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TEMPORAL VARIATION OF THE GEOMAGNETIC CONJUGACY IN SYOWA–ICELAND PAIR

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Abstract: The locations of geomagnetically conjugate points of Syowa and Iceland were examined by using the geomagnetic field models with internal and external magnetic fields. A large secular excursion of the magnetic conjugate point was shown from 1960 to 1990 by tracing the IGRF geomagnetic field lines. The conjugate point of Syowa Station moved from a south-west area to a middle-north region in Iceland during the last 30 years. The seasonal and daily variations of conjugate points show that the excursion of the conjugate footpoint is minimum around midnight in equinox seasons and it is maximum around summer and winter solstice seasons.

1. Introduction

The observation of conjugate auroras provides important information for investigating auroral substorms and related auroral phenomena occurring in the magnetosphere and in the upper atmosphere. The Syowa–Iceland conjugate pair stations (at $L\approx 6$) are located in the auroral zone (HAKURA, 1965; SATO *et al.*, 1986), and the two sites are suitable at present for observing the conjugate visible auroras from the ground.

STASSINOPOULOS *et al.* (1984) calculated the conjugate point of Siple Station (at $L\approx 4$) using the Barraclough 1975, IGRF 1980, MAGSAT (LANGEL *et al.*, 1982) and MEAD and FAIRFIELD (1975) models. They showed that the conjugate point of Siple Station should have significant secular, seasonal and daily variations. On the other hand, observational results of ground based Syowa–Iceland conjugate visible aurora showed that the location of the conjugate auroras observed at Husafell (67.67°N, 21.03°W) in Iceland shifted year by year in latitude direction between the 1978 campaign (MAKITA *et al.*, 1981) and the 1984 campaign (SATO *et al.*, 1986). This difference seems to be caused mainly by the secular variation of conjugate point location. In order to evaluate the variation of conjugacy in Syowa–Iceland pair, in this paper, (i) we examine the secular variation of the geomagnetic absolute values at Syowa Station in Antarctica and Leirvogur Magnetic Observatory in Iceland, and (ii) calculate the conjugate point of Syowa Station and Leirvogur by carrying out the field line tracing with reliable geomagnetic and magnetospheric field models.

2. Geomagnetic Field Models

2.1. *Internal field*

The internal geomagnetic field is usually given by spherical harmonic terms (MER-

RILL and MCELHINNY, 1983). Among many proposed magnetic field models, the IGRF model is one of the most reliable and convenient model to synthesize the global configuration of the Earth's internal magnetic field.

Recently, Gauss coefficients of the harmonic expansion for degree-and-order eight were presented for the period 1945–1955, and coefficients for degree-and-order 10 were presented for the period 1960–1985 by the IAGA DIVISION I WORKING GROUP 1 (1986). The definitive Gauss coefficients (DGRF) were given for 1965–1980, and provisional secular variation coefficients were given for the period after 1980. According to a recommendation from IAGA, we used a linear interporation of coefficients for 1965–1985 and used the secular variation terms for 1985–1990 in order to calculate the internal field for a given epoch. The IAU ellipsoid (INTERNATIONAL ASTRONOMICAL UNION, 1966) is adopted for the Earth's geodetic surface model in order to calculate the position of given stations (IAGA DIVISION I WORKING GROUP 1, 1986). To derive the dipolar geomagnetic coordinates, we used the first-degree coefficients for given epoch; in other words, we used the centered dipole field. The location of the geomagnetic axis pole is given as

$$\text{its geocentric longitude; } \varphi_0=\tan^{-1}\left(\frac{h_1^{\,1}}{g_1^{\,1}}\right), \tag{1}$$

$$\text{and colatitude; } \lambda_0=\tan^{-1}\frac{((g_1^{\,1})^2+(h_1^{\,1})^2)^{\frac{1}{2}}}{g_1^{\,0}}, \tag{2}$$

where $g_1^{\,0}$, $g_1^{\,1}$ and $h_1^{\,1}$ are the first degree Gauss coefficients of the spherical harmonic terms of the geomagnetic field.

