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On the Geomagnetic Lunar Daily Variation Field

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Abstract. The geomagnetic lunar daily variation field, *L*, was studied using all available results of lunar analysis of geomagnetic data from a total of 37 stations. Equivalent external (overhead) and internal (induced within the earth) electric current systems responsible for *L* variations with respect to dip latitude were estimated by the method of spherical harmonic analysis for each season. The external and internal current systems obtained for a mean lunation during the average solar activity period show more plausible current patterns with reasonable amount of total current intensities than any previously obtained.

INTRODUCTION

It was more than a century ago that *Kreil* [1850], using declination data obtained at Prague, discovered the lunar influence on geomagnetic variation. After that discovery, *Sabine* [1853, 1856] and a few other workers studied this phenomenon for the three geomagnetic components. *Van Bemmelen* [1912] first treated the geomagnetic lunar variation as a worldwide phenomenon and analyzed his data by the spherical harmonic method developed by *Schuster* [1889]. The geomagnetic data used by van Bemmelen were the three components taken separately over the summer and winter half-years from 15 stations ranging in geographic latitude from 60°N to 45°S. Since his method of calculation was slightly in error, his external current intensity became smaller than his internal current intensity. Later, the error was corrected [*van Bemmelen*, 1913].

Chapman [1913, 1914*a* and *b*, 1917] then made detailed studies of geomagnetic lunar variations at individual stations, and expanded the values he obtained in spherical harmonics [*Chapman*, 1919]. Although he used data from only 5 stations (Pavlovsk, Pola, Zikawei, Manila, and Batavia) he included not only the lunar semidiurnal variation term but also other daily variation terms, and after careful application of the method of spherical harmonic analysis he listed detailed values of spherical harmonics. From these listed values Bartels later drew the well-known diagrams of the external lunar current system for equinoxes and June solstice [*Chapman and Bartels*, 1940]. However, no diagrams of the internal current system were shown.

The enhancement of the amplitude of the horizontal component of lunar variation at Huancayo was discovered by *Bartels and Johnston* [1940]. Since the same type of enhancement was reported at Kodaikanal [*Egedal*, 1956*a*; *Raja Rao and Sivaraman*, 1958; *Raja Rao*, 1961], Ibadan [*Onwumechilli and Alexander*, 1959], and Addis Ababa [*Gouin*, 1960], *Matsushita* [1962*b*] inferred that there was a lunar electrojet effect in the magnetic equatorial zone. The equatorial electrojet must then be included in the lunar current system.

Extensive studies of lunar variations at individual stations have recently been made by several workers: for example, at Sitka by *Cain* [1957], at Greenwich by *Chapman* [1957], and at San Fernando by *Wilkes* [1962]. However, no one has obtained a lunar current system different from that of Chapman and Bartels. Only *Matsushita* [1962*b*, 1964] has made an approximate estimation of a different *L* current system in order to explain lunar tidal variations in the ionosphere. The purpose of this paper is to present new lunar current systems for both external and internal fields, which include the equatorial electrojet. We have used the same basic method here as in our study of the geomagnetic solar quiet daily variation field S_q, the preceding paper in this issue of the journal [*Matsushita and Maeda*, 1965].

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TABLE 1. Stations Used in L Study

Zone	Name of Station	Geographic Latitude	Geographic Longitude	Dip Latitude
1	Pavlovsk	59.7°	030.5°E	57.7°
	Rude Skov	55.9	012.5	53.8
	Kazan	55.8	048.9	56.4
	Potsdam	52.4	013.1	50.1
	Seddin	52.3	013.1	50.1
	Kew	51.5	359.7	49.7
	Greenwich	51.5	000.0	49.5
	Prague	50.1	014.4	47.4
	Val-Joyeux	48.8	002.3	46.7
	Pola	44.9	013.8	41.2
	San Fernando	36.5	353.8	33.0
	Tamanrasset	22.8	005.5	15.4
	Alibag (Colaba)	18.6	072.9	12.9
	Kodaikanal	10.2	077.5	01.7
	Addis Ababa	09.0	038.8	−00.5
	Trivandrum	08.5	077.0	−00.3
	Ibadan	07.4	003.9	−03.1
	Mogadiscio	02.0	045.4	−08.6
	St. Helena	−16.0	354.3	−24.5
	Hermanus (Cape Town)	−34.4	019.2	−46.8
2	Sitka	57.0	224.7	60.4
	Kakioka	36.2	140.2	30.1
	Zikawei	31.2	121.5	26.9
	Honolulu	21.3	201.9	22.0
	Manila	14.6	121.2	07.8
	Batavia	−06.2	106.9	−17.6
	Apia	−13.8	188.2	−16.3
	Melbourne	−37.8	145.0	−51.2
	Hobarton	−42.9	147.5	−57.5
	Amberley	−43.2	172.8	−51.3
3	Toronto	43.7	280.5	61.3
	Philadelphia	40.0	284.8	57.0
	Cheltenham	38.7	283.2	55.8
	Fredericksburg	38.2	282.6	54.4
	Tucson	32.3	249.2	40.3
	San Juan	18.4	293.9	32.1
	Huancayo	−12.1	284.7	01.0

Data

To study the geomagnetic L field on a worldwide scope it is certainly desirable to make a lunar analysis of the geomagnetic data obtained at many stations in different longitudinal zones during the *same* period in each season for each solar activity period; the method of lunar data analysis used should be as dependable as possible, and the same method should be applied to all the data. Since a long period of data is usually needed to find geomagnetic lunar variations, dependable geomagnetic data obtained at more than 20 stations in each longitudinal zone during the same period of about 15 years are probably required. At the present time, however, both collection and analysis of this amount of data are difficult. Therefore a simplified method was followed in the present study.

All available results of lunar analysis obtained and referred to by various workers were collected; they include observations from a total of 37 stations (see Table 1). Some unreliable results obtained from very old data were ignored. As in the S_q analysis, the world is divided into three longitudinal zones with respect to geomagnetic longitude, namely, zone 1 (the Europe–Africa zone between geomagnetic longitude 45° and 165°E), zone 2 (the Asia–Australia zone between geomagnetic longitude 165° and 285°E), and zone 3 (the North America–South America zone between geomagnetic longitude 285° and 45° E), and the dip latitude ϕ (or colatitude θ) was used, where

$$\tan I = 2 \tan \phi \quad (\text{or } 2 \cot \theta)$$

and I is the dip angle at each station. Then, as shown in Figure 1, we have 20, 10, and 7 stations in zones 1, 2, and 3, respectively, ranging from dip latitude 61.3° to −57.5°. The number of stations in zones 2 and 3 are unfortunately too few to calculate the L current system in each zone, but all 37 stations combined may be enough to estimate a worldwide average L current system.

All available results of lunar semidiurnal variations at these 37 stations are listed for each component in Tables 2A, B, and C, where P_2 is the amplitude and t_2 is the time at which the maximum variation occurs. The results obtained by *Chapman* [1919] for each season and all results obtained by *van Bemmelen* [1912] were excluded from Table 2, because their values might be misleading. Since the semidiurnal variation is the main term of lunar daily variation, many workers have reported only this term. The present analysis was limited to the semidiurnal variation as an average of one lunation. The D, E, and J months in Tables 2 indicate northern winter (hence, southern summer), equinoxes, and northern summer (hence, southern winter), respectively. The period of data studied varies from 1840 to 1962 covering different solar activity periods. These results are not extensive enough to permit calculation of the worldwide L current system in each season during *each* solar activity period, but they may be sufficient to obtain the system for each season during an *average* solar activity period by taking all values from different periods together and estimating their average values.

The various workers listed in Tables 2 used different methods of obtaining the lunar variation from geomagnetic data [see *Matsushita*, 1964]; some followed rather questionable methods, and some results are, therefore, rather unreliable. However, this fact did not pose any particular problem for the present study, because the data were subjectively but carefully weighted in the process of obtaining average distribution curves. The effect of geomagnetic disturbances on lunar variations was eliminated.

Method

The basic principle of the method of analysis is the same spherical harmonic analysis as in the S_q study [*Matsushita and Maeda*, 1965]. The horizontal component (positive northward), declination (positive eastward), and vertical component (positive downward) of the L field at each station are denoted by ΔH, ΔD, and ΔZ, respectively, and are expressed in the Fourier series as follows:

$$\Delta H = \sum_m (h_a^m \cos m\lambda + h_b^m \sin m\lambda) = \sum_m h_c^m \sin (m\lambda + \gamma_h^m)$$

$$\Delta D = \sum_m (d_a^m \cos m\lambda + d_b^m \sin m\lambda) = \sum_m d_c^m \sin (m\lambda + \gamma_d^m)$$

$$\Delta Z = \sum_m (z_a^m \cos m\lambda + z_b^m \sin m\lambda) = \sum_m z_c^m \sin (m\lambda + \gamma_z^m)$$

where λ is the lunar time in angular measure. Since the main term of lunar variation is the semidiurnal variation, only the case $m = 2$ was considered in the above equations. The values of h_c^2, γ_h^2, d_c^2, γ_d^2, z_c^2, and γ_z^2 can be obtained at

