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RESEARCH OF GEOMAGNETICALLY CONJUGATE PHENOMENA IN ANTARCTICA SINCE THE IGY

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Abstract: The geomagnetically conjugate relationship studies of the magnetospheric phenomena between the southern auroral zone in Antarctica and the northern auroral zone over Europe and America are historically reviewed, starting with the IGY (1957–1958) results and then summarizing key results obtained by the international cooperative research programs such as the IGC (1959), the IQSY (1964–1965), the IASY (1967–1971) and the IMS (1976–1979).

The observed conjugate magnetospheric phenomena are divided into the following three topics according to the physical guiding processes for their conjugacy characteristics.

(I) The auroral particle precipitation by the field-line guidance, resulting in the visual auroras, the auroral X-rays, the cosmic noise absorption (CNA) by the ionosphere and the polar magnetic substorms.

(II) The field-aligned propagation of the whistler-mode plasma waves, which cover the ELF and VLF magnetospheric plasma waves that are often bouncing along the field lines between the conjugate ionospheric areas.

(III) The hydromagnetic resonance system of the earth's magnetosphere, which covers most parts of the conjugate characteristics of the Pc 3–5 hydromagnetic waves. The Pc 1 pulsations are summarized under topic (III), though their wave characteristics are more similar to the whistler-mode waves under topic (II).

1. Introduction

As one of the main programs of the International Geophysical Year (IGY), 1957–1958, a regional observation network to continuously observe auroras, geomagnetic and ionospheric variations, ELF-VLF emissions and the cosmic-rays was internationally organized in Antarctica. It is well known in the world scientific community of upper atmospheric physics that physics of the northern upper atmospheric phenomena have been revolutionally developed at the opportunity of the Second International Polar Year (II-PY), 1932–1933, and since then. As far as the southern polar region is concerned, however, regular routine observations of the Antarctic features of upper atmospheric phenomena were limited within Antarctic Peninsula, though occasional measurements of these phenomena were carried out at some other localities in Antarctica during the II-PY period.

For the general guiding principle for the IGY, the Special Committee of International Geophysical Year (CSAGI) of the International Council of Scientific Unions

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(ICSU) put special emphasis on the significance of regional observation networks for the worldwide geophysical phenomena, in addition to the importance of satisfactorily prepared technical coordination and standardization of each disciplinary observation as well as the collection and the analysis of the observed data. The specifically selected regions or zones for the IGY programs were the Antarctic region in addition to the Arctic region and the equatorial zone with respect to the latitudinal distribution, and the three zones along the meridians passing through Europe–Africa, Eastern North America–Western South America, and West Pacific Ocean zone were selected in regard to the longitudinal distribution. Namely, the Antarctic and the Arctic were equally the specially selected IGY research fields which are geographically symmetric with respect to another IGY research field, the equatorial circular zone.

The physical concept of the conjugate points of the geomagnetic field line for auroras and related upper atmospheric physical phenomena had already been recognized before the IGY (VESTINE, 1959; VESTINE and SIBLEY, 1960), and practical research of the geomagnetically conjugate phenomena between the two polar regions was undertaken during the periods of the IGY and the subsequent International Geophysical Cooperation (IGC) 1959. Here, the geomagnetically conjugate points were defined as the cross points of a line of force of the geomagnetic field of internal origin with the earth's surface.

A large number of scientific papers on the geomagnetic conjugacy of auroras, geomagnetic substorms, cosmic noise absorption (CNA) in the ionosphere, ULF and VLF emissions and other relevant phenomena based on the observed data in the Antarctic and the Arctic regions during the IGY, the IGC and since then were published in 1960s. Most key results of these IGY–IGC works on the geomagnetic conjugacy were reviewed and summarized in the latter half of 1960s (WESCOTT, 1966; NAGATA, 1967; OGUTI, 1969).

The first publication on an overall review and summary of the IGY results (ODISHAW, 1964) includes three articles on the geomagnetically conjugate problems in the polar regions. They are "Whistler and VLF emissions" by HELLIWELL, two sections on "Conjugate relationship of geomagnetic bay disturbances" and "Conjugacy of large amplitude pulsative variations" in an article on "Magnetic field at the poles" by NAGATA, and "Rapid variations of the electromagnetic field of the earth" by TROITSKAYA. A brief discussion only was made about the conjugate problem of auroral phenomena in an article on "Aurora" by CHAPMAN and AKASOFU in the same volume, probably because available auroral data in the Antarctic during the IGY–IGC period were only those obtained by all-sky cameras.

Five years after the end of the IGC 1959, another international cooperative research program on "The International Year of the Quiet Sun" (IQSY), 1964–1965, newly started as a continuation of the IGY–IGC coordinated research programs specifically for the quiet sun period, and SCAR was officially represented by F. JACKA of Australia in the Special Committee for the IQSY. Since the geomagnetically conjugate problems between the Antarctic and the Arctic had been largely advanced since the beginning time of the IGY through the IQSY research works, "Annals of the IQSY," Vol. 5, Solar-Terrestrial Physics (STICKLAND, 1969) includes two articles on the conjugate problems, *i.e.* "Conjugate point phenomena" by ROEDERER and "Polar magnetic disturbances and conjugate point phenomena in the IQSY period" by NAGATA. In the review report on the conjugate problems, ROEDERER (1969) attempted to classify the conjugate phenomena into three classes on the basis of source mechanism of the phenomena; namely (1) Those in which the source is located on or around the equator zone, (2) Those in which the source is located at, or near, one end of the field line closed through the earth's surface and (3) Those observable at the earthward end of open field lines, the other end of which reaches out into the magnetospheric tail. It was further suggested that each of the three classes may be topologically divided into (a) "The point conjugacy" type where the source is well localized in space, (b) "The shell conjugacy" type where the conjugate area are well stretched along constant-L lines, and (c) "The area conjugacy" type where the source occupies an extended, but finite, region in the magnetosphere. It seems that the conceptional classification of the conjugate phenomena proposed by ROEDERER can be taken into consideration in understanding various conjugate phenomena still at present.

When the Japanese Antarctic Research Expedition (JARE) program was set up as one of the IGY programs, the candidate location for the first JARE wintering station was selected within the southern auroral zone along the sea coast of East Antarctica. Syowa Station thus built up at 69°00′S in latitude and 39°35′E in longitude in early 1957 was soon realized as being located very close to the geomagnetically conjugate point of Reykjavik (Leirvogur) Magnetic Observatory (64°10′N, 21°42′W) in Iceland. Since the Reykjavik Observatory is a well established magnetic observatory, located within the northern auroral zone, comparative analyses and studies of the ordinary and the rapid-run magnetograms simultaneously obtained at Syowa and Reykjavik started with the IQSY data, and the comparative studies have been continued since then on a routine work basis. At the occasion of the International Magnetosphere Study (IMS) program, 1976–1978, the conjugate pair observatory system consisting of Syowa in Antarctica and Iceland was consolidated by setting up a new station at

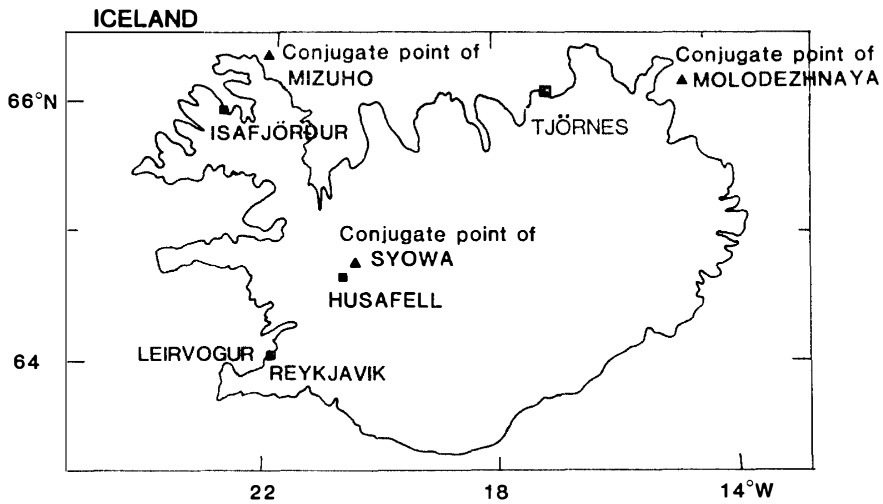

Fig. 1. The positions of the tripartite station network in Iceland (full square marks: Husafell, Isafjördur, Tjörnes and Reikjavik (Leirvogur magnetic observatory). The positions of the geomagnetic conjugate points of the Antarctic tripartite station network (full triangle marks: Syowa Station, Mizuho Station and Molodezhnaya).

Husafell near Reykjavik (see Fig. 1) for simultaneously observing visual auroras (all-sky images, scanning spectrophotometry), geomagnetic variations (ordinary geomagnetic variations, ULF waves), VLF-ELF emissions and CNA of the ionosphere by use of the same standardized observing equipments and the same time-keeping system as those at Syowa. This IMS conjugacy program was specifically planned to be in coordination with a geostationary satellite, GEOS-1, which, in the equatorial plane, would come near the field line linking the two conjugate stations on ground. On the Antarctic side, Mizuho Station (70°42′S, 44°20′E), which is located on geomagnetic south of Syowa (see Fig. 1), also joined the IMS conjugacy network with the same observing system as that at Syowa.

Since 1983, two stations, Isafjördur and Tjörnes, have been newly in operation in addition to the main station at Husafell (Fig. 1) for continuously monitoring the polar upper atmospheric disturbances by means of a flux-gate magnetograph for geomagnetic variations, an induction magnetograph for ULF waves, an ELF-VLF receiving system, a riometer for CNA, an auroral all-sky camera, a meridian scanning spectrophotometer for λ5577Å and Hβ auroras, a three-axis fixed direction photometer for λ4278Å aurora and an all-sky auroral TV camera.

As shown in Fig. 1, Husafell, Isafjördur and Tjörnes respectively in Iceland are close to the conjugate points of Syowa, Mizuho and Molodezhnaya (USSR station) in Antarctica, and the three stations in each of the northern and the southern auroral zones compose a respective tripartite observatory network. The continuous monitoring program is going on now on a routine basis at Syowa and the tripartite stations in Iceland. Figure 2 illustrates an example of a set of quick-look daily summaries of simultaneous observations at Syowa and Husafell. The real-time digital and analog records of any event in these data are available at the "WDC-C2 for Aurora" in the National Institute of Polar Research, Tokyo.

In this somewhat historic review of research of the conjugate phenomena in Antarctica since the IGY, emphasis will be put, to a certain extent, particularly on experimental results of the conjugate studies on the polar upper atmospheric and magnetospheric phenomena obtained from the conjugate pair of Syowa area and Iceland, because of its long standing life since the IGY up to the present, though a number of key findings obtained from the other Antarctic–Arctic conjugate pairs also will be discussed. The conjugate phenomena linking the Antarctic and the Arctic by the geomagnetic field lines may be roughly divided into the following three groups from the viewpoint of particle and plasma physics.

(I) The auroral particle precipitation by the field-line guidance.

(II) The field-aligned propagation of the whistler-mode plasma waves.

(III) The hydromagnetic resonance systems of the earth's magnetosphere.

It will be obvious here that appropriate reflection by the ionosphere must be taken into account for the magnetospheric plasma waves in (II) and (III), and the mirroring and the drifting effects caused by the geomagnetic field must be considered for the motion of charged particles trapped by the field lines. It seems very likely that the major interest of polar geophysicists during the IGY–IGC period was mostly concerned with (I) the auroral particle precipitation by the field-line guidance. NAGATA's first review article on the conjugate relationship of geomagnetic bay disturbances

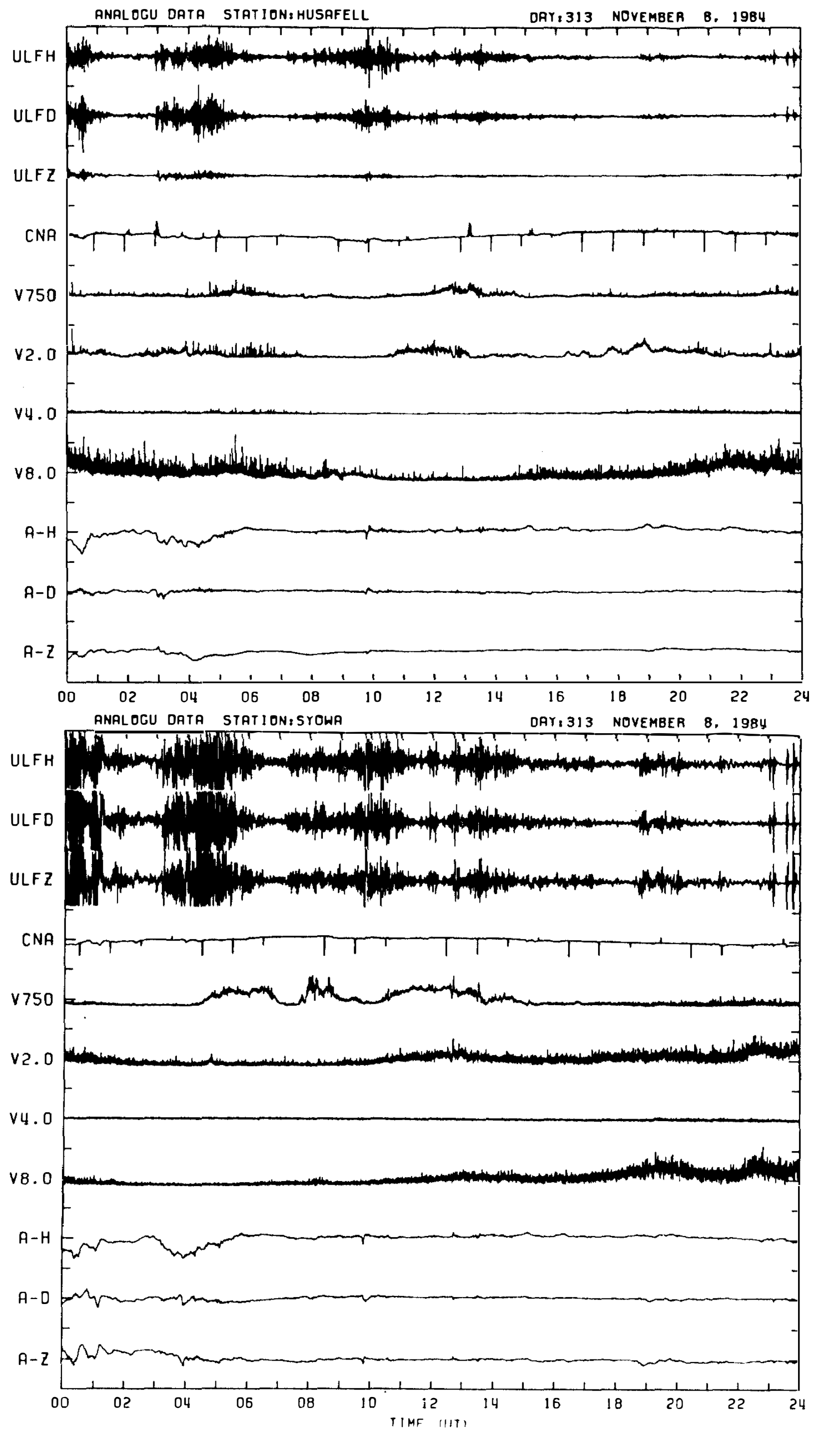

Fig. 2. Examples of the simultaneous quick-look daily summaries of upper atmosphere physics data observed at Syowa and Husafell.

(1964) mentioned that "one of the great merits of the IGY was its initiation of extensive controlled studies on the geomagnetic conjugacy using not only geomagnetic data but also direct measurements of precipitating particles, Bremsstrahlung X-rays auroral displays, ionospheric disturbances, cosmic noise absorption etc.".

Historically mentioning, (II) the field-aligned propagation of the whistler atmospherics had been recognized before the IGY. As first reviewed by HELLIWELL (1964), however, many questions still faced investigators of whistlers and VLF emissions at the beginning of the IGY, but the gross features of the distribution of whistlers and their propagation characteristics were revealed and the physical classification of the polar VLF emissions, *i.e.* hiss, dawn chorus, periodic emission, etc. was much advanced from the IGY–IGC data.

As for (III) the hydromagnetic resonance system of the earth's magnetosphere, it was mentioned in NAGATA's review article on the conjugacy of large amplitude pulsative variation (1964) that the simultaneous occurrence of pulsative variations in the geomagnetic field at conjugate areas was discovered by SUGIURA (1961) from the IGY magnetograms obtained at College and Kotzebue in the north and Macquarie Island in the south.

Although the three groups mentioned above are mostly controlled by (I) the injecting high energy particles and the associated electric field, (II) the whistler-mode plasma waves and (III) the hydromagnetic waves, respectively, in the magnetospheric plasma, there exist the wave-particle and the wave-wave interaction effects among them so that each of the three phenomena cannot be independent of one another. As already mentioned, the classification schemes of the polar conjugate phenomena from other viewpoints, such as classes (1), (2) and (3) based on the source mechanism, and the topological types (a), (b) and (c) would be still helpful in understanding observed conjugate phenomena.

In Table 1, the invariant latitude and longitude (MCILWAIN, 1961) and the L-value of selected approximately conjugate pair stations are listed for the sake of convenience for reference for later discussions of individual conjugate phenomena.

Table 1. Approximately conjugate pair stations.

South				North			
Station	Invariant Lat.	Invariant Long.	L	Station	Invariant Lat.	Invariant Long.	L
Scott Base	−79.68	327.86	31.14	Resolute Bay	83.94	311.27	89.86
Davis	−74.58	98.91	14.04	Ny Ålesund	78.09	100.56	23.47
Byrd	−67.63	353.61	6.96	Great Whale	66.91	356.64	6.50
Syowa Station	−66.12	70.71	6.10	Reykjavik	65.64	69.05	5.88
				Husafell	66.09	70.27	6.09
Macquarie Is.	−64.17	245.57	5.27	College	64.46	261.41	5.38
Halley Bay	−60.99	28.23	4.25	St. Anthony	60.16	28.46	4.04
Siple	−60.61	3.06	4.15	Roberval	60.08	4.44	4.02
Eights	−59.51	5.78	3.89	Deep River	58.05	356.18	3.57
Kergulen	−58.49	121.28	3.66	Borok	53.44	114.49	2.82

2. Conjugate Studies during the IGY (1957–1958)–IGC (1959) Period

2.1. Auroras and geomagnetic substorms

Although the observed fact that active auroras tend to occur simultaneously in the northern and the southern high latitude zones had been known before the IGY, a direct comparison of all-sky camera images of auroras simultaneously observed at approximately conjugate stations, Campbell Island (L=4.02) in Antarctica and Farewell (L=4.27) in Alaska during the IGY may be the first systematic conjugate study on visual auroras (DEWITT, 1962). Figure 3 shows an example of the all-sky camera auroral images obtained at the conjugate pair stations. The original all-sky camera data taken at every one minute interval showed that the forms and the motions of auroras are similar to and the breakup times of auroral substorms are almost simultaneous with each other at the approximately conjugate stations. As Farewell is located about 100 km poleward of the conjugate point of Campbell Island, the auroral arcs observed at Farewell are shifted equatorwards in comparison with those observed at Campbell Island. The two curves in the bottom of Fig. 3 are variations with time of the average all-sky auroral luminosity at the two conjugate stations. As far as these data of conjugate auroras are concerned, it appears that the geomagnetically conjugate relationship holds well for visual auroras between the conjugate stations of $L \simeq 4$.