2.2. *External field*

The geomagnetic field lines connecting the Syowa–Iceland conjugate areas must be strongly deviated from dipolar field lines due to the solar wind and magnetosphere interaction. The magnetic field in the magnetosphere $\vec{B}_M$ can be decomposed as

$$\vec{B}_M=\vec{B}_I+\vec{B}_E, \tag{3}$$

where $\vec{B}_I$ and $\vec{B}_E$ are the internal and external magnetic fields, which are originated respectively inside or outside the solid earth. In this paper, the IGRF model is adopted for the internal $\vec{B}_I$. In order to obtain the configuration of the external field, theoretical (distributed current models) and empirical external field models have been proposed in many papers (*e.g.*, SUGIURA and POROS, 1973; OLSON and PFITZER, 1974; MEAD and FAIRFIELD, 1975; FUCHS and VOIGT, 1979; TSYGANENKO and USMANOV, 1982; etc., see the reviews by WALKER 1976, 1979). In this paper we used TSYGANENKO and USMANOV's model of electric current distribution in the magnetosphere (TSYGANENKO and USMANOV, 1982). Their model includes the effects from electric currents at magnetosphere boundary, in the equatorial ring and tail regions, and it takes account of the seasonal change in the tilt angle between the dipolar axis and the sun-earth direction.

3. Results

3.1. Geomagnetic absolute values and corrected geomagnetic coordinates

Table 1 gives absolute values of the geomagnetic field elements and corrected geomagnetic coordinates at eight stations in Syowa–Iceland conjugate areas. Absolute values are calculated from the IGRF model for the epoch 1985.0. Absolute values have been measured from 1966 at Syowa Station (69.00°S, 39.58°E) and from 1957 at Leirvogur Magnetic Observatory (64.18°N, 21.70°W). As shown in Fig. 1, the calculated values agree well with measured values at Syowa Station, while at Leirvogur, there are significant disagreements between the calculated and measured values. These discrepancies at Leirvogur must be attributable to a local crustal field existing in Iceland (LANGEL *et al.*, 1982). Since the differences are almost of a fixed magnitude from 1960 to 1984, it will be reasonable to apply only a small offset to the calculated geomagnetic parameters in obtaining the actual geomagnetic field values.

Table 1. Absolute values of the magnetic field elements and geomagnetic parameters for the stations located in Syowa-Iceland conjugate areas at 1985.0.

Station name	Location geographic		Absolute value				Corrected geomagnetic coordinate	
	Lat.	Long.	Total(nT)	H(nT)	D	I	Lat.	Long.
Syowa Station	−69. 00°	39. 58°	44365	18959	−46. 50°	−64. 70°	−66. 22°	71. 44°
Asuka Camp	−71. 53°	24. 14°	43447	18980	−35. 81°	−64. 10°	−65. 05°	58. 50°
Mizuho Station	−70. 70°	44. 43°	46481	18941	−51. 10°	−65. 95°	−68. 09°	71. 69°
Molodezhnaya	−67. 67°	45. 85°	45089	18949	−50. 72°	−65. 15°	−66. 61°	77. 62°
Leirvogur	64. 18°	−21. 70°	52118	12867	−22. 13°	75. 71°	65. 49°	68. 44°
Husafell	64. 67°	−21. 03°	52151	12677	−22. 00°	75. 93°	65. 87°	69. 36°
Isafjördur	66. 08°	−23. 13°	52563	11972	−24. 29°	76. 83°	67. 65°	68. 81°
Tjörnes	66. 20°	−17. 12°	52145	12161	−20. 29°	76. 51°	66. 80°	73. 76°

Table 1 includes also the corrected geomagnetic coordinates of seven stations located at Syowa–Iceland conjugate areas, based on the geomagnetic field model of IGRF 1985.0. The corrected geomagnetic latitude is equivalent to the L-parameter defined by MCILWAIN (1961). The corrected geomagnetic longitude is defined as the dipolar geomagnetic longitude of the point where the geomagnetic field line of the given station crosses the dipolar equatorial plane, as defined by HAKURA (1965), where the dipolar geomagnetic field is obtainable from the IGRF coefficients as mentioned in Subsection 2.1.

The magnetic local time (MLT) is usually used to describe the local time dependence of auroral phenomena. The MLT value can be determined as

$$\mathrm{MLT}=(M_l-M_s)/15.0+12 \text{ (in hours)}, \tag{4}$$

where M_l and M_s are geomagnetic longitudes of a given station and the subsolar point, respectively. Depending on variations of the subsolar geomagnetic longitude, the difference between UT and MLT shows daily and seasonal variations, as shown in Fig. 2. An approximate value of MLT can be defined as