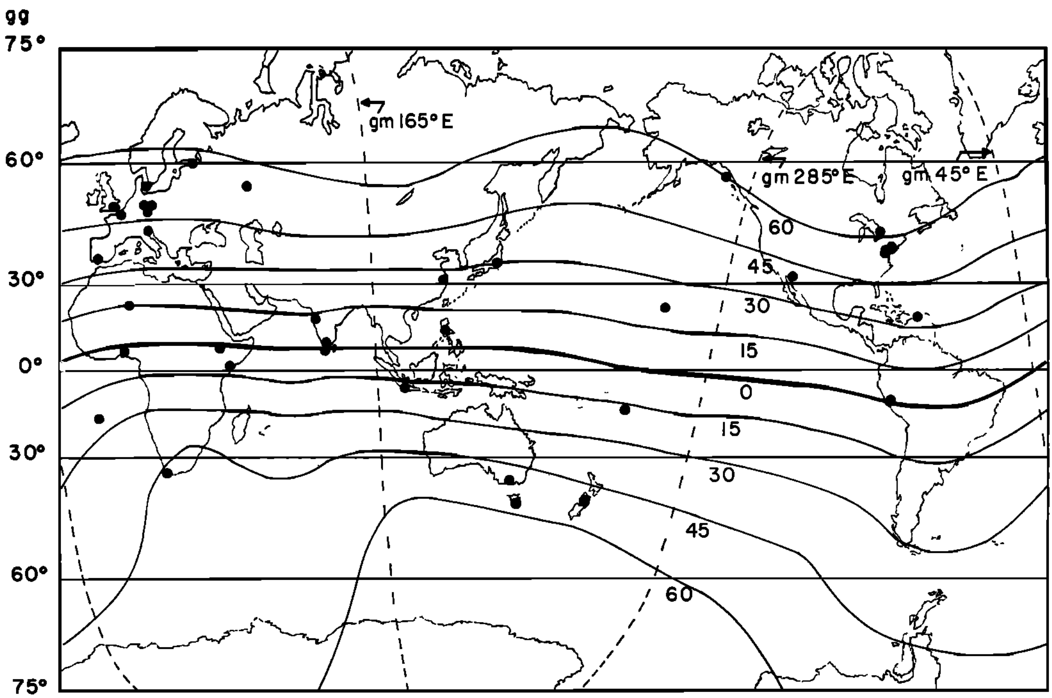

Fig. 1. Distribution of 37 geomagnetic stations used in the present L study, with respect to geographic latitude (ordinate) and dip latitude (solid curves). The three geomagnetic longitudes shown by the broken curves indicate the boundaries of three longitudinal zones.

TABLE 2A. Lunar Semidiurnal Variations of the Horizontal Component

Name of Station	Dip Latitude	Zone	D Months P_2	D Months t_2	E Months P_2	E Months t_2	J Months P_2	J Months t_2	Yearly Average P_2	Yearly Average t_2	Data Period	Reported by
Toronto	61.3°	3	γ	h	γ	h	γ	h	0.47γ	h	1843–1848	*Egedal* [1926]
Sitka	60.4	2	1.48	03.3	2.21	04.0	2.59	04.3	2.02	04.0	1902–1952	*Cain* [1957]
			±0.09	±00.1	±0.15	±00.1	±0.16	±00.1	±0.13	±00.1		
			1.53	03.8	2.43	04.0	2.48	04.7	2.08	04.2	1950–1957	*Matsushita* [1964]
			±0.69		±0.57		±0.32		±0.31			
Pavlovsk	57.7	1					1.18			02.7	1897–1903	*Chapman* [1914*a*]
Kazan	56.4	1	0.68	09.9?	0.94	10.0?	1.06	09.8?	0.81	10.0?	1952–1955	*Fatkullin* [1962]
Cheltenham†	55.8	3	0.75	01.9	1.35	02.8	0.81	03.3	0.94	02.7	1950–1957	*Matsushita* [1962*a*]
			±0.28		±0.15		±0.14		±0.11			
Potsdam	50.1	1							0.34		1891–1905	*Egedal* [1926]
Seddin	50.1	1							0.36‡		1917–1921	*Egedal* [1926]
Greenwich	49.5	1	0.51	01.8	1.30	01.9	1.82	01.8	1.22	01.9	1848–1863	*Chapman* [1957]
			±0.06		±0.07		±0.08		±0.04		and	
											1867–1914	
Prague	47.4	1							0.72		1840–1849	*Egedal* [1926]
Pola	41.2	1							0.79	01.7	1897–1903	*Chapman* [1914*a*]
Tucson	40.3	3	0.77	03.3	1.06	04.0	0.47	04.2	0.73	03.7	1950–1957	*Matsushita* [1962*a*]
			±0.24		±0.15		±0.17		±0.14			
San Fernando	33.0	1	0.88	01.0	1.64	01.4	2.51	01.8	1.65	01.5	1911–1947	*Wilkes* [1962]
			±0.19		±0.22		±0.19		±0.12			
San Juan	32.1	3	0.6*	00.8*	0.91	01.4	1.44	01.4	0.98	01.3	1951–1957	*Matsushita* [1962*a*]
			±0.4		±0.20		±0.24		±0.15			
			1.10	10.0	0.81	10.4	1.39	10.0			1950–1954	*Raja Rao* [1962]
			±0.38		±0.29		±0.42					
Kakioka	30.1	2	0.90	08.4	0.87	11.6	1.05	11.7	1.00	10.9	1937–1939	*Yamaguchi* [1958]
Zikawei	26.9	2							0.48	11.1	1897–1903	*Chapman* [1917]
									0.59	11.5	1890–1900	*Chapman* [1917]
									1.20	11.1	1890–1908	*Chapman* [1917]
Honolulu	22.0	2	0.9*	01.8*	0.3*	01.5*	0.3*	01.8*	0.5*	01.9*	1952–1957	*Matsushita* [1962*a*]
			±0.4		±0.4		±0.4		±0.2			
			1.08	11.5	1.01	03.6	1.22	01.9			1950–1954	*Raja Rao* [1962]
			±0.38		±0.34		±0.41					
Tamanrasset	15.4	1	1.77	09.1	0.68	10.6	0.87	11.9	0.99	10.2	1948–1955	*Duclaux and Will* [1958]
			±0.22		±0.27		±0.22		±0.16			
Alibag	12.9	1			1.2	00.9?					1940–1944	*Raja Rao* [1960]
					±0.3							

TABLE 2A. (Continued)

Name of Station	Dip Latitude	Zone	D Months		E Months		J Months		Yearly Average		Data Period	Reported by
			P_2	t_2	P_2	t_2	P_2	t_2	P_2	t_2		
Alibag	129°	1	γ	h	γ	h	γ	h	γ	h		
			1.27 ±0.26	07.9	1.02 ±0.26	09.3	1.07 ±0.29	08.2			1950–1954	*Raja Rao* [1962]
									1.31		1871–1888	*Chapman* [1914*b*]
			1.30								1871–1889	*Egedal* [1926]
Kodaikanal	01.7	1	3.32 ±0.90	04.3	2.28 ±0.85	08.1	1.43 ±0.55	05.1			1950–1955	*Raja Rao and Sivaraman* [1958] *Raja Rao* [1961]
					3.9 ±0.58	08.6					Sept. 1950	*Egedal* [1956*a*]
Huancayo	01.0	3	8.0		5.9		2.4				1922–1934	*Bartels* [1936]
			7.62 ±0.21	08.2	5.53 ±0.19	09.1	2.55 ±0.20	09.9	5.24 ±0.15	09.1	1922–1947	*Matsushita* [1964]
Addis Ababa	−00.5	1	6.36 ±1.33	07.1	6.17 ±1.85	08.5	2.30 ±0.90	06.6			1958–1959	*Gouin* [1960]
Ibadan	−03.1	1	4.70	07.0	3.82	07.3	3.37	07.3	3.99	07.2	1955–1957	*Onwumechilli and Alexander* [1959]
Mogadiscio	−08.6	1	1.63	06.9	2.23	10.0	0.57	06.7	1.03 ±0.19	09.1	1932–1933	*Egedal and Bossolasco* [1941]
Apia	−16.3	2	1.21 ±0.36	04.0	0.98 ±0.28	09.4	1.08 ±0.34	03.2			1950–1954	*Raja Rao* [1962]
Batavia	−17.6	2							0.89		1874–1899	*Chapman* [1914*b*]
			1.20							08.1		*Chapman and Bartels* [1940]
									0.64		1883–1899	*Egedal* [1926]
Hermanus§	−46.8	1	1.36 ±0.18	03.4							1941–1962	*van Wijk and Bergh* [1963]
			1.52 ±0.19	03.6							1932–1935 and 1940	*van Wijk and Bergh* [1963]
			1.88 ±0.22	03.4							1936–1939	*van Wijk and Bergh* [1963]
Amberley	−51.3	2	1.63 ±0.50	03.5	1.10 ±0.42	03.9	0.59 ±0.47	04.0	1.09 ±0.33	03.7	1931–1935	*Bullen and Cummack* [1953]

* Less significant.
† Fredericksburg after January 1956.
‡ X component.
§ Cape Town before 1940.