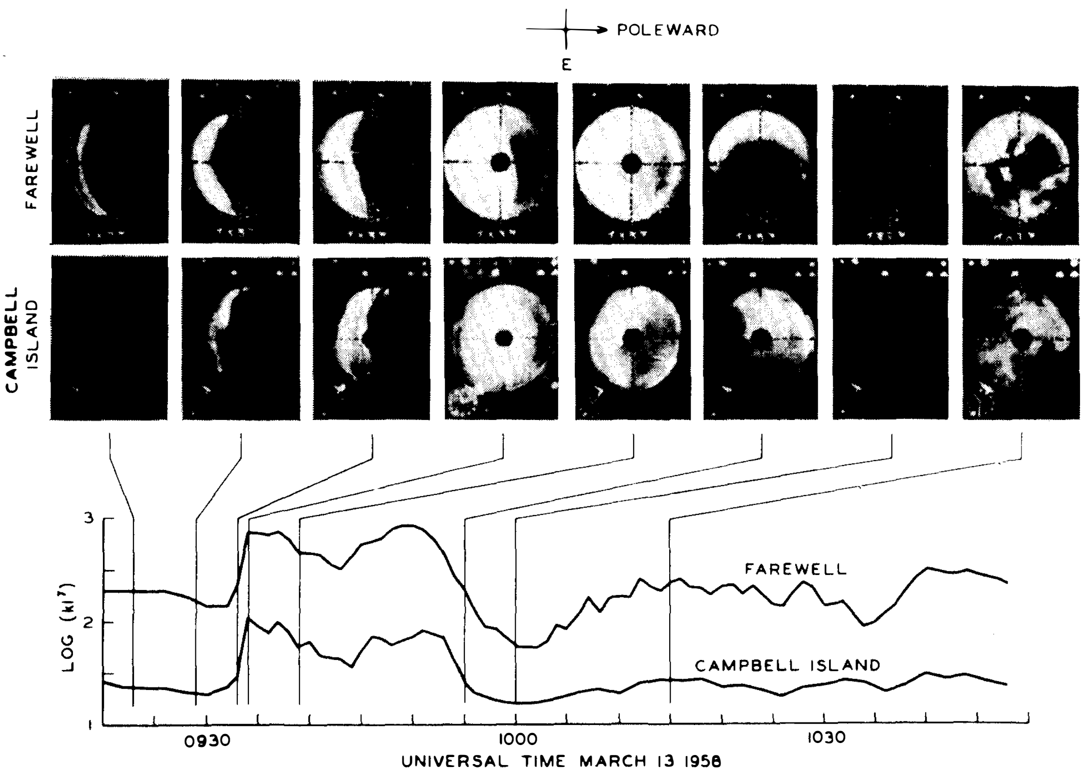

Fig. 3. All-sky camera auroral images (top) and the all-sky average auroral luminosity (bottom) observed at Campbell Island and Farewell (DEWITT, 1962).

It was reported by WESCOTT (1966), however, that all-sky camera data of visual auroras observed at Syowa (L=6.10) and Reykjavik (L=5.88) during the IGC period show somewhat more complicated relation between the approximately conjugate stations as follows. Swirling motions and latitudinal movements of auroras are similar for some time intervals, apparently identical auroral patterns over Syowa being located about 100 km polewards of Reykjavik, whereas the correlation of auroral activity between the conjugate pair stations are not good in general for other intervals, suggesting that the geomagnetic conjugacy may be considerably deformed at $L \simeq 6$ or higher L-value zones during active substorm periods.

The first study of the conjugate relationship of polar magnetic substorms on the basis of concept of the linkage of two surface points of the earth by a geomagnetic field line, which was initiated by VESTINE (1959), would be probably a comparative study on substorms observed simultaneously at Little America (78°18′S, 162°02′W), Baker Lake (64°18′N, 96°05′W) and Churchill (58°45′N, 94°02′W), where the conjugate points of Baker Lake and Churchill are given by (75°23′S, 173°47′W) and (74°22′S, 154°34′S) respectively (NAGATA and KOKUBUN, 1960). The correlation coefficients (r) of the horizontal component of isolated magnetic substorms (geomagnetic negative bays) observed during night times for all the three stations in 1957 during the IGY period were given by

r (Little America, Baker Lake) $=0.85$,
r (Little America, Churchill) $=0.64$,
r (Baker Lake, Churchill) $=0.50$.

It was found in this analysis that the geomagnetic conjugacy for night time isolated substorms between Little America and Baker Lake is fairly good, though the conjugate point of Baker Lake and Little America are separated by about 600 km along the iso-L line, while the correlation between Baker Lake and Churchill, separated by about 500 km approximately along the geomagnetic meridian line, is considerably poorer than that between Little America and Baker Lake. The Little America-Baker Lake conjugate pair is located on the poleward side of the auroral zone ($L \sim 15$) so that the conjugacy becomes much worth in the cases of severe magnetic substorms, though a good conjugate relation is observable for isolated magnetic negative bay phenomena.

The "shell conjugacy" characteristics of polar magnetic substorms were extensively studied by WESCOTT and MATHER (1965) by use of the IGY magnetograms obtained at Macquarie Island and eleven IGY stations in Alaska and Siberia including College (see Table 1). Figure 4 illustrates an example of the contour maps of the equi-cross-correlation coefficient of H component of geomagnetic field variations at Macquarie Island and those at the eleven stations in Alaskan region for (a) the pre-substorm, (b) the active substorm and (c) the post-substorm stages of a six-hour long substorm event. It will be noted in Fig. 4 that the conjugate area is elongated along the $L=5.2$ iso-L line, having a sharp poleward boundary along about $L=6.5$. The cross-correlation during and after the substorm is much higher than before the substorm, the correlation coefficient amounting to 0.9 around the conjugate point of Macquarie Island. However, such an apparent point conjugacy does not always take place. In another example, the contour map of the equi-cross-correlation coefficient in Alaska shows a conjugate area centered 800 km east the conjugate point of Macquarie Island.

As the Macquarie Island–Alaska pair is of $L=5.3$ which is close to the equatorward boundary of the auroral oval, the conjugacy of magnetic substorms for the Syowa–Reykjavik pair of $L \simeq 6.0$ was of special interest in regard to the so-called auroral zone disturbances. Figure 5 illustrates examples of the simultaneous magnetograms of H components of substorms observed at Syowa and Reykjavik during the IGC period (NAGATA, 1964; NAGATA *et al.*, 1966). As shown in Fig. 5, the variation

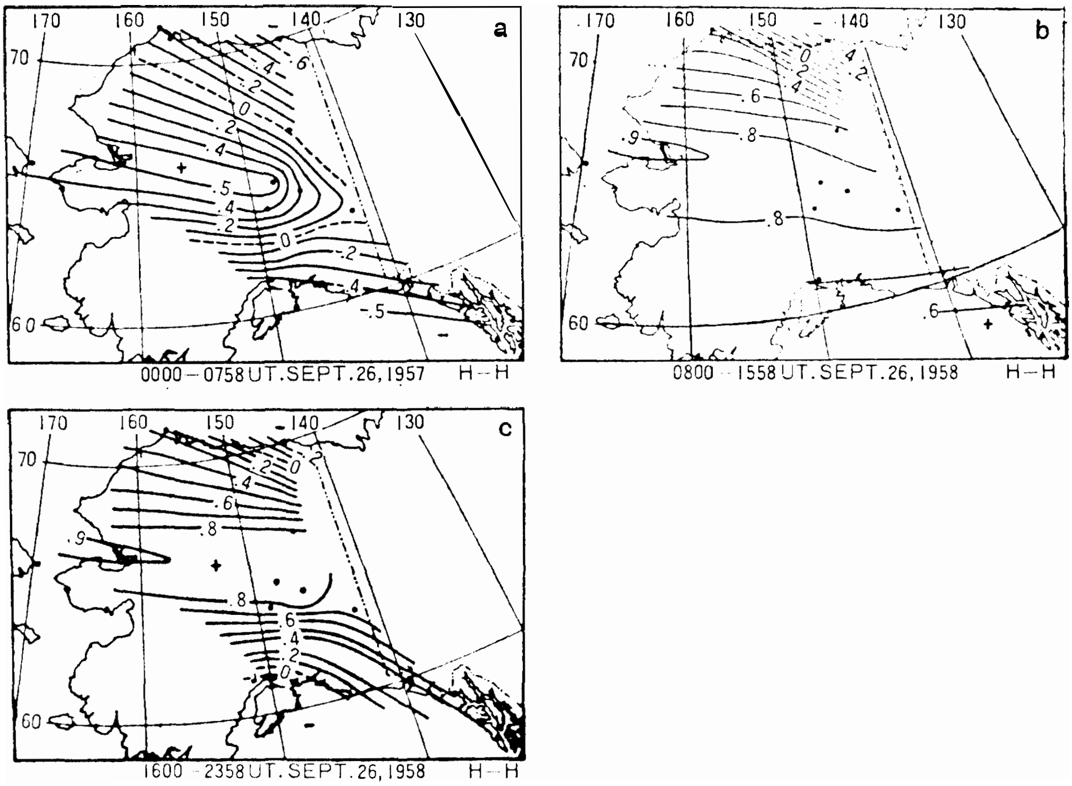

Fig. 4. *Contour maps of the equi-correlation coefficients between Macquarie Island and Alaskan stations for the H component of geomagnetic substorms. (a) Pre-substorm stage, (b) active substorm stage, (c) post-substorm stage (*WESCOTT *and* MATHER, *1965).*

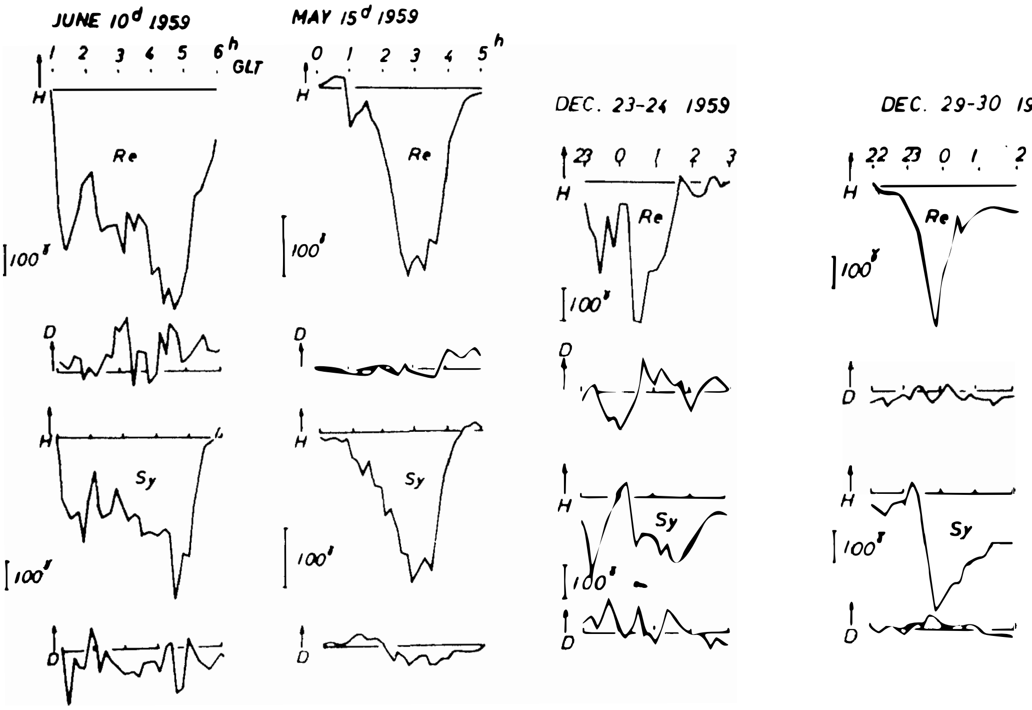

Fig. 5. *Examples of the conjugate negative magnetic substorms observed at Syowa (Sy) and Reykjavik (Re) (*NAGATA *et al., 1966).*

forms and the dynamic spectra of the isolated negative substorms are very similar to each other between Syowa and Reykjavik, the average cross-correlation coefficient amounting to 0.86.

Since it was well recognized that a sharp negative magnetic substorm is always associated with a simultaneous auroral display and the sharp increase of electron density of the lower ionosphere in the auroral zone (*e.g.* OGUTI, 1963), it was concluded from the IGY–IGC data that, in an event of negative substorm, each of the conjugate stations in the auroral zones is simultaneously attacked by a sharp stream of auroral particles coming from the tail-side equatorial region of the magnetosphere, resulting in simultaneous occurrences of a negative magnetic substorm, auroras and a cosmic noise absorption (CNA) event. As for the positive magnetic substorms (positive bays), all the IGY–IGC data in high latitudes indicated considerably poorer similarity and correlation between the conjugate pair stations in comparison with the case of a negative magnetic substorm. Since the major part of a positive magnetic substorm is attributable to the return currents of the auroral electrojet through the ionosphere, the distribution and the time-variation patterns of a positive substorm are much controlled by the ionospheric condition which is dependent on the solar radiation. This problem therefore was discussed in some detail, together with the conjugacy of the polar magnetic disturbance patterns over the whole polar region including the polar cap, on the basis of the IGY–IGC data (NAGATA, 1964; WESCOTT, 1966; NAGATA *et al*., 1966).

2.2. *Whistler-mode waves*

During the IGY–IGC period, propagation characteristics of the whistler atmospherics caused by the lightnings in the troposphere were extensively studied. In Antarctica, VLF observatories were set up at Byrd and later at Eights (see Table 1) by HELLIWELL and his Stanford University group. As summarized by HELLIWELL himself (1964), the general behaviors of whistler waves bouncing along the field lines between the geomagnetically conjugate ionospheric areas were established, and two important discoveries were derived from the IGY–IGC data. One is the whistler duct which is a fixed duct aligned with the field lines trapping the whistler wave energy. The other is the particular distribution pattern with a sharp "knee" of electron density with respect to the L-value in the magnetosphere, which later led to a definite establishment of the plasmasphere (CARPENTER, 1966).

The natural VLF emissions of whistler-mode plasma waves and their conjugacy also were systematically studied in Antarctica during the IGY–IGC period. A close relationship between auroral hiss of 2–20 kHz and auroral substorms was confirmed by MARTIN *et al.* (1960) with the VLF data observed at Byrd, and by MOROZUMI (1963, 1965) with observed data from South Pole. However, coordinated systematic studies on the auroral hiss phenomena at conjugate pair stations started after the IGC. As for the VLF chorus phenomena, the source of which is attributed to the cyclotron resonance of the whistler-mode plasma wave with high energy electrons in the radiation belt near the equatorial plane, the IGY–IGC data could ascertain the observed fact that the VLF chorus emissions are simultaneously observed at approximately conjugate stations in the northern and the southern high latitudes, and that the periodic VLF emissions recorded at conjugate stations are in out-of-phase to each other, suggesting a back and forth bounce between the conjugate areas through the field lines (Fig. 6) (HELLIWELL, 1964).

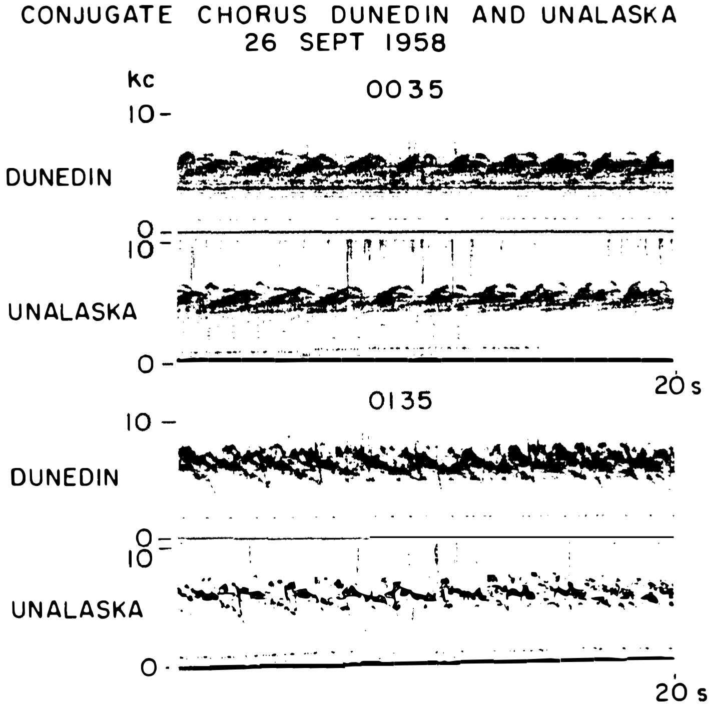

Fig. 6. Periodic VLF emissions recorded at the conjugate stations. The emissions demonstrate the antiphase relationship at the opposite hemispheres (HELLIWELL, 1964).

2.3. *ULF emissions (geomagnetic pulsations)*

The simultaneous occurrence of pulsative variations of large amplitude in the geomagnetic field at conjugate areas was discovered by SUGIURA (1961) from the IGY magnetograms obtained at Macquarie Island and College and Kotzebue. The same problem of the conjugate relationship of low frequency hydromagnetic waves was studied by NAGATA *et al.* (1963) by use of the IGY–IGC rapid-run magnetograms obtained at the Syowa–Reykjavik conjugate stations. Figure 7 shows examples of the simultaneous records of 3 component magnetograms at Syowa (Sy) and Reykjavik (Re), where the magnetic pulsations of 100–200 γ in amplitude and 3.5–8 min in period (Pc 5 pulsations) are presented. The wave forms of H component variations are almost parallel to each other at the conjugate stations, while those of D component variations are nearly antiparallel. All events of the Pc 5 pulsations selected from the Syowa magnetograms during the IGC period correspond, without exception, to simultaneous events of similar pulsations at Reykjavik having the above-mentioned characteristics. So that the correlation coefficient between the H components of the pulsation amounts to 0.85 on average and 0.95 at maximum. As suggested by SUGIURA and WILSON (1964), the simultaneous coherent occurrence and the symmetric phase relation of Pc 5 pulsations at the conjugate points are in good agreement with a theoretical model of resonant hydromagnetic Alfvén waves along the field line linking the conjugate points, or in other words, resonant oscillations of the field line in the magneto-

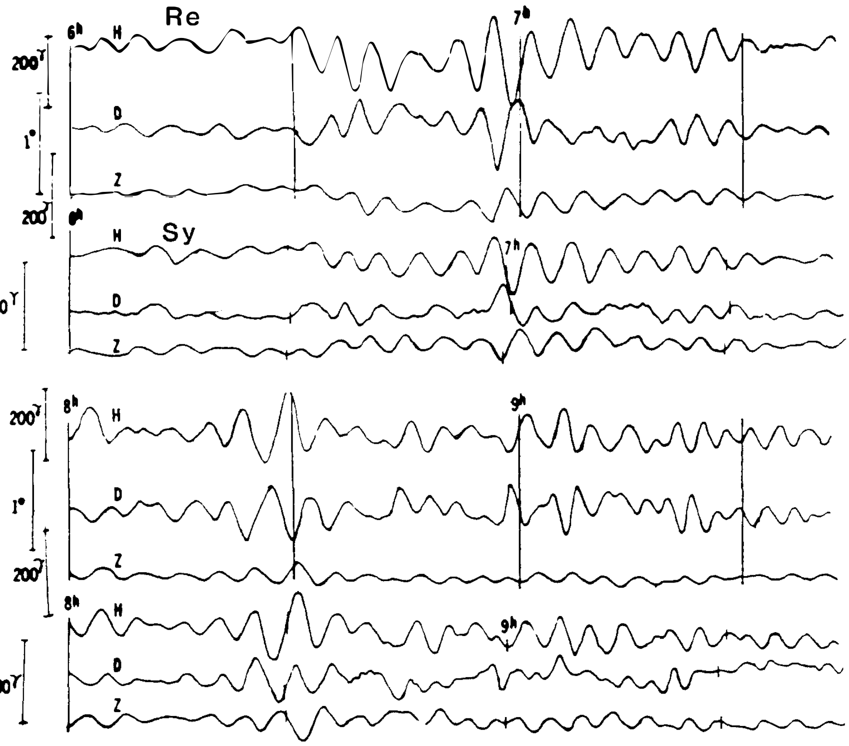

Fig. 7. Examples of three-component (H, D, Z) rapid-run magnetograms of large amplitude low frequency pulsation (Pc 5) simultaneously observed at Reykjavik (Re) and Syowa (Sy) (NAGATA et al., 1963).

spheric plasma, which can be mathematically represented by lateral oscillations of an idealized elastic string, as already pointed out by ALFVÉN (1950). The mode of symmetricity of the magnetic pulsations at the conjugate points is different between the odd-mode standing waves and the even-mode one. This simple model, therefore, has been often adopted in analytical studies of the magnetospheric hydromagnetic waves in the post IGY–IGC period too.