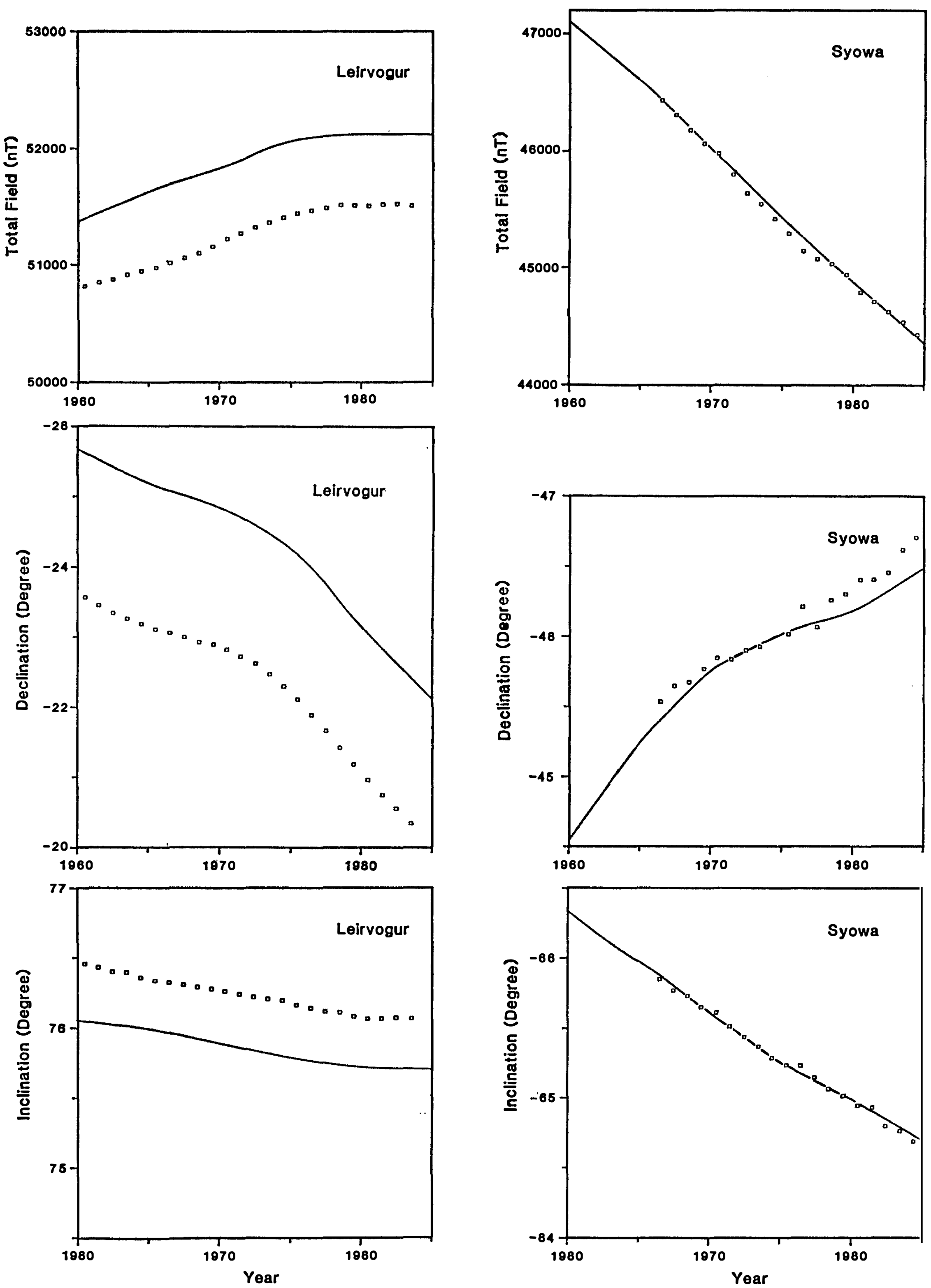

Fig. 1. Comparison of absolute magnetic field values between calculated IGRF field (solid curves) and measured field (squares) at Syowa Station and Leirvogur.

$$MLT=(M_l-M_p)/15.0+UT\,, \tag{5}$$

where M_p is the geomagnetic longitude of the geographic north pole given

$$M_p=-\tan^{-1}\left(\frac{\tan\varphi_0}{\sin\lambda_0}\right), \tag{6}$$

and UT is the universal time. For an example, the difference between the approximate MLT at Syowa Station and UT is about one minute in 1985 (see Appendix). Figure 2 gives daily variations of the MLT–UT values for four seasons at Syowa Station. The MLT in Fig. 2 is calculated according to formula (4). As shown in Fig. 2, the approximated MLT derived by formulae (5) and (6) agrees with the MLT defined by formula (4) within an accuracy of about ±20 min.

