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# Modulation of Geomagnetic Lunar Daily Variation in *H* at Alibag with Lunar Distance

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*Summary*

The dependence of geomagnetic lunar daily variation ($L$) on lunar distance in different seasons and for varied epochs of solar activity is investigated using the long series of horizontal intensity observations at Alibag. The close agreement of the observed ratio of $L$ when the moon is at perigee to that when it is at apogee during different seasons and for the total period to that expected from gravitational tide theory clearly indicates that the direct effect of the moon on the upper atmosphere is primarily gravitational and also suggests that the amplitudes ratio $N_2 : M_2$ in all seasons departs insignificantly from that expected from tidal theory. A systematic increase of the ratio of $L$ at lunar perigee to apogee with change in phase of solar cycle implies that $N_2 : M_2$ has a measure of dependence on solar activity. Ionospheric and oceanic parts of $L$ are poorly determined and no definite cause for their behaviour could be given.

## Introduction

The observed geomagnetic lunar daily variations are the consequence of the currents in the ionosphere and ocean due to tidal movement of conducting layers of the ionosphere and the ocean, under the gravitational attraction of the Moon, across the main magnetic field of the Earth. The variation in $L$ at a station will thus depend upon the magnitude of the tidal oscillation and the electrical state of ionospheric and oceanic layers. The variation in the electrical conductivity with season as well as with solar and magnetic activity is primarily responsible for seasonal and solar cycle variations in $L$ and this fact has received considerable attention (Chapman, Gupta & Malin 1971; Gupta & Malin 1972). According to the gravitational equilibrium tide theory, the tide producing force of the Moon varies inversely as the cube of distance of the Moon from the Earth. An estimate of $L$ as a function of lunar distance enables one to test whether $L$ effects are in direct proportion to the gravitational pull of the moon or not. Considering the eccentricity of the Moon's orbit and assuming the linear dependence of $L$ on gravitational pull, one may expect the amplitude of $L$ to vary in the ratio of 100 : 139 as the Moon moves from apogee to perigee. Chapman (1957) and Leaton, Malin & Finch (1962), using data of Greenwich and Abinger, showed that the observed ratio is in good agreement with the expected value. The lunar magnetic variations from coastal observatories are found to have a significantly large part due to the oceanic dynamo. Malin (1970) has proposed a method for the separation of $L$ into parts of oceanic and ionospheric origin. Gupta

(1974) successfully applied Malin's method to Abinger and Batavia data to separate $L$ into oceanic and ionospheric parts and showed that the observed increase of both components from apogee to perigee is close to what one would expect from theory. In this communication, the modulation of lunar daily variation and its components with lunar distance for different seasons and varied epochs of solar activity is investigated using the long series of horizontal intensity observations at Alibag.

## Treatment of data

The data used in the analysis are the absolute hourly values of horizontal intensity, $H$, at Alibag for the period 1927–1970. Following Leaton *et al.* (1962), each day has been coded according to lunar distance as follows:

1, for every day whose date is that of the mean Moon's apogee and three adjacent days on either side; 3, for every day whose date is that of the mean Moon's perigee and three adjacent days on either side; 2, for the remaining days when the Moon is approaching perigee; 4, for the remaining days when the Moon is receding from perigee. The group of days with codes 1–4 form the lunar distance groups Apogee, Nearing, Perigee and Receding respectively. To study the variation of $L$ with varying lunar distance for different conditions of ionospheric conductivity, the data have been divided into:

(1) Three seasons; Winter, Equinox and Summer.

(2) Four phases of solar activity, Quiet, Low, Medium and High, with mean annual sunspot numbers in the ranges 0–25, 26–50, 51–100 and > 100, respectively.

(3) Entire period of 44 years.

**Table 1**

*$L_2$, $R(L)$ and ratio of $R(L)$ at Perigee to Apogee during different seasons and entire periods [$L_2$, $R(L)$ and pe in units of $0 \cdot 01\ \gamma$ and $\lambda_2$ in degrees]*