A systematic behavior of the polarization characteristics of the Pc 5 pulsation at conjugate points was another finding from the IGY–IGC data. Figure 8A shows an example of a set of the elliptic polarization in the horizontal and the magnetic meridian planes at Syowa and Reykjavik. As schematically illustrated in Fig. 8B, the sense of rotation of a transverse elliptic polarization vector is counterclockwise on the morning side and clockwise on the afternoon side, if we view the rotation along the direction of field line from the south to the north. The daily change in the systematic polarization characteristics generally holds at the auroral zone conjugate stations such as the Macquarie Island–College conjugate pair (WILSON, 1966). However, a theoretical interpretation of the hydromagnetic resonance phenomena including the polarization characteristics came up in 1974 (SOUTHWOOD, 1974; CHEN and HASEGAWA, 1974) after more comprehensive features of the field line resonance phenomena were clarified in detail.

As summarized by TROITSKAYA (1964), on the other hand, special emphasis was put on the global studies on the rapid magnetic pulsations of 0.2–5 Hz (Pc 1 and Pi

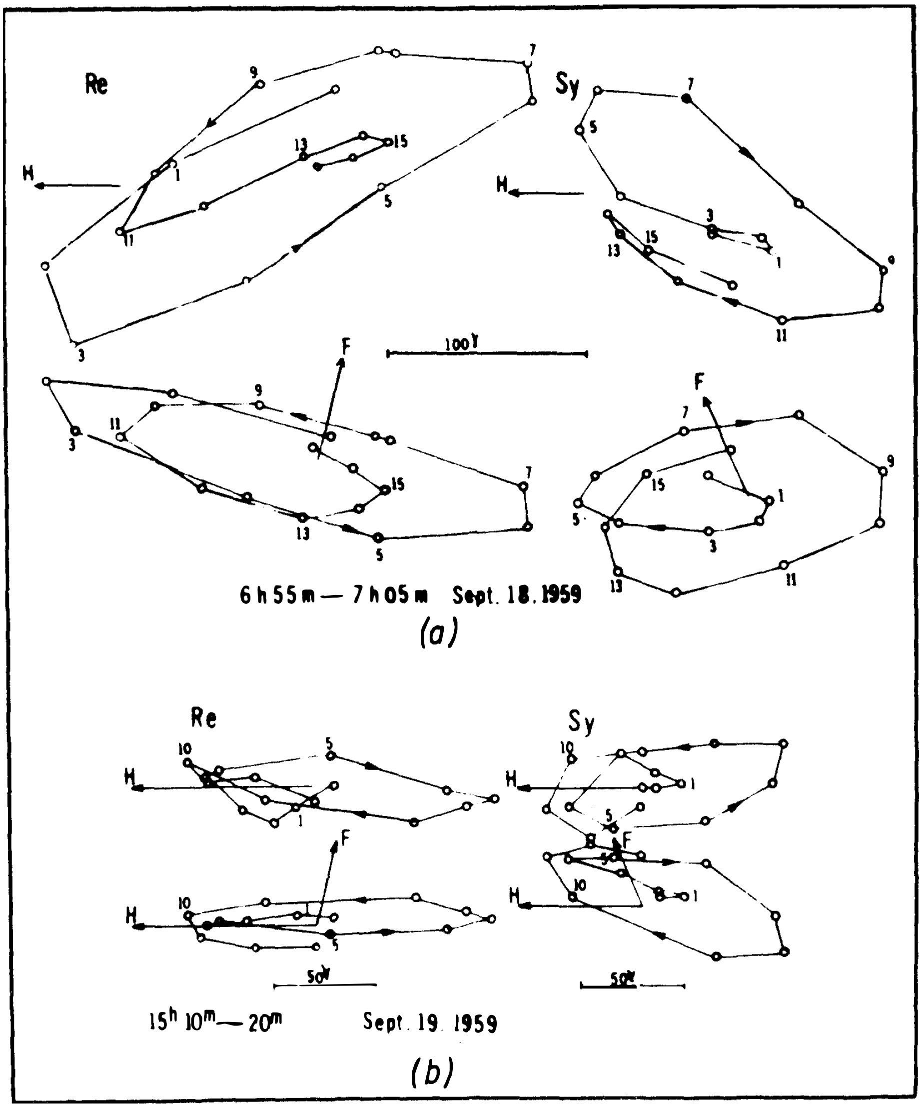

Fig. 8(A). Examples of the simultaneous change of the disturbance vectors of Pc 5 magnetic pulsations observed at Reykjavik (Re) and Syowa (Sy). (a) Pulsations in the local morning, (b) Pulsations in the local afternoon. Upper diagram in each of (a) and (b): Projection on the horizontal plane. Lower diagram in each of (a) and (b): Projection on the vertical magnetic meridian plane (NAGATA et al., 1963).

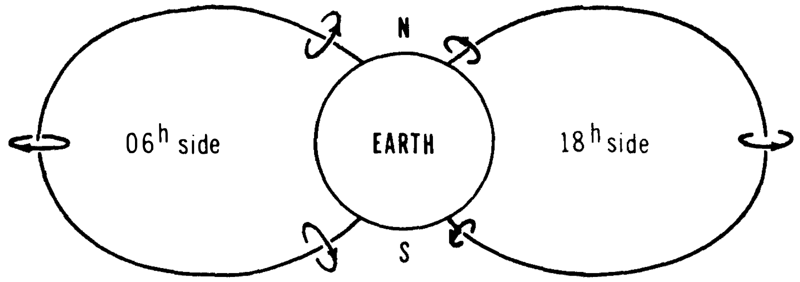

Fig. 8(B). Schematic presentation of the rotation of the polarization vector of Pc 5 magnetic pulsations viewed from the Sun (NAGATA et al., 1963).

pulsations) during the IGY–IGC period. It was because the Pc 1 frequency range is characterized by a periodic repetition of a wave burst group as shown in Fig. 9, suggesting that the wave group is bouncing along the field lines between the conjugate ionospheric areas. For instance, the simultaneous records of the so-called "pearl-type" Pc 1 pulsation observed at Byrd in Antarctica and Great Whale, Churchill and Victoria in Canada, shown in Fig. 9, indicate that the time interval (period) between successive buldges of wave burst is 2.0 min throughout all the records, and the periodic appearance of the wave buldge at all the three Canadian stations are in-phase while the phase at Byrd is just out of phase compared with that at Canadian stations.

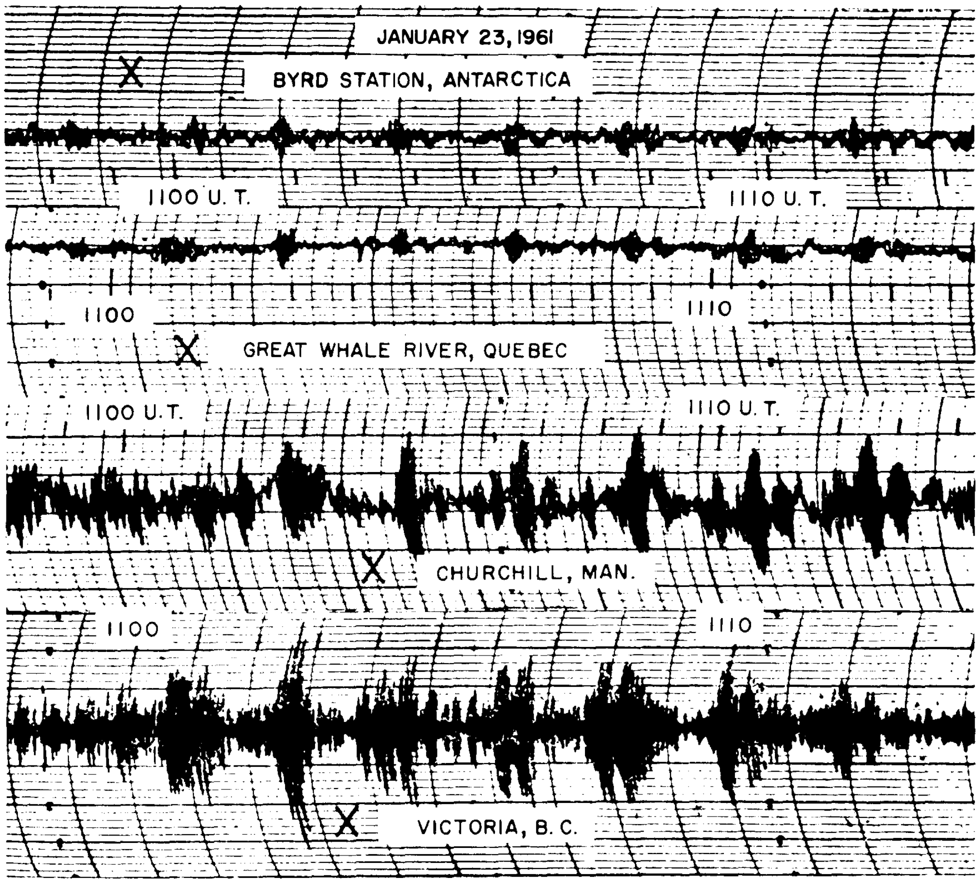

Fig. 9. Simultaneous records of the pearl-type magnetic pulsations observed at Byrd in Antarctica and its near-conjugate stations, Great Whale and Churchill in Quebec and at Victoria, British Columbia (LOKKEN et al., 1963).

It was under consideration on those days that the generation mechanism for the HM waves of Pc 1 range is probably due to the ion cyclotron resonance of protons in the magnetospheric plasma around the equatorial plane, just as the periodic VLF emissions is very likely to be generated by the electron cyclotron resonance in the same source region. Because of the theoretical background, joint observational and theoretical studies on the ULF-ELF-VLF emissions and their conjugacy in the magnetosphere have been continued and extensively promoted after the IGY–IGC.

3. Conjugate Studies in the IQSY (1964–1965) and the IASY (1969–1971)

During the International Year of the Quiet Sun (IQSY, 1964–1965) and the International Years of the Active Sun (IASY, 1969–1971), global coordinated studies on the ionosphere and the magnetosphere including the conjugate problems were further developed, particularly with the aid of sounding rockets and satellites in addition to the ground-based observations.

3.1. Auroras and geomagnetic substorms

In the IQSY–IASY period, the conjugacy studies for visual auroras were extensively carried out by the research group of University of Alaska by use of the all-sky cameras and the auroral TV cameras aboard aircrafts flying along the conjugate L-lines in the south and the north respectively (STENBAEK-NIELSEN *et al.*, 1972, 1973). Figures 10 and 11 show examples of the simultaneous all-sky auroral images taken on the air-

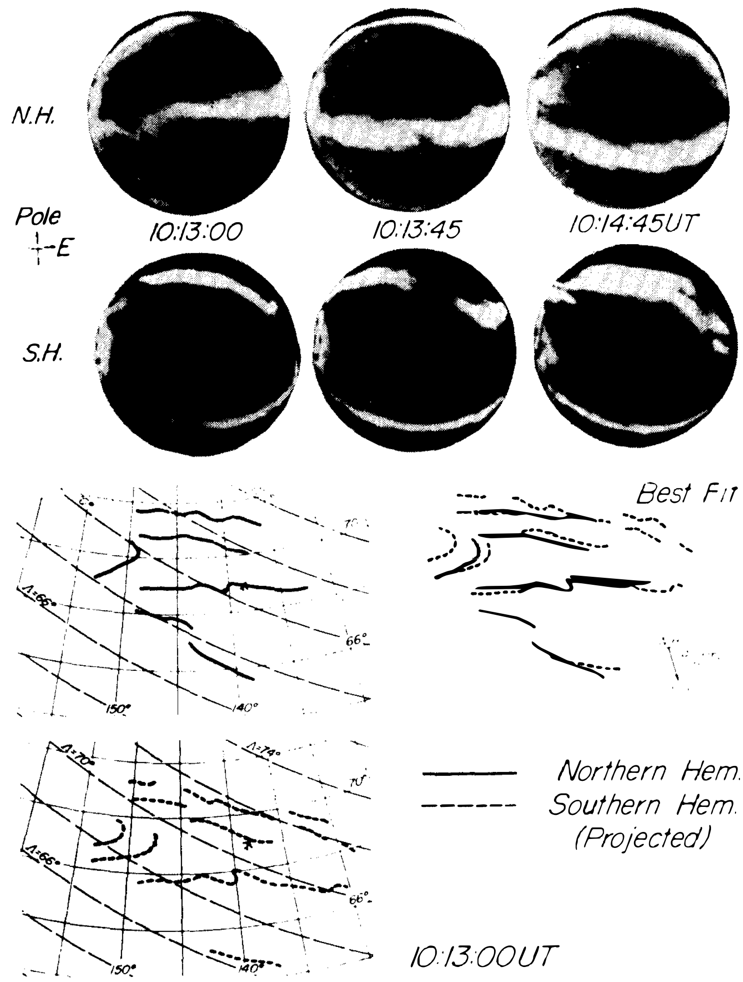

Fig. 10. Conjugate multiple broken auroral bands observed simultaneously by the aircrafts flying about 69° in geomagnetic latitude in the northern (N.H.) and the southern (S.H.) hemispheres on March 26, 1968 (see text) (STENBAEK-NIELSEN et al., 1972).

crafts flying on the conjugate points near an Alaskan geomagnetic meridian line during the IASY period.

It appears in the corresponding all-sky images in Fig. 10 (top) that the conjugacy holds well for the two main auroral arcs between the conjugate areas. With respect to some more detail of the auroral positions projected on the earth's surface coordinates (bottom, left), however, the auroral arcs in the north are shifted poleward by about 140 km into the NWN direction in comparison with the exactly conjugate positions of the southern auroral arcs. If the auroral patterns in the north are shifted by 140 km into the SES direction, they get the best fitting to the southern auroral patterns (bottom, right). In Fig. 11, the all-sky auroral images are in good conjugate relationship and the relative all-sky auroral intensities at the conjugate areas are in reasonably good agreement with each other except for those at 0946:00 in time. It was concluded from these observations in the neighborhood of the auroral zones around the Alaskan geomagnetic meridian line that the varying auroral intensities observed at conjugate points are well correlated to each other for the low latitude arcs at geomagnetic latitude (Λ) $<66°$, but large non-correlated variations occur in the high latitude arc systems of $\Lambda>66°$.

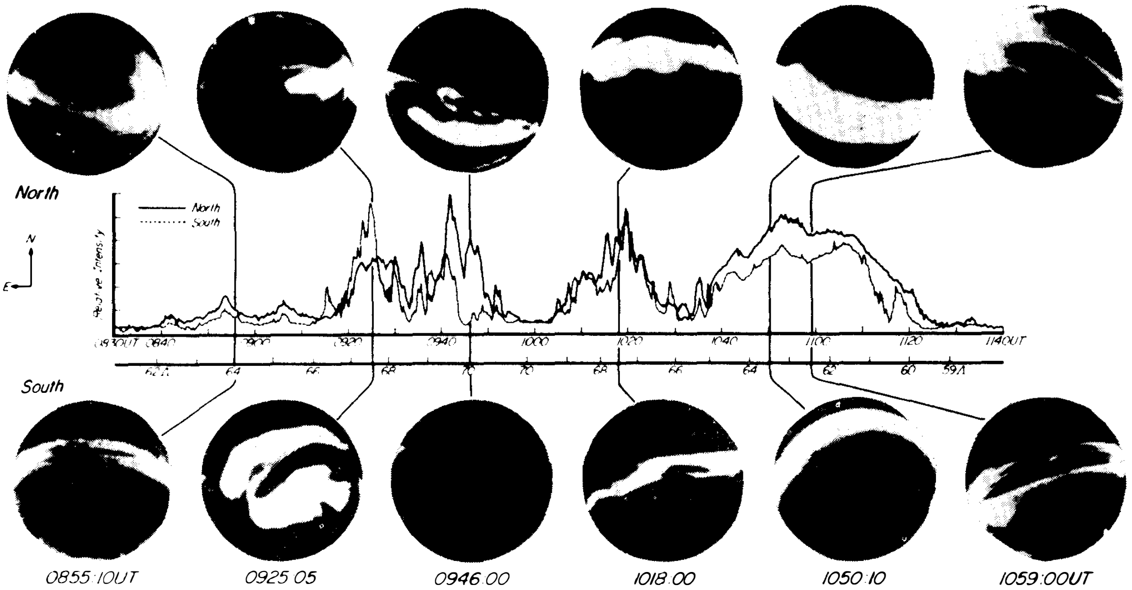

Fig. 11. Relative all-sky auroral intensities at the conjugate areas along College Alaska meridian line on March 29, 1968. The two auroral arc systems are identifiable from the two traces of relative intensity (see text) (STENBAEK-NIELSEN et al., 1973).