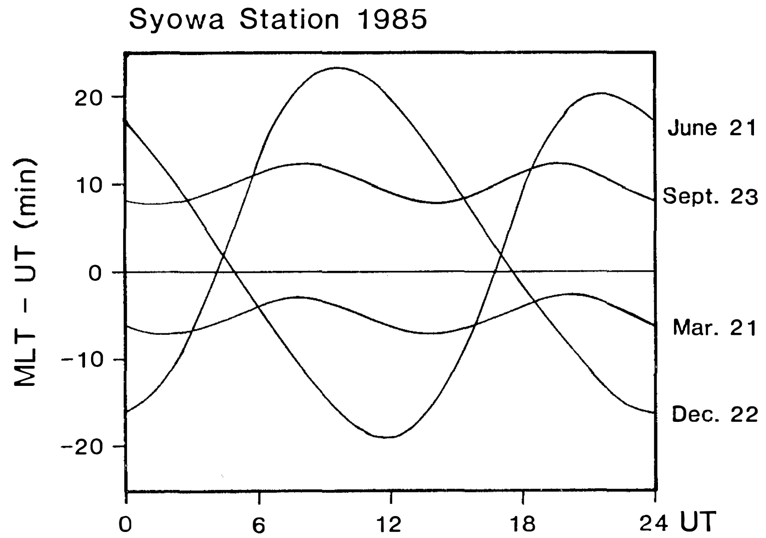

Fig. 2. Daily variation of the differences between MLT and UT for four seasons in 1985 at Syowa Station.

3.2. Secular variation of conjugate points

Figure 3 gives the secular variations in the conjugate points of Syowa Station (Fig. 3a) and Leirvogur Magnetic Observatory (Fig. 3b) from 1960 to 1990. The 'conjugate point' in Fig. 3 is the point where a field line, starting from an altitude of 110 km above the station, reaches the same level in the opposite hemisphere. The position is calculated with the IGRF model for each year. As shown in Fig. 3a, the conjugate point of Syowa Station moved from a south-west area to a middle-north area (about 250 km in distance) in Iceland during the last 30 years. In 1985, the conjugate point is located just in the middle between Husafell and Tjörnes Stations.

3.3. Seasonal and daily variations of conjugate points

The configuration of magnetospheric field line changes daily and seasonally depending on the tilt angle between the sun-earth direction and geomagnetic axis. Figure 4 shows a daily variation of Syowa Station conjugate point in Iceland, which is calculated with the TSYGANENKO-USMANOV model (1982) for $Kp=1$. As shown in Fig. 4, the conjugate foot point shows a maximum excursion in summer and winter solstice

(a)

(b)

