Mem. Natl Inst. Polar Res., Spec. Issue, **48**, 121–133, 1987

CONJUGATE STUDIES OF HYDROMAGNETIC WAVES

L. J. LANZEROTTI

AT & T Bell Laboratories, Murray Hill, New Jersey 07974, U.S.A.

Abstract: Geophysical studies at conjugate points on the surface of the Earth have played an important role in discovering and elucidating plasma processes in the Earth's magnetosphere. Prof. T. NAGATA has long been an advocate of the importance of conjugate research in studying space phenomena. This review discusses early studies of hydromagnetic waves at conjugate points, including some of the important work of NAGATA and his colleagues and students. This paper also briefly reviews selected important work of the last decade and notes where some advances can be expected in the future at very high and very low latitudes.

1. Introduction

It is a pleasure for me to contribute on this topic to the Nagata Symposium on Geomagnetically Conjugate Studies which was held during the XIX Meeting of the Scientific Committee on Antarctic Research (SCAR). Prof. T. NAGATA has been a most important proponent and advocate of the unique insights of space plasma phenomena which can be obtained by conjugate studies. The early work by him and his colleagues and students established the importance of conjugate studies for hydromagnetic waves and, indeed, provided the framework for the interpretation of such data for many years. This paper, then, is my selective and abbreviated review of some of the history of this research area. I also comment briefly upon some current interesting problems which I consider important ones to pursue. The paper is adapted from a talk on this topic presented at SCAR XIX.

Research on what are now called hydromagnetic waves was given a significant observational foundation by the early work of SUGIURA (1961a, b), where he showed that at one location (College, Alaska) the locus of the measured magnetic variation projected onto the horizontal plane gave a clear polarization pattern (Fig. 1) in the case of an obvious, approximately 8-min quasi-sinusoidal oscillation of the field amplitude. SUGIURA concluded that his results confirmed the prediction of ALFVÉN (1942, 1950) of the existence of "electromagnetic-hydromagnetic" waves and the subsequent considerations of others, particularly DUNGEY (1954, 1955), as to the hydromagnetic nature of geomagnetic field fluctuations SUGIURA's result stimulated much of the subsequent conjugate work, carried out intensively in Alaska, Canada and Japan. Indeed, soon thereafter several authors (*e.g.*, SUGIURA, 1961a, b; WILSON and SUGIURA, 1961; WESCOTT and MATHER, 1963) pointed out that since geomagnetic field fluctuations could be interpreted as resonant oscillations of a geomagnetic field line (the plasma conditions must be such that the wave lengths of the hydromagnetic waves are

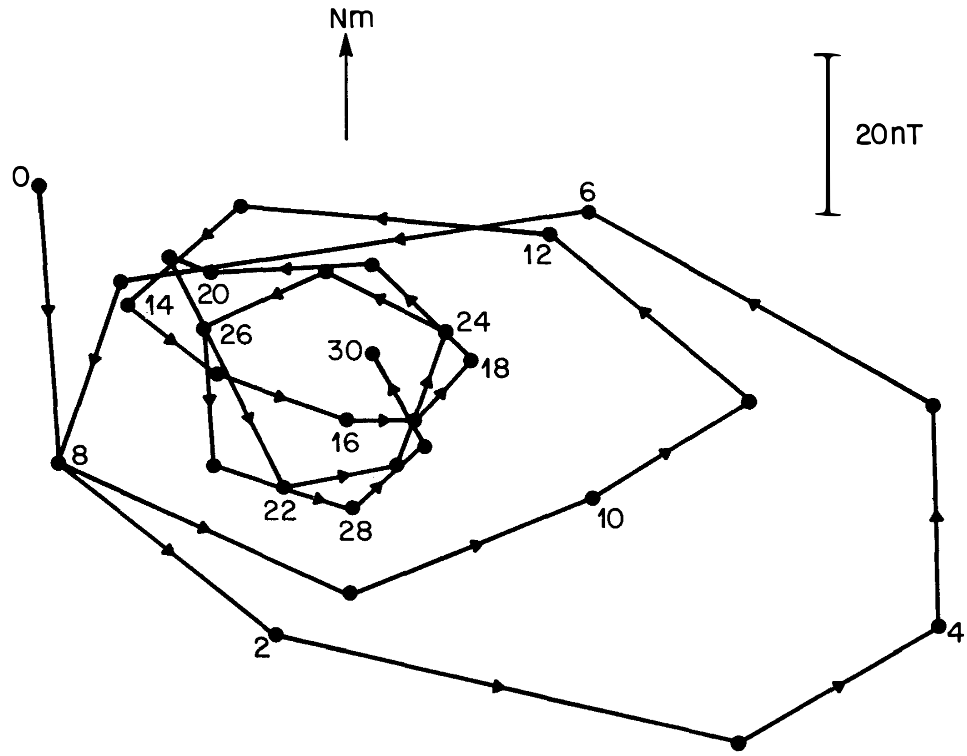

Fig. 1. *Locus of the end point of magnetic field vector in the horizontal plane as measured at College, Alaska, on 4 April 1960. The points plotted are separated by one minute and begin at 0459 UT. (From* SUGIURA, *1961a).*