In the case of the auroral conjugacy study along the Alaskan meridian line, the intensity (J_N) of auroral arcs in the northern auroral zone is larger than that of the conjugate arcs in the southern auroral zone (J_S) in most cases, J_N/J_S being 1.3 on average, as suggested by the relative auroral intensity traces in Fig. 11. On the contrary, the auroral intensity observed at Syowa is larger than the conjugate auroral intensity simultaneously observed at Husafell in Iceland (MAKITA *et al.*, 1981). Such a difference in the auroral intensity between conjugate points is attributable to a difference in the geomagnetic field total intensity (B) at the conjugate points. The B-values at

College and at its conjugate point (near Macquarie Island) are about 49000 γ and 56200 γ respectively. For comparison, B is about 45000 γ at Syowa and 52000 γ at Husafell. Since the larger value of B on the earth's surface results in the higher altitude of the mirror point for the auroral particles having the same initial energy and pitch angle, the loss-cone of the auroral particles at the auroral emission height is larger for the smaller value of B, thus resulting in the larger flux of the particle for exciting auroral emissions. Assuming an appropriate initial pitch angle distribution, the larger flux of the aurora exciting particles at the smaller B-value end of field line and the smaller flux at the conjugate larger B-value end can be evaluated. In the case of Alaska–Macquarie Island pair, the ratio of the auroral particle flux in the north (I_N) to that in the south (I_S) is estimated as $I_N/I_S \simeq 1.3$ on an assumption that the initial pitch angle distribution is isotropic (Stenbaek-Nielsen *et al.*, 1973). In the case of the Syowa–Husafell conjugate pair, the reversed relation for the auroral intensity that the intensity of conjugate auroras is larger at Syowa than at Husafell is attributable to the same mechanism caused by a difference in the B-value.

Synthetic studies on deviations of visual auroral patterns from the conjugacy, particularly in high latitudes, started based on the IASY data. A typical example of such early studies on the conjugacy and its deformation due to the magnetospheric disturbances was concerned with the conjugate pulsative auroras (*e.g.* Stenbaek-Nielsen *et al.*, 1972). The conjugacy of the polar magnetic substorm events also was observationally and analytically studied by taking into consideration possible deviations from the defined conjugacy. As the polar magnetic substorms are integrated events of the effects of electric fields and currents in the magnetosphere as well as in the ionosphere, it seems that their structure may be much more complicated than auroras, ULF-ELF-VLF waves and CNA. One of representative characteristics of polar magnetic storms may be their power spectral structures. Figure 12 shows an example of the power spectra of a conjugate polar magnetic substorm dependent on time for the Syowa–Reykjavik conjugate pair (Nagata, 1969). In the figure, an approximate agreement of the intensity and the general form of the spectra between the two stations can be observed, but the spectral structure in detail is considerably different from each other. For reference, the HM waves of a long period such as Pc 5 pulsations and the sudden impulses (SI) have substantially the same characteristics of their power spectra between the conjugate areas in the auroral zones. Probably because of the complexity, the conjugate study on the polar magnetic substorms has not much progressed after the IASY time.

In relation to the precipitation of the auroral particles, measurements of CNA systematically started with the aid of the riometer at a number of Antarctic stations after the IGY–IGC period. Since the antenna system of a riometer covers a fairly broad area of the ionosphere, it is generally difficult for a riometer to identify a sharp conjugate point relationship in detail. However, the CNA observation is a convenient useful method for continuously detecting the auroral particle precipitation regardless of the sun-light or weather condition. The CNA observations at approximately conjugate pair stations such as Eights–Deep River and Quebec ($L \simeq 3.5$), Macquarie Island–College and Kotzebue ($L \simeq 5.3$), and Byrd–Great Whale ($L = 6.5$–7.0) have shown a considerably good conjugacy for the CNA events between the pair stations,

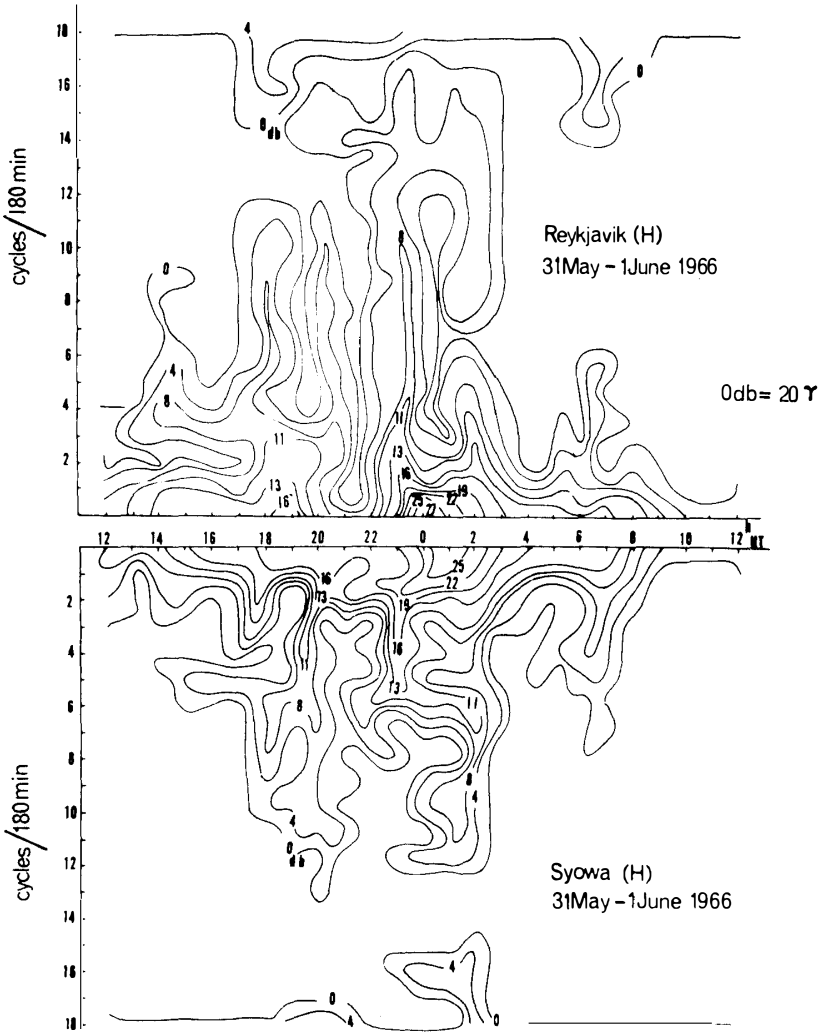

Fig. 12. Comparison of the dynamic spectra vs. time diagrams of a polar magnetic storm observed at the conjugate stations, Reykjavik and Syowa (NAGATA, 1969).

with some exceptional deviations with respect to time and space, as summarized by WESCOTT (1966). The continuous routine observation of the CNA phenomena at Syowa started in 1966.

As the Bremsstrahlung X-ray emissions should be more direct evidence for the precipitation of auroral particles into the upper atmosphere, simultaneous observations of the auroral X-rays by the balloon-borne counters were carried out near the Macquarie Island–College conjugate pair stations (BROWN *et al.*, 1965). Figure 13 shows an example of the auroral X-ray intensity data obtained by the balloon flights, together with simultaneous data of CNA at College and Kotzebue. Each of the three events of anomalous X-ray burst is accompanied by a CNA event and a negative magnetic substorm. From the conjugate X-ray data obtained by eleven balloon flights in February–March 1964, it was concluded that a close correspondence, in similarity and simultaneity, exists in regions of near conjugacy for a wide range of geomagnetic activity ($Kp = 0_+ - 6_0$), but disimilarities become quite evident at locations well removed from near conjugacy, whereas gross features activity remain intact.

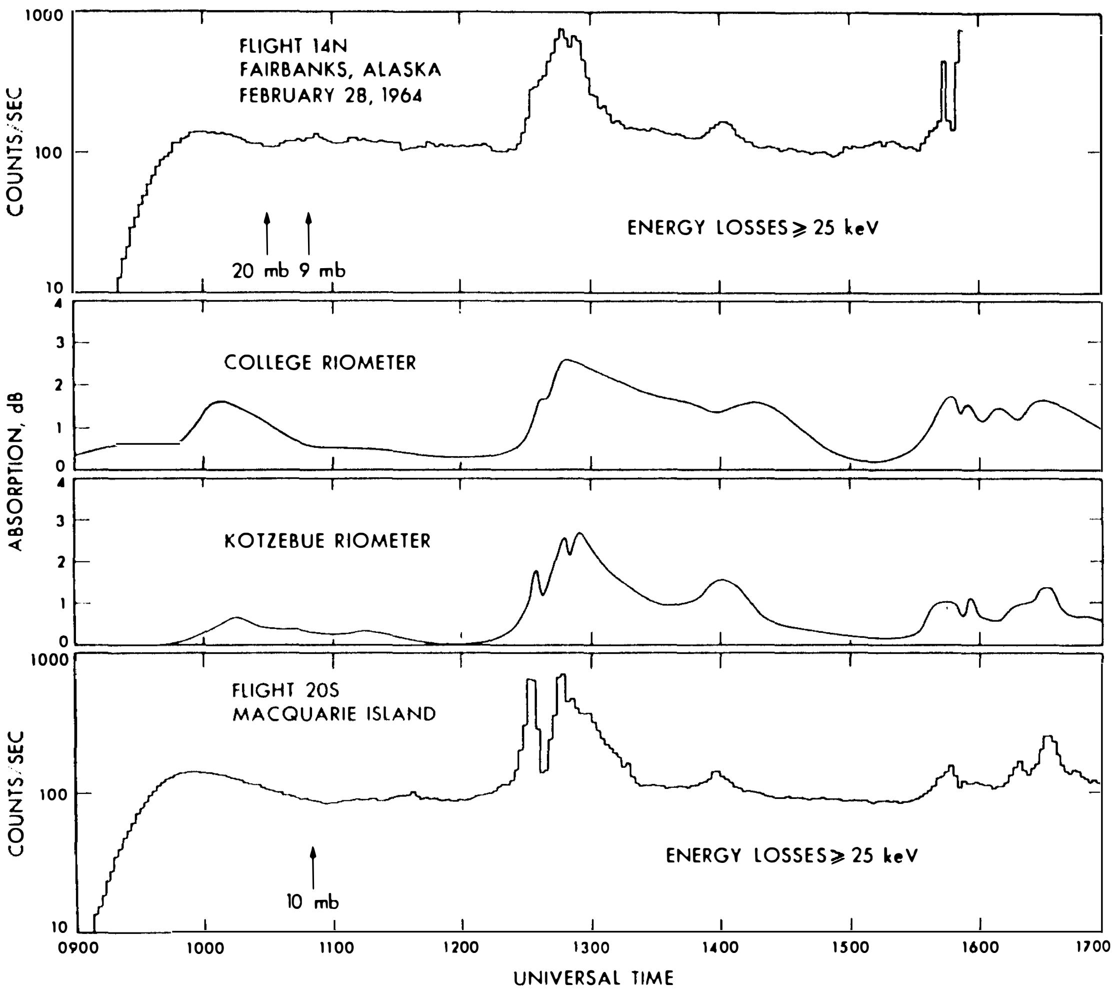

*Fig. 13. Auroral X-ray intensities simultaneously observed on the balloons flying near Fairbanks, Alaska and near Macquarie Island, respectively, and the simultaneous CNA data obtained at College and Kotzebue in Alaska (*Brown *et al., 1965).*

Similar simultaneous balloon-borne observations of the auroral X-rays were performed in 1969 near the Syowa–Iceland conjugate areas, together with CNA measurements on ground (Barcus *et al.*, 1973). Results of the measurements were given by a summary that disimilarities were noted between the observations in the two hemispheres, especially for midnight events, probably because of balloon drift and narrow precipitation regions, while for a dayside event, close conjugate relations were found even though the X-ray detectors were out of conjugacy by approximately 700 km (Fig. 14).

3.2. *Whistler-mode waves*

The VLF periodic emissions which were discovered in high latitudes during the IGY period have been extensively studied since then. Figure 15 shows an example of a pair of the conjugate sonagrams of the VLF discrete periodic emissions observed at Byrd and Great Whale (Helliwell, 1965). As clearly shown in the sonagrams, the discrete VLF emissions alternately appear at Byrd and Great Whale, indicating

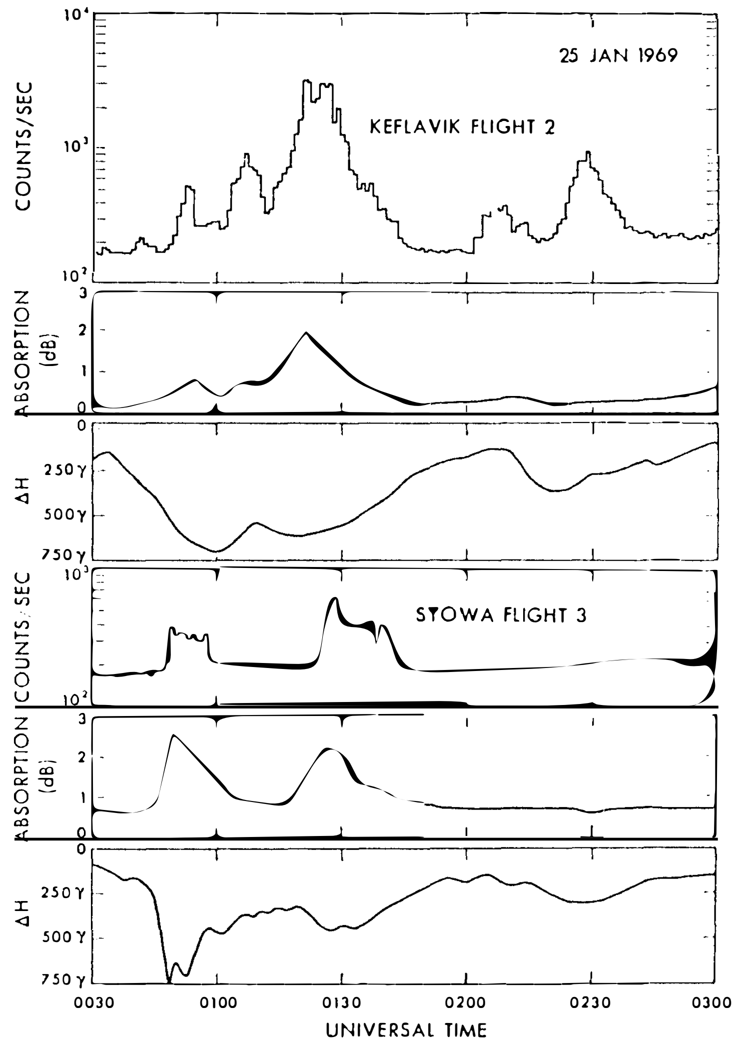

Fig. 14. Simultaneous auroral X-ray intensity records observed on the balloons flying near Syowa and near Iceland, respectively, and the simultaneous data of CNA and the horizontal geomagnetic disturbances (ΔH) observed at Syowa and Reykjavik respectively (BARCUS et al., 1973).

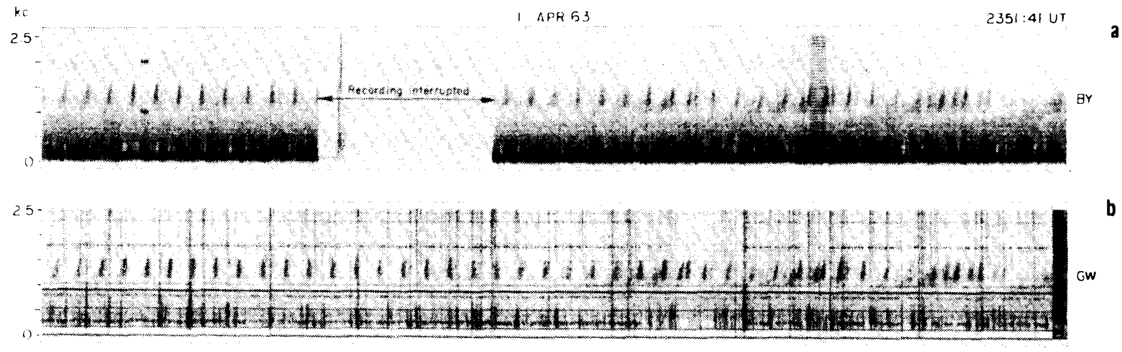

Fig. 15. Examples of the discrete periodic VLF emissions simultaneously observed at Byrd (a) and Great Whale (b). The alternate appearance characteristic is clearly seen (HELLIWELL, 1965).

that a discrete VLF wave pocket is bouncing back and forth between the two conjugate points for a long time, several tens of minute. From these data, a possible physical mechanism for the generation of the discrete VLF emission in the magnetosphere has been proposed on the basic concept of the cyclotron resonance between whistler waves and electrons of 10–10^2 keV in the radiation belt (HELLIWELL, 1967). The observed long life of the bouncing VLF wave pocket suggests that the excitation process by the resonance mechanism is repeated whenever the wave pocket passes through the source region which is located around the equatorial plane along the field-aligned duct.

A significant discovery in relation to the discrete VLF emissions may be a Bremsstrahlung X-ray burst event in association with a VLF burst event observed at Siple (L=4.15) (ROSENBERG *et al.*, 1971). The observed X-ray burst was reasonably interpreted as due to the electron beam of 35–100 keV which excited the VLF burst in the equatorial region and then reflected at the conjugate point of Siple over Roberval (see Table 1), finally coming down into the ionosphere over Siple. Because, in the cyclotron resonance theory for generating the VLF waves, only the transverse component of kinetic energy of electrons is transfered to the VLF wave energy, while the kinetic energy of the parallel component to the field line is increased.

3.3. *Hydromagnetic waves*

Observational studies on the conjugate relationship for the long period HM waves such as Pc 4 and Pc 5 pulsations had been continued on routine basis after the IGY–IGC at the conjugate pair stations such as Macquarie Island–College, Syowa–Reykjavik, Byrd–Great Whale and others. From these results, the presence of both the odd and the even modes of the resonant oscillations of field lines in the magnetosphere was confirmed (*e.g.* WILSON, 1966; LANZEROTTI, 1974).

Simultaneous observations of Pc 5 pulsations of the ground-mode (m=1 odd-mode) at the Byrd–Great Whale conjugate pair on ground, together with Ogo 5 satellite orbiting near the field line linking the two stations, gave rise to additional evidence for justifying the model of hydromagnetic resonance of the field line for Pc 5 pulsations (KOKUBUN *et al.*, 1976).

On the other hand, the elliptic polarization characteristics of Pc 5 HM waves in the conjugate auroral zones that their rotation is left-handed (counterclockwise) in the morning side and right-handed (clockwise) in the evening side, viewed along the direction of the field line (Fig. 8B), was certainly confirmed by observed data at an array network of magnetograph extended from 55° to 80° in geomagnetic latitude along a magnetic meridian through Canada (SAMSON *et al.*, 1971). The extended observations have established the fact that the daily variation of the elliptic polarization characteristics takes place in geomagnetic latitude below about 67° line, where the amplitude of the long period pulsation takes the maximum value and the polarization becomes linear. It was reported, however, that the conjugate Pc 3 pulsations (10–50 mHz in frequency) observed at Siple and its conjugate point do not show the polarization characteristics dependent on local time (LANZEROTTI, 1974).