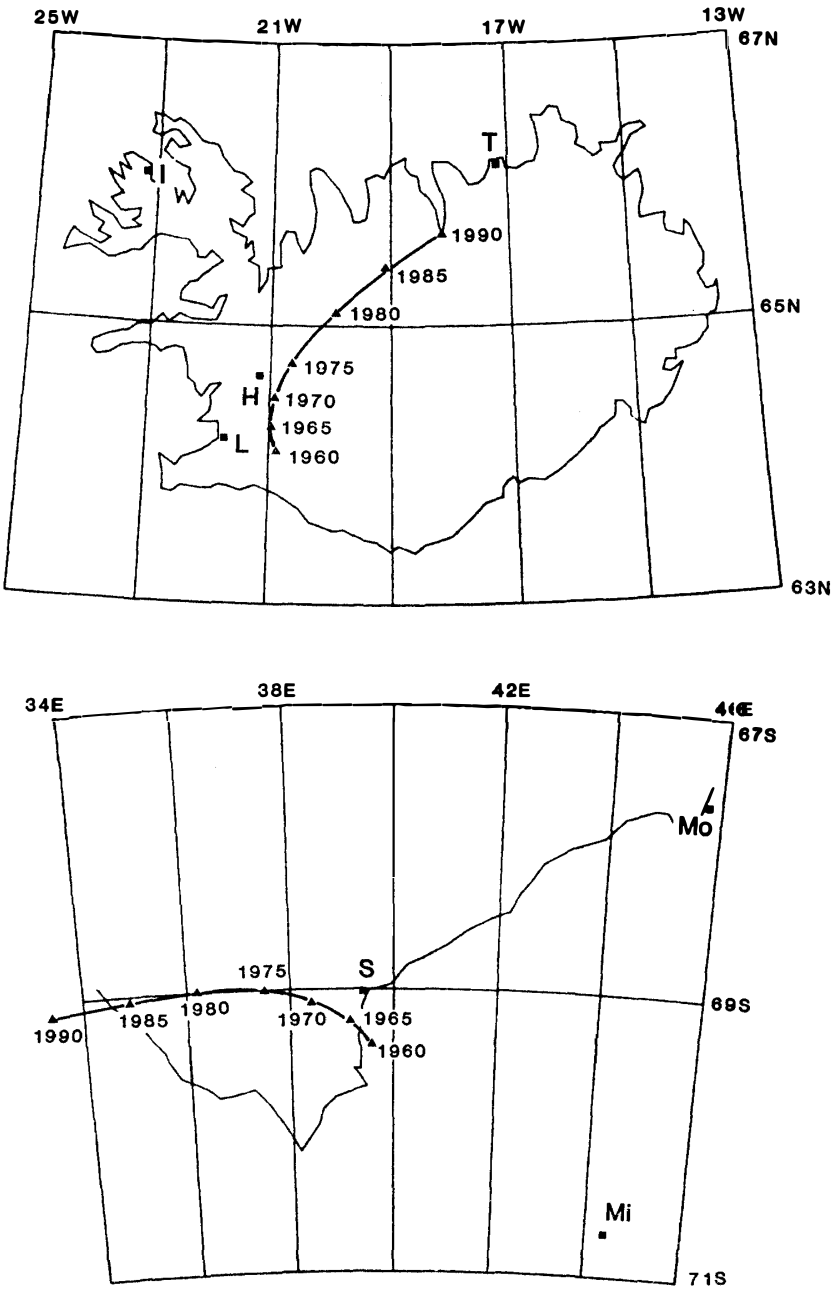

Fig. 3. Secular variation of the auroral conjugate point of Syowa Station (a), and Leirvogur (b) from 1960 to 1990, calculated by using IGRF model. L, H, T, I, S, Mo, Mi are the locations of the observation stations for upper atmosphere physics named Leirvogur, Husafell, Tjörnes, Isafjördur, Syowa, Molodezhnaya, and Mizuho respectively.

seasons, and a minimum in autumnal and vernal equinox seasons. The basic characteristics of the seasonal and daily variations of the conjugate point shown in Fig. 4 are almost the same as the results by FUKUNISHI (1983) who calculated the variations using the OLSON-PFITZER model.

The configuration of magnetospheric field line also depends on the activity of geomagnetic disturbances. Therefore, the conjugate point moves depending on the