TABLE 2B. Lunar Semidiurnal Variations of Eastward Declination

Name of Station	Dip Latitude	Zone	D Months P_2	D Months t_2	E Months P_2	E Months t_2	J Months P_2	J Months t_2	Yearly Average P_2	Yearly Average t_2	Data Period	Reported by
Toronto	61.3°	3	′	h	′	h	′	h	0.22′	h	1842–1848	*Egedal* [1926, 1927]
									0.32			
Sitka	60.4	2	0.23	04.8	0.23	07.3	0.29	07.4	0.20	06.5	1902–1922	*Chapman* [1957]
			±0.03	±00.2	±0.03	±00.3	±0.04	±00.2	±0.02	±00.2		
			0.24	04.8	0.27	07.0	0.27	07.3	0.24	06.9	1902–1952	*Cain* [1957]
			±0.02	±00.2	±0.03	±00.2	±0.04	±00.3	±0.01	±00.1		
			0.26	05.1	0.34	07.0	0.30	07.7	0.26	06.8	1950–1957	*Matsushita* [1964]
			±0.11		±0.03		±0.06		±0.03			
Pavlovsk	57.7	1					0.25	05.6			1897–1903	*Chapman* [1957]
							±0.02	±00.2				
									0.10		1897–1903	*Egedal* [1927]
Philadelphia	57.0	3							0.21		1840–1845	*Egedal* [1926, 1927]
Kazan*	56.4	1	0.19	04.6	0.32	05.7	0.23	05.5	0.21	04.8	1952–1955	*Fatkullin* [1962]
Cheltenham†	55.8	3	0.28	05.4	0.40	06.7	0.41	07.6	0.33	06.7	1950–1957	*Matsushita* [1962*a*]
			±0.06		±0.04		±0.05		±0.03			
Rude Skov	53.8	1							0.11	06.7	1908–1951	*Egedal* [1953]
Potsdam	50.1	1							0.14		1891–1905	*Egedal* [1927]
Seddin	50.1	1							0.14		1917–1923	*Egedal* [1927]
Kew	49.7	1							0.17		1858–1862	*Egedal* [1927]
Greenwich	49.5	1							0.23		1848–1863	*Chapman* [1914*b*]
			0.15	08.3	0.21	06.7	0.33	06.7	0.22	07.0	1848–1863	*Chapman* [1957]
			±0.01	±00.1	±0.01	±00.1	±0.02	±00.1	±0.01	±00.1	and	
											1867–1914	
Prague	47.4	1							0.15		1840–1849	*Egedal* [1927]
Val-Joyeux	46.7	1	0.13	08.7	0.20	06.8	0.36	06.9	0.22	07.2	1912–1937	*Rougerie* [1950]
									±0.03			
Pola	41.2	1							0.09	06.7	1897–1903	*Chapman* [1914*a*]
Tucson	40.3	3	0.19	05.3	0.28	06.9	0.26	07.3	0.22	06.7	1950–1957	*Matsushita* [1962*a*]
			±0.06		±0.06		±0.04		±0.02			
San Fernando	33.0	1	0.11	03.8	0.19	04.4	0.30	05.3	0.19	04.7	1911–1947	*Wilkes* [1962]
			±0.02		±0.03		±0.03		±0.01			
San Juan	32.1	3	0.17	06.1	0.34	07.1	0.28	07.8	0.25	07.2	1951–1957	*Matsushita* [1962*a*]
			±0.02		±0.03		±0.04		±0.02			
Kakioka	30.1	2	0.14	02.4	0.12	05.7	0.24	05.7	0.11	05.2	1925–1945	*Yamaguchi* [1957]
Zikawei	26.9	2							0.14	05.9	1897–1903	*Chapman* [1917]
									0.13	05.0	1890–1900	*Chapman* [1917]
									0.25	06.1	1890–1908	*Chapman* [1917]

TABLE 2B. (Continued)

Name of Station	Dip Latitude	Zone	D Months P_2	D Months t_2	E Months P_2	E Months t_2	J Months P_2	J Months t_2	Yearly Average P_2	Yearly Average t_2	Data Period	Reported by
Honolulu	22.0°	2	0.11′ ±0.02	04.7^h	0.18′ ±0.02	06.2^h	0.22′ ±0.03	06.5^h	0.16′ ±0.01	05.8^h	1952–1957	*Matsushita* [1962a]
Alibag	12.9	1							0.10		1871–1888	*Chapman* [1914b]
Manila	07.8	2					0.12				1897–1903	*Egedal* [1927]
Huancayo	01.0	3	0.08 ±0.01	09.3	0.19 ±0.01	08.3	0.14 ±0.01	07.9	0.14 ±0.01	08.5	1922–1947	*Matsushita* [1964]
			0.08 ±0.01	09.1 ±00.3							1922–1930	*Schneider* [1936]
Trivandrum	−00.3	1							0.04		1854–1864	*Chapman* [1914b]
Addis Ababa	−00.5	1	0.33 ±0.05	11.8	0.20 ±0.05	09.7	0.13 ±0.03	07.3			1958–1959	*Gouin* [1960]
Ibadan	−03.1	1	0.20 ±0.03	10.6	0.07 ±0.07	06.4	0.18 ±0.04	06.0			1955–1960	*Onwumechilli* [1960]
Mogadiscio	−08.6	1	0.32	11.7	0.26	01.8	0.05	07.8			1932–1933	*Bossolasco and Egedal* [1937]
Batavia	−17.6	2							0.17		1884–1899	*Chapman* [1914b]
			0.15							00.3		*Chapman and Bartels* [1940]
			0.27 ±0.02‡	00.1 ±00.1							1906–1929	*Schneider* [1936]
St. Helena	−24.5	1							0.08		1842–1847	*Egedal* [1926]
Hermanus§	−46.8	1			0.20 ±0.10	11.1					1933–1950	*van Wijk and Bergh* [1963]
			0.65 ±0.05	11.9							1936–1939	*van Wijk and Bergh* [1963]
			0.60 ±0.07	00.5							1932–1935 and 1940	*van Wijk and Bergh* [1963]
									0.16		1842–1846	*Egedal* [1927]
Melbourne	−51.2	2							0.15		1858–1863	*Egedal* [1927]
Amberley	−51.3	2	0.42 ±0.09	02.0	0.20 ±0.09	01.7	0.11 ±0.06	02.5	0.24 ±0.07	02.0	1931–1935	*Bullen and Cummack* [1953]
Hobarton	−57.5	2							0.15		1841–1849	*Egedal* [1927]

* Both the unit and direction of the declination are uncertain.
† Fredericksburg after January 1956.
‡ *Y* component.
§ Cape Town before 1940.

TABLE 2C. Lunar Semidiurnal Variations of the Vertical Component

Name of Station	Dip Latitude	Zone	D Months		E Months		J Months		Yearly Average		Data Period	Reported by
			P_2	t_2	P_2	t_2	P_2	t_2	P_2	t_2		
Sitka	60.4°	2	0.52$^{\gamma}$ ±0.12	11.3^{h} ±00.4	0.55$^{\gamma}$ ±0.12	00.9^{h} ±00.4	0.53$^{\gamma}$ ±0.17	02.6^{h} ±00.8	0.30$^{\gamma}$ ±0.12	01.2^{h} ±00.8	1902–1952	*Cain* [1957]
			0.2* ±0.8	01.8*	0.6* ±0.9	01.9*	1.23 ±0.55	02.6	0.62 ±0.58	02.4	1950–1957	*Matsushita* [1964]
Pavlovsk	57.7	1					0.13				1897–1903	*Chapman* [1914*a*]
Kazan	56.4	1	0.75	11.1	1.01	11.0	0.84	10.6	0.97	10.7	1952–1955	*Fatkullin* [1962]
Cheltenham†	55.8	3	0.02* ±0.2	03.3*	0.50 ±0.09	04.8	0.65 ±0.07	06.0	0.37 ±0.11	05.5	1950–1957	*Matsushita* [1964]
Seddin	50.1	1							0.41		1917–1921	*Egedal* [1926]
Pola	41.2	1							0.39	10.6	1897–1903	*Chapman* [1914*a*]
Tucson	40.3	3	0.52 ±0.08	01.6	0.40 ±0.06	04.0	0.20 ±0.11	06.4	0.23 ±0.12	03.2	1950–1957	*Matsushita* [1964]
San Juan	32.1	3	0.23 ±0.08	04.7	0.74 ±0.10	05.2	0.74 ±0.10	06.0	0.56 ±0.07	05.5	1951–1957	*Matsushita* [1964]
Kakioka	30.1	2	0.78	08.2	0.65	11.4	1.85	11.5	1.20	10.8	1937–1939	*Yamaguchi* [1958]
Zikawei	26.9	2							1.05	06.6	1897–1903	*Chapman* [1917]
									1.00	05.8	1890–1900	*Chapman* [1917]
									0.99	05.6	1890–1908	*Chapman* [1917]
Honolulu	22.0	2	0.54 ±0.14	11.8	0.15 ±0.18	07.5	0.1* ±0.2	08.5*	0.30 ±0.04	09.8	1952–1957	*Matsushita* [1964]
Huancayo	01.0	3	1.52 ±0.18	03.3	1.33 ±0.18	05.0	0.71 ±0.12	05.2	1.00 ±0.09	04.4	1924–1945	*Matsushita* [1964]
Addis Ababa	−00.5	1	1.62 ±0.23	01.4	0.79 ±0.20	07.7	0.64 ±0.10	11.1			1958–1959	*Gouin* [1960]
Ibadan	−03.1	1	3.04	07.2	2.07	07.6	2.69	07.8	2.60	07.5	1955–1957	*Onwumechilli and Alexander* [1959]
Mogadiscio	−08.6	1	1.53	07.6	1.77	08.9	0.90	08.6	1.12 ±0.05	08.1	1932–1933	*Egedal and Bossolasco* [1941]
Hermanus§	−46.8	1	1.58 ±0.27	10.2							1932–1935 and 1940	*van Wijk and Bergh* [1963]
			1.63 ±0.30	09.5							1936–1939	*van Wijk and Bergh* [1963]
Amberley	−51.3	2	2.39 ±0.23	08.2	2.07 ±0.23	08.3	1.96 ±0.16	08.1	2.14 ±0.10	08.2	1931–1935	*Bullen and Cummack* [1953]
			2.3 ±0.2								1953	*Egedal* [1956*b*]

* Less significant.
† Fredericksburg after January 1956.
§ Cape Town before 1940.