The observational and analytical studies on the conjugate Pc 1 pulsations also had been further promoted after the IGY–IGC. Figure 16a is an example of the cross correlation diagram with time shifting for the envelopes of Pc 1 pulsations received at the Kerguelen–Borok conjugate pair stations (see Table 1) (BORSOUKOV and PONSOT, 1964). The correlation diagram indicates that the Pc 1 bursts appeared at

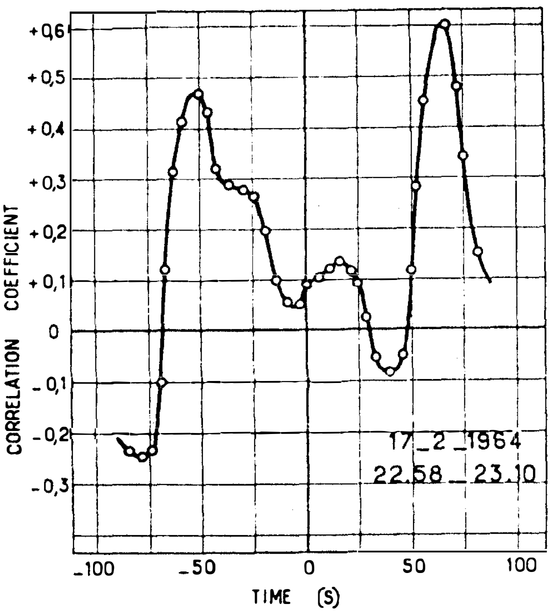

Fig. 16a. *Cross correlation coefficient with time schifting of the envelopes of Pc 1 pulsations received at Kerguelen and Borok (see text) (*BORSOUKOV *and* PONSOT*, 1964).*

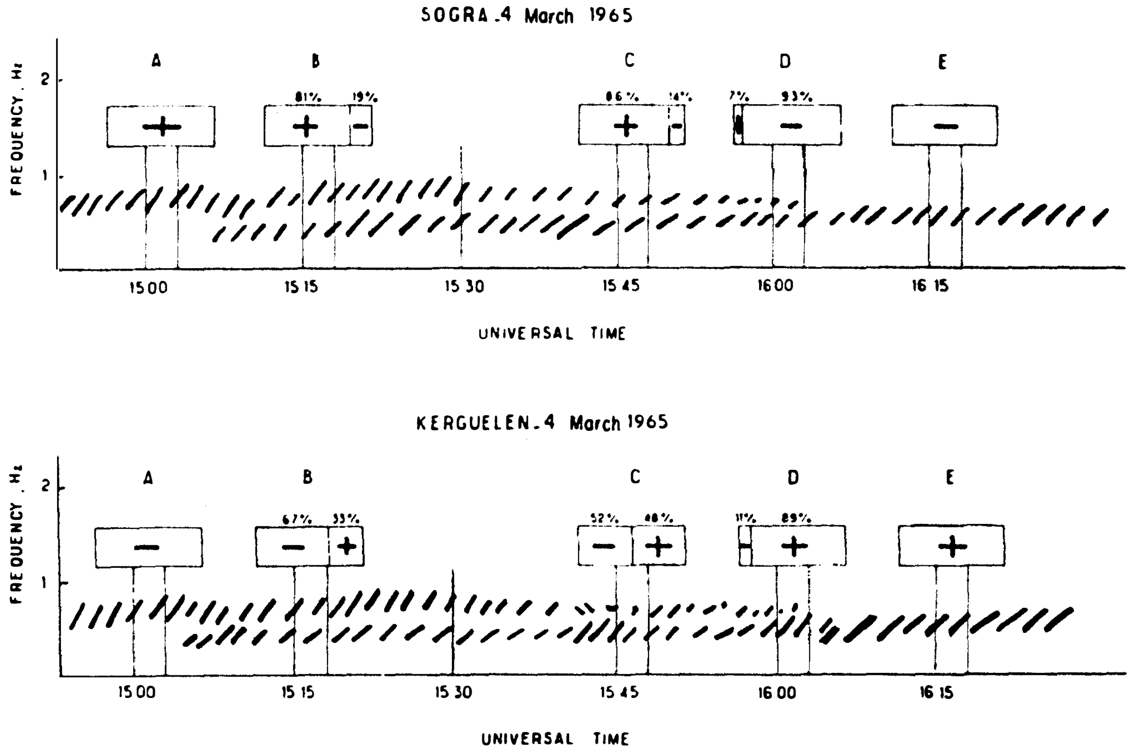

Fig. 16b. *Average polarization sense in the horizontal plane for Pc 1 events measured simultaneously for the periods indicated at Sogra, USSR, and Kerguelen (see text) (*GENDRIN *et al., 1966).*

Kerguelen about 70 s. After their arrival at Borok, although their round travel time between the two conjugate points is about 120 s. This asymmetricity is an open question. Another example shown in Fig. 16b is a schematic illustration of the sonagram of Pc 1 pulsations and their average polarization sense in the horizontal plane, which were received at Kerguelen and its approximate conjugate point (GENDRIN *et al.*, 1966). Symbols (+) and (−) in the figure indicate the left-handed and the right-handed polarization senses respectively, and the attached numerical figures give the percentages of (+) and (−) senses during the indicated 3 min intervals. The occurrence intervals and the mode of polarization sense (and its reversal at the conjugate points) of the observed Pc 1 pulsations generally show the alternate occurrence of the Pc 1 events for a fairly long time, which are caused by the bouncing motion of the HM wave pocket between the conjugate areas with an appropriate energy supply system for maintaining the bouncing event for a long time. However, the observed evidence for the mixing of the plus and the minus polarization senses of the HM waves during the 3 min intervals was an unsolved problem.

4. Conjugate Studies before and during the IMS (1976–1979)

Since the time of the IGY, physics of the magnetosphere, including basic physics of the magnetospheric plasma, has made great progress, particularly by means of satellite borne experiments. As stated by LANZEROTTI (1974), at the same time, the use of the measurements made simultaneously at conjugate points on the earth's surface still has the potential of serving well for the study of the nature and the global extent of the magnetospheric phenomena as a continuous routine monitoring system from the earth's surface.

In the course of the post-IGY development of the magnetospheric physics, a number of discovery related to physics of the geomagnetically conjugate phenomena have come out. They are

1) The field-aligned electric current in the auroral zones;
2) The electric field along the field lines over the auroral zones due to the V-shape equipotential surfaces;
3) Nature and characteristics of the proton auroras;
4) The energy spectra of auroral electrons and protons measured aboard rockets and satellites;
5) Rapid-run moving characteristics of auroral disturbances;
6) The electron cyclotron resonance for generating the discrete VLF waves;
7) The Cherenkov radiation for generating the auroral VLF hiss;
8) The auroral kilometric radiations;
9) The VLF emissions triggered by artificial radio waves;
10) VLF wave characteristics observed by satellites in the magnetosphere;
11) The proton cyclotron resonance for generating the short period ULF waves such as Pc 1 pulsations;
12) ULF characteristics observed by satellites in the magnetosphere;
13) Interactions between ULF and VLF waves in the magnetosphere.

These items mentioned above, and probably some others, are directly or indirectly related to understanding the conjugate phenomena in the magnetosphere.

The conjugate studies in the polar regions in the International Magnetosphere Study (IMS) 1976–1979 were promoted on the basis of the recently advanced magnetospheric physics.

4.1. Auroras

Figure 17 shows an example of the simultaneous conjugate diagrams of varying auroral intensity distribution along the magnetic meridian for λ5577Å line of electron aurora observed at Syowa and Husafell (MAKITA *et al.*, 1981). The new observatory established for the IMS at Husafell in Iceland is located about 50 km north of the conjugate point of Syowa (see Table 1). The meridian scanning spectrophotometers for electron auroras of λ5577Å and proton auroras of Hβ, an all-sky auroral camera and a wide-range auroral TV-camera were used at the conjugate pair stations. In the "meridian-time" diagrams for the λ5577Å line in Fig. 17, periods A, B and C indicated at the bottom correspond to the pre-breakup, the breakup and the post-breakup phases, respectively, of an auroral substorm and an associating magnetic substorm. As confirmed with the simultaneous all-sky and wide-range TV auroral images, the auroras in period A were the quiet auroral arcs, whose intensity was 7–8 k*R* at maximum at both the stations, and the positions of the quiet auroral arcs extending along the E-W direction were in a good conjugate relation. Looking at the auroral enhancement characteristics in detail, however, considerable discrepancies between the Husafell diagram consisting of three active stages and the Syowa diagram giving only a single activated stage can be observed. Since the meridian-scanning spectrophotometer can give information about the auroral intensity distribution within a narrow slit zone along the magnetic meridian passing through the zenith but no information about

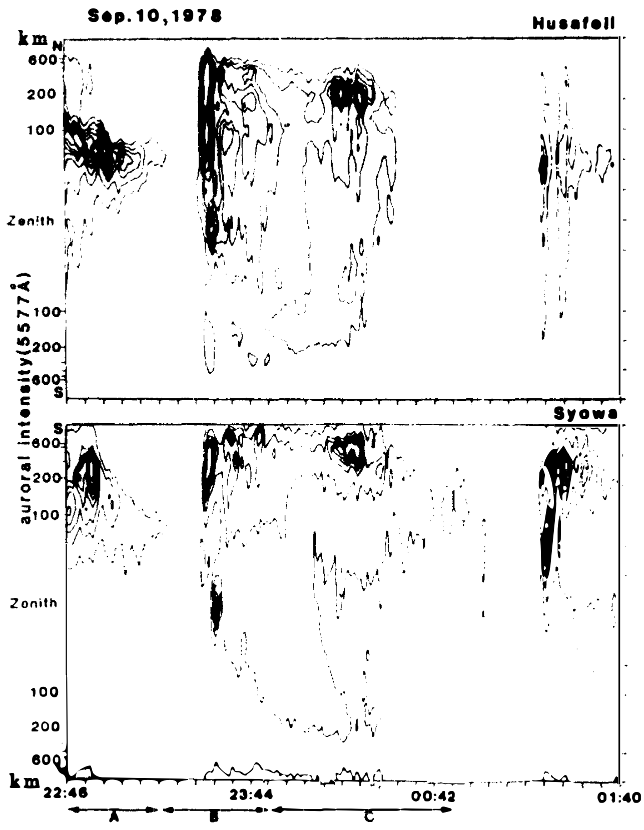

Fig. 17. Simultaneous meridian distribution vs. time diagrams of λ5577Å auroral intensity associated with a magnetic substorm at the Syowa–Husafell conjugate stations (MAKITA et al., 1981).

the auroral activity in the outside of the slit zone is recorded, a slight deviation along the magnetic E-W line of the auroral particle beam, therefore, should cause a breakdown of the conjugacy of minor structures of observed auroras at the conjugate stations. It is the weakest point in the auroral intensity measurements by means of the meridian-scanning spectrophotometer.

In the breakup phase in period B and the post-breakup phase in period C, the conjugate correspondence between individual patches of enhanced aurora within the meridian zone appears to be worse than those in the quiet pre-breakup phase, though the general variation pattern of auroral intensity with time well holds the conjugacy between Syowa and Husafell. In the same sequence of the auroral conjugacy study, it was found that the conjugacy of the auroral meridian-time diagram pattern in association with the positive magnetic substorms is generally much worse than that accompanied by the negative magnetic substorms.

Figure 18 shows a typical example of nearly simultaneous observations of the auroral electron precipitations in the polar conjugate areas made on two DMSP satellites, DMSP-F2 and F3 (MAKITA *et al.*, 1983). In two panels on the right side, the auroral electron precipitations observed at about 840 km in height are given in terms of the electron number flux (electrons/cm^2•s•sr), the energy flux (ergs/cm^2•s•sr) and the average energy (keV) along the trajectories of DMSP-F2 and F3 satellites in the northern and the southern polar regions respectively, which are shown in the bottom left panel. The top left panel illustrates the AE-index and the arrow indicates the time when the two satellites passed over the polar regions. An intense substorm ($AE \simeq 650\ \gamma$) occurred about 2 h before the observing time and the polar crossing by

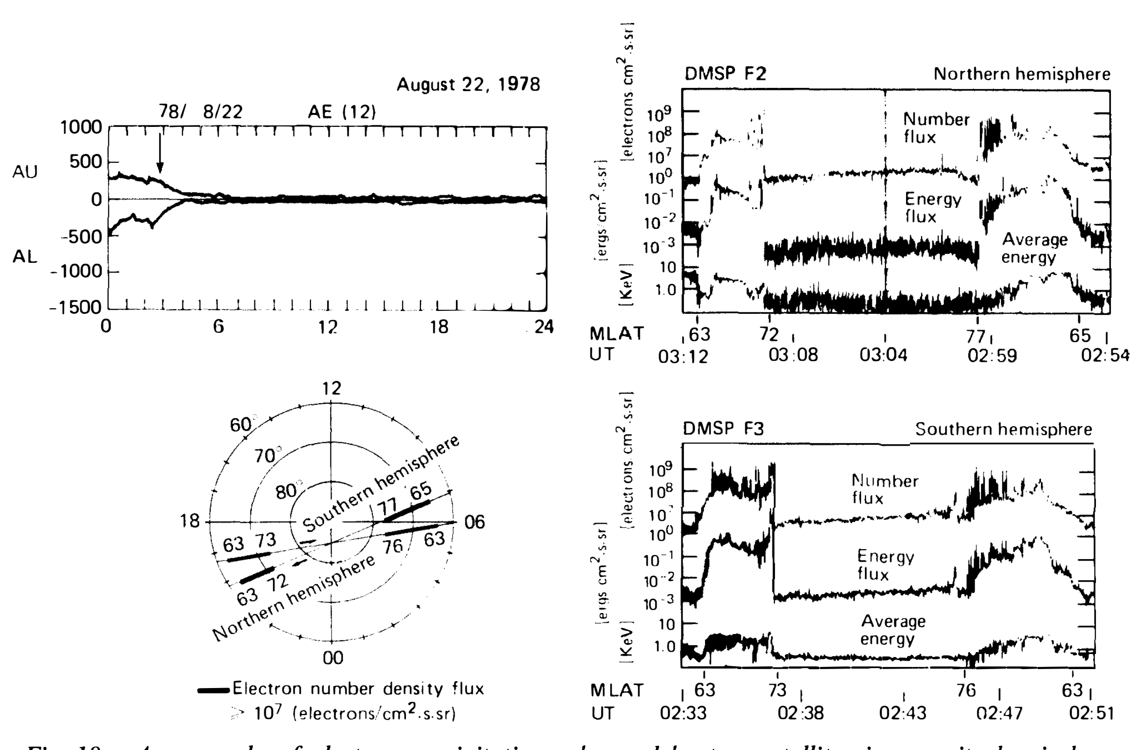

Fig. 18. An example of electron precipitations observed by two satellites in opposite hemispheres during the high activity period of substorm recovery phase (see text) (MAKITA et al., 1983).

the two satellites took place during the recovery phase of substorm when AE-index was about 500 γ. DMSP-F2 satellite traversed the northern polar region from the dawn side to the dusk side during 18 min from 0254 to 0312 UT, and DMSP-F3 satellite traversed the southern polar region from the dusk side to the dawn side during 18 min from 0233 to 0251 UT. In the dusk sector, the high energy auroral electron (larger than 1 keV on average) precipitation region was detected from 63° to 72° (in geomagnetic latitude) in the northern hemisphere and from 63° to 73° in the southern hemisphere. In the dawn sector, the high energy electron precipitation region was extended from 65° to 72° in the northern hemisphere and from 63° to 74° in the southern hemisphere, and the low energy electron (less than 1 keV on average) precipitation region can be found from 72° to 77° in the north and from 71° to 76° in the south. On the other hand, no dusk low energy auroral electron precipitation region could be identified in either hemisphere. This event shows therefore that the width and the location of the high and the low energy auroral electron precipitation regions in both the dawn and the dusk sectors are similar between the two conjugate regions.

4.2. Whistler-mode waves

The quasi-periodic VLF emissions (QP emissions) were defined as a sequence of repeated noise bursts of relatively long period, in which each burst may consist of a number of discrete events, periodical emissions or chorus; the period between bursts is usually measured in tens of second and is relatively irregular compared with that of the periodic emissions (HELLIWELL, 1965). The conjugate characteristics of the QP emissions were extensively studied during the IMS period. It was found that the QP emissions can be classified into the QP emissions associated with the geomagnetic pulsations of the approximately same period (Type 1) and those without corresponding pulsation (Type 2), where the Type 2 QP emissions have a more regular periodicity than Type 1 (SATO and KOKUBUN, 1980, 1981). Figure 19 shows an example of the simultaneous intensity records of the Type 1 QP emissions and the ULF waves observed at Husafell in Iceland and Syowa and Mizuho in Antarctica. Figure 20 shows the frequency-time spectra for 5 min from 1046 to 1051 UT of the same QP emission event as given in Fig. 19. Figure 20 may indicate that the conjugacy of the Type 1 QP emissions between Syowa and Husafell was very good with respect to their occurrence time as well as their dispersion characteristics. Figure 19 shows that the intensity of the Type 1 QP emissions was well correlated with that of the simultaneous Pc 3 pulsations observed at Syowa and Husafell. All the power spectra of these QP emissions and the $\dot{H}$ and $\dot{D}$ components of the HM pulsations have the peak at 25 mHz at both Syowa and Husafell. It may be further noted in Fig. 19 that the coherency of both the VLF QP emissions and the ULF waves was high between Syowa and Mizuho which is located about 270 km magnetically poleward from Syowa, though their amplitudes are larger at Mizuho than at Syowa.

These QP emissions were simultaneously observed on GEOS-1 satellite too, as shown in Fig. 21a, when the satellite was located near the field line linking Syowa and Husafell, as illustrated by the field-line foot-prints of GEOS-1 in Fig. 21b.

Figure 22 shows an example of the coherency and the phase-lag diagrams of the Type 1 QP emissions and the $\dot{H}$ and $\dot{D}$ components of the associated Pc-pulsations

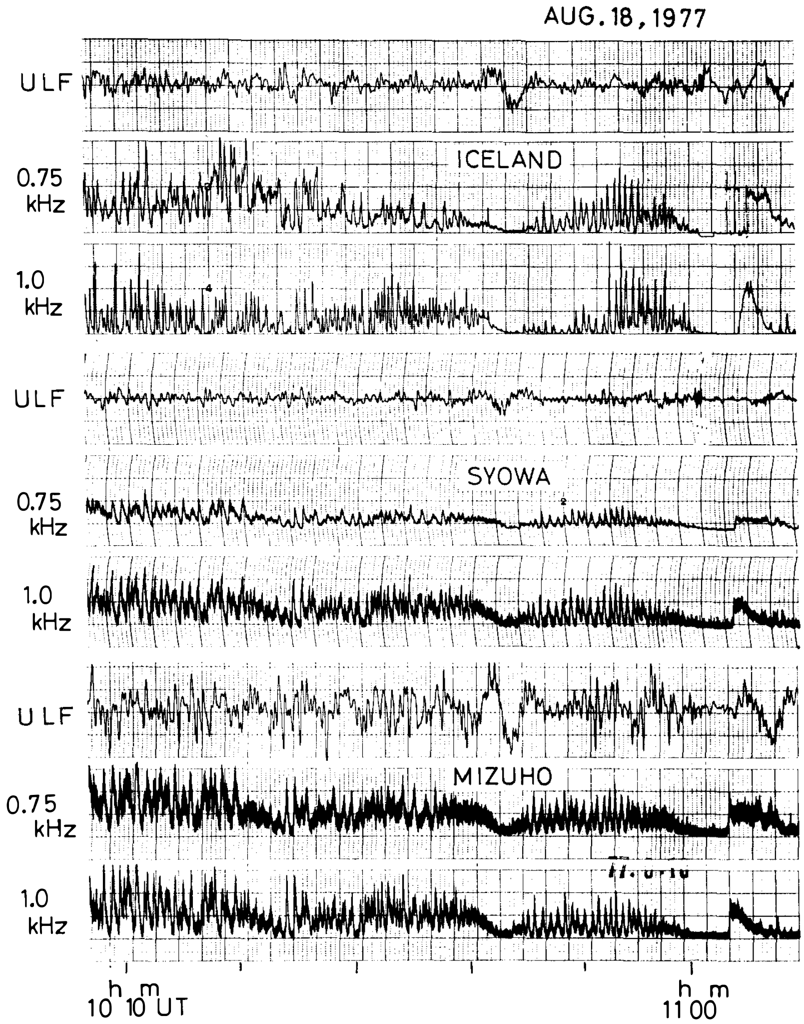

Fig. 19. An example of simultaneous intensity records of ULF and Type 1 QP emissions observed at Husafell in Iceland and Syowa and Mizuho in Antarctica (SATO et al., 1980).

