Solar Activity Dependence on Lunar Daily Variations of the Ionospheric Total Electron Content Near the Equatorial Anomaly Crest

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ABSTRACT

Solar activity dependence on the lunar daily variations of ionospheric total electron content at the equatorial anomaly crest region was studied using the Chapman-Miller method by use of the total electron content data observed at Lunping from March 4, 1977 to December 31, 1989. The result shows that the amplitudes of lunar daily variations increase with increasing sunspot numbers but become saturated when the sunspot number becomes larger than about 100.

1. INTRODUCTION

The subject of the present study is an analysis of solar activity dependence on the lunar daily variations of ionospheric total electron content observed at Lunping (geographic coordinates: $25.00^{\circ}N$, $121.17^{\circ}E$; geomagnetic coordinates: $13.8^{\circ}N$, $189.5^{\circ}E$). The total electron content data was reduced from the observed Faraday rotation angle of a VHF radio beacon signal transmitted from a geostationary satellite using a formula proposed by Titheridge (1972):

$$I_F = \Omega / K M_F \tag{1}$$

where $k = 2.36\ X\ 10^4/f^2$ in mks units, Ω is the observed Faraday rotation angle, M_F is the Faraday factor determined at a fixed height of 420 km above the subionospheric point, I_F is the total electron content integrated up to an altitude of 2000 km and f represents the frequency of the beacon signal in Hz.

The lunar daily variation L of any geophysical parameter can be expressed by the following formula (Chapman and Bartels, 1940):

$$L = \sum_{n=1}^{\infty} l_n \sin\left[t(n-2) + 2\tau + \lambda_n\right] \tag{2}$$

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where the subscript n represents the nth harmonic component; l_n and λ_n represent the amplitude and phase angle of the nth component for the lunar daily variation, t represents the solar time in hours, increasing from 00 to 24 between one local midnight to the next, and τ represents the lunar time in hours, increasing from 00 to 24 from one local lower transit of the moon to the next. t and τ are related by

$$\nu = t - \tau \tag{3}$$

where ν is the phase of the moon measured by the hour angle between the sun and the moon increasing from 00 at one new moon to 24 at the next. In terms of ν, (2) can be rewritten as

$$L = \sum_{n=1}^{\infty} l_n \sin(nt - 2\nu + \lambda_n) \tag{4}$$

The most important component of the lunar daily variation has a period of half a lunar day and is expressible as

$$L_2 = l_2 \sin(2\tau + \lambda_n) \tag{5}$$

Besides L_2, which is a purely lunar daily variation, L has a part $(L - L_2)$ which is dependent on both lunar and solar time and is called the lunisolar component.

In the present report, the Chapman-Miller method (Chapman and Miller, 1940; Malin and Chapman, 1970) was used to determine the harmonic components and the respective probable errors for solar and lunar daily variations up to $n = 4$. The total electron content (TEC) data observed at Lunping from March 4, 1977 to December 1989, by measuring the Faraday rotation angle of the 136.1124 MHz beacon signal transmitted from the Japanese ETS-II geostationary satellite were used for analysis. The subionospheric point of ETS-II observed at Lunping is located at 23.0°N, 121.9°E geographic coordinates, which is near to the crest zone of the so-called equatorial anomaly.

2. SOLAR ACTIVITY DEPENDENCE OF LUNAR DAILY VARIATIONS

Lunar daily variations of the ionospheric parameters, such as $f_0\ F_2$, $h'\ F_2$, hmax F_2, $h_p\ F_2$, $f_0\ E_s$, and $h'\ E_s$, have been studied by many workers (e.g., Rastogi and Alurkar, 1964, Matsushita, 1967, and references therein). However, the lunar daily variation of total electron content has been studied only by a few (Rao and Stubenrauch, 1967; Bernhardt *et al.*, 1976; Huang, 1978). The present study is an extension of a previous work (Huang, 1978; 1979) in order to further investigate the solar activity dependence of the lunar daily variations of total electron content.

In order to see the solar activity dependence of lunar daily variations, the whole of the TEC data was divided into five groups that have different mean sunspot numbers, R, as shown in Table 1. For each group, the lunar harmonic components were determined as given in Table 2. The letters l_n, e_n, and λ_n represent respectively the amplitude, probable error, and phase angle of the nth harmonic component of the lunar daily variation of TEC.

The amplitude l_n can be considered to be statistically significant at the 5% level if it is larger than 2.08 times the probable error (Leaton *et al.*, 1962). The statistically insignificant values are in parenthesis. It can be seen from Table 2 that the lunar components determined for each group are all significant except L_3 for group 5 and L_4 for group 2, 3, 4 and 5.