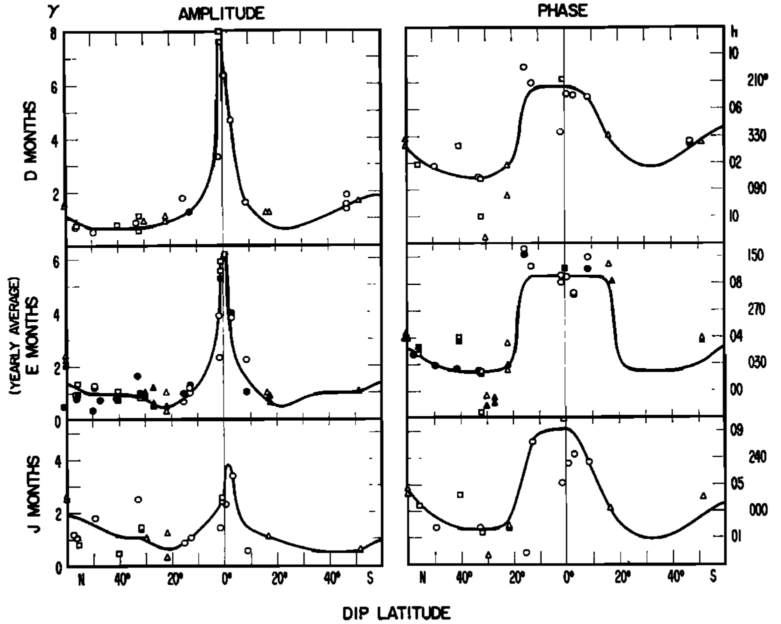

Fig. 2*a*. Horizontal component.

each station from Tables 2, and these values in each season are plotted with respect to the dip latitude as shown in Figures 2; the left-hand diagrams of Figures 2*a*, 2*b*, and 2*c* are for h_o^2, d_o^2, and z_o^2, respectively, and the right-hand diagrams are for γ_h^2, γ_d^2, and γ_z^2, respectively. The circles identify zone 1; the triangles, zone 2; and the squares, zone 3. Finding definite differences among three zones is difficult even at middle latitudes in the northern hemisphere. These distributions, regardless of zone, were approximated by smooth curves in which the weights of the values at each station were considered. A symmetrical distribution between the northern and southern hemispheres was assumed for all three components during equinoxes combined with yearly average (middle diagrams of Figure 2). Since the phase of the vertical component was widely distributed, subjective distribution curves were assumed. For the amplitude of the horizontal component, a large enhancement over the magnetic equatorial zone, particularly during D months, and a slight shift of the peak toward the winter hemisphere, can be seen in Figure 2*a*.

From these smoothed distribution curves, average lunar semidiurnal variations of three geomagnetic components at different latitudes for three seasons were obtained; they are shown in Figures 3*a*–*c*. Clear amplitude and phase changes can be seen at certain latitudes in different seasons.

The horizontal and vertical components were chosen for spherical harmonic analysis. From the smoothed distribution curves of the *H* and *Z* components, the amplitude, $h_{nc}^2(\theta)$ and $z_{nc}^2(\theta)$, and the phase, $\gamma_{nh}^2(\theta)$ and $\gamma_{nz}^2(\theta)$, were read at every 5° of dip colatitude θ between $\theta = 30°$ and $\theta = 150°$. Since

$$h_{nc}^2(\theta) \sin [2\lambda + \gamma_{nh}^2(\theta)] = h_{na}^2(\theta) \cos 2\lambda + h_{nb}^2(\theta) \sin 2\lambda$$

and

$$z_{nc}^2(\theta) \sin [2\lambda + \gamma_{nz}^2(\theta)] = z_{na}^2(\theta) \cos 2\lambda + z_{nb}^2(\theta) \sin 2\lambda$$

the coefficients, $h_{na}^2(\theta)$, $h_{nb}^2(\theta)$, $z_{na}^2(\theta)$, and $z_{nb}^2(\theta)$, were easily calculated for every 5°. These coefficients can be expanded in spherical functions as follows:

$$h_{na}^2(\theta) = \sum_{n=2}^{11} a_n^2 X_n^2(\theta)$$

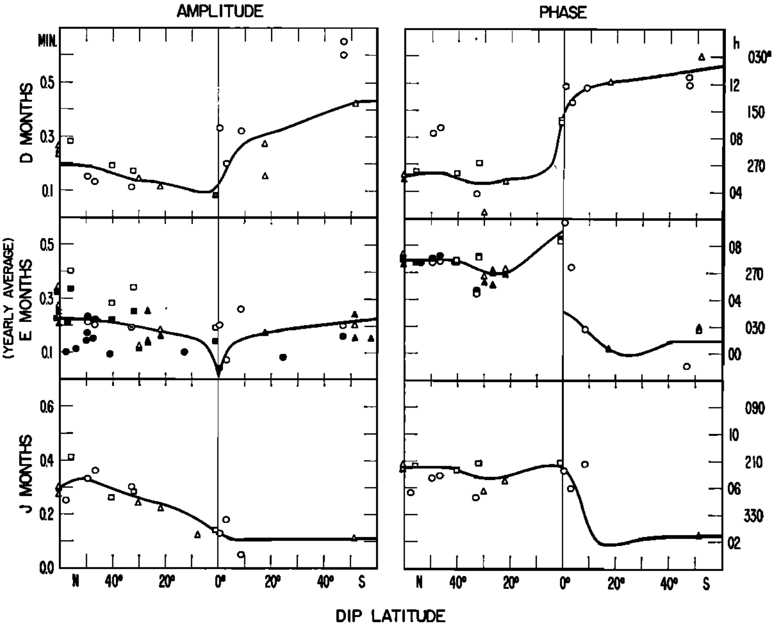

Fig. 2*b*. Declination component.

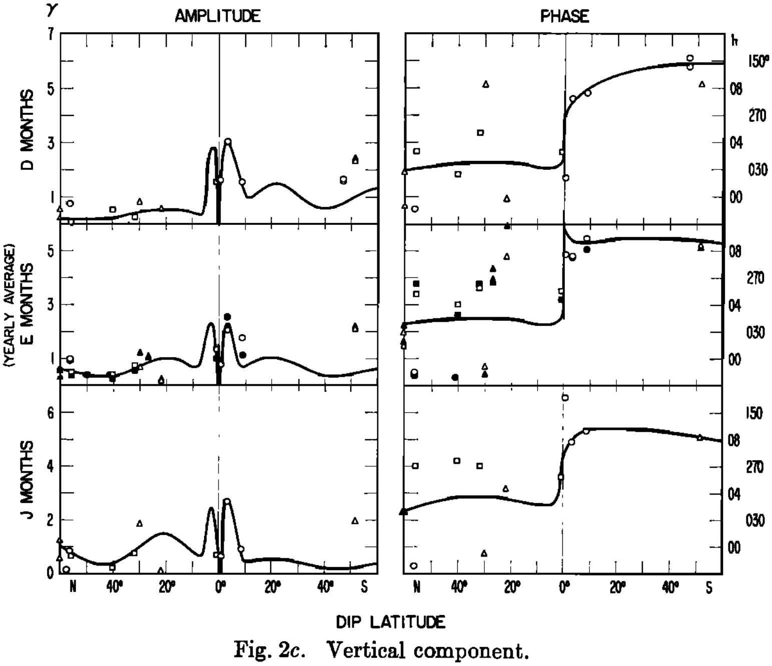

Fig. 2*c*. Vertical component.

Fig. 2. Dip-latitudinal distributions of the lunar semidiurnal amplitudes and phase angles of the horizontal component, the declination component, and the vertical component for D months, E months and yearly average, and J months. These distributions are approximated by smooth curves. The circles, triangles, and squares are used to identify zones 1, 2, and 3, respectively; in the middle diagrams the solid symbols show yearly average and the open symbols show E months. In the right diagrams the ordinate with the unit of hours indicates the lunar time at which the maximum lunar variation occurs.

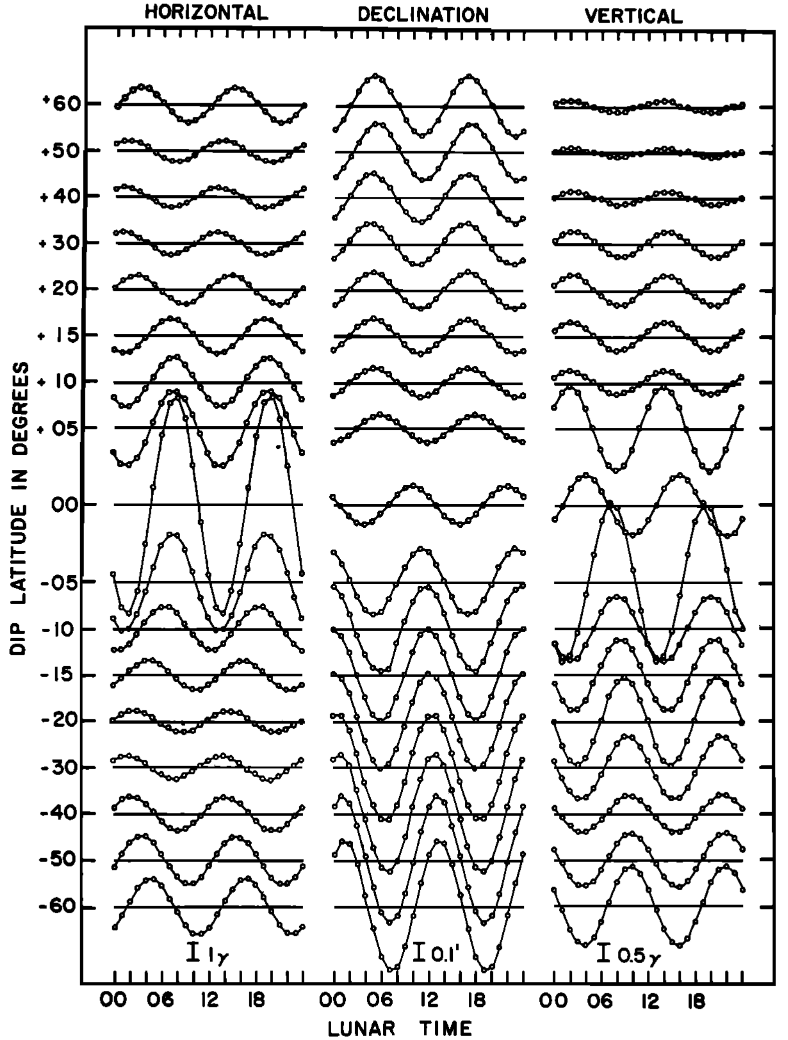

Fig. 3*a*. D months.

