetic ion detector on a single spacecraft. The method is closely related to that used by Su *et al.* /2/. It was also discussed by Kivelson and Southwood /3/. We have used the medium energy particle detectors on board the ISEE-1 and 2 /4/ whose spin axes were approximately parallel to the ambient magnetic field during the event.

ISEE-1 OBSERVATIONS

The compressional wave reported here was observed between 2145 UT, August 21, 1978, and 0100 UT of the next day. The ISEE-1 magnetometer record for the event is shown in Figure 1. The spacecraft was traveling inbound at $\sim$ 1700 local time from $L \sim 11$ to 7 near the equatorial plane. During the first 2-hour interval, the pulsation was irregular, containing wave periods of 250 s, 165 s and 100 s. Starting at $\sim$ 0100 UT, a quasi-sinusoidal wave with a period of 165 s developed and reached a maximum amplitude in B_z at $\sim$ 0030 UT. Figure 2 shows the proton intensity measured in energy channels 3 to 6 of the detector. Data for the two lowest energy channels were not usable because of interference from another experiment. The smoothed particle flux data show very similar variations to those of magnetic data containing waves with major periods of 250 s for the first two hour interval and 165 s for the quasi-sinusoidal wave after 0000 UT. This suggests that the dominant fluctuations of the particle fluxes were produced by the Pc 5 waves. The magnetic field oscillated out of phase with the variation of the ion intensity (not shown).

DETERMINATION OF THE WAVE PROPAGATION

During the event, the ISEE-1 MEPE instrument was in the low bit rate mode taking samples in eight azimuthal sectors each spin (one sample per sector). Figure 3*a* shows the count rate variation of protons in

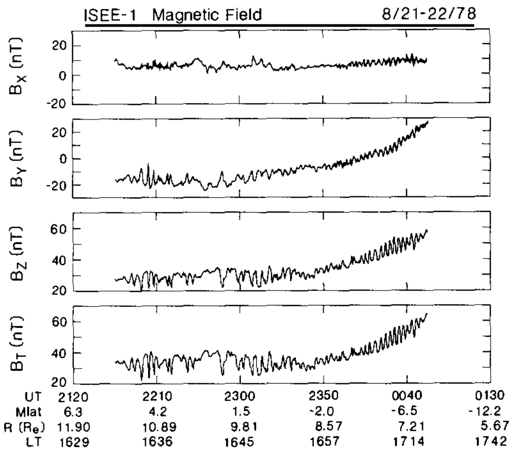

Fig. 1. The magnetic field in GSE coordinates B_T is the total magnetic field.

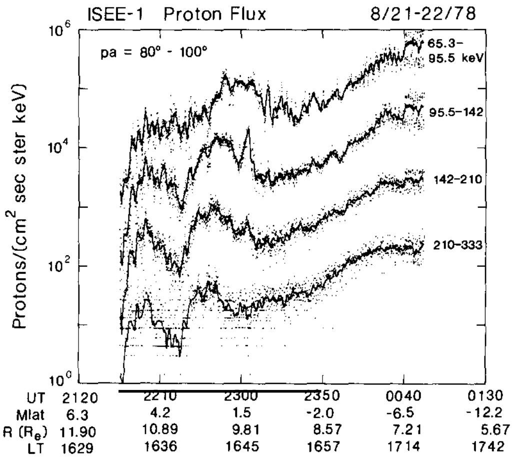

Fig. 2. Spin average of 90° ± 10° pitch angle proton fluxes (scatter plots) overplotted by 80-s running average curves (solid lines). Flux bursts starting near 0040 UT represent interference from another experiment.