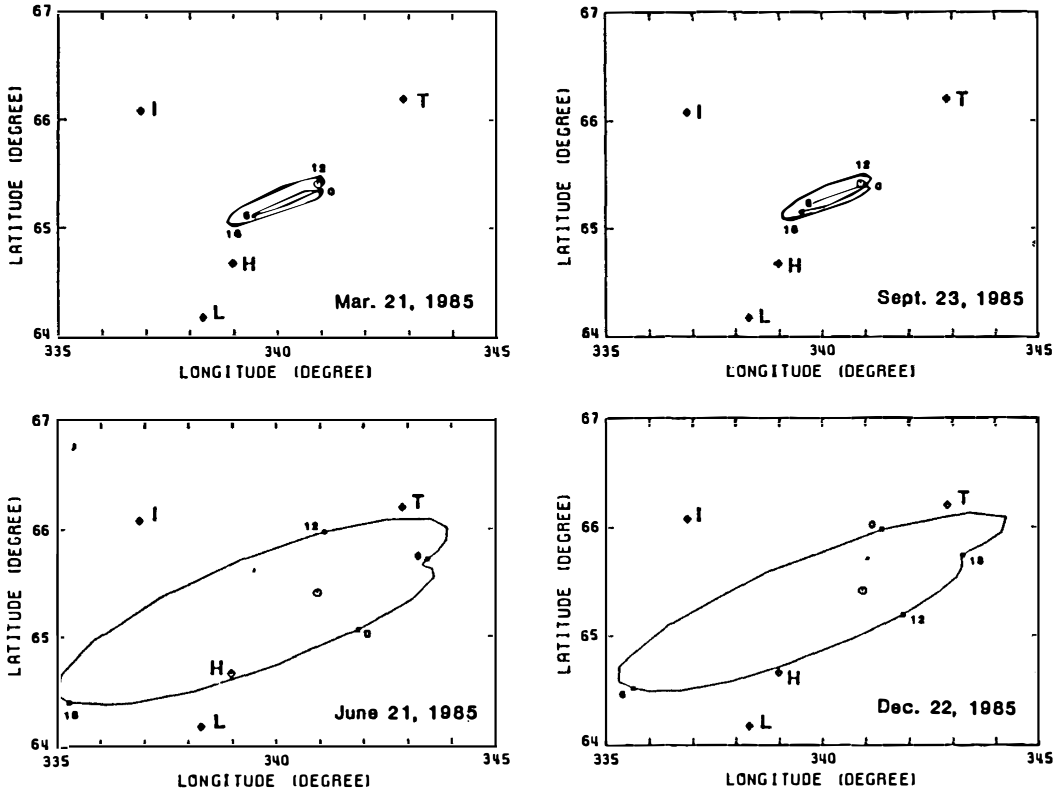

Fig. 4. Daily variation in the location of the conjugate point of Syowa Station for four seasons in 1985. The Tsyganenko-Usmanov model is used in this calculation. The circles indicate the conjugate point calculated by the IGRF internal field only.

auroral activities (OLSON and PFITZER, 1982; STASSINOPOULOS *et al.*, 1984). In Fig. 5, daily variations of the Syowa Station conjugate point are calculated for geomagnetic activity conditions of $Kp=0$ and $Kp=3$ by using the TSYGANENKO-USMANOV model (1982). As shown in Fig. 5, the daily variations of the conjugate point becomes large with the geomagnetic activity.

4. Discussion

As shown in Fig. 3a, the location of the conjugate point of Syowa Station moves from a site near Leirvogur to the northern coast of Iceland from 1960 to 1990. Especially after 1975, the movement of the conjugate point speeded up, in association with a rapid decrease in the westward declination at Leirvogur as seen in Fig. 1. This traveling feature may affect the conjugacies of auroral, geomagnetic and CNA phenomena observed at a fixed conjugate-pair stations in Syowa–Iceland areas. For example, the region of conjugate visible auroras observed at Husafell significantly shifted in latitude during 1978 to 1984 (MAKITA *et al.*, 1981; SATO *et al.*, 1986). The shift is qualitatively consistent with the present results.

The daily variation in the location of conjugate points is smallest in the equinox seasons. In these seasons, the conjugate aurora will be observed simultaneously from both Syowa Station and Iceland areas because of the simultaneous darkness.