$$h_{nb}^2(\theta) = \sum_{n=2}^{11} \mathbf{b}_n^2 X_n^2(\theta)$$

$$z_{na}^2(\theta) = \sum_{n=2}^{11} a_n^2 P_n^2(\theta)$$

$$z_{nb}^2(\theta) = \sum_{n=2}^{11} b_n^2 P_n^2(\theta)$$

where $P_n^2(\theta)$ is the Schmidt's function (or normalized associated Legendre function) $P_n^m(\theta)$ for the case $m = 2$, and

$$X_n^2(\theta) = \frac{1}{n}\frac{dP_n^2(\theta)}{d\theta}$$

[*Schmidt,* 1935]. All these coefficients were obtained by the least-squares method. Then, the coefficients e_{na}^2 and e_{nb}^2 of the external part and i_{na}^2 and i_{nb}^2 of the internal part were calculated, and the magnetic potential Ω of the L field at the earth's surface was approximated by

$$\Omega = C + R \sum_{n=2}^{11} [(e_{na}^2 + i_{na}^2) \cos 2\lambda + (e_{nb}^2 + i_{nb}^2) \sin 2\lambda] P_n^2(\theta)$$

$$= C + R \sum_{n=2}^{11} [E_n^2 \cos (2\lambda + \epsilon_n^2) + I_n^2 \cos (2\lambda + \iota_n^2)] P_n^2(\theta)$$

$$\equiv C + \sum_{n=2}^{11} (\Omega_n^{2e} + \Omega_n^{2i})$$

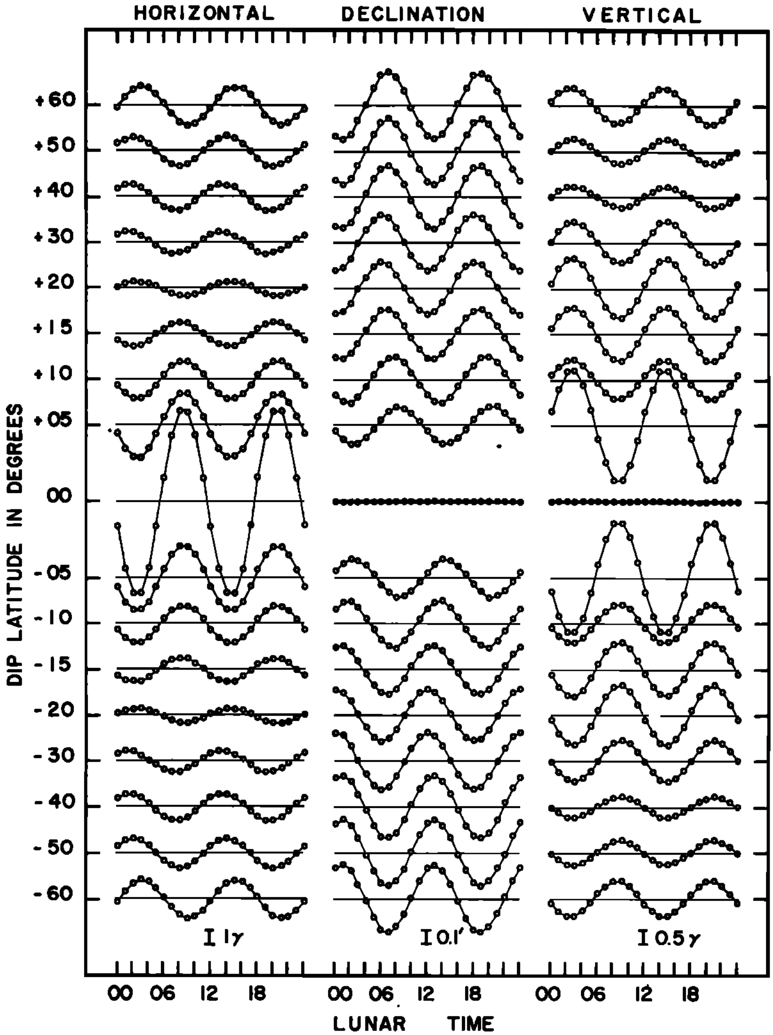

Fig. 3*b*. E months.

The current functions (in amperes) of the external and internal fields, J_n^{2e} and J_n^{2i}, can be obtained by

$$J_n^{2e} = -\frac{10}{4\pi}\frac{2n+1}{n+1}\left(\frac{a}{R}\right)^n \Omega_n^{2e}$$

and

$$J_n^{2i} = \frac{10}{4\pi}\frac{2n+1}{n}\left(\frac{R}{a}\right)^{n+1} \Omega_n^{2i}$$

where R is the earth's radius (taken as 6.37×10^8 cm) and a is the radius of the sphere at which currents are flowing; however, $a = R$ is assumed because $|a - R| \ll R$. Most of these calculations and the plotting of the final currents were done on a CDC 3600 computer.

Results

External current systems for a mean lunation in three seasons and their average, which are plotted by computer for every 10^3 amperes of electric current intensity, are shown in Figure 4. Lunar electrojet currents are seen in the magnetic equatorial zone (near dip latitude 0°). The current system for E months is obtained from the assumption of a symmetric distribution of the lunar variation between the northern and southern hemispheres. This symmetric distribution is based on lunar analysis for both E months and yearly average. The average current system shown in the bottom right of Figure 4 was obtained as an average of the current systems for three seasons: D, E, and J months; it shows a remarkable resemblance to the system for E months.

Internal current systems for a mean lunation plotted by computer are shown in Figure 5. The yearly averages of external and internal current systems are compared in Figure 6; these systems were drawn from contour distributions plotted by computer. Central positions of current vortices and total current intensities for these external and internal current systems are listed in Table 3A. It is very interesting that the total external current intensity for E months is comparable with or sometimes even larger than the intensity in local summer, similar to our result for S_q systems. Contrary to the S_q case, however, the center of current vortices in summer appears later than that in winter. As

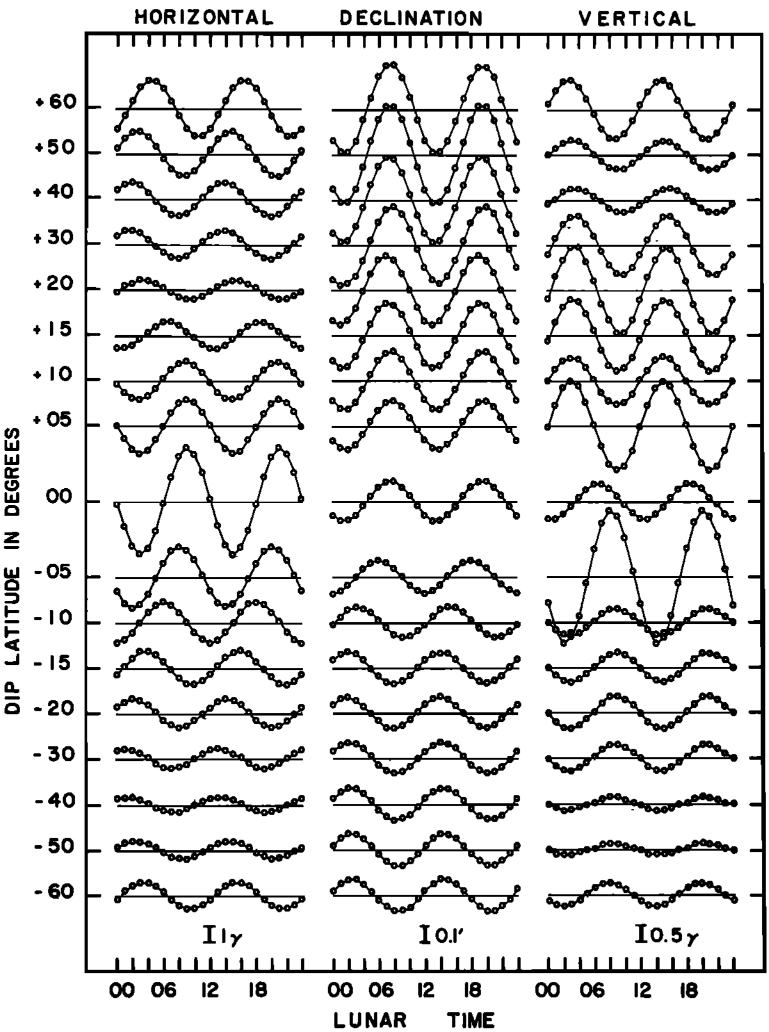

Fig. 3c. J months.

Fig. 3. Lunar semidiurnal variations of the geomagnetic three components at several dip latitudes from 60° to —60° for D, E, and J months.