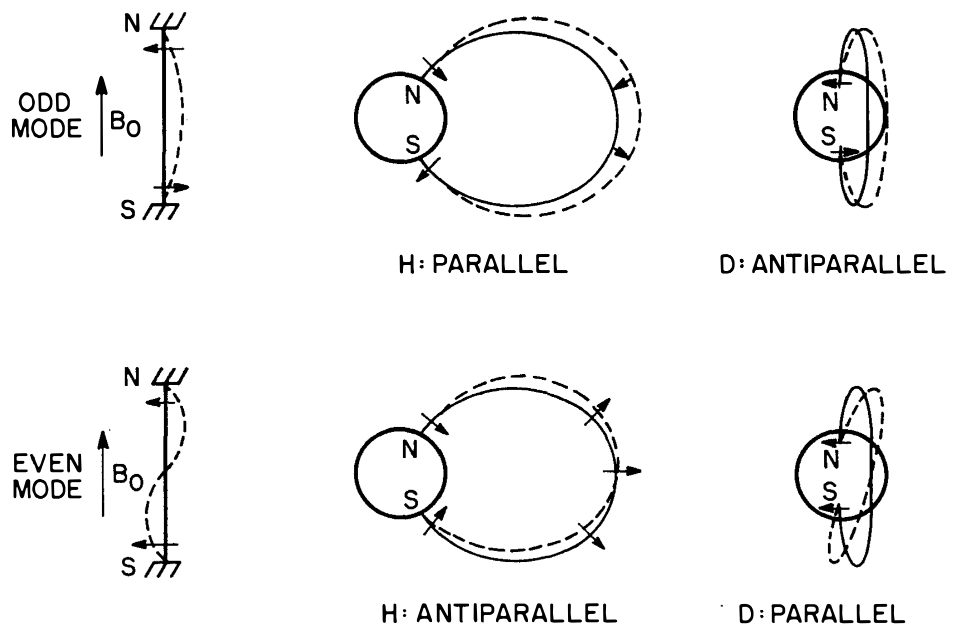

Fig. 2. *Symmetry relations at magnetically conjugate points for oscillation of a line of magnetic force. H is the horizontal, north-south component; D is the east-west component. The arrows give the direction of magnetic perturbation. (From* SUGIURA *and* WILSON, *1964).*

comparable to a field line length), similar polarizations and amplitude variations should be seen at opposite ends of a magnetic field line (*i.e.*, at conjugate points).

An explanatory sketch originally developed by SUGIURA and WILSON (1964) that remains a reasonable conceptual visualization of the magnetic field line motion is shown in Fig. 2. The frequencies of the hydromagnetic waves describable in terms of the concepts of Fig. 2 range from the order of 1 mHz to the order of a fraction of a Hertz. The upper frequency limit is determined by the physics of the problem: ion cyclotron waves in the magnetosphere typically have frequencies around 1 Hz; the hydromagnetic regime extends to lower frequencies (see, *e.g.*, LANZEROTTI and SOUTHWOOD, 1979). The hydromagnetic wave frequency band is broken into sub-bands for convenience. These are listed in Table 1. At the present stage of research, there are few, if any,

Table 1. Classification of geomagnetic pulsations (hydromagnetic waves).

Designation		Frequency range, Hz
	Continuous pulsations	
Pc 1		0.2–5
Pc 2		0.1–0.2
Pc 3		0.0222–0.1
Pc 4		$6.67 \cdot 10^{-3}$–$2.22 \cdot 10^{-2}$
Pc 5		$1.67 \cdot 10^{-3}$–$6.67 \cdot 10^{-3}$
Pc 6		$<1.67 \cdot 10^{-3}$
	Irregular pulsations	
Pi 1		0.025–1
Pi 2		$6.67 \cdot 10^{-3}$–$2.5 \cdot 10^{-2}$
Pi 3		$<6.67 \cdot 10^{-3}$

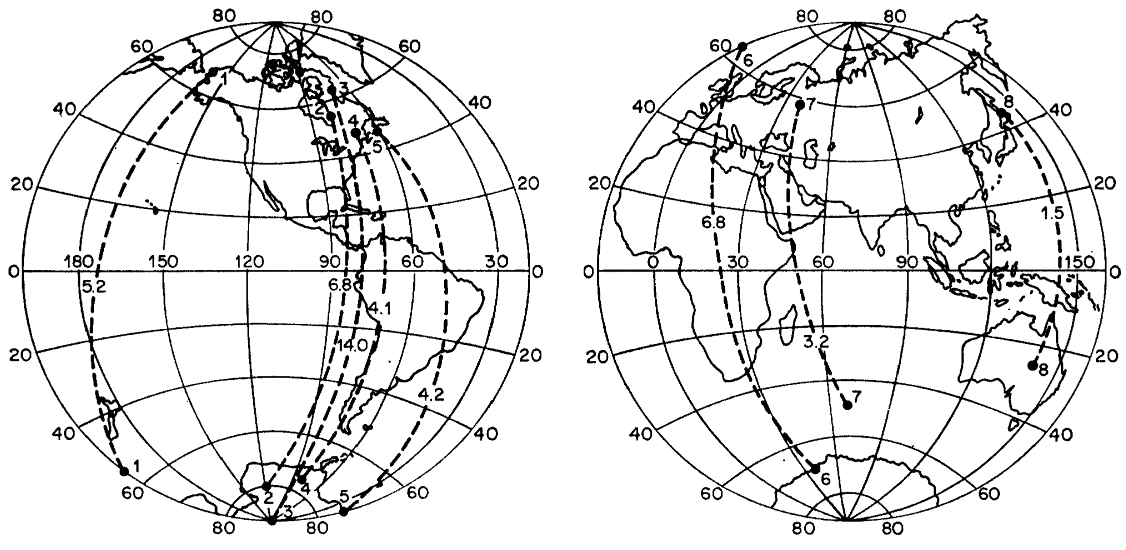

Fig. 3. Some magnetoconjugate pairs in the Western (left) and Eastern (right) hemispheres: 1. Kotzebue, Alaska–Macquarie Island. 2. Great Whale River–Byrd Station. 3. Frobisher Bay–South Pole. 4. Roberval–Siple Station. 5. St. Anthony, Newfoundland–Halley Bay. 6. Reykjavik, Iceland–Syowa Station. 7. Borok, U.S.S.R.–Kerguelen Island. 8. Moshiri, Japan–Birdsville, Australia. Approximate mean L-values are shown. (Adapted from WESCOTT, 1966).

differences in the fundamental physical processes involved at conjugate areas with the various bands.