| | Lunar distance group | No. of days | $L_2$ | pe | $\lambda_2$ | Lunar-range $R(L)$ | pe | Ratio of $R(L)$ at perigee to apogee |
|---|---|---|---|---|---|---|---|---|
| | 1 | 4070 | 72 | 10 | 161 | 334 | 21 | |
| | 2 | 3958 | 68 | 11 | 182 | 322 | 22 | |
| Entire period | 3 | 4067 | 91 | 11 | 165 | 442 | 29 | $1 \cdot 32 \pm 0 \cdot 12$ |
| | 4 | 3919 | 78 | 11 | 145 | 392 | 26 | |
| | 5 | 7877 | 70 | 9 | 162 | 348 | 18 | |
| | 1 | 1354 | 127 | 15 | 160 | 636 | 34 | |
| | 2 | 1329 | 150 | 16 | 180 | 638 | 33 | |
| Winter | 3 | 1372 | 169 | 14 | 177 | 914 | 41 | $1 \cdot 44 \pm 0 \cdot 10$ |
| | 4 | 1298 | 119 | 16 | 152 | 672 | 46 | |
| | 5 | 2627 | 131 | 11 | 167 | 634 | 28 | |
| | 1 | 1357 | 49 | 13 | 148 | 244 | 32 | |
| | 2 | 1323 | 15 | 24 | 173 | 174 | 50 | |
| Equinox | 3 | 1346 | 69 | 16 | 141 | 340 | 34 | $1 \cdot 39 \pm 0 \cdot 23$ |
| | 4 | 1326 | 77 | 21 | 121 | 483 | 54 | |
| | 5 | 2649 | 43 | 16 | 127 | 312 | 33 | |
| | 1 | 1359 | 47 | 17 | 187 | 402 | 41 | |
| | 2 | 1306 | 40 | 18 | 189 | 264 | 33 | |
| Summer | 3 | 1349 | 48 | 29 | 145 | 264 | 62 | $0 \cdot 66 \pm 0 \cdot 17$ |
| | 4 | 1295 | 44 | 12 | 174 | 188 | 30 | |
| | 5 | 2601 | 42 | 12 | 181 | 200 | 24 | |

Days in each of the above divisions are further subdivided according to lunar distance and are analysed to obtain the first four harmonics of the well-known Chapman phase law tide and the partial tide of Schneider (1963), following the numerical procedure given by Winch (1970a). The vector probable errors for the harmonics are also calculated. Since the mean lunar distances for coded groups 2 and 4 are the same, the data of these groups are combined and the analysis is repeated. The results of the analysis are given under the lunar distance code 5. The amplitudes are considered statistically significant if they exceed 2·08 times the corresponding probable errors.

The lunar range, $R(L)$, for all the above mentioned groups are computed using the relation (Chapman *et al.* 1971):

$$R(L) = 2 \sum_{n=1}^{4} L_n.$$

Where $L_n$ is the amplitude of $n$th harmonic of phase law tide. The probable error of the range is computed by

$$= 1{\cdot}146 \left( \sum_{n=1}^{4} \rho_n^{\,2} \right)^{\frac{1}{2}}.$$

Where $\rho_n$ represents the probable error associated with the amplitude of the individual harmonic. The change in lunar daily variation with lunar distance is measured by the ratio of ranges at Perigee to Apogee. The probable error associated with this ratio is given by

$$= \frac{[\rho^2_{(\text{Perigee})} + \text{Ratio}^2 \times \rho^2_{(\text{Apogee})}]^{\frac{1}{2}}}{\text{Range}_{(\text{Apogee})}}.$$

$L_2$, the principal component of the $M_2$ tide, ranges, ratio of range at perigee to

**Table 2**

*$L_2$, $R(L)$ and ratio of $R(L)$ at perigee to that at apogee during different epochs of solar activity [$L_2$, $R(L)$ and pe in units of 0·01 $\gamma$ and $\lambda_2$ in degrees]*

| Solar activity group | Lunar distance group | No. of days | $L_2$ | pe | $\lambda_2$ | Lunar-range $R(L)$ | pe | Ratio of $R(L)$ at perigee to apogee |
|---|---|---|---|---|---|---|---|---|
| | 1 | 926 | 55 | 15 | 166 | 334 | 36 | |
| | 2 | 905 | 44 | 18 | 193 | 376 | 34 | |
| Quiet | 3 | 918 | 70 | 17 | 168 | 350 | 32 | 1·02±0·14 |
| | 4 | 888 | 82 | 14 | 156 | 508 | 36 | |
| | 5 | 1793 | 60 | 11 | 169 | 426 | 19 | |
| | 1 | 923 | 68 | 17 | 145 | 410 | 48 | |
| | 2 | 899 | 60 | 14 | 172 | 260 | 49 | |
| Low | 3 | 926 | 79 | 23 | 164 | 490 | 53 | 1·20±0·19 |
| | 4 | 886 | 71 | 18 | 154 | 342 | 44 | |
| | 5 | 1785 | 64 | 12 | 162 | 276 | 38 | |
| | 1 | 1011 | 108 | 26 | 162 | 458 | 48 | |
| | 2 | 980 | 54 | 25 | 226 | 244 | 49 | |
| Medium | 3 | 1023 | 148 | 19 | 164 | 680 | 63 | 1·48±0·21 |
| | 4 | 992 | 60 | 19 | 141 | 404 | 50 | |
| | 5 | 1792 | 43 | 16 | 180 | 274 | 36 | |
| | 1 | 1210 | 56 | 16 | 164 | 330 | 40 | |
| | 2 | 1174 | 118 | 19 | 169 | 686 | 36 | |
| High | 3 | 1200 | 68 | 28 | 162 | 508 | 70 | 1·54±0·28 |
| | 4 | 1153 | 100 | 26 | 136 | 462 | 63 | |
| | 5 | 2327 | 105 | 18 | 154 | 464 | 37 | |

that at apogee and other associated parameters for all the groups of lunar distance in different seasons and for the entire period are given in Table 1. Similar results for each of the solar activity divisions are presented in Table 2. As three days on either side of apogee or perigee are considered to represent the appropriate lunar distance group, the theoretically expected ratio of the magnitude of $L$ at perigee to that at apogee will reduce from 1·39 to 1·29.