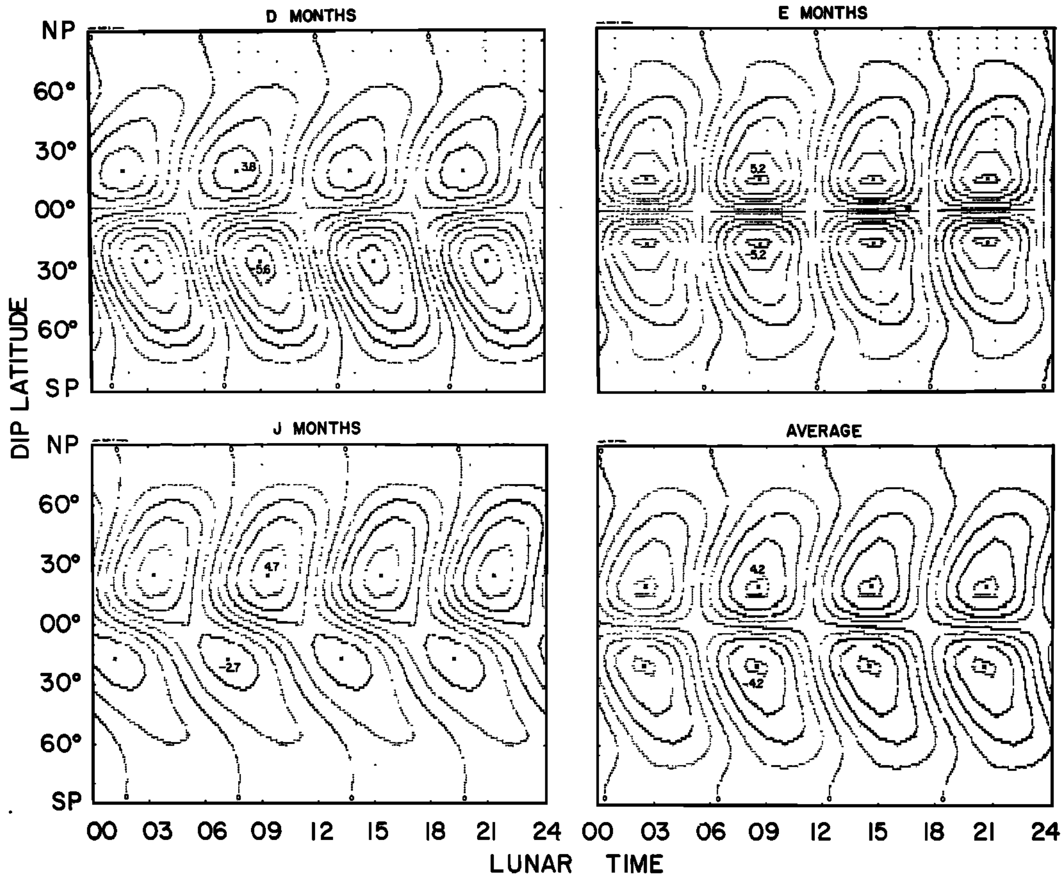

Fig. 4. External L current systems averaged worldwide for D, E, and J months, and their yearly average. They were plotted by computer for every 10^8 amperes of electric current intensity. The zero lines are made clearer by adding larger zero figures at their ends. The zones in which the currents flow in counterclockwise and clockwise directions are plotted by positive and negative signs, respectively, at each hour for every 5° of dip latitude. The cross marks show the central positions of these current vortices, and the numbers near the cross marks indicate the total current intensities of the vortices in units of 10^8 amperes.

has already been suggested by *Matsushita* [1962*b*] the latitude of the central position for the external system in summer is higher than that in winter. Matsushita's estimated values of the external total current intensity and the central position were 4.9×10^8 amperes at dip latitude 19° (dip angle 35°) at 7 h for E months, 7.3×10^8 amperes at dip latitude 23° (dip angle 40°) at 7 h in the northern hemisphere for J months, and -2.4×10^8 amperes at dip latitude 16° (dip angle 30°) at 7 h in the southern hemisphere for J months; these values are in good agreement with the present results, except for the total current intensity and longitude in summer.

When the present external current systems are compared with those of *Chapman and Bartels* [1940; see their Figures 4 and 5], the following differences are apparent:

1. There is a continuous phase shift from low to high latitudes in the present results, but none is seen in theirs. Also the equatorial electrojet is not included in their results. Dip latitude, used in our study, shows the equatorial electrojet much better than geographic latitude, used in their study.

2. As compared in Table 3B, remarkable differences between the two results can be seen in the total current intensity during equinoxes and particularly during winter, and in the latitude of the central position in winter relative to its position in summer.

The coefficients of spherical harmonic terms, $\mathbf{a}_n^2$ and $\mathbf{b}_n^2$ from the H component and a_n^2 and b_n^2 from the Z component, are listed in Table 4 for three seasons and their average. Amplitude ratios, E_n^2/I_n^2, and phase differences, $\epsilon_n^2 - \iota_n^2$, for the external and internal fields (see equation 1) are given in Table 5.

The previous results for the amplitude and phase obtained by other workers for the second harmonics ($m = 2$) are compared with the present results in Table 6. In the S_q field, E_3^2/I_3^2 is 2.0 to 2.4 and $\epsilon_3^2 - \iota_3^2$ is $-10°$ to $-19°$ (see Table 5 of *Matsushita and Maeda* [1965]). Comparing the values in Table 6 with these S_q values, our results of E_3^2/I_3^2 and $\epsilon_3^2 - \iota_3^2$ for the L field seem to be slightly large. Previous results are smaller, except for van Bemmelen's phase difference, which is extremely large. The values of E_3^2 (and I_3^2) are larger than those of E_2^2 (and I_2^2) in our result, but the relation is reversed in Chapman's result; this leads to Chapman's result of a very large difference between the current systems for summer and winter. Data from too few stations might be a possible cause of this large apparent seasonal change.

Discussion

The present L current systems obtained from all available results of lunar semidiurnal analysis of the horizontal and vertical components show fairly plausible current patterns with reasonable total current intensities for a mean lunation dur-

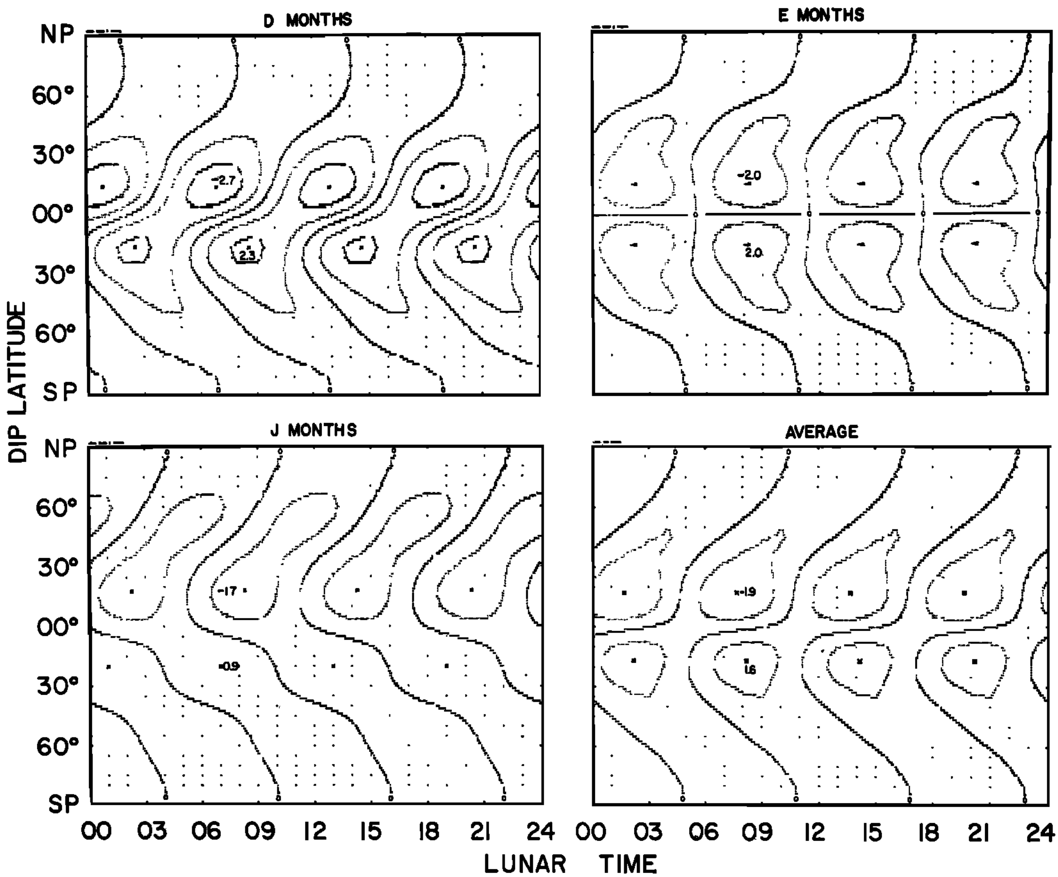

Fig. 5. Internal L current systems averaged worldwide for D, E, and J months, and their yearly average. See the legend of Figure 4 for other details.

ing an average solar activity period. The equatorial electrojet is indicated in the current diagrams by the zone near dip latitude 0°, where the consecutive lines of current intensity are close together. This computed electrojet seems to show slightly less intensity in a broader magnetic equatorial zone than the actual electrojet, owing to the nature of the method of spherical harmonic analysis.

Lunar current systems can also be derived from the declination and vertical components of the geomagnetic field. Since the declination does not show very drastic changes in the magnetic equatorial zone (see Figure 2*b*, particularly *L*(*D*) during D and J months), the vertical component, which is the least reliable one, becomes in this case the main factor determining the equatorial electrojet. In the analysis of the horizontal and vertical components, however, both components determine the equatorial electrojet. An analysis using both thus appears to be a better way to avoid possible errors involved in the electrojet effect. A comparison between the two methods will be made in the future, after more reliable results have been obtained from the vertical component.

When solar local time is taken into consideration, the external *L* current during the solar daylight hours should be very much enhanced and the current at night would approach zero because of the solar daily variation of electric conductivity. These lunisolar variations and lunar variations at a given lunar age need to be

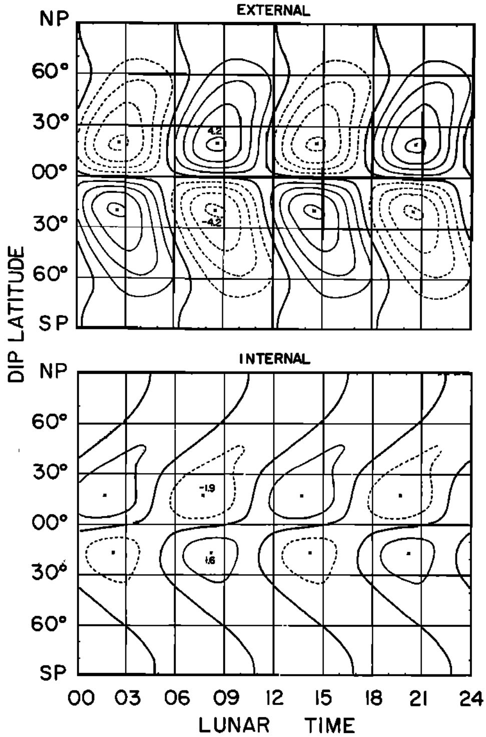

Fig. 6. External and internal *L* current systems averaged yearly and worldwide. The current intensity between two consecutive lines is 10^3 amperes, and the thick solid curves indicate the zero-intensity lines. The thin solid and broken curves show counterclockwise and clockwise current vortices, respectively. The numbers near the cross marks are the total current intensity of the vortices in units of 10^3 amperes.