Figures 1 and 2 show the variations of amplitude l_n and phase λ_n, respectively, for each harmonic component with respect to the sunspot number. The regression lines were determined by assuming

$$l_n = m_n(L)R + c_n(L) \qquad n = 1,2,3,4 \tag{6}$$

for amplitude variation and

$$\lambda_n = m'_n(L)R + c'_n(L) \qquad n = 1,2,3,4 \tag{7}$$

for phase variation. The coefficients $m_n(L)$, $c_n(L)$, $m'_n(L)$ and $c'_n(L)$ together with correlation coefficients $\rho(L)$ and $\rho'(L)$ for amplitude and phase respectively are given in Table 3.

The regression lines for phase variations all show a slight increase with increasing sunspot numbers except for the component L_2. The present result is similar to the previous work (Huang, 1979). As for the amplitude variations, it can be seen that only the component L_2 shows a relatively good positive correlation with sunspot numbers; the others all show poor correlations and even a negative correlation for the component L_3. This result is quite different from that obtained in the previous result (Huang, 1979) which shows that the amplitude of each harmonic component increases with increasing solar activity, showing a good positive correlation ($\rho > 0.764$) between amplitude and sunspot number. It is also worthy of note that the slope of the regression line, which measures the sensitivity of the amplitude variation to the solar activity, is larger for L_2 compared to L_1. This result is also quite different from that obtained in the previous work (Huang, 1979) which shows that the slope of the regression line increases from L_4 to L_1.

With a detailed investigation of Figure 1, it can be observed that the amplitudes of L_1, L_2 and L_3 suddenly decrease or cease to increase with increasing sunspot numbers as the sunspot number becomes larger than 100. Unusual increases of phase variations for L_1, L_2 and L_3 when the sunspot number becomes

Table 1

Group 1 SUNSPOT NUMBER R < 40

1977/3 ⟶ 1977/9

1984/8 ⟶ 1987/9

Mean Sunspot Number = 21.5

Group 2 SUNSPOT NUMBER 40 ≤ R < 80

1977/10 ⟶ 1978/4

1983/50 ⟶ 1984/7

1987/10 ⟶ 1988/4

Mean Sunspot Number = 60.1

Group 3 SUNSPOT NUMBER 80 ≤ R < 120

1978/5 ⟶ 1978/12

1982/5 ⟶ 1983/40

1988/5 ⟶ 1988/80

Mean Sunspot Number = 100.8

Group 4 SUNSPOT NUMBER 120 ≤ R < 160

1979/1 ⟶ 1979/10

1980/4 ⟶ 1982/40

1988/9 ⟶ 1989/40

Mean Sunspot Number = 142.9

Group 5 SUNSPOT NUMBER R ≥ 160

1979/11 ⟶ 1980/30

1989/50 ⟶ 1989/12

Mean Sunspot Number = 172.0

Table 2. Lunar Harmonic Component of TEC

Group	NUMBER OF DAYS	l_1	e_1	λ_1	l_2	e_2	λ_2	l_3	e_3	λ_3	l_4	e_4	λ_4	MEAN SUNSPOT NUMBER
1	1156	124	18	315	98	8	102	45	5	267	15	3	77	21.5
2	721	142	30	326	132	16	108	55	10	275	(4)	6	135	60.1
3	605	286	45	316	254	25	91	66	11	262	(18)	11	35	100.8
4	966	178	48	309	226	21	93	48	12	269	(11)	8	94	142.9
5	264	156	71	348	232	48	104	(33)	30	307	(19)	21	129	172.0

Amplitude in 10^{14} *electron*/m^2 and phase angle in degrees.

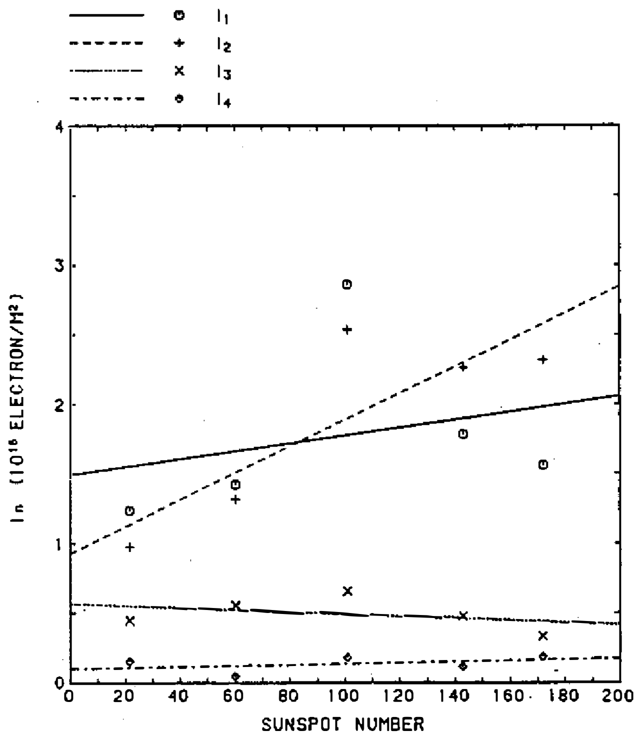
I1
I2
I3
I4
In (10^16 ELECTRON/M^2)
SUNSPOT NUMBER
0
1
2
3
4
0 20 40 60 80 100 120 140 160 180 200