Early conjugate studies of geomagnetic phenomena investigated magnetic field fluctuations which covered both the $\sim$1 Hz waves as well as the lower frequency waves (*e.g.*, ANNEXSTAD and WILSON, 1968; YANAGIHARA, 1963; LOKKEN *et al.*, 1963; JACOBS and WRIGHT, 1968; general review of conjugate phenomena by WESCOTT, 1966). Selected pairs of stations where conjugate studies have been carried out in the past are shown in Fig. 3, adapted from the review by WESCOTT (1966). The mean L-values of the conjugate pairs are indicated. The principle pairs being used today for magnetosphere research, particularly for studies of hydromagnetic waves, are Siple/Roberval, South Pole/Frobisher Bay, and Syowa/Reykjavik. The importance of the Antarctic continent for conjugate studies is evident from the maps of both Figs. 3 and 4. In Fig. 4, the Antarctic continent has been mapped into the northern hemisphere along geomagnetic field lines. The locations of the above noted three conjugate pairs are

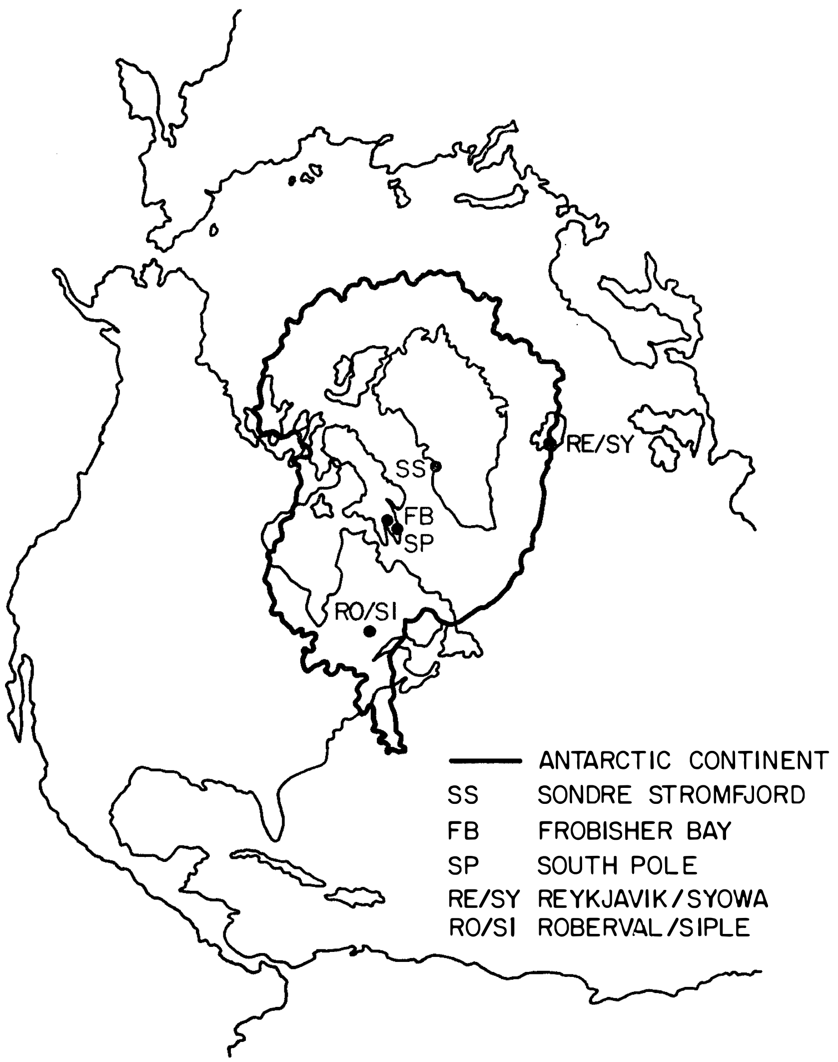

Fig. 4. Mapping of the Antarctic Continent into the Northern Hemisphere. Locations of selected stations in both hemispheres are shown.

indicated, as is the station in Sondre Stromfjord, Greenland, where an incoherent scatter radar is sited. However, because of the secular change of the geomagnetic field, the conjugate areas slowly change with time. STASSINOPOULOS *et al.* (1984) have discussed this change in the case of the Siple/Roberval conjugate pair.

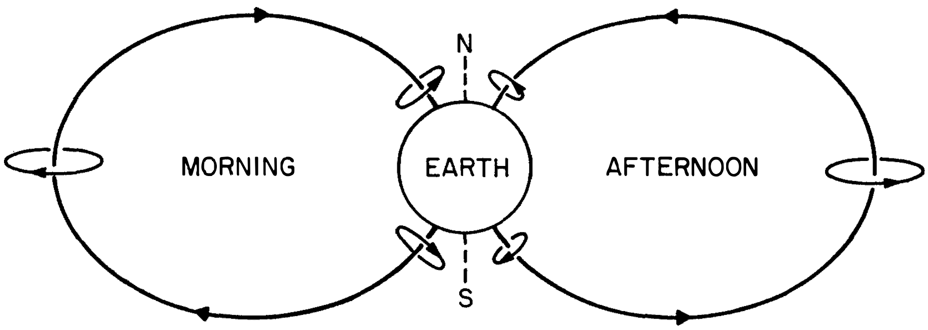

Fig. 5. Rotation of polarization vector of low frequency hydromagnetic waves corresponding to magnetic pulsations viewed from the sun. (From NAGATA et al., 1963).

In the August 1, 1963 issue of the Journal of Geophysical Research, a letter by Prof. T. NAGATA and his two colleagues, S. KOKUBUN and T. IIJIMA appeared which provided a key conceptual foundation for hydromagnetic wave phenomena for the next decade and more (NAGATA *et al.*, 1963). This letter was followed by a more detailed report appearing as Chapter 5 of the Scientific Reports Series A, No. 3 from the Japanese Antarctic Research Expedition 1956–1962 (NAGATA *et al.*, 1966). The observational advance in the NAGATA *et al.* (1963) work was the use of rapid-run magnetograms from each hemisphere, and therefore the capability of analyzing more wave events in the Pc 5 frequency range. The conceptual advance was summarized in their Fig. 5, reproduced here also as Fig. 5. Their results showed that the wave events could be "consistently interpreted as due to elliptically polarized hydromagnetic waves generated in the magnetosphere and propagated along the line of force toward its intersection with the Earth". Further, NAGATA *et al.* (1966) noted that the sense of polarization reversed around local noon and that "the sense of rotation of the polarization vector near the magnetic equator in the magnetosphere is as if the rotation is generated by hydromagnetic shear caused by the solar wind blowing outside the geomagnetic cavity in the sun-Earth direction".

Much important work followed in the next years, including proposals for the Kelvin-Helmholtz instability at the magnetopause as the driving mechanism for the waves (see, in particular, ATKINSON and WATANABE, 1966) and detailed studies of the latitude and local time dependence of polarization reversals, using a latitudinal array of stations in the northern hemisphere (SAMSON *et al.*, 1971). A review of conjugate work on hydromagnetic waves through much of the 1960's was presented by CAMPBELL (1968) while more general reviews were published by TROITSKAYA (1967), TROITSKAYA and GUL'ELMI (1967), SAITO (1969), JACOBS (1970).

