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Lunar tidal oscillations in horizontal magnetic intensity at Kodaikanal during periods of low and high sunspots

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ABSTRACT. The paper describes the lunar daily (L) variations at fixed lunar ages and the lunar monthly (M) variations at fixed solar hours in horizontal magnetic intensity (H) at Kodaikanal for the low sunspot period, Jan. 1951 to Dec. 1955; and for the high sunspot period Jan. 1956 to Dec. 1960. The lunar daily variations at any of the seasons or solar activity epochs are found to follow Chapman's phase law: $L=C_n \sin[n\tau+(n-2)\nu+\alpha_n]$. With the increase of solar activity the phase of L_2 wave remains constant for each of the seasons, but the amplitude increases during D- and E- months and slightly decreases during the J-months. The lunar semi-monthly (M_2) waves at fixed solar hours vary with the solar time in the same way as the electrojet current, *i.e.*, the amplitude starts increasing with sunrise, reaches a maximum near noon and decreases to a low value by sunset. The ratio of lunar semidiurnal (L_2) wave to the solar semi-diurnal (S_2) wave for any of the seasons decreases with solar activity. The amplitudes of L_2 or M_2 wave at Kodaikanal are much smaller than the corresponding values at Huancayo indicating the longitudinal variation in the lunar daytime effects in H along the magnetic equator. The lunar semi-monthly tides for the daytime hours are predominantly under the control of lunar time during the D-months and of lunar age during the J-months.

1. Introduction

The lunar tidal oscillations in the horizontal magnetic field (H) have been shown to be abnormally large at equatorial stations, *viz.*, Huancayo (Bartels 1936), Ibadan (Onwumechilli and Alexander 1959) and Kodaikanal (Raja Rao and Sivaraman 1958). It has been also shown that the latitudinal as well as the longitudinal variations of the amplitude of lunar tidal oscillations in the solar daily range of H at the equatorial stations is very similar to the corresponding variations of electrojet current itself, suggesting that lunar tides in the magnetic field at equatorial stations are closely associated with the electrojet current (Rastogi 1963, 1964, 1965). Recently lunar diurnal as well as lunar monthly variation in H at Huancayo have been described in detail for the low sunspot period 1951-55 and for the high sunspot period 1957-59 (Rastogi 1968 a, b). As the strength of electrojet currents at Indian zone is found to be much weaker than that in the American zone (Rastogi 1962, Maynard and Cahill 1965 a, b) it was thought desirable to compare lunar tidal oscillations in the magnetic field at equatorial stations in Indian zone with the results obtained for Huancayo. The recordings of the magnetic data at Kodaikanal on a regular basis have been done since 1951 and so, work was undertaken to compute lunar daily and lunar monthly oscillations in horizontal field H at Kodaikanal for two periods covering minimum sunspots and maximum sunspots, namely January 1951 to December 1955 and January 1956 to December 1960. The data utilised for these studies were taken from the yearly bulletins of the Kodaikanal Observatory. The symbols used in the present article are given in Appendix I.

From each of the hourly mean values of H, the corresponding monthly mean values are subtracted to get the deviations ΔH for each hour which are used for further analysis. Only the days having International Planetary Index C_p <1·2 have been considered in the present analysis to avoid the effect of magnetic disturbances contaminating the results of lunar oscillations. The lunar oscillations are computed in two ways, *viz.*, (1) $L(H)$ lunar tide in H with lunar time at fixed lunar ages ν and (2) the $M(H)$ lunar tide in H with lunar age ν at fixed solar times t.

In Fig. 1 are shown the mean deviations of H against lunar age and lunar time averaged for the entire period 1951—60 for Kodaikanl and these are compared with similar results obtained by Rastogi (1968 b) for Huancayo covering the period 1951—59. The diagram show the contours of constant deviations. For Kodaikanal these contours are drawn in steps of 1 γ, while for Huancayo in steps of 3 γ to avoid the concentration of contour lines. The solar night-time portion is indicated by shaded portion in the diagram. It is seen that the diagram for Kodaikanal is very similar to that for Huancayo, but the amplitudes at Kodaikanal are about one third in magnitude compared to that at Hauncayo. The contour lines are mostly confined within the solar daytime, indicating that the major deviation due to lunar tidal oscillations occur during the solar daytime hours. There are two