TABLE 3A. Central Positions and Total Intensities of *L* Current Systems

Season	Hemisphere	External System: Position: Dip Lat.	External System: Position: Lunar Time	External System: Intensity* ($\times 10^3$ amp)	Internal System: Position: Dip Lat.	Internal System: Position: Lunar Time	Internal System: Intensity* ($\times 10^3$ amp)
D	N	21°	7.8^h	3.8	15°	6.9^h	−2.7
months	S	24	9.0	−5.6	15	8.6	2.3
E	N	16	8.6	5.2	15	8.3	−2.0
months	S	16	8.6	−5.2	15	8.3	2.0
J	N	25	9.3	4.7	18	8.3	−1.7
months	S	17	7.2	−2.7	20	7.0	0.9
Yearly	N	20	8.6	4.2	17	7.7	−1.9
ave.	S	20	8.5	−4.2	17	8.2	1.6

* The sign of the intensities changes every 6 hours, a complete cycle occurring every 12 hours.

TABLE 3B. Comparison of Central Positions and Total Intensities of the External L Current Systems

Months	Hemisphere	*Chapman and Bartels** [1940]		Matsushita and Maeda	
		Central Position			
		Geographic Lat.	Lunar Time	Dip Lat.	Lunar Time
E		35°	9.0^h	16°	8.6^h
J	N	25	9.3	25	9.3
J	S	52	8.8	17	7.2
		Total Intensity ($\times 10^3$ amp)			
E		2.6		5.2	
J	N	5.4		4.7	
J	S	−0.6		−2.7	

* Measured from their diagrams.

studied with other harmonics in addition to the semidiurnal component.

Chapman and Bartels [1940] concluded that the external L field has a large seasonal variation and a very small solar activity period dependence in comparison with the external S_q field. Between summer and winter, in fact, the ratios of the total current intensity are 9:1 and 2.5:1 for the external L and S_q fields, respectively. However, as was briefly mentioned in the previous section, the present study shows that the seasonal variation of the L field is similar to that of the S_q field. The summer to winter ratios for our L field are 1.2:1 for the northern hemisphere and 2.1:1 for the southern hemisphere. For our S_q field the ratios are 1.6:1 for the northern and 1.5:1 for the southern hemisphere. Concerning solar activity period dependence, Chapman's S_q field for the maximum period, 1905, is about 1.4 times larger than that

TABLE 4. Coefficients of Spherical Harmonic Terms for the L Field (in gammas)

Harmonics		D Months				E Months			
		From H		From Z		From H		From Z	
m	n	a_n^m	b_n^m	a_n^m	b_n^m	a_n^m	b_n^m	a_n^m	b_n^m
2	2	0.57	−0.48	−0.10	−0.15	0	0	0	0
	4	0.17	0.01	0.46	−0.46	0	0	0	0
	6	−0.05	0.08	−0.06	0.14	0	0	0	0
	8	−0.05	0.04	0.21	−0.24	0	0	0	0
	10	0.00	−0.05	−0.04	0.06	0	0	0	0
	3	0.37	2.45	−0.21	1.01	0.36	2.63	0.17	1.16
	5	−1.82	−1.26	0.03	−0.12	−1.25	−1.71	−0.03	−0.37
	7	0.64	0.84	−0.28	0.26	0.20	1.39	0.34	1.07
	9	−0.15	−0.59	0.14	0.01	−0.11	−1.65	0.03	0.05
	11	0.29	0.24	−0.08	0.08	0.35	1.16	0.23	0.54

Harmonics		J Months				Year			
		From H		From Z		From H		From Z	
m	n	a_n^m	b_n^m	a_n^m	b_n^m	a_n^m	b_n^m	a_n^m	b_n^m
2	2	−0.44	0.54	−0.35	0.13	0.06	0.03	−0.23	−0.01
	4	−0.07	0.14	0.14	0.27	0.05	0.08	0.30	−0.10
	6	−0.12	−0.15	−0.10	−0.07	−0.08	−0.04	−0.08	0.04
	8	0.05	0.06	0.08	0.13	0.00	0.05	0.15	0.06
	10	0.00	−0.03	−0.05	−0.05	0.00	−0.04	−0.04	0.00
	3	−0.10	1.76	−0.05	0.86	0.21	2.28	−0.04	1.01
	5	−1.55	−0.82	0.16	−0.20	−1.54	−1.26	0.05	−0.23
	7	0.13	0.29	0.19	0.34	0.32	0.84	0.08	0.56
	9	−0.02	−0.41	−0.06	−0.02	−0.09	−0.88	0.04	0.01
	11	0.20	0.02	0.05	0.04	0.28	0.47	0.07	0.22

TABLE 5. Amplitude Ratios E_n^m/I_n^m and Phase Differences $\epsilon_n^m - \iota_n^m$ for the External and Internal L Fields

Harmonics		Amplitude Ratios				Phase Differences			
m	n	D	E	J	Year	D	E	J	Year
2	2	1.5	*	3.3	2.4	22°	*	−34°	−6°
	4	1.5	*	1.8	1.7	−24	*	−53	−38
	6	3.8	*	4.5	4.2	−17	*	36	10
	8	0.6	*	3.0	1.8	4	*	11	8
	10	0.3	*	1.5	0.9	−70	*	−34	−52
	3	2.8	3.2	3.6	3.2	−18	1°	−0	−6
	5	1.2	1.6	1.1	1.3	−6	−10	−15	−10
	7	1.2	7.7	11.0	10.0	−37	−144	−23	−68
	9	1.0	1.1	1.2	1.1	−24	−2	−164	−63
	11	1.0	3.0	1.8	1.9	−32	8	−20	−15

* There are no values of E_n^m, I_n^m, ϵ_n^m, or ι_n^m in these cases, because a symmetric distribution of the L field between the northern and southern hemispheres is assumed.

TABLE 6. Comparison of the Amplitude and Phase of the External and Internal L Fields Obtained by Different Workers

Harmonics		External		Internal					
m	n	E_n^m	ϵ_n^m	I_n^m	ι_n^m	E_n^m/I_n^m	$\epsilon_n^m - \iota_n^m$	Season*	Worker†
		(× $10^{-2}\gamma$)		(× $10^{-2}\gamma$)					
2	3	34.1	106°	27.1	92°	1.3	14°	$(A_n + A_s)/2$	*van Bemmelen* [1913]
		38.0	83	20.9	112	1.8	−29	$(A_n + A_s)/2$	*Chapman* [1919]
		42.6	73	28.7	104	1.5	−31	$(E_n + E_s)/2$	*Chapman* [1919]
		67.3	98	21.3	97	3.2	01	$(E_n + E_s)/2$	Matsushita and Maeda
		53.5	91	17.1	103	3.1	−12	$(A_n + A_s)/2$	Matsushita and Maeda
		58.2	93	18.8	99	3.2	−06	$(Y_n + Y_s)/2$	Matsushita and Maeda
2	2	51.3	77	27.0	83	1.9	−06	$(\Delta_n + \Delta_s)/2$	*Chapman* [1919]
		25.3	46	10.6	44	2.4	02	$(\Delta_n + \Delta_s)/2$	Matsushita and Maeda
		25.3	46	11.6	52	2.4	−06	$(Y_n - Y_s)/2$	Matsushita and Maeda

* S, W, and E indicate summer, winter, and equinoxes, respectively; the subscript n stands for northern hemisphere, and s stands for southern hemisphere. The yearly average, Y, is $(S + E + W)/3$; the average of summer and winter, A, is $(S + W)/2$; and the mean difference between summer and winter, Δ, is $(S - W)/2$.

† van Bemmelen's and Chapman's values in this table were obtained by calculation of their results in a different form.

for the minimum period, 1902. The intensity of the S_q field during the IGY (an extremely active period) is about 1.8 times that during the Second Polar Year (minimum period) [*Matsushita and Maeda,* 1965]. Neither 1.4 nor 1.8 is a very large number. Accordingly, we need to examine the possibility that the L field may also show this small solar activity dependence, since the L field behaves similarly to the S_q field for seasonal variations, contrary to the conclusion reached by

TABLE 7. Amplitude Ratios of Lunar Semidiurnal Variations for the Solar Activity Maximum and Minimum Periods

Station	H Component	Declination	Z Component	Reported by
Sitka	0.9	1.5	1.9	*Cain* [1957]
	1.8 (E)	1.5 (E)		*Matsushita* [1964]
Cheltenham		1.5 (E)		*Matsushita* [1964]
Greenwich	1.1			*Chapman* [1957]
	1.4 (E)			*Chapman* [1957]
		1.2		*Chapman and Bartels* [1940]
		1.2 (E)		*Chapman and Bartels* [1940]
Tucson	1.3 (E)	1.5 (E)	1.7 (E)	*Matsushita* [1962*a*]
San Fernando	1.2	1.0		*Wilkes* [1962]
San Juan	1.3 (E)	1.3 (E)	1.0 (E)	*Matsushita* [1962*a*]
Kakioka		1.6		*Yamaguchi* [1958]
Honolulu	1.8 (E)	1.1 (E)		*Matsushita* [1964]
Huancayo	1.5 (E)			*Bartels and Johnston* [1940]
	1.3 (E)	1.4 (E)		*Matsushita* [1964]
Hermanus		1.4 (E)		*van Wijk and Bergh* [1963]
Average	1.4	1.4	1.5	

Numbers with (E) indicate the values obtained for equinoctial months. Other numbers are for the yearly mean. Average values at the bottom are obtained from both equinoctial and yearly values.