2. Conjugate Studies Near the Plasmapause

For a number of years in the 1970's a series of four magnetometer stations were

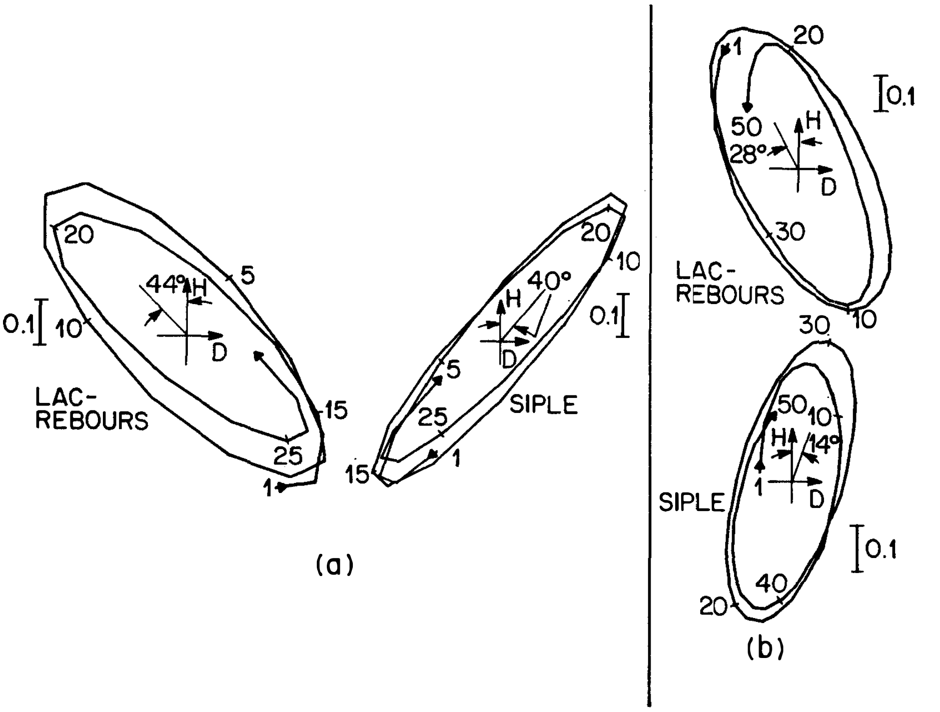

Fig. 6. *In each set of hodograms, five points correspond to 10 s. (a) Odd mode Pc 3 event observed on 17 December 1970. (b) Even mode Pc 3 event observed on 11 January 1971. (After* LANZEROTTI *et al., 1972).*

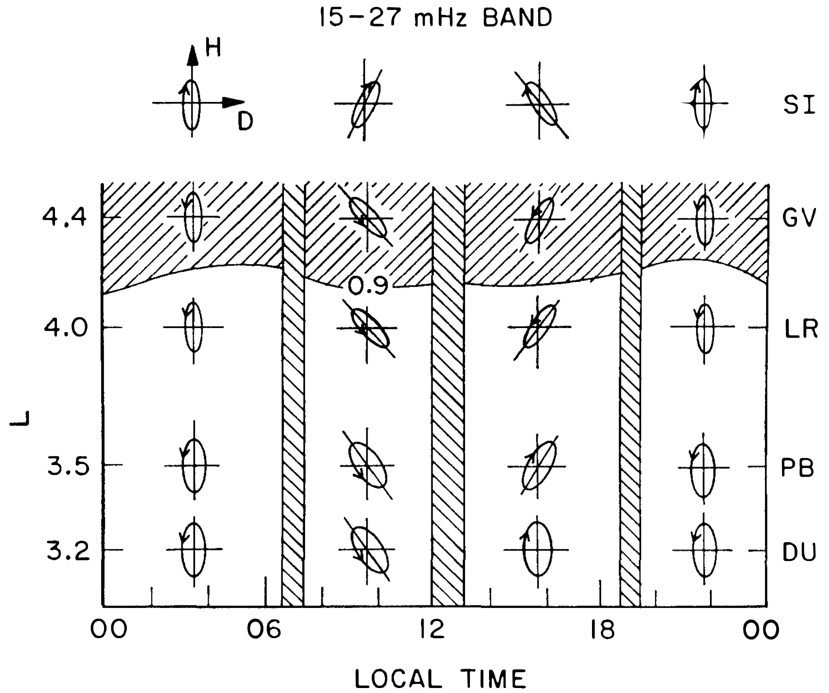

Fig. 7. *Schematic representation as a function of local time of the average 0.9 relative power contours and ellipticities and tilt angles in the H-D plane for the 15–27 mHz frequency band. The stations DU (Durham, N.H.), PB (Pittsburg, N.H.), LR (LacRebours, Quebec), and GV (Girardville, Quebec) are spaced in latitude in the Siple Station (SI) conjugate area. (From* LANZEROTTI *et al., 1976b).*

spaced in latitude in the nominal conjugate area of Siple Station (LANZEROTTI *et al.*, 1972). A student of NAGATA's from the University of Tokyo, H. FUKUNISHI, played an important role in the analyses and interpretations of these data. An important observational issue in the mid-1970's was the mode of a "typical" hydromagnetic wave event as deduced from conjugate observations. A review by LANZEROTTI and FUKUNISHI (1974) concluded that, to the date of the reviewed literature, most wave events reported in the literature could be interpreted in terms of an odd-mode oscillation of the geomagnetic field line (Fig. 2) rather than a even mode. Nevertheless, they showed an example of each type of event from the Siple/Quebec conjugate study, reproduced here as Fig. 6. Subsequent published work on a large body of Siple/Quebec conjugate data confirmed this conclusion and presented summary plots showing dominant polarizations, ellipticities, and orientations of the major axes (FUKUNISHI *et al.*, 1974a, b; LANZEROTTI *et al.*, 1976a, b). Figure 7 presents a summary of the results in the Pc 3 band as a function of local time.