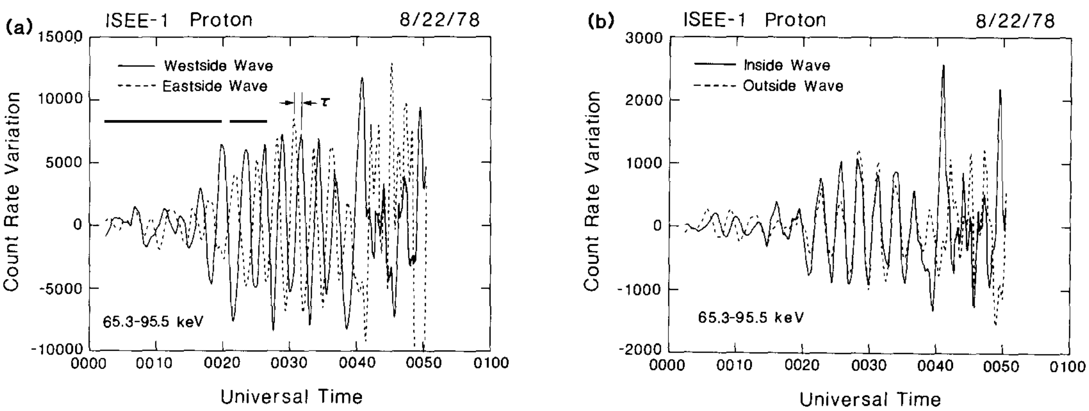

Fig. 3. (*a*) The variation of counts/sector of 90° ± 10° pitch angle protons (65.3 to 95.5 keV) with gyrocenters at the east side (dashed line) and the west side (solid line) of the satellite. Irregular fluctuations after 0040 UT result from interference with another experiment. (*b*) Same as 3*a* but for outside wave and inside wave.

TABLE 1 Possible Wavelengths of Azimuthal Propagation of the 165 s Wave as Determined From Proton Fluxes for the Interval 0020 to 0040 UT (ISEE-1)*

Channel Pair	ΔR, km	Correlation Coefficient	Lag (τ), s	λ_1, km ($n = 0$)	λ_2, km	n
6w–6e	3011	0.78	84	5915	−402	−8
5w–3e	2032	0.85	66	5079	−442	−5
5w–4e	2208	0.82	66	5520	−394	−6
5w–5e	2424	0.68	66	6061	−432	−6
5w–6e	2718	0.73	87	5155	−420	−7
4w–3e	1815	0.87	63	4754	−393	−5
4w–4e	1992	0.81	63	5216	−431	−5
4w–5e	2208	0.77	63	5783	−393	−6
4w–6e	2501	0.76	84	4913	−456	−6
3w–3e	1638	0.91	51	5302	−444	−4
3w–4e	1815	0.86	54	5546	−388	−5
3w–5e	2032	0.73	54	6208	−435	−5
3w–6e	2325	0.76	78	4918	−421	−6
average				5413	419	

*Negative values of λ and n represent eastward propagation of the wave.
In the calculations we have used $B = 50$ nT, wave period $T = 165$ s, and $L = 8$.

channel 3, for the interval 0000 to 0100 UT, 22 August 1978, when the detector was looking radially earthward (solid curve representing the flux variation of protons with gyrocenters to the west of the spacecraft, or the "westside wave"), and outward (dashed curve, the "eastside wave"). The time shift τ between the two waves indicates that the wave propagated azimuthally. The phase velocity of the wave is $V_P = \Delta R/(nT+\tau)$ and the wavelength is $\lambda = V_P \cdot T$, where T is the wave period. The integer n can be greater than or equal to zero (implying westward propagation), or less than zero (implying eastward propagation). It corresponds to the number of wavelengths contained between the two gyrocenters. ΔR is the distance between the two gyrocenters. τ can be obtained from cross-correlation analysis of the two wave forms under investigation.

An apparent time shift τ may correspond to a family of possible phase velocities and thus wavelengths. To remove the uncertainty we used the data in channels 3 to 6 to find a unique wavelength consistent with all measurements (data for channels 7 and 8 were not usable owing to very low count rates). Since each channel provides measurements of wave phases at the gyrocenters of ions at the two sides of the spacecraft, 4 energy channels can provide information about wave phases at eight effective measurement points aligned azimuthally when the detector looks in the radial direction. We have applied cross-correlation analyses to all pairs of proton flux waves measured at two effective measurement points located at different sides of the spacecraft. From solutions thus obtained we select the ones that appear consistent with one another. The results are shown in Table 1. The effective measurement point of each flux oscillation in Table 1 is denoted by the channel number followed by w (the flux of protons whose gyrocenters are west of the spacecraft) or by e (east of the spacecraft). There are two groups of possible wavelengths which are consistent with all pairs of measurements: $\overline{\lambda} = 5413$ km, for $n = 0$ implying westward propagation, and $\overline{\lambda} = 419$ km with negative n, implying eastward propagation. Other solutions corresponding to even smaller wavelengths that may fit all the observations are discarded as they are too small compared to the proton gyroradii for the proton flux to be modulated by the wave field. Using the above two possible wavelengths, we simulated the time variation of fluxes at the 8 effective measurement points x_i as $j_i(x_i, t) = a_i \cos 2\pi(x_i/\lambda \pm t/T)$ where the amplitude a_i is taken as unity, and the wave period $T = 165$ s. The model wave forms are compared to the real flux data. Figure 4a shows that the wave models with $\lambda = 5413$ km agree well with the principal features of the actual data at all effective measurement points, but the model with $\lambda = 419$ km (Figure 4b) is not consistent with all observations; there are obvious phase discrepancies between the models and the data at some measurement points. The above studies show that the wave was propagating westward with a wavelength of about 5400 km and a phase velocity of $\sim$33 km/s, which gives an azimuthal wave number $m \sim 60$ at 8 R_e from the earth. Figure 3b displays the count rate variations of protons in channe 3 when the detector was looking eastward (measuring flux variations for gyrocenters at positions radially earthward of the spacecraft, or the "inside wave") and looking westward (the "outside wave"). The two wave forms are highly correlated and show no time delay. Other channels gave similar results. This implies that the quasi-sinusoidal wave does not propagate radially.