Fig. 1

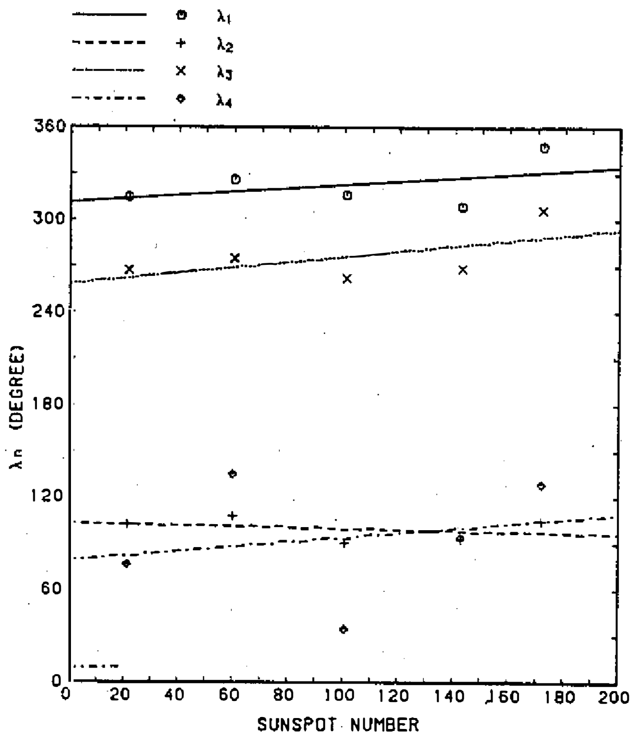
λ1
λ2
λ3
λ4
λn (DEGREE)
SUNSPOT NUMBER
0
60
120
180
240
300
360
0 20 40 60 80 100 120 140 160 180 200

Fig. 2

Table 3. Correlation Coefficients and Coefficient of the Regression Lines for the Lunar Harmonic Components

n	1	2	3	4
$m(L)$	0.28	0.96	−0.08	0.04
$c(L)$	148.88	93.00	56.80	10.02
$\rho(L)$	0.269	0.845	−0.377	0.374
$m'(L)$	0.1154	−0.0353	0.1781	0.1485
$c'(L)$	311.4	103.2	258.1	79.0
$\rho'(L)$	0.457	−0.296	0.607	0.220

The units of m and c are in 10^{14} *electron/m^2/sunspot* number and 10^{14} *electron/m^2*, respectively. The units of m' and c' are in *degree/sunspot* number and degree, respectively.

larger than 100 can also be seen in Figure 2. These are the major differences observed in the present study as compared to the previous one (Huang, 1979). The fact that both amplitude and phase of L_1, L_2 and L_3 change their tendency of variations with respect to sunspot number when the sunspot number becomes larger than 100 may be due to the saturation effect of the F_2 layer when sunspot numbers become larger than a certain value (Huang, 1963;1975).

3. CONCLUSIONS

The solar activity dependence on the lunar daily variations of the ionospheric total electron content observed at Lunping have been analyzed using the Chapman-Miller method. The hourly total electron content data for the period between March 4, 1977 to December 1989 have been used for the analysis. The results were tabulated, discussed and compared with a previous work (Huang, 1979) in which only the data obtained from March 4, 1977 to December 31, 1978 when the sunspot number, R, was less than 110 was used.

Following are the major findings of the present study.

(1) Unlike the previous work (Huang, 1979) for low sunspot activity ($R <$ 110) that shows that the amplitudes of all harmonic components increased linearly with increasing solar activity, the present results, which includes high solar activity, show that only the component L_2 indicates a relatively good positive correlation with sunspot numbers while the others all show poor correlations.

(2) The sensitivity of the amplitude variation of component L_2 to the sunspot is larger than that of component L_1. This is also quite different from the previous results that show that the sensitivity increases in order from components L_4 to L_1.

(3) The amplitudes of components L_1, L_2 and L_3 suddenly decrease or cease to increase with respect to sunspot number when the sunspot number becomes larger than 100. Similaly a sudden change of phase variation with respect to sunspot number is also found. This seems due to the saturation effect of the maximum electron density of the F_2 layer (Huang, 1963) and total electron content of the ionosphere (Huang, 1975) when the sunspot number becomes larger than a certain value. Further study seems worthwhile.

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赤道異常頂峰地區附近之電離層全電子含量之太陰日變化對太陽活動性之依賴性

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摘要

本文使用1973年3月4日起至1989年12月31日止，在崙坪觀測台所觀測到之電離層全電子含量之每小時觀測數據，用Chapman-Miller法分析電離層全電子含量之太陰日變化成分之太陽週期變化。結果發現太陽黑子數少時，太陰日變化成分與太陽黑子數俱增，但黑子數增加到超過約100時，太陰日變化成分即呈現飽和現象。