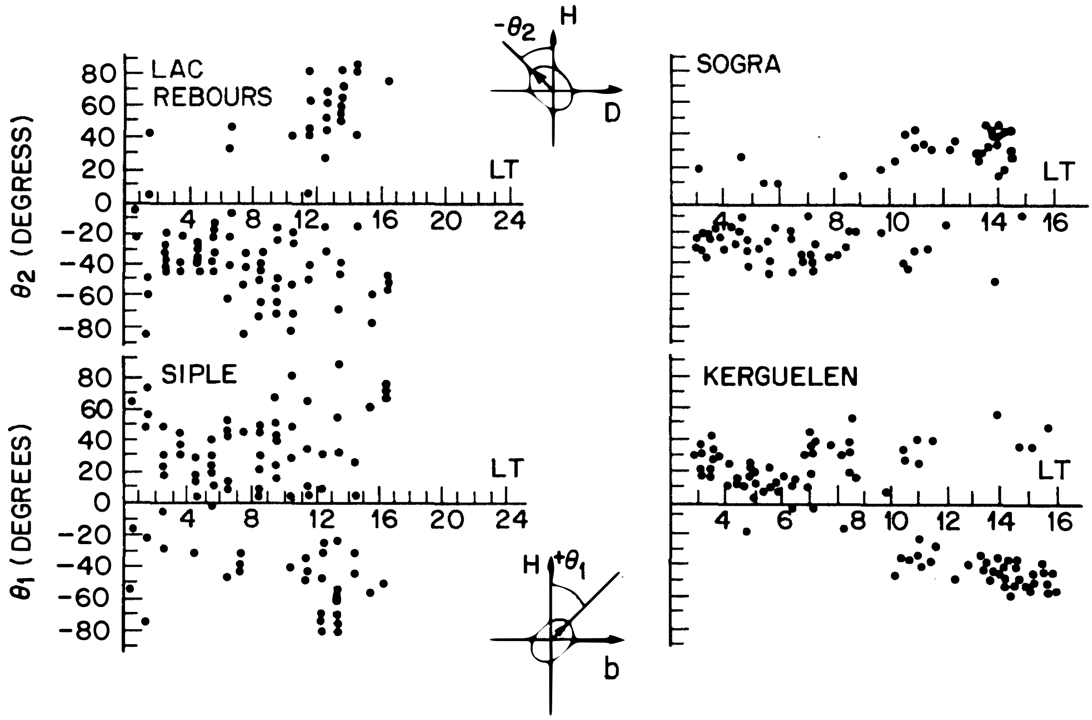

Fig. 8. Diurnal variation of the major axis orientation of the H-D plane polarization ellipses at the two sets of conjugate points. A rotation to the northeast is positive; to the northwest is negative. (After RASPOPOV and LANZEROTTI, 1976).

RASPOPOV and LANZEROTTI (1976) summarized the near-plasmapause results obtained in two widely-separated conjugate areas, Siple/Quebec and Kerguelen/Sogra, and demonstrated that the western hemisphere results were not unique. For example, their summary results of Fig. 8 show that, on a statistical basis, a similar local time dependence of the orientation of the major axis of the polarization ellipse is observed at the two sets of stations. The magnetometer array work and the conjugate studies around the world provided some of the major impetus for new theoretical ideas on the production of hydromagnetic wave resonances in the magnetosphere (CHEN and HASEGAWA, 1974a, b; SOUTHWOOD, 1974; RADOSKI, 1974).

In recent years it has become clear from detailed spectral analysis studies of both spacecraft and ground-based data that the resonant structure of hydromagnetic waves in the magnetosphere is more complex than the simple picture of Fig. 2 would suggest. In particular, it is now evident that under certain, as yet not well-known, conditions, higher order harmonics of the fundamental standing wave are observed (*e.g.*, TAKAHASHI and McPHERRON, 1982; TAKAHASHI *et al.*, 1984; ENGEBRETSON *et al.*, 1986). Analyses of conjugate data from the Syowa/Reykjavik pair have played an important role in these studies of the harmonic structure of magnetospheric hydromagnetic waves (TONEGAWA and FUKUNISHI, 1984; TONEGAWA *et al.*, 1985).

3. Conjugate Studies at Near-Cusp Latitudes

In the last year or two the attention of several U.S. investigators has turned to studies of magnetospheric cusp-related geophysical phenomena. A "Cusp Lab" was established at South Pole Station and WOLFE *et al.* (1986) and R.L. ARNOLDY and his colleagues (ARNOLDY *et al.*, 1986) have begun measurements at Frobisher Bay and at Sondre Stromfjord to study cusp-related hydromagnetic phenomena in opposite hemispheres. One major objective of these investigations is to understand problems of energy transfer from the solar wind, because these conjugate stations, during local

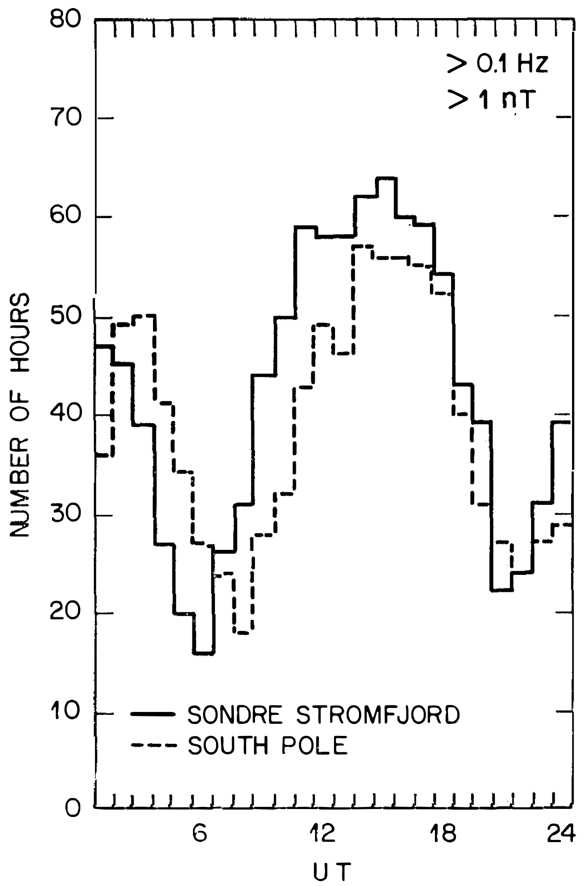

Fig. 9. Number of hours of observance of Pc 1 and Pc 2 activity with >1 nT amplitude as a function of UT at Sondre Stromfjord and at South Pole during equinox conditions in 1984. (From R. L. ARNOLDY, private communication).

day, usually lie close to the magnetopause (or in the dayside polar cap). Other objectives include the determination of methods for identifying the cusp from hydromagnetic activity, and basic studies of magnetospheric conjugacy at such high geomagnetic latitudes.