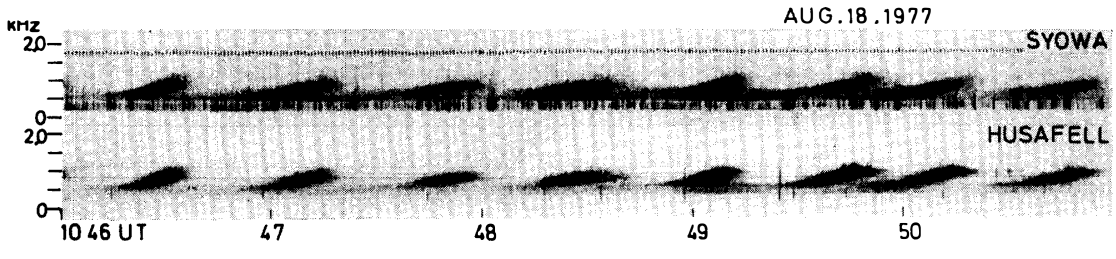

Fig. 20. The f-t diagrams of Type 1 QP VLF emissions observed simultaneously at Syowa and Husafell (SATO et al., 1980).

simultaneously observed at Syowa and Husafell. The Type 1 QP emissions have a good coherency and the phase-lag is approximately zero in the frequency range smaller than 70 mHz between the conjugate pair stations. It was observed, in addition, that the propagation time-lag between the QP emissions and the HM pulsations is approximately the same (20–30 s; 26 s on average) at both the conjugate pair stations. These results indicate that the Type 1 QP emissions are generated near the equatorial plane

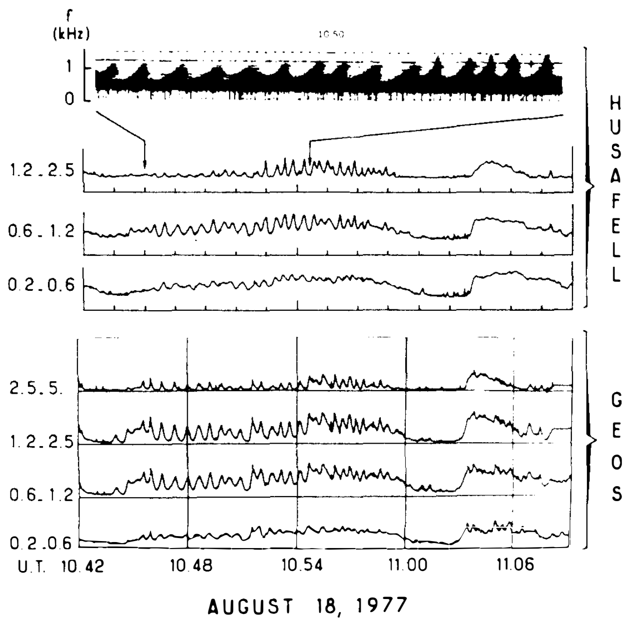

Fig. 21a. Type 1 QP emissions simultaneously observed on GEOS-1 satellite and at Husafell (CORNILLEAU-WEHRLIN et al., 1978).

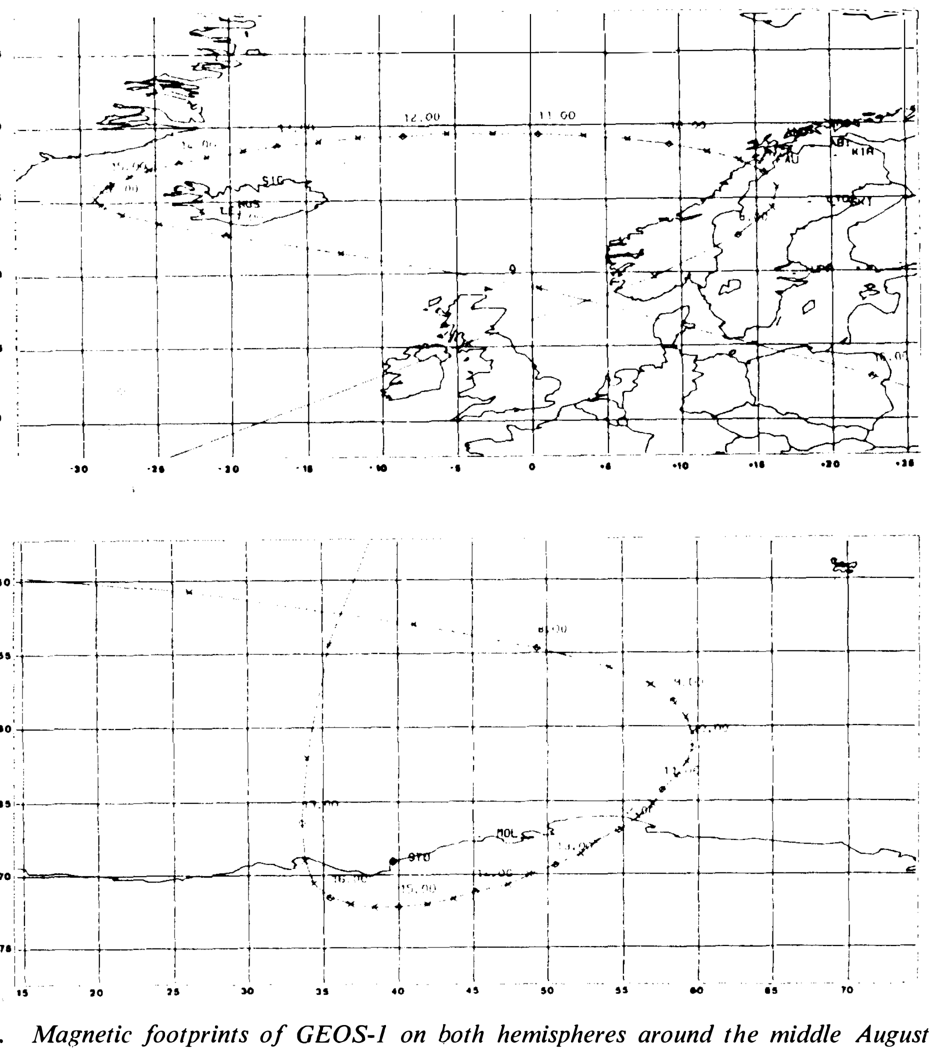

Fig. 21b. Magnetic footprints of GEOS-1 on both hemispheres around the middle August 1977.

in the outer magnetosphere and propagate simultaneously to the both hemispheres along the field line. As for the Pc magnetic pulsation in the frequency range smaller than 30 mHz, the phase relation is almost in-phase for the $\dot{H}$ component and out-of-phase for the $\dot{D}$ component and the $\dot{D}$ component has a larger coherency than the $\dot{H}$ component. These results suggest that the Pc pulsations have the odd-mode HM wave characteristics. Since an excitation and/or a modulation of VLF waves by the compressional Alfvén waves are observationally confirmed in the cases of the excitation and/or the modulation of VLF waves by SSC and SI events in the geomagnetic field (HUDSON, 1971; HIRASAWA, 1981), it will be highly probable that the Type 1 QP waves are excited and modulated by the associated HM waves, though an exact theoretical model has not yet been established.

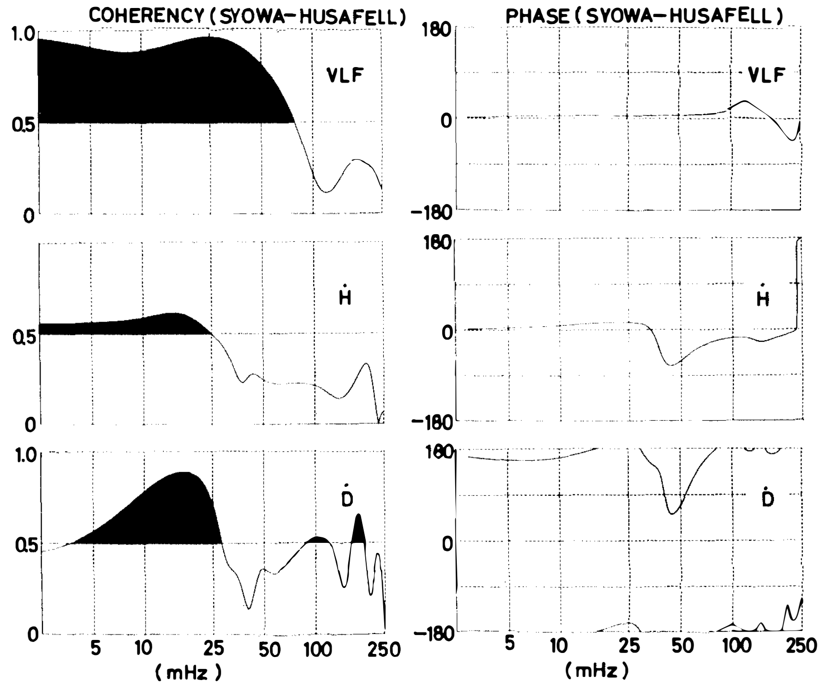

Fig. 22. The coherency and the phase-lag of the simultaneous records of Type 1 QP emissions and $\dot{H}$ and $\dot{D}$ components of the associated Pc pulsations for the Syowa–Husafell conjugate stations (August 19, 1977) (SATO and KOKUBUN, 1980).

Figure 23 shows a typical example of the frequency-time spectra (f-t spectra) of the Type 2 QP emissions observed at Syowa and Husafell (SATO and KOKUBUN, 1981). In these spectrograms, the Type 2 QP emissions of a regular period (11 s) occur almost simultaneously at the two stations. The regular periodicity of the Type 2 QP emissions was confirmed by a sharp maximum peak at 90 mHz in the power spectra. The regular periodicity and the good conjugacy of the Type 2 QP emissions can be seen in another example of their f-t spectra for a longer time interval, shown in Fig. 24.

In comparison with the Type 1 QP emissions, the ULF waves of the same frequency as the repitition frequency of the VLF emission were not observed in association with the Type 2 QP emissions, particularly during geomagnetically quiet periods.

In some cases of moderate geomagnetic activities (*i.e.* Kp=2–3), comparatively irregular ULF waves of relatively much smaller amplitudes appear coherently with the Type 2 QP emissions (SATO and KOKUBUN, 1981).

Although a fully reliable theoretical interpretation of the generation and the propagation mechanisms has not yet been established, several possibilities for the theoretical model have been proposed. One is an idea that the Type 2 QP emissions may be modulated by an electrostatic ULF waves within the magnetosphere which cannot be observed on ground. The other is a theoretical model that the repetition period of the relatively regular Type 2 QP waves represents the bouncing period of the VLF wave pocket along the field line and the occasionally associating ULF waves are caused by a quasi-periodic enhancement of the auroral zone ionosphere owing to electron precipitations accerelated by the VLF waves, because the H component of

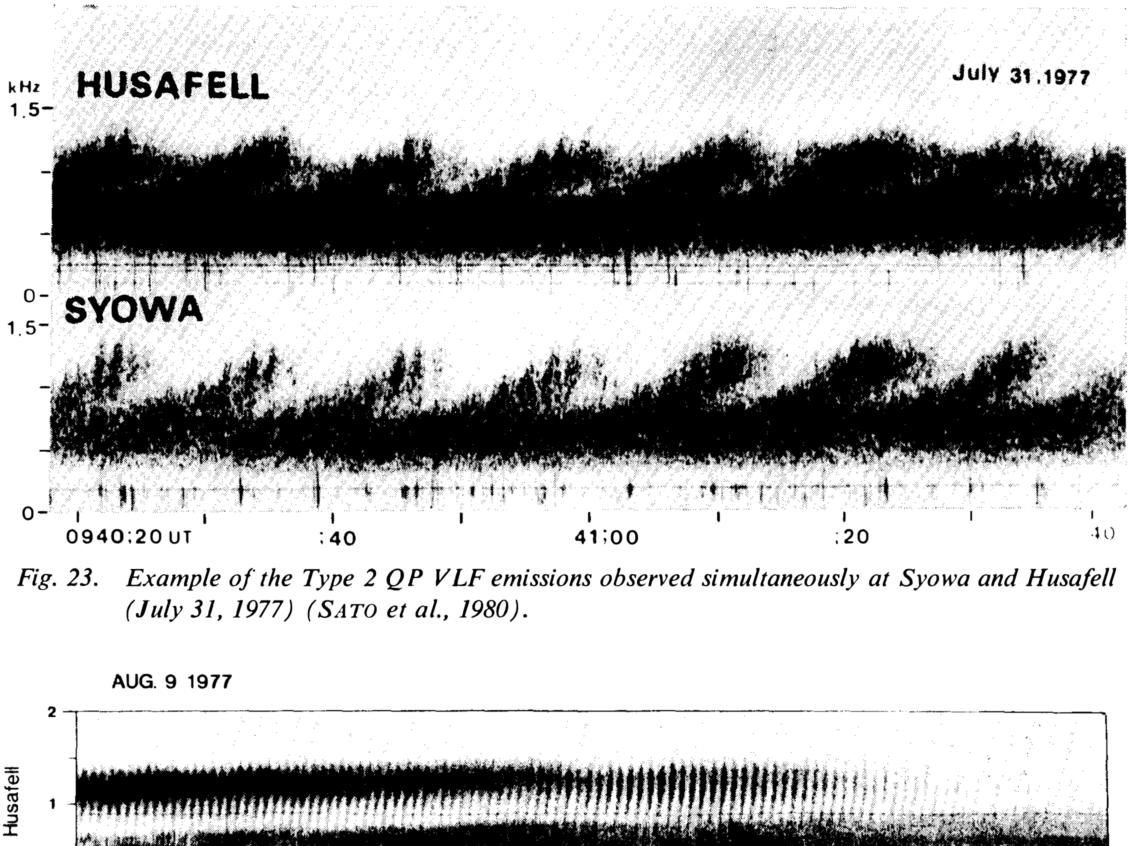

Fig. 23. Example of the Type 2 QP VLF emissions observed simultaneously at Syowa and Husafell (July 31, 1977) (SATO et al., 1980).

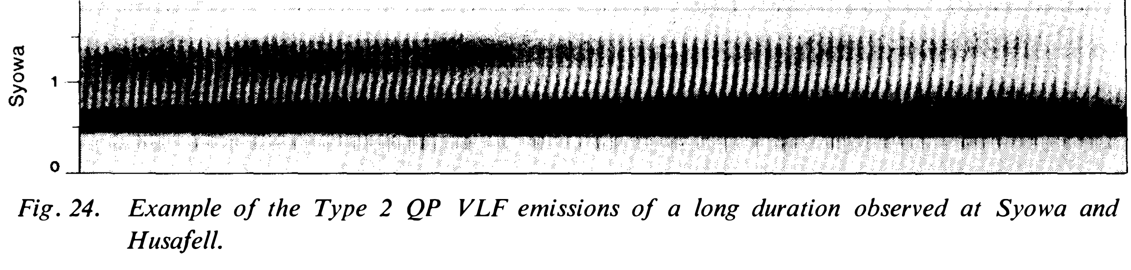

Fig. 24. Example of the Type 2 QP VLF emissions of a long duration observed at Syowa and Husafell.

the ULF waves is dominantly coherent with the simultaneous Type 2 QP waves in this case (SATO and KOKUBUN, 1981).

Figure 25 shows an example of the *f-t* spectra of the ELF-VLF polar chorus emissions observed simultaneously at Syowa and Husafell. Figure 26 is an example of the intensity of the polar chorus at 0.75 and 1.0 kHz together with the ULF records observed at Syowa and Mizuho in Antarctica and Husafell in Iceland (SATO *et al*., 1980). It will be obvious in these results that the polar chorus emissions are suddenly enhanced simultaneously in the both hemispheres and the conjugacy with respect to

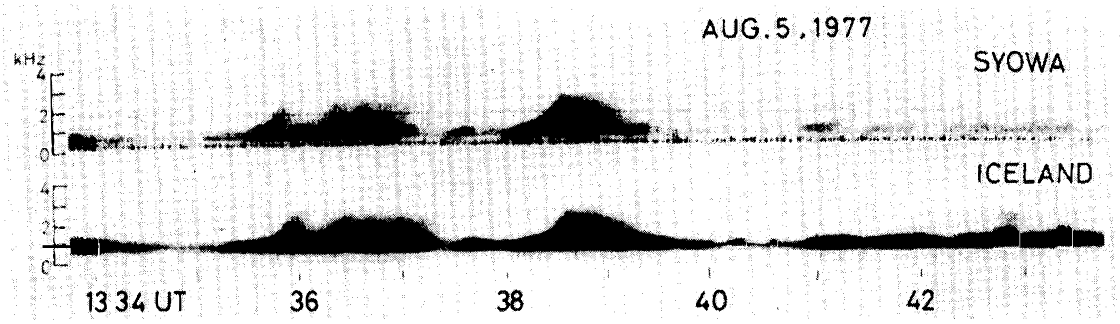

Fig. 25. Example of the frequency-time spectra of the VLF polar chorus emissions observed simultaneously at Syowa and Husafell (SATO et al., 1980).

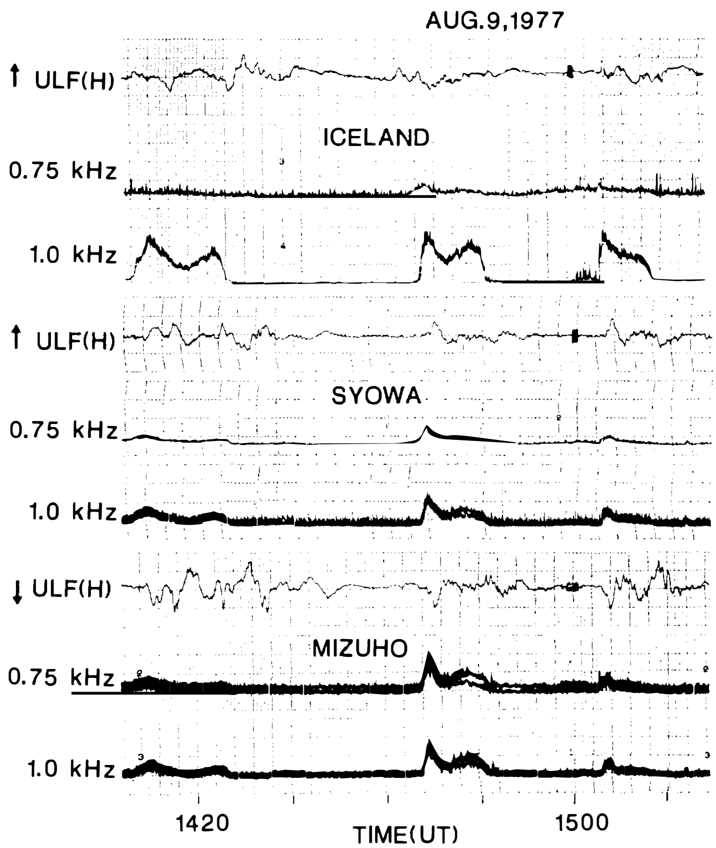

Fig. 26. Example of the intensity records of the VLF polar chorus emissions at 0.75 and 1.0 kHz and the associated ULF variations ($\dot{H}$ component) observed simultaneously at Syowa and Mizuho in Antarctica and Husafell in Iceland (SATO et al, 1980).