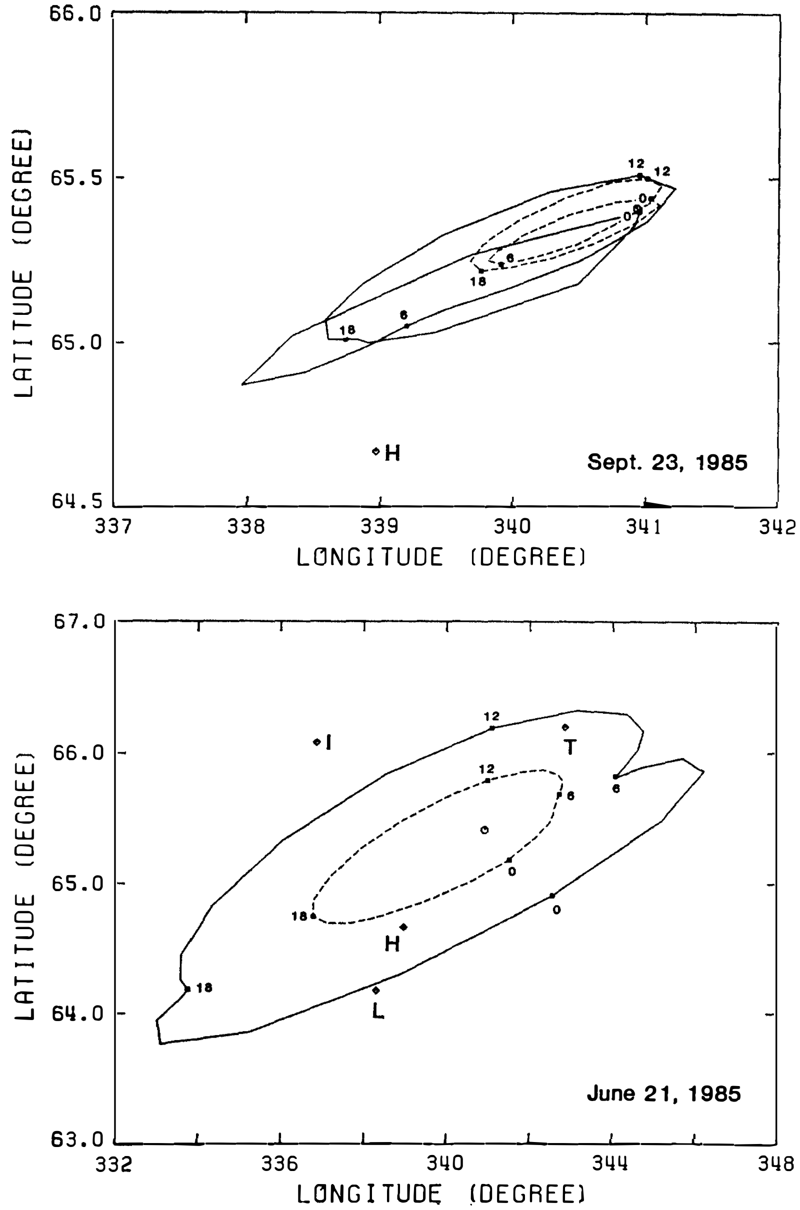

Fig. 5. Daily variation in the conjugate point location of Syowa Station for geomagnetic activity conditions of $Kp=0$ (broken lines) and $Kp=3$ (solid lines) in autumnal equinox and winter solstice seasons in 1985.

It is remarkable that the excursion of the conjugate point location is very small in the time interval of 22–01 UT when the conjugate point is close to the point calculated from the internal field only, as seen in Figs. 4 and 5. Hence, a large displacement of the conjugate point of visible auroral arcs in the time interval around 22 UT (FUJII, 1986, private communication) could be attributed to an asymmetric field-aligned current or a special deformation of magnetospheric field lines as discussed by OLSON and PFITZER (1974).

5. Conclusion

A large displacement in the conjugate point location of Syowa Station was confirmed by tracing the IGRF geomagnetic field between Syowa–Iceland conjugate pair, and the result obtained is what expected by the ground-based conjugate aurora experimenters. During 25 years from 1960 to 1985, the conjugate point of Syowa Station moved about a distance of 200 km in Iceland. It is predicted that the conjugate point will reach the coast of northern Iceland in 1990. The seasonal and daily variations of the conjugate point reveal that they show a greatest excursion during solstice seasons and smallest during equinox seasons. Around the midnight in equinox seasons, the conjugate point becomes very close to the point calculated from the internal field only.

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Appendix A

Secular variations in the north-pole location of the geocentric dipole after eqs. (1) and (2) are listed in Table A-1. The locations are calculated in geocentric coordinates. The M_p values are calculated by eq. (6).

Table A-1. Secular variations of north axis pole of geomagnetic dipole.

Epoch	North axis pole of geomagnetic dipole, Geocentric: Lat.	North axis pole of geomagnetic dipole, Geocentric: Long.	M_p
1960.0	78.53°	−69.49°	69.86
1965.0	78.54°	−69.85°	70.22
1970.0	78.59°	−70.18°	70.54
1975.0	78.69°	−70.47°	70.82
1980.0	78.81°	−70.76°	71.10
1985.0	78.98°	−70.91°	71.24
1990.0	79.19°	−70.98°	71.29

Appendix B

Secular variations in the IGRF conjugate points, corrected geomagnetic coordinates and approximate values of MLT-UT after formula (5) at eight stations located at Syowa–Iceland conjugate areas are listed in Table B-1.

Table B-1. Secular variations of conjugate points and geomagnetic parameters.