An example of Pc 1–Pc 2 activity during equinox conditions as studied by R.L. ARNOLDY and his colleagues at South Pole and Sondre Stromfjord is shown in Fig. 9. The number of hours of wave activity is found to be larger in the northern hemisphere in the pre-noon hours.

WOLFE *et al.* (1986) have reported the local time dependence of geomagnetic power

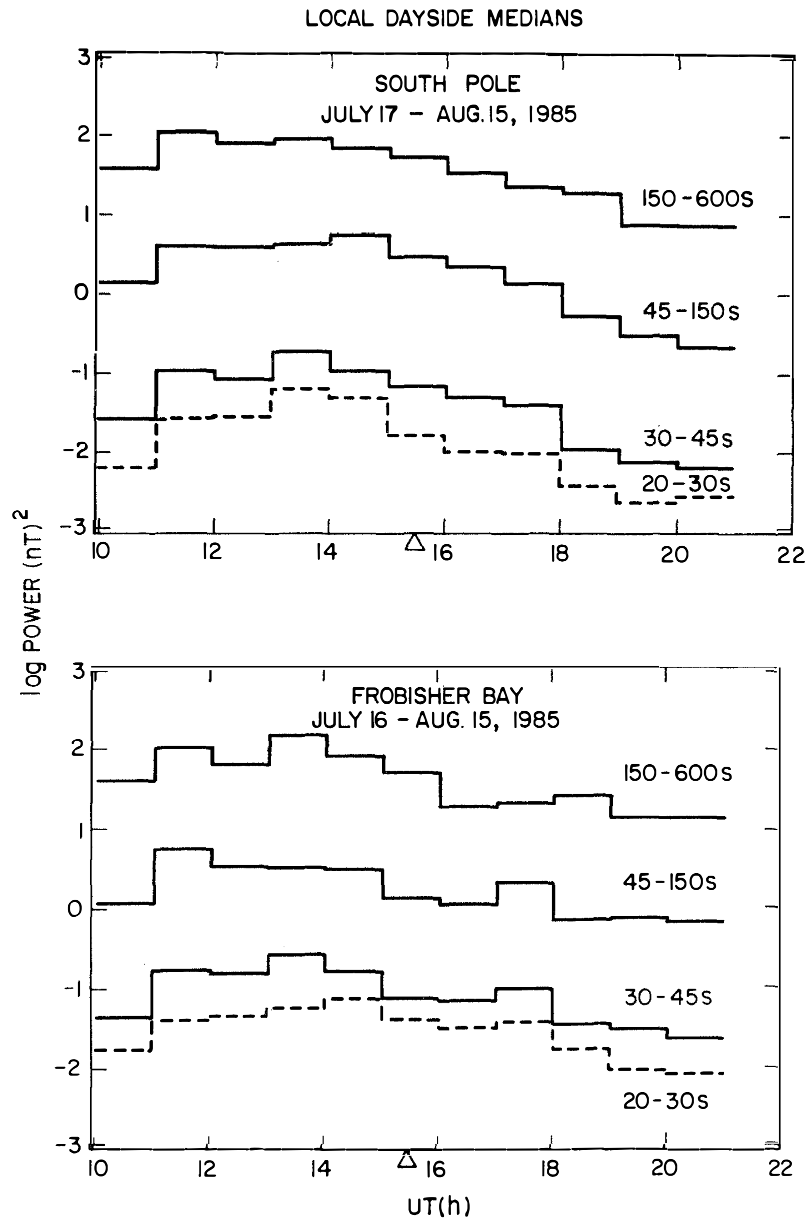

Fig. 10. Hourly median geomagnetic power levels during local daytime hours, in four period bands, for Frobisher Bay and South Pole. The open triangle signifies local geomagnetic noon at South Pole.

in four period bands from 20–600 s at cusp latitudes. These results for more than a month of overlapping data from South Pole and from Frobisher Bay are shown in Fig. 10. The power levels and local time dependence are very similar at these two stations, with higher powers occurring in all four bands at both stations during local morning hours. The nearly identical power levels and local time dependence indicate that there is good conjugacy on the average during local daytime hours between these two very high latitude stations.

Finally, work has begun at the South Pole/Frobisher Bay conjugate pair to study

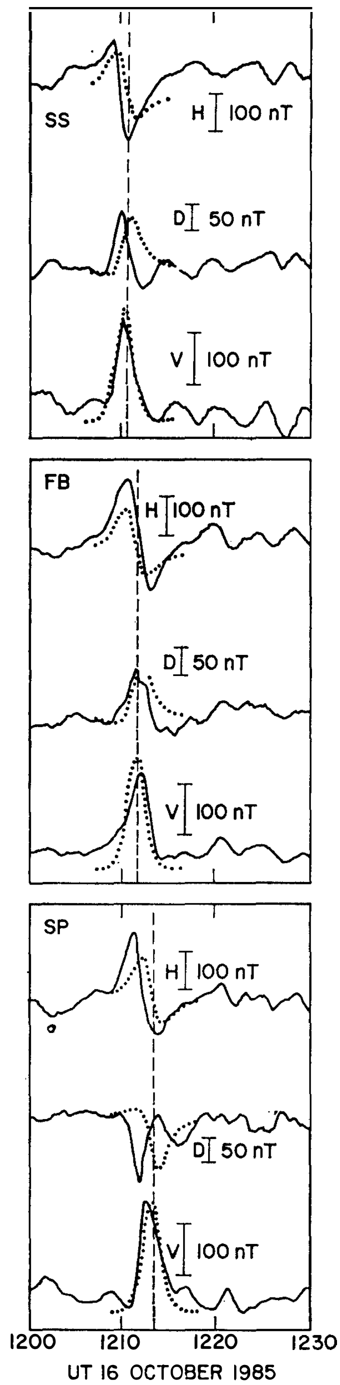

Fig. 11. Magnetic field data from Frobisher Bay (FB), Sondre Stromfjord (SS) and South Pole (SP) during an intense field-aligned current event. The dotted lines represent model fits to the event at each site. (From LANZEROTTI *et al., 1987).*