## Results and discussion

*(a) Variation of L with lunar distance during different seasons*

While most of the phase-law terms are found to be well determined, the partial terms lack significance in many cases. Many of the amplitudes of phase law and partial terms exhibit in general an increase from Apogee to Perigee. During summer, both $L_1$ and $L_2$ are poorly determined at Perigee and hence their inclusion in the determination of range, $R(L)$, renders the change, observed from Apogee to Perigee, unreliable. The principal term of lunar daily variation, $L_2$, shows an increase of 33, 41 and 26 per cent from Apogee to Perigee during Winter, Equinoxes and Year respectively. Similar change in ranges from Apogee to Perigee can be noticed from the results in Table 1. Ratio of the range at Perigee to that at Apogee during the year and in different seasons are close to the theoretically expected value of 1·29. From the analysis of the observations at high latitude stations, Chapman (1957) and Leaton *et al.* (1962) found the phase angle of second harmonic ($\lambda_2$) to be smaller by 11° to 15° when the Moon was at Apogee than when the Moon was at Perigee. However, such a trend in $\lambda_2$ at Alibag, a low-latitude station, is observed only during winter. The reverse trend in $\lambda_2$ observed during summer may not be important because of the large probable error associated with its amplitude at Perigee. Another feature of interest which emerges from examination of the results is that neither the amplitudes of the first two harmonics of phase law tide nor the range for the groups 2 and 4 are equal to each other and, in many cases, their magnitudes are not of the order as would be expected by theory. The expected values for these groups should lie between the values for the groups 1 and 3. There are also marked differences between the phase angles of $L_2$ obtained for groups 2 and 4 and they also differ appreciably from the value for groups 1 and 3. Leaton *et al.* (1962) observed similar differences in the phase angles of $L_2$ for groups 2 and 4 at Greenwich and Abinger. They explained these in terms of the differences in the hour angle of true moon and mean moon. When phase angles are corrected for this effect, differences are found to be small and are not systematic. Results obtained here are thus in conformity with the findings of Leaton *et al.* (1962). In group 5, where days are symmetrically combined about the lines of apsides, the phase angle of $L_2$ is close to the values for groups 1 and 3 which further confirms that differences in the values of $\lambda_2$ for groups 2 and 4 arise from the non-coincidence of mean moon and true moon positions over these parts of Moon's orbit. The ranges for groups 1, 5 and 3 are in the ratios of 100 : 128 : 139 and 100 : 104 : 132 during Equinoxes and Year respectively which are in fair agreement with the expected ratios of 100 : 115 : 129. The absence of such systematic changes during summer and winter may be due to the contamination of $L(M_2)$ terms by lunar declinational tide, $L(O_1)$, which contributes substantially but spuriously to $L(M_2)$ tide during these seasons (Winch 1970b).

*(b) Variation of L with lunar distance during different epochs of solar activity*

It is interesting to note that $L_2$ is well determined for all the divisions listed in Table 2 and its amplitude generally increases with increasing sunspot number. The general increase of $L$ with sunspot number at Alibag has been reported earlier (Rao 1972). The tendency for $L_1$ and $L_2$ to increase from Apogee to Perigee is clearly seen in different phases of solar activity but in many cases the amplitudes are not largest at Perigee. The phase angle of $L_2$ is nearly the same for groups 1, 5 and 3, but it differs appreciably between the groups 2 and 4, which was also observed in the seasonal subdivisions. A marked increase in the amplitudes of the first two harmonics of the lunar partial terms with diminishing lunar distance is seen, even though they are not significantly determined. It can be noticed from the results in Table 2 that the ratio of range at Perigee to that at Apogee increases with increasing activity.