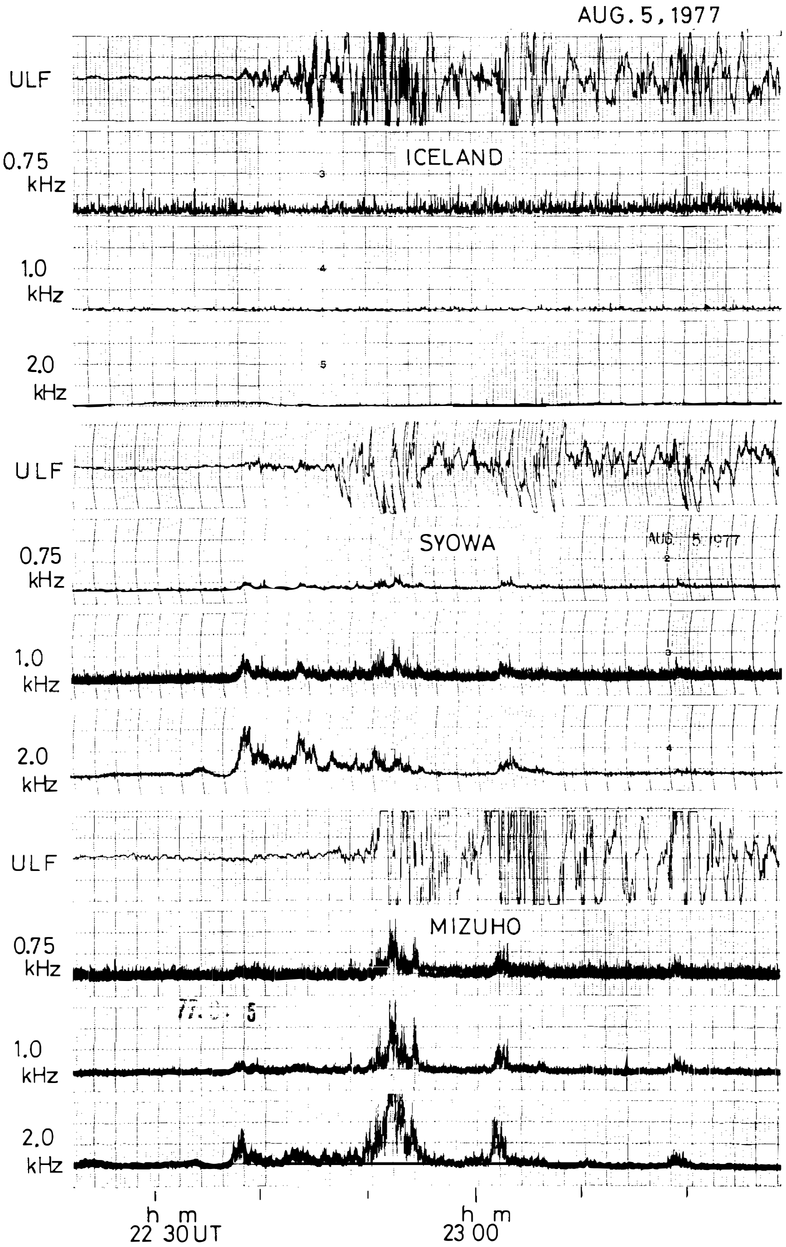

Fig. 27. Example of the intensities of the auroral hiss emissions at 0.75, 1.0 and 2.0 kHz and the $\dot{H}$ component of the associated ULF waves observed simultaneously at Syowa and Mizuho in Antarctica and Husafell in Iceland (SATO et al., 1980).

the frequency spectrum and the intensity between the conjugate pair stations, Syowa and Husafell, holds satisfactorily well. It may be noted in Fig. 26 that the sudden enhancements of the polar chorus emissions were associated with impulsive pulsations in the ULF frequency range.

Figure 27 shows an example of the simultaneous records of the intensities of the auroral hiss emissions at 0.75, 1.0 and 2.0 kHz and the ULF waves received at Syowa, Mizuho and Husafell (SATO *et al.*, 1980). In this example, marked auroral hiss emission events occurred in association with intense magnetic disturbances accompanied by auroral displays at Syowa and Mizuho in Antarctica, but no considerable VLF emissions was observed at Husafell, where magnetic disturbances similar to those in the southern auroral zone were recorded. Generally speaking, the conjugacy of the auroral hiss emissions between the auroral zone conjugate pair stations is much poorer than that of the ELF-VLF emissions of the other types such as the periodic emissions, the QP emissions and the polar chorus.

As the auroral hiss emission event, in its theoretical model, may be due to the initial Cherenkov radiation by the auroral electrons and an amplification process for the generated VLF waves by the high energy auroral electron beam which is sensitively dependent on the local condition of the auroral zone ionosphere (MAGGS, 1976; YAMAMOTO, 1979), a possible mechanism of the generation and the growth of the auroral hiss waves would be more complicated than the visual auroras themselves. The auroral hiss amplification theory predicts, for instance, that a larger number density of the ambient electrons in the upper ionosphere results in a smaller magnitude of the amplification coefficient for the VLF waves. In the case of Fig. 27, the ionosphere over Syowa and Mizuho was in the condition of a low density of the ambient electrons in the middle winter season, while Husafell was in the middle summer season.

4.3. Hydromagnetic waves

The model of hydromagnetic resonance of the field lines with the magnetospheric HM waves has been observationally and theoretically examined by use of observed data in space as well as on ground more extensively since the time of the IMS. From Ogo 5 satellite data KOKUBUN *et al.* (1977) derived a conclusion that the Pc 5 waves in space are the standing shear Alfvén waves along the field lines. From the particle and the magnetic field data observed on ATS6 satellite, CUMMINGS *et al.* (1978) found that the Pc 4 waves observed on the satellite are predominantly the odd-mode harmonics of the standing shear Alfvén waves. From ATS6 satellite magnetic data, TAKAHASHI and MCPHERRON (1982) found the simultaneous excitation of multiple-harmonic modes (from 2nd to 6th harmonics) of the standing Alfvén wave in a frequency range of 6.6–100 mHz.

It was suggested on the other hand that the HM surface waves on the magnetopause excited by the Kelvin-Helmholtz instability mechanism owing to the energy input from the solar wind will be the most probable source for the Pc 5 pulsations observed on ground and in the magnetosphere. SOUTHWOOD (1974) and CHEN and HASEGAWA (1974) proposed a linear resonance theory for the generation of the Pc 4–5 HM waves on a basic concept of a resonance coupling between a monochromatic surface wave and a shear Alfvén wave through appropriate field lines within the magnetosphere. This theory can give rise to a reasonable theoretical explanation for the observed reversal of the polarization sense of the Pc 4–5 pulsations across the magnetic local noon meridian.

The model system of HM resonance of the field lines for the Pc 4–5 pulsations was further supported by clarifying a conjugate harmonic structure of the Pc 4–5 pulsations observed at the Syowa–Husafell conjugate stations (TONEGAWA and FUKUNISHI, 1984). Figure 28 shows an example of two specially combined diagrams representing both the coherency and the phase relation of the cross correlation between the HM waves of 2–100 mHz received simultaneously at Syowa and Husafell, as a function of the wave frequency and time through a day. In the figure, each circle (○) and cross (×) represents a point defined by the wave frequency (f) and the time (t), where the coherency between Syowa and Husafell is larger than 0.5 in the cross dynamic spectrum. The phase difference is ($0\pm60°$) for the cross mark and ($180\pm60°$) for the circle mark, so that the cross and the circle marks approximately represent a coherent in-phase condition and a coherent out-of-phase condition, respectively. In the top panel for the H component, the harmonic structure of the HM waves of Pc 3–5 range can be seen, particularly during 09–19 UT, and the phase relation is in-phase for the odd-mode harmonics while it is out-of-phase for the even-mode harmonics. The straight lines in the figure present the mid-frequency *vs.* time lines which have a mutually harmonic relationship with respect to frequency. In the bottom panel for the D component, the harmonic relationship is much less clear than for the H component, though the phase-relation of the ground mode is definitely out of phase.

Figure 29 shows the power spectra *vs.* time diagram for the same H component

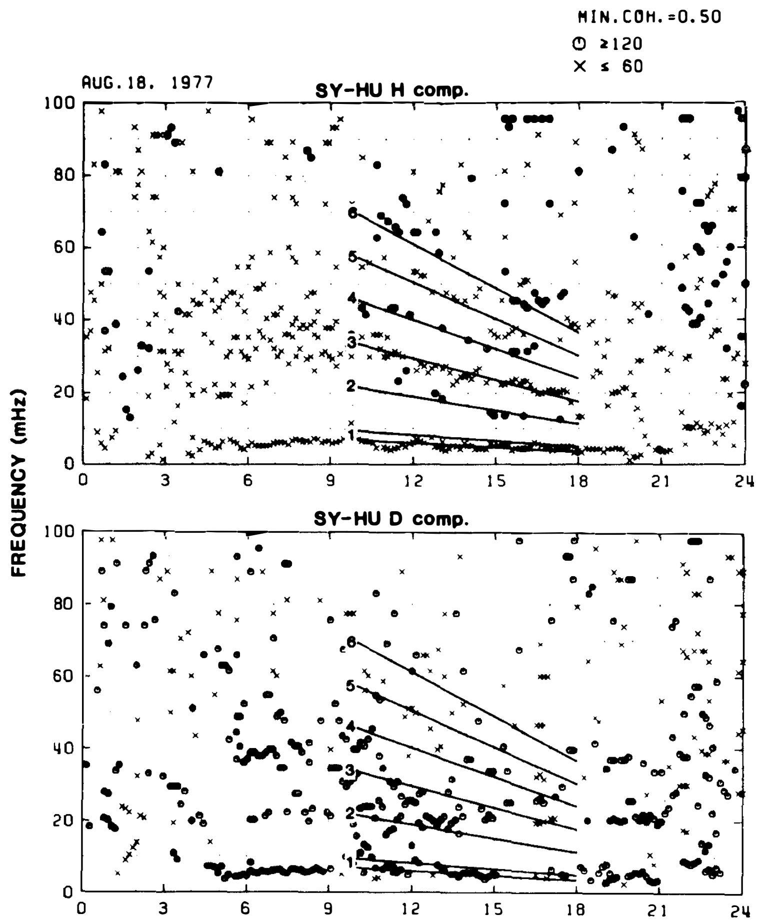

Fig. 28. The harmonic structure inferred from the phase relation of the H and D components of the HM waves observed simultaneously at Syowa and Husafell. Top: H component. Bottom: D component. Circle marks (○): Phase-lag$=\pm(180°\pm60°)$, coherency>0.5, cross marks (×): phase-lag$=0°\pm60°$, coherency>0.5 (see text) (TONEGAWA and FUKUNISHI, 1984).

of the HM waves observed at Syowa as in Fig. 28 in the top panel and the dynamic cross spectrum *vs.* time between the *H* components at Syowa and Husafell in the bottom panel. The straight lines are the same harmonic lines dependent on time as given in Fig. 28. The enhanced power spectral peaks have a general tendency to concentrate on and around the harmonic lines, particularly the ground and the third harmonic lines. The harmonic structure of the HM waves was one of general characteristics of the HM waves of Pc 3–5 frequency range observed at the Syowa–Husafell conjugate stations.

It appears thus that the skelton structure of the HM wave resonance system model for physically understanding the Pc 3–5 pulsations and their conjugate characteristics was almost established with the IMS research works. However, there still remain several problems with respect to some detail of the low frequency HM wave characteristics and their conjugacy. A problem is concerned with the fact that the harmonic structure is obscure for the *D* component of the low frequency HM waves (Figs. 28

(a)

(b)

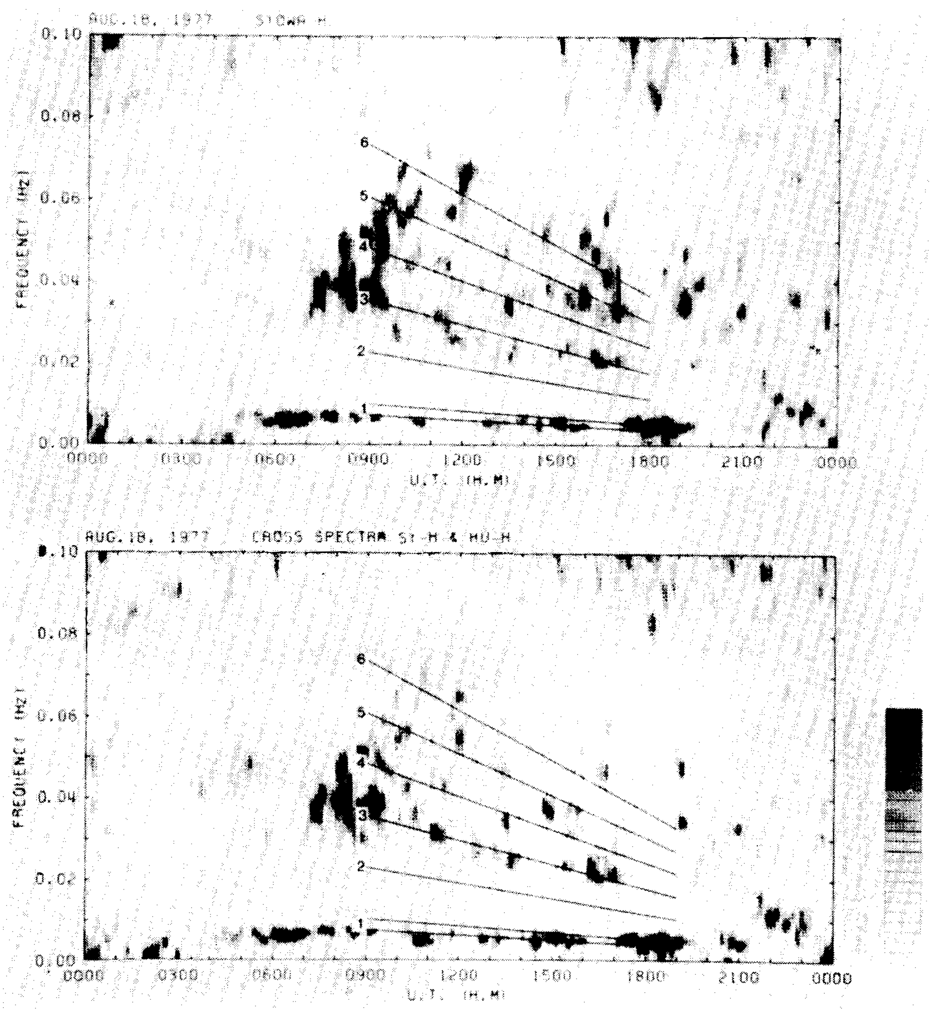

Fig. 29. The harmonic structure in the power spectra of magnetic pulsations observed simultaneously at Syowa and Husafell. (a) Autopower spectrum of H component at Syowa, (b) cross-power spectrum of H component between Syowa and Husafell (see text) (TONEGAWA and FUKUNISHI, 1984).

and 29). As briefly discussed in Section 2.3, the D component oscillations arise from the poloidal oscillations (the radial oscillations) of the field lines while the H component oscillations correspond to the toroidal oscillations (the azimuthal oscillations). Since the modes of Pc 3–5 pulsations in the source regions observed by ATS6 satellite are the multi-harmonic toroidal oscillations, it would be assumed that the toroidal-mode oscillation is primary and the poloidal mode is secondary.

It must also be taken into consideration that the Pc pulsations observed on ground are not exactly the HM waves in the magnetosphere themselves but the EM waves after being filtered and modulated by the ionosphere, so that the Pc pulsations received on ground could be synthetic wave group consisting of different frequencies resonating with different L-shells (TONEGAWA and FUKUNISHI, 1984).

Another problem is concerned with the observed decrease of the resonating HM wave harmonic frequencies with time from the morning toward the evening (Figs. 28 and 29). This decreasing change in frequency with time could be interpreted as due to an increase of the ambient cold plasma density in the magnetosphere. These problems and probably some others may need further studies in detail.

Figure 30 shows an example of the simultaneous occurrence of the Pi 2 pulsations accompanying a sharp commencement of a negative magnetic substorm at Syowa and Reykjavik (KUWASHIMA, 1981). It will be obvious in the figure that the Pi 2 pulsation waves are in-phase for the H component and out-of-phase for the D component between Syowa and Reykjavik. Other aspects of the conjugate Pi 2 pulsation characteristics also are the same as those of the conjugate Pc 4–5 pulsations between the $L=6$ conjugate pair stations.

Similar studies on the Pi 2 pulsations were continued between Syowa (and Mizuho) and Husafell conjugate stations through the IMS period, obtaining the substantially

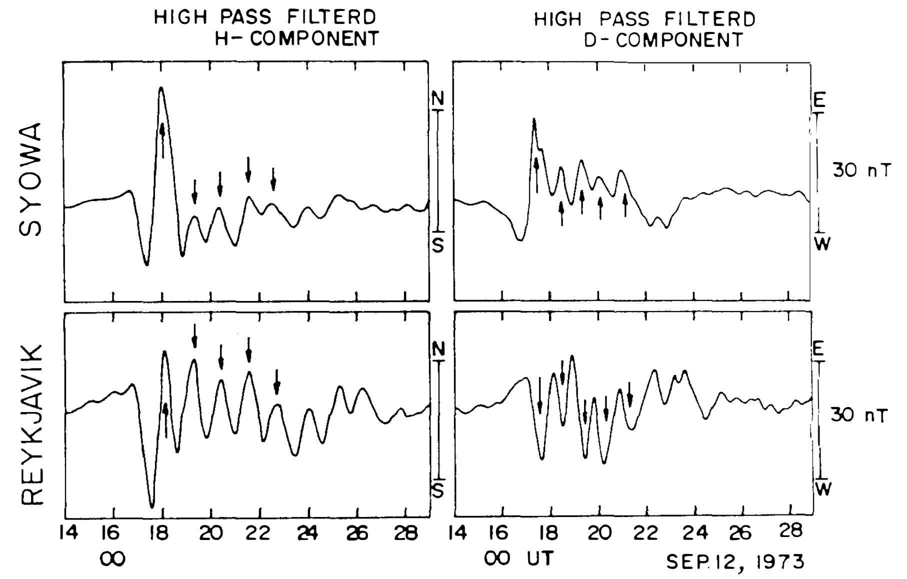

Fig. 30. Example of the simultaneous occurrence of Pi 2 pulsation at the conjugate stations, Syowa and Reykjavik. In the H diagrams on the left side, the HM wave is in-phase while it is out-of-phase in the D diagrams on the right side between Syowa and Reykjavik (KUWASHIMA, 1981).

same conclusion (KUWASHIMA, 1981). Namely, the Pi 2 pulsation is the odd-mode hydromagnetic standing oscillation along the field line linking the conjugate points. In the case of the Pi 2 pulsation, however, the excitation mechanism for the generation of the HM waves would be an energization caused by an injection of the auroral electron and proton streams into the auroral zones, which simultaneously results in an auroral substorm associated with a magnetic substorm (KUWASHIMA, 1981). As to possible excitation mechanisms of the Pi 2 pulsation, several different processes have been proposed. In all these possible theoretical processes, it is assumed that the excitation energy source comes from the night-side magnetosphere in association with a breakup of the polar auroral and magnetic substorm.