possible ionosphere evidences of magnetic field flux transfer events in the high latitude dayside magnetosphere (LANZEROTTI *et al.*, 1986). Illustrated in Fig. 11 are magnetic field data from South Pole, Frobisher Bay and Sondre Stromfjord during an interval when a large perturbation was observed at all three stations (LANZEROTTI *et al.*, 1987). Such perturbations have been proposed to be indicative of field-aligned currents being convected over the stations (LANZEROTTI *et al.*, 1986). These authors showed that the event illustrated in Fig. 11 occurred at the dayside convection reversal boundary. The fact that the magnetic field perturbations in the vertical components were the same in both hemispheres suggests that the field-aligned currents were on closed field lines and could not be interpreted directly in terms of the interplanetary field By-dependence of a flux transfer event as proposed by LEE (1986). Whether the observed event represented a convected, larger-scale plasma cloud, rather than a flux tube, remains unsettled (LANZEROTTI *et al.*, 1987). Additional work studying many more such events is required; such work is in progress.

4. The Future

Two particular areas of recent conjugate research require more effort in order to elucidate magnetospheric processes and hydromagnetic wave generation and propagation. Both research areas are ones where conjugate studies can make significant progress because satellites normally pass quickly through the spatial regions involved. The first research area is the high latitude dayside cusp region discussed briefly in the previous section. The second area is conjugate research at very low latitudes, $L \sim 1.5$ or so. The recent work of T. SAITO and his colleagues (YUMOTO *et al.*, 1985) have provided evidence of intriguing local time and ionospheric conductivity-dependent behavior on the observed wave activity. Their work has also raised, again, the fundamental question as to the mechanisms for the transfer of solar wind energy as hydromagnetic waves so deep into the magnetosphere.

It can thus be expected that conjugate point research at both very high and very low latitudes will in future years provide new and significant information on hydromagnetic waves in the Earth's magnetosphere, information and understanding which would be difficult, if not impossible, to obtain by *in-situ* techniques.

Acknowledgments

I thank C.G. MACLENNAN, L.V. MEDFORD, and A. WOLFE for helpful comments on this paper and for enthusiastic collaborations over the years in pursuing conjugate studies.

References

ALFVÉN, H. (1942): On the existence of electromagnetic-hydromagnetic waves. Ark. Astron. Fys., **298**, 2.

ALFVÉN, H. (1950): Cosmical Electrodynamics. Oxford, Oxford Univ. Press.

ANNEXSTAD, J. O. and WILSON, C. R. (1968): Pc 1 fine structure phase shift at high latitude conjugate points. J. Geophys. Res., **73**, 3063–3065.

ARNOLDY, R. L., CAHILL, L. J., Jr., EATHER, R. H. and ENGEBRETSON, M. J. (1986): Greater than 0.1-Hz ULF magnetic pulsations measured at South Pole, Antarctica. J. Geophys. Res., **91**, 5700–5710.

ATKINSON, G. and WATANABE, T. (1966): Surface waves on the magnetospheric boundary as a possible origin of long period geomagnetic micropulsations. Earth Planet. Sci. Lett., **1**, 89–91.

CAMPBELL, W. H. (1968): Rapid geomagnetic field variations observed at conjugate locations. Radio Sci., **3**, 726–739.

CHEN, L. and HASEGAWA, A. (1974a): A theory of long-period magnetic pulsations, 1. Steady-state excitation of field line resonance. J. Geophys. Res., **79**, 1024–1032.

CHEN, L. and HASEGAWA, A. (1974b): A theory of long-period magnetic pulsations, 2. Impulse excitation of surface eigenmode. J. Geophys. Res., **79**, 1033–1037.

DUNGEY, J. W. (1954): Electrodynamics of the outer atmosphere. Ionos. Res. Lab., Pa. State Univ., Sci. Rep., **69**, 229–236.

DUNGEY, J. W. (1955): Electrodynamics of the outer atmosphere. The Physics of the Ionosphere, London, Physical Society London.

ENGEBRETSON, M. J., ZANETTI, L. J., POTEMRA, T. A. and ACUNA, M. H. (1986): Harmonically structured ULF pulsations observed by the AMPTE CCE magnetic field experiment. Geophys. Res. Lett., **13**, 905–908.

FUKUNISHI, H. and LANZEROTTI, L. J. (1974a): ULF pulsation evidence of the plasmapause, 1. Spectral studies of Pc 3 and Pc 4 pulsations near $L=4$. J. Geophys. Res., **79**, 142–158.

FUKUNISHI, H. and LANZEROTTI, L. J. (1974b): ULF pulsation evidence of the plasmapause, 2. Polarization studies of Pc 3 and Pc 4 pulsations near $L=4$ and at a latitude network in the conjugate region. J. Geophys. Res., **79**, 4632–4647.

JACOBS, J. A. (1970): Geomagnetic Micropulsations. New York, Springer, 179p. (Physics and Chemistry in Space, Vol. 1).

JACOBS, J. A. and WRIGHT, C. S. (1968): Some features of geomagnetic micropulsations observed during the recent quiet sun years, with particular reference to data obtained at the near conjugate stations of Great Whale River and Byrd. Geophys. J. R. Astron. Soc., **15**, 53–67.

LANZEROTTI, L. J. and FUKUNISHI, H. (1974): Mode of magnetohydrodynamic waves in the magnetosphere. Rev. Geophys. Space Phys., **12**, 724–729.

LANZEROTTI, L. J. and SOUTHWOOD, D. J. (1979). Hydromagnetic waves. Solar System Plasma Physics, Vol. 3, ed. by L. J. LANZEROTTI *et al.* Amsterdam, North Holland, 109–135.

LANZEROTTI, L. J., HASEGAWA, A. and TARTAGLIA, N. A. (1972). Morphology and interpretation of magnetohydrodynamic plasma waves at conjugate points during December solstice. J. Geophys. Res., **77**, 6731–6745.