Chapman and Bartels. In fact, there are some results that support this possibility, as are shown in Table 7, although detailed studies are required to establish the result. If this relation is correct, the external L current may flow in the same zone as the external S_q current; *Martyn*'s [1947] suggestion of different zones for the S_q and L currents based on Chapman and Bartels' conclusion needs to be reexamined.

An approximate ratio of the intensities between the average external S_q and L currents is 30:1, and both current systems seem to be caused by dynamo action in the ionospheric E region. One remaining question concerns the effects of geomagnetic disturbances on lunar variations, such as an apparent enhancement of the amplitude during these disturbances. These phenomena, probably caused by an increase of electric conductivity, require detailed statistical studies and physical interpretation.

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References

Bartels, J., Aufschlüsse über die Ionosphäre aus der Analyse sonnen- und mondentägiger erdmagnetischer Schwankungen, *Z. Geophysik, 12,* 368–378, 1936.

Bartels, J., and H. F. Johnston, Geomagnetic tides in horizontal intensity at Huancayo, 1 and 2, *Terrest. Magnetism Atmospheric Elec., 45,* 269–308, 485–512, 1940.

Bossolasco, M., and J. Egedal, Our knowledge of the lunar-diurnal variation of the magnetic declination and new results obtained from observations at Mogadiscio, *Terrest. Magnetism Atmospheric Elec., 42,* 123–126, 1937.

Bullen, J. M., and C. H. Cummack, The lunar diurnal variation of the earth's magnetic field for all elements at Amberley, New Zealand, *J. Geophys. Res., 58,* 554–556, 1953.

Cain, J. C., An analysis of the solar and lunisolar daily variations in the geomagnetic field at Sitka, Alaska, 1902–1952, *Rept. Geophys. Inst., Univ. Alaska, AFCRC TR,* pp. 57–272, 1957.

Chapman, S., On the diurnal variations of the earth's magnetism produced by the moon and sun, *Phil. Trans. Roy. Soc. London, A, 213,* 279–321, 1913.

Chapman, S., On the lunar variation of the earth's magnetism at Pavlovsk and Pola, 1897–1903, *Phil. Trans. Roy. Soc. London, A. 214,* 295–317, 1914*a*.

Chapman, S., The moon's influence on the earth's magnetism, *Terrest. Magnetism Atmospheric Elec., 19,* 39–44, 19614*b*.

Chapman, S., On the influence of lunar declination on the lunar diurnal variation of magnetic declination at Zikawei, *Terrest. Magnetism Atmospheric Elec., 22,* 121–124, 1917.

Chapman, S., The solar and lunar diurnal variations of terrestrial magnetism, *Phil. Trans. Roy. Soc. London, A, 218,* 1–118, 1919.

Chapman, S., The lunar and solar daily variations of the horizontal geomagnetic vector at Greenwich, 1848–1913, with an appendix on the lunar daily variation of magnetic declination at Pavlovsk and Sitka, *Abhandl. Akad. Wiss. Göttingen, Math. Physik. Kl.*, Sonderheft Nr. 3, Göttingen, 1957.

Chapman, S., and J. Bartels, *Geomagnetism*, Clarendon Press, Oxford, 1940.

Duclaux, F., and M. R. Will, Premiers résultats sur la variation diurne lunaire de la composante horizontale du champ magnétique terrestre à Tamanrasset, *Compt. Rend.*, *247*, 1220–1222, 1958.

Egedal, J., The lunar-diurnal magnetic variation and its relation to the solar-diurnal variation, *Terrest. Magnetism Atmospheric Elec.*, *31*, 193–199, 1926.

Egedal, J., The lunar-diurnal magnetic variation and its relation to the solar-diurnal variation, *Terrest. Magnetism Atmospheric Elec.*, *32*, 139–141, 1927.

Egedal, J., The lunar-diurnal variation of the magnetic declination in Rude Skov 1908–1951, *Publ. Danske Meteorol. Inst., Commun. Magnét.*, *21*, 1953.

Egedal, J., On the computation of lunar daily variations in geomagnetism. Two simple methods, *Publ. Danske Meteorol. Inst.*, *22*, 1956*a*.

Egedal, J., The lunar-diurnal magnetic variation and its relation to the solar-diurnal variation, *J. Geophys. Res.*, *61*, 748–749, 1956*b*.

Egedal, J., and M. Bossolasco, The lunar diurnal variation of the horizontal and vertical magnetic forces at the Polar Year station Mogadiscio, *Terrest. Magnetism Atmospheric Elec.*, *46*, 59–60, 1941.

Fatkullin, M. N., Lunar-diurnal magnetic field variations according to observations at the Kazan' observatory, *Geomag. Aeronomy*, *2*, 623–625, 1962.

Gouin, P., Preliminary determination of the lunar diurnal influence on the geomagnetic components *H*, *D*, and *Z* at Addis Ababa, *Bull. Geophys. Obs., Univ. Coll. Addis Ababa*, *2*, 1–8, 1960.

Kreil, K., Einfluss des Mondes auf die magnetische Deklination, *Denkschr. Akad. Wiss. Wien, Math.-Naturw. Kl.*, *3*, 1–47, 1850.

Martyn, D. F., Atmospheric tides in the ionosphere, 2, Lunar tidal variations in the *F* region near the magnetic equator, *Proc. Roy. Soc. London, A*, *190*, 273–288, 1947.

Matsushita, S., Lunar variations of geomagnetic fields, *Geomagnetica*, Publicação Comemorativa do 50° Aniversário do Observatório Magnético de S. Miguel, Açores, pp. 209–215, 1962*a*.

Matsushita, S., Lunar tidal variations of sporadic *E*, *Ionospheric Sporadic E*, edited by E. K. Smith and S. Matsushita, Pergamon Press, Oxford, pp. 194–214, 1962*b*.

Matsushita, S., Lunar tides in the ionosphere, *Encyclopedia of Physics (Handbuch der Physik)*, *49/1*, Springer-Verlag, Heidelberg, 1964.

Matsushita, S., and H. Maeda, On the geomagnetic solar quiet daily variation field during the IGY, *J. Geophys. Res.*, *70*(11), 1965.

Onwumechilli, C. A., Lunar daily variation of the magnetic declination at Ibadan, Nigeria, *J. Geophys. Res.*, *65*, 3433–3435, 1960.

Onwumechilli, C. A., and N. S. Alexander, Variations in the geomagnetic field at Ibadan, Nigeria, 2, Lunar and lunisolar variations in *H* and *Z*, *J. Atmospheric Terrest. Phys.*, *16*, 115–123, 1959.

Raja Rao, K. S., Lunar daily variation of geomagnetic horizontal intensity at Alibag, *J. Geophys. Res.*, *65*, 119–121, 1960.

Raja Rao, K. S., On the seasonal variation in lunar and solar geomagnetic tides in the geomagnetic equatorial region, *J. Atmospheric Terrest. Phys.*, *20*, 289–294, 1961.

Raja Rao, K. S., Lunar geomagnetic tides in the low latitudes region, *Indian J. Meteorol. Geophys.*, *13*, 97–105, 1962.

Raja Rao, K. S., and K. R. Sivaraman, Lunar geomagnetic tides at Kodaikanal, *J. Geophys. Res.*, *63*, 727–730, 1958.

Rougerie, P., l'Évolution diurne lunaire de la déclinaison magnétique au Val-Joyeux, Transactions of the Oslo Meeting, 1948, *I.A.T.M.E. Bull. 13*, 459–463, 1950.

Sabine, E., On the influence of the moon on the magnetic declination at Toronto, St. Helena, and Hobarton, *Phil. Trans. Roy. Soc. London, A*, *143*, 549–560, 1853.

Sabine, E., On the lunar diurnal variation at Toronto, *Phil. Trans. Roy. Soc. London, A*, *146*, 499–506, 1856.

Schmidt, A., *Tafeln der normierten Kugelfunktionen*, Engelhard-Reyher Verlag, Gotha, 1935.

Schneider, O., Einflüsse der Sonne auf die lunare Variation des Erdmagnetismus, *Veroeffentl. Meteorol. Inst. Univ. Berlin*, *1*(3), 1936.

Schuster, A., The diurnal variation of terrestrial magnetism, *Phil. Trans. Roy. Soc. London, A*, *180*, 467–518, 1889.

van Bemmelen, W., Die lunare Variation des Erdmagnetismus, *Meteorol. Z.*, *29*, 218–225, 1912.

van Bemmelen, W., Berichtigung zu meiner Abhandlung über die lunare Variation des Erdmagnetismus, *Meteorol. Z.*, *30*, 589–594, 1913.

van Wijk, A. M., and H. W. Bergh, Preliminary investigation into the lunar semidiurnal variation in the magnetic elements at Cape Town and Hermanus, *J. Geophys. Res.*, *68*, 2061–2062, 1963.

Wilkes, M. V., The solar and lunisolar harmonic components of geomagnetic variation at San Fernando, *J. Atmospheric Terrest. Phys.*, *24*, 73–92, 1962.

Yamaguchi, Y., The lunar diurnal variation of the magnetic declination at Kakioka, *Mem. Kakioka Magnetic Obs.*, *8*, 13–25, 1957.

Yamaguchi, Y., Note on the average lunar diurnal variation at Kakioka, *Mem. Kakioka Magnetic Obs.*, *8*, 41–46, 1958.

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