Figure 31 shows an example of the Pc 1 event simultaneously observed on GEOS-1 satellite and the conjugate stations on ground during the time when GEOS-1 was located near the field line linking the Syowa–Husafell conjugate stations (GENDRIN *et al.*, 1978). As shown in the figure, the Pc 1 event occurred nearly simultaneously on GEOS-1 and on the ground, but their frequency power spectra are not exactly the same, the Pc 1 event observed on GEOS-1 having a burst-like structure. Results of comparative studies on the HM waves of the Pc 1 range on GEOS-1 and on the ground are summarized (NAGATA and HIRASAWA, 1982) as follows:

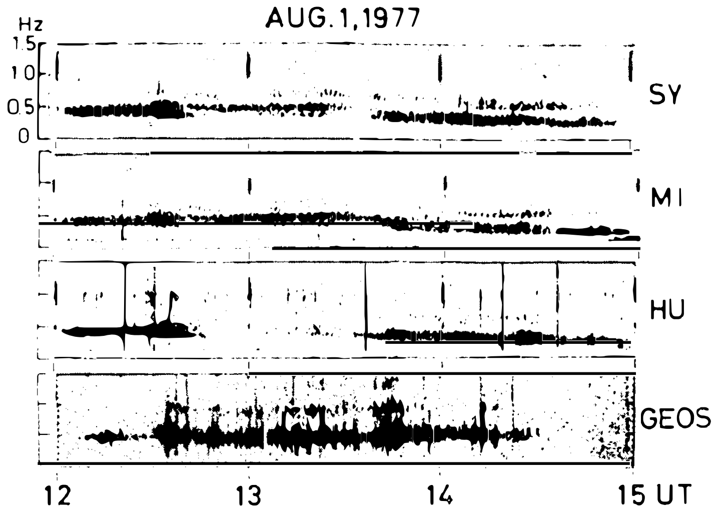

Fig. 31. Example of Pc 1 pulsation event simultaneously observed on GEOS-1 satellite and at Syowa (SY), Mizuho (MI) and Husafell (HU) on ground (GENDRIN et al., 1978).

It was found from the Syowa–Husafell conjugate data that the HM periodic emissions of smaller than 0.5 Hz in frequency were observed simultaneously at the conjugate pair stations, while those of larger than 0.5 Hz in frequency were often observed only at Syowa. The HM emission events were frequently observed on GEOS-1 satellite, but the HM whistler and the HM periodic emissions were very rare among the HM waves observed aboard.

On the other hand, general behaviors of the HM emissions of the Pc 1 frequency range in the equatorial regions less than 30° in geomagnetic latitude and L=3–6 in altitude in the magnetosphere have become clarified by the particle-wave interaction observations of GEOS-1 and a geostationary satellite GEOS-2 (GENDRIN *et al.*, 1978).

The results of GEOS observations, together with previous data obtained by ATS 1, ATS 6 and Ogo 5 satellites (BOSSEN *et al.*, 1976) have almost certainly confirmed that the HM emissions of Pc 1 frequency range are generated by the ion-cyclotron instability of protons on and near the outside region of the plasmapause in the neighborhood of the geomagnetic equatorial plane. These results obtained from the observations on satellites and on the ground have led to a strong suggestion for the presence of a duct structure along the field lines for the propagation of the HM waves of Pc 1 frequency range from the source region toward the earth surface. The formation and the persistency of the duct structures in the magnetosphere will be problems at present after the IMS for studying the propagations of the short-period HM waves as well as the whistler-mode VLF waves.

5. Conjugate Studies between Antarctica and Iceland after the IMS

The conjugate studies made during the IMS period have solved a number of key problems concerning the physical understanding of the conjugacy of auroras, polar magnetic substorms, ELF-VLF waves, ULF waves and related particle precipitations into the ionosphere in the northern and the southern polar regions. In accordance with the progress of physical understanding of the processes of the particle-particle and the particle-wave interactions as well as the wave-wave interaction in the magnetosphere and the ionosphere, the conjugacy and the non-conjugacy between the two conjugate points have become much more understandable than in the past. However, there still remain various unsolved problems, such as the formation and the destruction of the magnetospheric ducts for the VLF and the ULF wave propagations, a possible distortion of the geomagnetic field configuration caused by the magnetospheric and the ionospheric electric currents of various sources, and others. As shown in Fig. 1, therefore, the continuous routine observations by use of a tripartite station network consisting of Syowa, Mizuho and Molodezhnaya in Antarctica and the corresponding nearly conjugate tripartite station network composed of Husafell, Isafjördur and Tjörnes in Iceland started in 1983 for the purpose of continueing and extending the conjugate studies.

Figure 32 shows an example of the *f-t* diagrams of the periodic VLF emissions observed simultaneously at Isafjördur, Tjörnes and Husafell in Iceland and Syowa in Antarctica. It is noted in these simultaneous diagrams that the intensity of the lower frequency VLF is stronger and the intensity of the higher frequency is weaker with an increase in the geomagnetic latitude from Husafell toward Isafjördur in Iceland, and the phase-relation for the periodic VLF wave between Syowa and the three Icelander stations is out of phase. The conjugate studies on the ELF-VLF waves in detail are going on between the tripartite station networks in the southern and the northern auroral zones (SATO and SAEMUNDSSON, 1987; SUZUKI and SATO, 1987).

Figure 33 shows an example of the simultaneous conjugate diagrams of the time variation of the auroral intensity (J) along the magnetic meridian for λ5577Å line of the electron aurora and Hβ line of the proton aurora observed at Syowa and Husafell (SATO *et al.*, 1986, 1987). General features of the *J-t* diagrams appear to be in a good conjugate relationship between Syowa and Husafell for both the λ5577Å and the Hβ

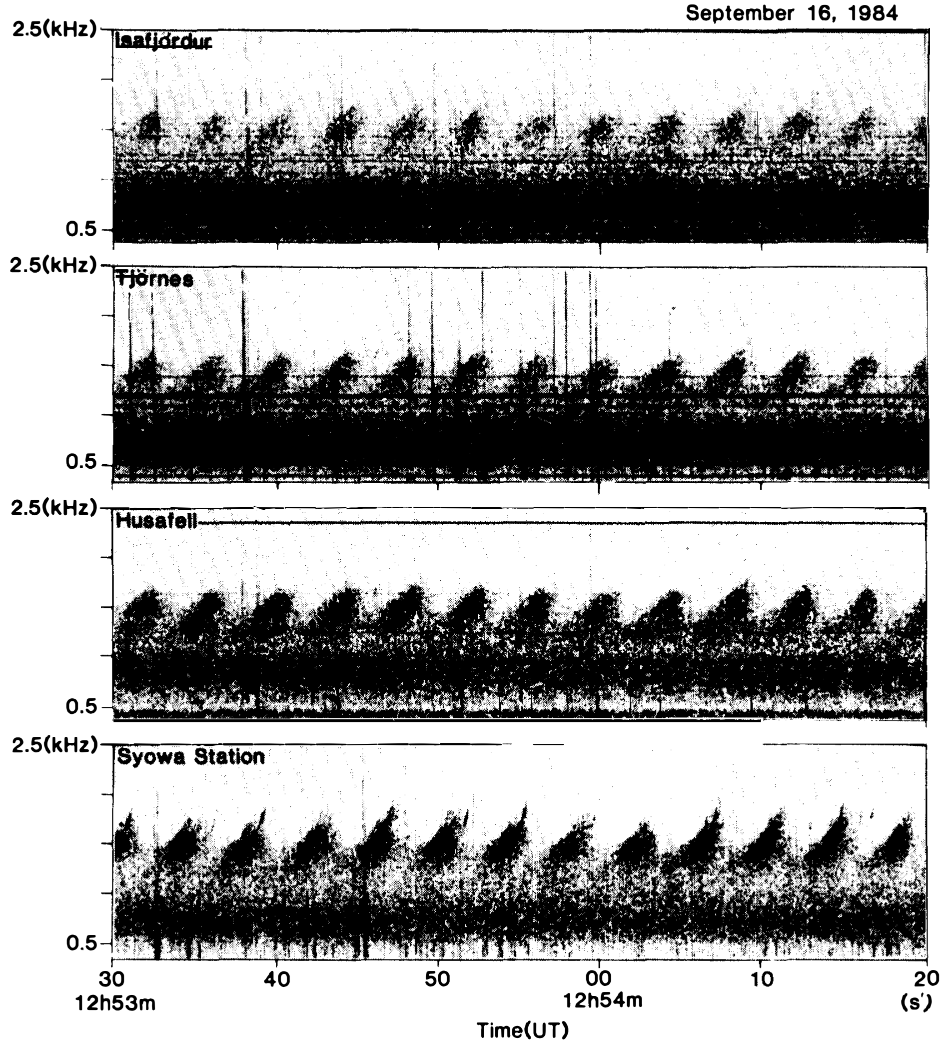

Fig. 32. Example of the frequency-time spectra of the periodic VLF emissions observed simultaneously at Syowa in Antarctica and at Husafell, Tjörnes and Isafjödur in Iceland.

lines. As for detail of individual auroral luminosity variations, however, noticeable discrepancies between Syowa and Husafell are found in both the λ5577Å diagram and the Hβ diagram. With the aid of simultaneous all-sky auroral TV camera images obtained at the two stations, the cause of the observed non-exact conjugacy for the auroral inner-structure is attributable to (i) spatial fluctuations of the conjugate points, or (ii) a time-lag for an auroral display or enhancement between the conjugate areas, or (iii) a lack of an observable event on one side of the conjugate pair in correspondence to an event observed on the other side.

Relative motions of the auroral conjugate points have already been pointed out by STENBAEK-NIELSEN *et al.* (1972) for the airborne observation data of the all-sky auroral images. Extended studies on the relative motions of the conjugate auroras, particularly those of the conjugate pulsative auroras, by means of the auroral TV cameras, the all-sky auroral cameras and the meridian scanning spectrophotometers are going on at the conjugate pair stations, Syowa and Husafell (FUJII *et al.*, 1987a, b).

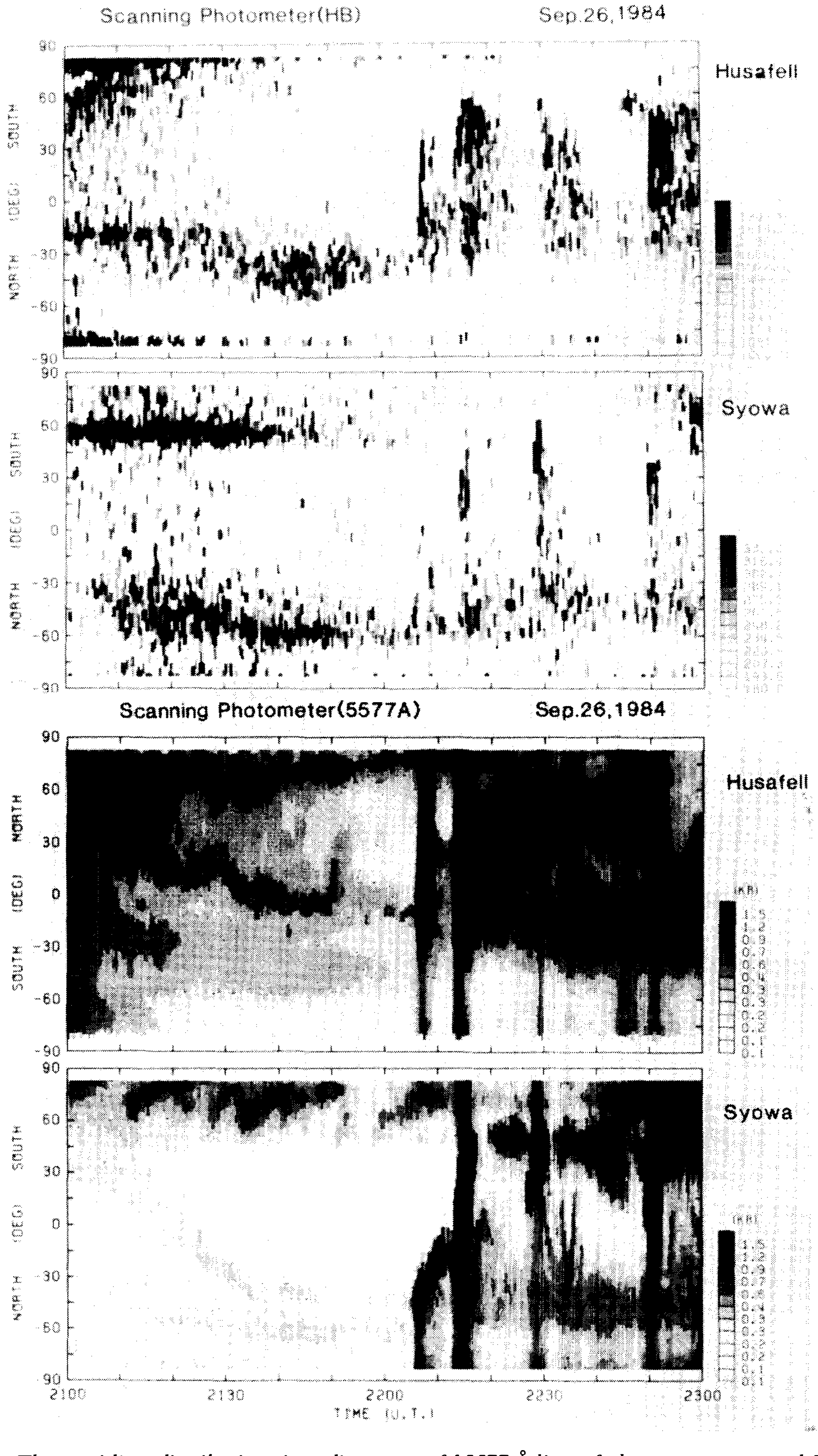

Fig. 33. The meridian distribution-time diagrams of λ5577Å line of electron aurora and Hβ line of proton aurora observed simultaneously by the meridian-scanning spectrophotometers at Syowa and Husafell (September 26, 1984).

Similarly, the conjugate studies on the ULF waves also are going on by use of the tripartite network system. An advantage of the tripartite network system may be a possibility of determining the location of the exact conjugate point of a station on the other hemisphere. Assuming that the almost stationary Pc 5 pulsations are controlled by the field line resonance of the odd-mode, the conjugate point of Syowa can be determined with the aid of the triangulation method from the phase differences of the Pc 5 pulsations among Husafell, Isafjördur and Tjörnes.

Figure 34 shows examples of the instantaneous locations of the conjugate point of Syowa on Iceland thus determined from the simultaneous Pc 5 pulsation data. As shown in the figure, the conjugate point of Syowa thus determined was momentarily moving, probably owing to a rapid variation of the geomagnetic field configuration with time (The cross mark (×) in the figure is the calculated static conjugate point of Syowa on the basis of the internal origin geomagnetic field at epoch 1982.). As the screening and the modifying effects of the ionosphere upon the Pc 5 pulsations observed on ground are ignored in the present discussion, the above-mentioned method to determine the conjugate point still faces several problems concerning these effects. When the true conjugate pair points, that is, Antarctic and Arctic pair points linked by a varying geomagnetic field line, are currently determined by an appropriate method, the synthetic conjugate studies on various magnetospheric phenomena would become possible to analyze their much more detail.

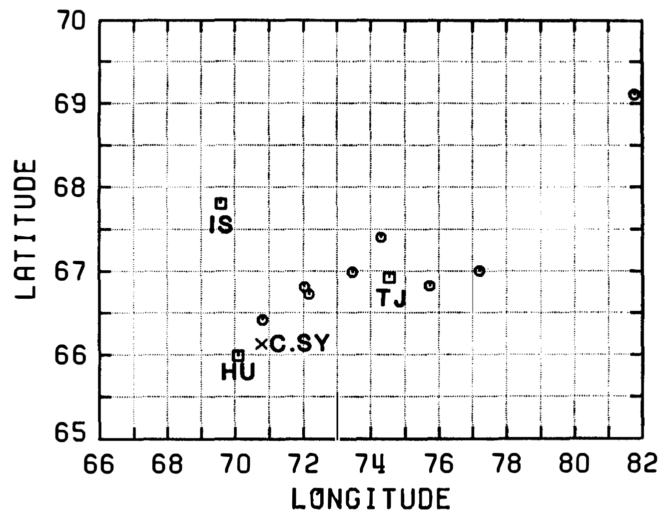

Fig. 34. The positions of the conjugate point of Syowa in Iceland, determined on an assumption that the Pc 5 pulsation is a standing HM wave of the odd-mode linking Syowa and its conjugate point (see text).

6. Concluding Remarks

Summarizing a large number of the observed data of the conjugate studies in the southern and the northern auroral zones since the IGY period, it may be generally concluded that the quiet auroral arcs which occur in the pre-breakup stage of an auroral substorm, the periodic and the quasi-periodic VLF emissions in relatively quiet period, and the Pc 3–5 ULF pulsations in relatively quiet period have a reasonably good conjugate relationship between the conjugate pair points, which are so defined that they are linked by a line of force of the geomagnetic field of the internal origin. An isolated negative magnetic substorm also has a good conjugate relationship between the southern and the northern auroral zones. In the cases of these good conjugate phenomena during relatively quiet periods, it still appears that the asymmetric conditions between the conjugate points, such as a difference in the geomagnetic force intensity, a difference and irregularities in the ionospheric condition, mostly owing to the seasonal and the local time differences, a certain inhomogeneity of the duct condition for the ELF-VLF and the ULF wave propagations and others, result in systematic and/or irregular deviations from the exact conjugate relationship.

In the magnetospheric storm periods, much more complicated patterns of the conjugate relation take place between the southern and the northern auroral zones in general. The asymmetricity of the magnetic field configuration caused by a distortion of the magnetosphere may be the main source for a breakdown of the conjugacy in the disturbed period. In addition, an asymmetricity in the electron and proton precipitation associated with the field-aligned currents and the electrostatic fields also may result in considerable perturbations of the conjugacy. The presence of the elctrostatic waves of various frequencies in the magnetosphere may considerably affect the ULF-ELF-VLF waves there.

It is hoped that the conjugate study programs at Syowa and its surrounding area in Antarctica in coordination with the Iceland tripartite stations on the routine basis will be able to solve these remaining problems in the conjugate phenomena during the magnetically disturbed periods.

It may be further hoped that a geostationary satellite for continuously monitoring the magnetospheric plasma parameters and the VLF-ELF-ULF plasma waves will be set up sometime in the future in conjunction with the Antarctic and Icelander tripartite station networks, because such a geostationary satellite located at $L \simeq 6.3$ on the equator together with the tripartite networks on ground ($L \simeq 6.1$) can form a much advanced three-dimensional monitoring network system for the magnetospheric conditions.

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