Similar cross corelation calculations for the 250 s wave in the interval 2200 to 2400 UT, (not shown), also indicate westward propagation of the wave with m numbers ranging from 20 to 44 for different channels. The correlations between two wave forms separated radially were poor in all channels. However, the flux variation during the first interval (2155 to 2230 UT) may have a radially earthward component of propagation (the "outside waves" lead the "inside waves" in all channels).

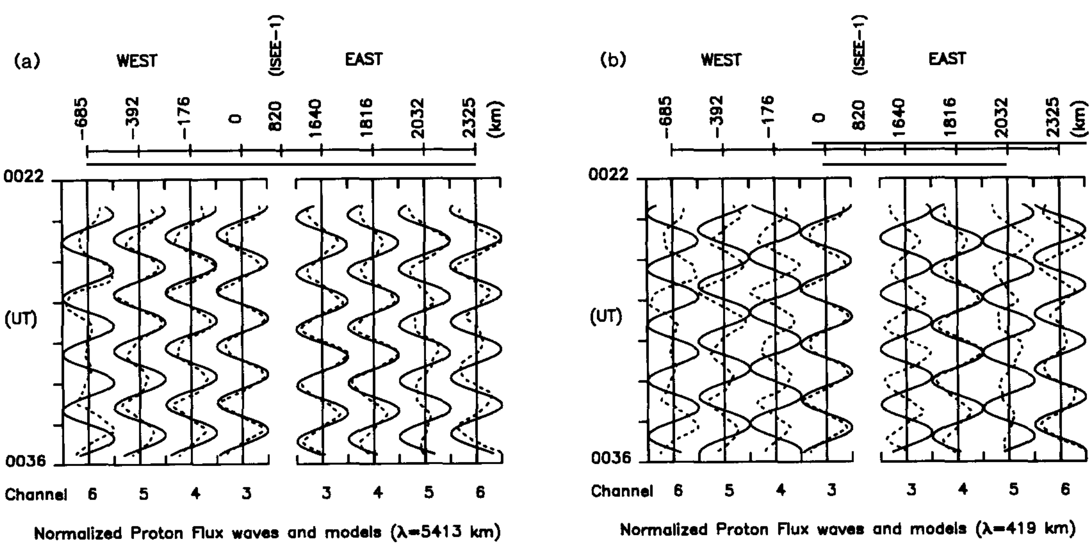

Fig. 4. Comparison of normalized observed proton flux oscillations (dashed lines) at 8 effective measurement points with modeled flux waves (solid lines): (a) for model waves with 5413-km wavelength propagating westward, and (b) for model waves with 419-km wavelength propagating eastward. The model curves are normalized to the data of channel 3w.

ISEE-2 OBSERVATIONS

We have also applied the above technique to proton data from the ISEE-2 MEPE WAPS for the 165-s wave. The WAPS detector took samples in four azimuthal sectors each spin. During this event two of the sectors were approximately radially oriented while the other two were azimuthally oriented. Figure 5 shows as an example proton flux variations observed by the detector looking nearly radially outward. The similarity to ISEE-1 observations is obvious. The phase differences between "westside waves" and "eastside waves" indicating wesward propagation are clear in all channels. This is shown in Figure 6*a* which displays the data of channel 5 as an example. In the radial direction, there was no time delay between "outside waves" and "inside waves" (Figure 6*b*). The results from 11 energy channels of WAPS proton data are listed in Table 2. Data in 9 out of 12 WAPS energy channels give consistent results with calculated m value ranges from $\sim$ 50 to 60, with an average 57 which is in a good agreement with the ISEE-1 result.

SUMMARY

We have demonstrated a technique which determines unambiguously the propagation characteristics of a wave in two orthogonal directions in the plane perpendicular to the background magnetic field. Our results confirm those obtained by Greenstadt *et al* /5/ in earlier study of the same event based on the ISEE-1 and 2 magnetic field data. Greenstadt *et al* merely assumed a purely azimuthal propagation but, with proton data, we are able to distinguish the wave propagation in the azimuthal and the radial directions. In our calculation we have assumed that the measured ions are protons. It has been shown (/6/) that the effect of heavy ions on results in the MEPE measurements is unimportant even a significant fraction of the ions are heavy ions. Possible generation mechanisms of the compressional waves are discussed in paper /6/ where the drift mirror instability and resonance of the wave with particles are suggested as candidates.