LANZEROTTI, L. J., MACLENNAN, C. G. and FUKUNISHI, H. (1976a): ULF geomagnetic power near $L=4$, 5. Cross-power spectral studies of geomagnetic variations 2–27 mHz in conjugate areas. J. Geophys. Res., **81**, 3299–3315.

LANZEROTTI, L. J., MACLENNAN, C. G. and FUKUNISHI, H. (1976b): Relationships of the characteristics of magnetohydrodynamic waves to plasma density gradients near $L=4$. J. Atmos. Terr. Phys., **38**, 1093–1110.

LANZEROTTI, L. J., LEE, L. C., MACLENNAN, C. G., WOLFE, A. and MEDFORD, L. V. (1986): Possible evidence of flux transfer events in the polar ionosphere. Geophys. Res. Lett., **13**, 1089–1096.

LANZEROTTI, L. J., HUNSUCKER, R. D., RICE, D., LEE, L. C., WOLFE, A., MACLENNAN, C. G. and MEDFORD, L. V. (1987): Ionosphere and ground-based response to field-aligned currents near the magnetospheric cusp regions. J. Geophys. Res., **92**, 7739–7743.

LEE, L. C. (1986): Magnetic flux transfer at the Earth's magnetopause. Proceedings of Chapman Conference on Solar Wind-Magnetosphere Coupling, ed. by Y. KAMIDE.

LOKKEN, J. E., SHAND, J. A. and WRIGHT, C. S. (1963): Some characteristics of electromagnetic background signals in the vicinity of one cycle per second. J. Geophys. Res., **68**, 789–794.

NAGATA, T., KOKUBUN, S. and IIJIMA, T. (1963): Geomagnetically conjugate relationships of giant pulsations at Syowa Base, Antarctica, and Reykjavik, Iceland. J. Geophys. Res., **68**, 4621–

4625.

NAGATA, T., KOKUBUN, S. and IIJIMA, T. (1966): Conjugate relationship of Pc 5 pulsations between Syowa Station and Reykjavik. JARE Sci. Rep., Ser. A (Aeronomy), **3**, 47–58.

RADOSKI, H. R. (1974): A theory of latitude-dependent geomagnetic micropulsations; The asymptotic fields. J. Geophys. Res., **79**, 595–603.

RASPOPOV, O. and LANZEROTTI, L. J. (1976): Investigation of Pc 3 frequency geomagnetic pulsations in conjugate areas around $L=4$; A review of some USSR and US results. Rev. Geophys. Space Phys., **14**, 577–589.

SAITO, T. (1969): Geomagnetic pulsations. Space Sci. Rev., **10**, 319–412.

SAMSON, J. C., JACOBS, J. A. and ROSTOKER, G. (1971): Latitude dependent characteristics of long-period geomagnetic pulsations. J. Geophys. Res., **76**, 3675–3683.

SOUTHWOOD, D. J. (1974): Some features of field line resonances in the magnetosphere. Planet. Space Sci., **22**, 483–491.

STASSINOPOULOS, E. G., LANZEROTTI, L. J. and ROSENBERG, T. J. (1984): Temporal variations in the Siple Station conjugate area. J. Geophys. Res., **89**, 5655–5659.

SUGIURA, M. (1961a): Some evidence of hydromagnetic waves in the Earth's magnetic field. Phys. Rev. Lett., **6**, 255–257.

SUGIURA, M. (1961b): Evidence of low frequency hydromagnetic waves in the exosphere. J. Geophys. Res., **66**, 4087–4095.

SUGIURA, M. and WILSON, C. R. (1964): Oscillations of the geomagnetic field lines and associated magnetic perturbations at conjugate points. J. Geophys. Res., **69**, 1211–1216.

TAKAHASHI, K. and MCPHERRON, R. L. (1982): Harmonic structure of Pc 4–5 pulsations. J. Geophys. Res., **87**, 1504–1516.

TAKAHASHI, K., MCPHERRON, R. L. and HUGHES, W. J. (1984): Multispacecraft observations of the harmonic structure of Pc 3–4 magnetic pulsations. J. Geophys. Res., **89**, 6758–6774.

TONEGAWA, Y. and FUKUNISHI, H. (1984): Harmonic structure of Pc 3–5 magnetic pulsations observed at the Syowa–Husafell conjugate pair. J. Geophys. Res., **89**, 6737–6748.

TONEGAWA, Y., FUKUNISHI, H., LANZEROTTI, L. J., MACLENNAN, C. G., MEDFORD, L. V. and CARPENTER, D. L. (1985): Studies of the energy source for hydromagnetic waves at auroral latitudes. Mem. Natl Inst. Polar Res., Spec. Issue, **38**, 73–82.

TROITSKAYA, V. A. (1967): Micropulsations and the state of the magnetosphere. Solar-Terrestrial Physics, ed. by J. W. KING and W. S. NEWMAN. London, Academic Press, 213–274.

TROITSKAYA, V. A. and GUL'ELMI, A. V. (1967): Geomagnetic micropulsations and diagnostics of the magnetosphere. Space Sci. Rev., **7**, 689–769.

WESCOTT, E. M. (1966): Magnetoconjugate phenomena. Space Sci. Rev., **5**, 507–561.

WESCOTT, E. M. and MATHER, K. B. (1963): Diurnal effects in magnetic conjugacy at very high latitude. Nature, **197**, 1259–1261.

WILSON, C. R. and SUGIURA, M. (1961): Hydromagnetic interpretation of sudden commencements of magnetic storms. J. Geophys. Res., **66**, 4097–4112.

WOLFE, A., LANZEROTTI, L. J., MACLENNAN, C. G. and MEDFORD, L. V. (1986): Geomagnetic studies near the magnetospheric cusps. Antarct. J. U. S., **21** (in press).

YANAGIHARA, K. (1963): Geomagnetic micropulsation with period from 0.03 to 10 seconds in the auroral zones with special reference to conjugate point studies. J. Geophys. Res., **68**, 3383–3397.

YUMOTO, K., SAITO, T. and TANAKA, Y. (1985): Low-latitude Pc 3 magnetic pulsations observed at conjugate stations ($L\sim1.5$). J. Geophys. Res., **90**, 12201–12207.

(Received January 26, 1987; Revised manuscript received March 20, 1987)