The variation of $L_2$ with season and lunar distance can more effectively be represented in terms of the three geomagnetic tidal components with the frequencies of $M_2$, $O_1$ and $N_2$ (Malin, private communication). The frequency of $N_2$ being very close to $M_2$, it is liable to contribute significantly to $L_2$ and as a result of this $L_2$ determined for the Perigee group of days is really $L(M_2)+L(N_2)$ and at Apogee it is $L(M_2)-L(N_2)$ (Malin & Chapman 1970). The close agreement of the ratio of lunar range at Perigee to that at Apogee, in different seasons and for total period, with that expected from gravitational tide theory not only strengthens the belief that the direct effect of the Moon on the upper atmosphere is primarily gravitational, but also suggests that the observed amplitude ratio $N_2 : M_2$ departs insignificantly from that given by tidal theory, namely 0·191 : 1. No direct values of geomagnetic $L(N_2)$ tide for different seasons and for varied epochs of solar activity are available (as far as the authors are aware). However, Winch & Cunningham (1972), obtained $L(N_2)$ tide for Watheroo using 40 years data without any subdivision into seasons and solar activity. It is interesting to note from their Table 8 that the second harmonic of $M_2$ and $N_2$ are nearly in phase. It appears that at Alibag also $M_2$ and $N_2$ are in phase and their magnitudes are in the ratio as expected by the theory. The increase of the ratio of lunar range at perigee to that at apogee with increasing solar activity would, however, suggest that the ratio $N_2 : M_2$ depends on solar activity. But the absence of such a systematic increase with solar activity in the ratio of $L_2$ at perigee to $L_2$ at apogee would further warrant that the increase in the ratio of lunar range may not be due only to the dependence of the ratio $N_2 : M_2$ on solar activity but may arise from the contamination of $L_1$ by $L(O_1)$. A study of the solar cycle influence on $L(M_2)$, $L(N_2)$ and $L\ (O_1)$ tides will be essential to identify the reality of the increase of ratio

**Table 3**

*Oceanic and Ionospheric parts of lunar daily variation near Apogee and Perigee ($L_0$, $L_I$ and pe in units of 0·01 $\gamma$ and $\lambda_0$ and $\lambda_I$ in degrees)*

| Solar activity groups | Lunar distance group | Oceanic part | | | Ionospheric part | | | Ratio of amplitude at Perigee to Apogee for Oceanic part | | Ionospheric part | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $L_0$ | $\lambda_0$ | pe | $L_I$ | $\lambda_I$ | pe | ratio | pe | ratio | pe |
| Entire | Apogee (1) | 35 | 72 | 21 | **79** | 187 | 18 | | | | |
| period | Perigee (3) | 26 | 341 | 27 | **117** | 164 | 25 | 0·74 | 0·91 | 1·47 | 0·46 |
| Quiet | Apogee (1) | 58 | 79 | 34 | **78** | 214 | 31 | | | | |
| | Perigee (3) | 29 | 59 | 33 | **84** | 187 | 28 | 0·50 | 0·64 | 1·08 | 0·56 |
| Low | Apogee (1) | 63 | 24 | 46 | **114** | 173 | 42 | | | | |
| | Perigee (3) | 40 | 345 | 52 | **119** | 164 | 46 | 0·63 | 0·94 | 1·04 | 0·56 |
| Medium | Apogee (1) | 49 | 212 | 50 | 85 | 136 | 42 | | | | |
| | Perigee (3) | 36 | 264 | 58 | **158** | 151 | 55 | 0·73 | 1·40 | 1·86 | 1·12 |
| High | Apogee (1) | 73 | 72 | 39 | **94** | 215 | 35 | | | | |
| | Perigee (3) | 49 | 350 | 67 | 116 | 165 | 61 | 0·67 | 0·99 | 1·24 | 0·81 |

of lunar range at perigee to apogee with solar activity. Such an analysis for three geomagnetic elements $D$, $H$ and $Z$ at Alibag is in progress.

*(c) Variation of Ionospheric and Oceanic parts of L with lunar distance*

The ionospheric and oceanic parts of $L$ for different lunar distance groups for all the sets analysed in earlier sections are computed by the method of Malin (1970). In Table 3, results for Apogee and Perigee during four divisions of solar activity and for the entire period are presented. The oceanic terms are not well determined in any of the groups. In view of the large probable errors associated with the ratios of amplitude at Perigee to that at Apogee for oceanic and ionospheric terms, no definite cause for their behaviour can be given. However, the ratio for the ionospheric part obtained using data for the entire period is significantly determined and is close to the expected value.

## Conclusion

The observed changes in the lunar daily variation with varying lunar distance for the total period and in different seasons at a low latitude station are in fair agreement with those expected from gravitational tide theory indicating that the amplitudes of $L(N_2)$ and $L(M_2)$ bear the same ratio in all seasons. At the same time a systematic increase of the ratio of lunar range at Perigee to that at Apogee with increase in solar activity implies that the amplitude ratio $N_2 : M_2$ has a measure of dependence on solar activity. Inconsistencies observed for lunar distance group 'Nearing' and 'Receding' appear to be due to the differences in the hour angle of the true moon and the mean moon over those parts of Moon's orbit.

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