Year	Conjugate point (IGRF)		Corrected geomagnetic coordinate		L	MLT-UT min
	Lat.	Long.	Lat.	Long.		
Syowa Station (69.00°S, 39.58°E)						
1960.0	64.12°	339.09°	−66.10°	69.99°	6.09	0
1965.0	64.28°	338.98°	−66.11°	70.05°	6.10	−1
1970.0	64.49°	339.07°	−66.13°	70.27°	6.11	−1
1975.0	64.77°	339.41°	−66.15°	70.62°	6.12	−1
1980.0	65.10°	340.07°	−66.19°	71.07°	6.14	0
1985.0	65.41°	340.93°	−66.22°	71.44°	6.15	1
1990.0	65.72°	341.94°	−66.24°	71.82°	6.16	2
Asuka Camp (71.53°S, 24.14°E)						
1960.0	60.25°	327.26°	−64.75°	56.79°	5.49	−52
1965.0	60.48°	327.13°	−64.77°	56.93°	5.51	−53
1970.0	60.78°	327.20°	−64.82°	57.23°	5.52	−53
1975.0	61.17°	327.45°	−64.88°	57.64°	5.55	−52
1980.0	61.63°	327.89°	−64.97°	58.10°	5.59	−52
1985.0	62.09°	328.51°	−65.05°	58.50°	5.62	−51
1990.0	62.55°	329.25°	−65.14°	58.91°	5.66	−50
Mizuho Station (70.70°S, 44.43°E)						
1960.0	65.85°	337.74°	−68.02°	70.36°	7.14	2
1965.0	65.98°	337.57°	−68.03°	70.37°	7.14	1
1970.0	66.17°	337.63°	−68.03°	70.56°	7.15	0
1975.0	66.43°	337.95°	−68.05°	70.90°	7.16	0
1980.0	66.75°	338.60°	−68.07°	71.32°	7.17	1
1985.0	67.05°	339.47°	−68.09°	71.69°	7.18	2
1990.0	67.35°	340.50°	−68.10°	72.07°	7.19	3
Molodezhnaya (67.67°S, 45.85°E)						
1960.0	65.72°	345.37°	−66.55°	76.37°	6.31	25
1965.0	65.85°	345.24°	−66.57°	76.38°	6.32	25
1970.0	66.02°	345.32°	−66.58°	76.55°	6.33	24
1975.0	66.25°	346.67°	−66.59°	76.87°	6.34	24
1980.0	66.52°	346.41°	−66.61°	77.28°	6.35	24
1985.0	66.76°	347.36°	−66.61°	77.62°	6.35	26
1990.0	66.99°	348.46°	−66.61°	77.97°	6.35	27
Leirvogur (64.18°N, 21.70°W)						
1960.0	−69.38°	39.54°	66.38°	69.50°	6.23	−2
1965.0	−69.21°	39.10°	66.22°	69.53°	6.15	−3
1970.0	−69.09°	38.44°	66.05°	69.51°	6.07	−4
1975.0	−69.01°	37.49°	65.85°	69.36°	5.98	−6
1980.0	−68.99°	36.20°	65.65°	69.00°	5.88	−8
1985.0	−69.05°	34.86°	65.49°	68.44°	5.81	−11
1990.0	−69.12°	33.39°	65.32°	67.79°	5.74	−14

Year	Conjugate point (IGRF)		Corrected geomagnetic coordinate		L	MLT-UT min
	Lat.	Long.	Lat.	Long.		
Husafell (64.67°N, 21.03°W)						
1960.0	−69.44°	41.14°	66.74°	70.46°	6.41	2
1965.0	−69.29°	40.72°	66.58°	70.49°	6.33	1
1970.0	−69.17°	40.08°	66.41°	70.46°	6.24	0
1975.0	−69.11°	39.16°	66.22°	70.31°	6.15	−2
1980.0	−69.11°	37.90°	66.03°	69.93°	6.06	−5
1985.0	−69.18°	36.60°	65.87°	69.36°	5.99	−8
1990.0	−69.27°	35.16°	65.72°	68.70°	5.91	−10
Isafjördur (66.08°N, 23.13°W)						
1960.0	−71.17°	44.99°	68.49°	69.99°	7.43	0
1965.0	−71.03°	44.60°	68.34°	70.01°	7.34	−1
1970.0	−70.95°	43.97°	68.17°	69.97°	7.23	−2
1975.0	−70.91°	43.03°	67.99°	69.81°	7.12	−4
1980.0	−70.95°	41.77°	67.81°	69.41°	7.01	−7
1985.0	−71.06°	40.44°	67.65°	68.81°	6.92	−10
1990.0	−71.19°	38.98°	67.50°	68.11°	6.83	−23
Tjörnes (66.20°N, 17.12°W)						
1960.0	−68.92°	46.59°	67.52°	74.96°	6.84	20
1965.0	−68.79°	46.25°	67.39°	74.97°	6.77	19
1970.0	−68.70°	45.71°	67.24°	74.93°	6.68	18
1975.0	−68.67°	44.91°	67.08°	74.77°	6.59	16
1980.0	−68.73°	43.81°	66.93°	74.36°	6.51	13
1985.0	−68.86°	42.68°	66.80°	73.76°	6.45	10
1990.0	−69.03°	41.43°	66.69°	73.06°	6.39	7