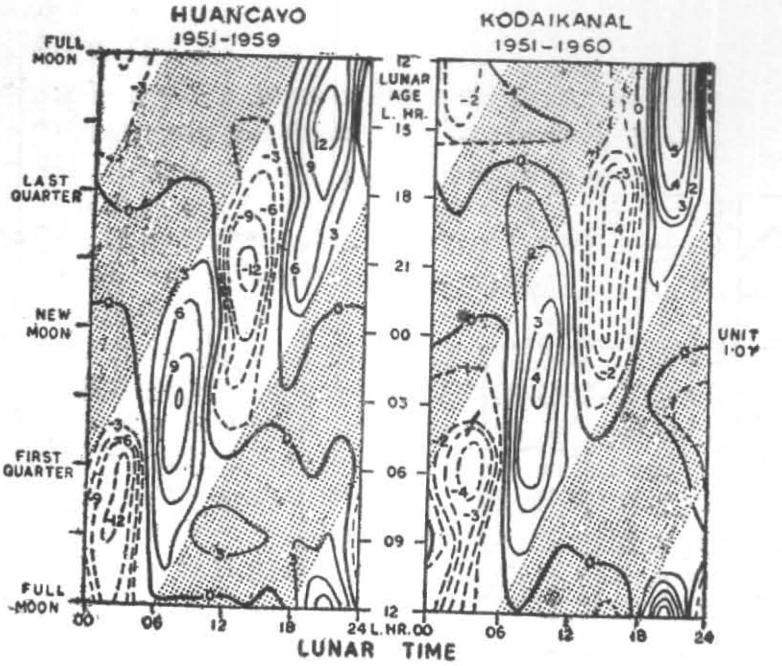


Fig. 1. Contour diagrams of $\triangle H$ at Kodaikanal (1951-60) and Huancayo (1951-59) as a function of lunar time and lunar age

loops of high values and two loops of low values within the whole lunar month indicating that the tidal oscillations are predominantly lunar semi-monthly in character. These loops are centered at the middle of the day indicating that the tidal oscillations are maximum around mid-day hours. The contour diagram representation of lunar oscillations during the same period for the stations Kodaikanal and Huancayo exhibits a great similarity pointing to same general characteristics of lunar oscillations at these two stations.

2. Annual average lunar daily variations at fixed lunar ages

The mean lunar daily variation in term of ΔH are derived separately for the days with different lunar ages, *i.e.*, $\nu = 00$ to 23. For further analysis we have grouped the days at intervals of three lunar age hours to get average lunar daily variation values for days with lunar age 00, 03, 06, 09, 12, 15, 18 and 21. The mean of the lunar daily variation on lunar ages 8, 9, 10 is represented as the lunar daily variation for each lunar age, such as 9 1-hr etc. The whole year average lunar variations in H at Kodaikanal for each of the eight lunar ages for the periods 1951-55 and 1956-60 are shown in Fig. 2. The positions of solar mid-day and midnight are indicated in the diagrams by means of upward and downward arrows respectively. The curve for any particular lunar age shows two peaks of unequal amplitude indicating the presence of lunar diurnal L_1 and lunar semi-diurnal L_2 oscillations of comparable magnitudes in both the periods. The part of the curve with greatest movement falls during day-light hours and is found to occur earlier and earlier in the lunar day as the lunation progresses from new moon to full moon. The whole lunation curve obtained by averaging eight individual curves is a sinusoidal wave having two peaks of nearly the same magnitude within one lunar day. Thus the lunar diurnal component seems to have largely cancelled out by the averaging of the curve over the whole lunation. The set of curves for the two periods are very similar in all respects except that the amplitudes are slightly larger for 1956-60 than for 1951-55.

Chapman (1919) gave an expression for lunar daily vairation in any element (upto fourth harmonic) as below—

$$L = \sum_{n=1}^{4} C_n \sin \left\{ n\tau + (n-2)\,\nu + \alpha_n \right\} \qquad (1)$$

The lunar daily curves for different lunar ages ($\nu = 0, 3, 6 \ldots .21$) were subjected to harmonic

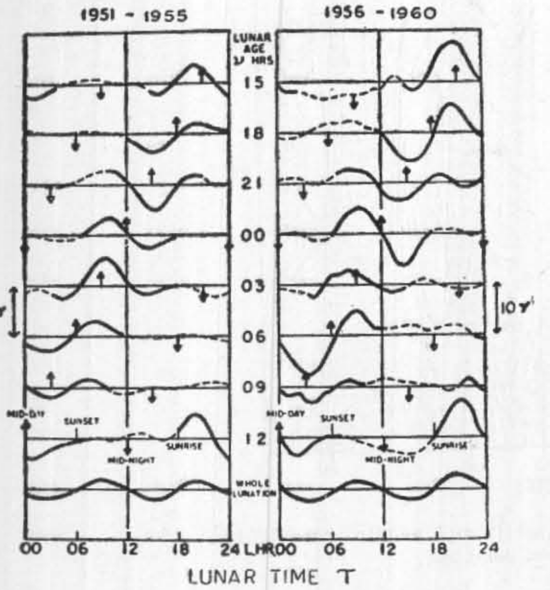


Fig. 2. Whole year average lunar daily varition in H at Kodaikanal on each of the eight lunar age groups for the low sunspot years 1951-55 and for high sunspot years 1956-60