TABLE 2 Wavelengths of Azimuthal Propagation of the 165 s Wave as Determined From Proton Fluxes for the Interval 0020 to 0040 UT (ISEE-2)

Channel Pair	ΔR, km	Correlation Coefficient	Lag (τ), s	λ, km ($n = 0$)	m number
1w−1e	948	0.93	15	9145	35
2w−2e	1092	0.91	30	5269	61
3w−3e	1220	0.94	33	5349	60
4w−4e	1362	0.96	33	5974	54
5w−5e	1522	0.97	42	5240	61
6w−6e	1704	0.98	45	5478	59
7w−7e	1924	0.98	48	5797	55
8w−8e	2175	0.93	48	6556	49
9w−9e	2464	0.84	60	5942	54
10w−10e	2800	0.89	78	5194	62
11w−11e	3400	0.95	63	7811	41

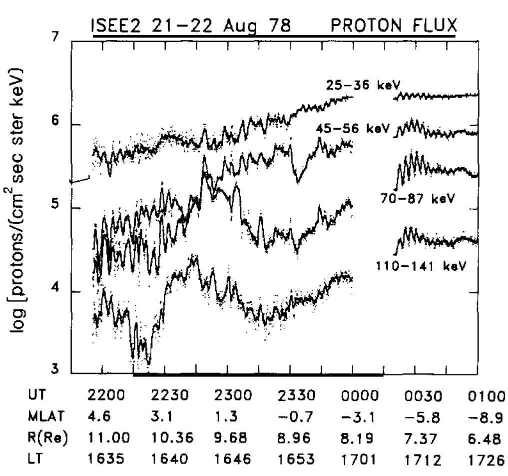

Fig. 5. Flux variations of $\sim 90^\circ$ pitch angle protons (scatter plots) observed by ISEE-2, overplotted by 80-s running average curves (solid lines).

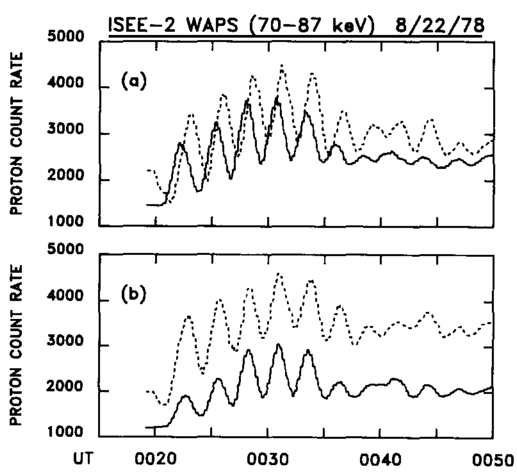

Fig. 6. (*a*) Comparison between the count rate of protons with gyrocenters at the westside (dashed line) and the eastside (solid line) of ISEE-2. (*b*) Same as 6*a* but for inside wave (dashed line) and outside wave (solid line).

ACKNOWLEDGMENTS

Work at UCLA has been supported by NSF grant ATM 87-21904, JPL contract 955232, NASA NGL-05-007-004, and ONR N00014-85-K-0556. Work at Johns Hopkins University is supported by NSF Atmospheric Science Section, grant ATM 8219436 to JHU/APL, NASA contract to JHU/APL, and the Department of the Navy under task I2UOS10, contract N00039-87-C-5301. Work at Los Alamos is supported by NASA Order No. S-12424.

REFERENCES

1. Hughes, W. J., R. L. McPherron, J. N. Barfield, and B. H. Mauk, *Planet. Space Sci.* *27*, 821, 1979.
2. Su, S.-Y., A. Konradi, and T. A. Fritz, *J. Geophys. Res.*,*82*, 1859, 1977.
3. Kivelson, M. G., and D. J. Southwood, *J. Geophys. Res.*,*88*, 174, 1983.
4. Williams, D. J., E. Keppler, T. A. Fritz, B. Wilken, and G. Wibberenz, *IEEE Trans. Geosci. Electron.*, *GE-16*, 270, 1978.
5. Greenstadt, E. W., R. L. McPherron, M. M. Mellott, R. R. Anderson, and F. L. Scarf, *J. Geophys. Res.*, *91*, 13,398, 1986.
6. Lin, N., R.L. McPherron, M.G. Kivelson, and D.J. Williams, *J. Geophys. Res.*, *93*, 5601, 1988.