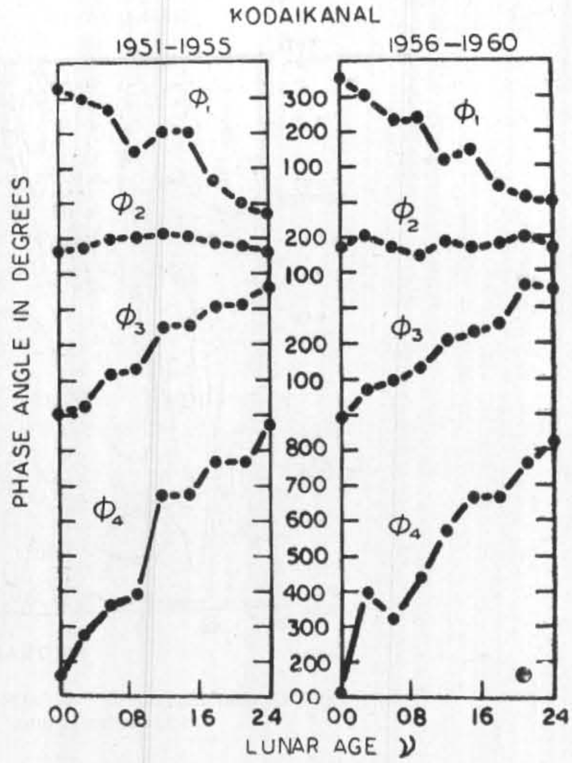


Fig. 3. Curves showing the relation between the phases of different harmonics of lunar daily variation in H at Kodaikanal with the lunar age for the periods 1951-55 and 1956-60

analysis upto fourth harmonic coefficients according to the equation—

$$L = \sum_{n=1}^{4} C_n \sin (n\tau + \phi_n) \qquad (2)$$

so that

$$\phi_n = \left\{ \alpha_n + (n-2)\, \nu \right\} \qquad (3)$$

According to these equations the phase of second harmonic (ϕ_2) should be independent of the lunar age ν, the phase of first harmonic ϕ_1 and phase of third harmonic ϕ_3 should decrease and increase by 2π respectively during one lunation. The phase angle of fourth harmonic component ϕ_4 should increase by 4π within one lunar month. The value of the phase constant (α_n) for any particular harmonic should be constant of the lunar age. The amplitudes (C_n) and phase constants (α_n) of the annual average lunar daily variation of H at Kodaikanal for individual lunar ages are given in Table 1 (*a*) and (*b*), while the relations between ϕ and ν for any particular harmonic are shown in Fig. 3.

It is seen from Fig. 3 that for both the periods 1951-55 and 1956-60 the phase angle ϕ_2 is constant at each lunar age. The phase angle ϕ_1 progressively decreases by about 360° with increasing lunar age and ϕ_3 increases by 360° within one lunar month. Similarly ϕ_4 is seen to follow through 720° during one lunation. Referring to Tables 1 and 2, it is seen that the amplitudes do not show any relationship with the lunar age and are nearly the same for all values of ν. The mean amplitude of C_1 has a value of $1{\cdot}28 \pm 0{\cdot}69$ during 1951-56 and $2{\cdot}07 \pm 0{\cdot}99$ during 1956-60. The mean value of C_2 is $1{\cdot}73 \pm 0{\cdot}25$ during 1951-55 and $2{\cdot}12 \pm 0{\cdot}89$ during 1956-60. The higher harmonics are progressively smaller in magnitude. It is thus seen that during individual ages the lunar semi-diurnal component is of the same order as the lunar diurnal component.

The phase constant α_1 is 325 ± 23 during 1951-55 and 334 ± 18 during 1956-60. The phase constant α_2 is $196° \pm 14$ during 1951-55 and 184 ± 18 during 1956-60. It is thus seen that the phase of L and L_2 oscillations are not affected by solar activity. Similarly the phase constants have almost identical values for the two solar epochs.

It is seen that the lunar tidal oscillations of H at Kodaikanal follow Chapman's phase law.

TABLE 1

Coefficients of annual average lunar daily variation in H at Kodaikanal for different lunar ages*

Lunar age	C_1 (γ)	α_1 (°)	C_2 (γ)	α_2 (°)	C_3 (γ)	α_3 (°)	C_4 (γ)	α_4 (°)
				(a) For 1951-55				
00	0·99	331	1·58	200	1·0	359	0·25	151
03	2·24	314	1·79	173	1·71	335	0·35	186
06	1·56	358	1·58	200	0·56	339	0·32	183
09	0·23	285	1·22	205	0·90	355	0·28	120
12	2·05	338	1·78	216	1·59	292	0·77	315
15	0·33	293	1·98	206	1·17	333	0·47	224
18	1·48	334	1·44	188	0·73	324	0·33	230
21	1·04	322	2·49	179	1·10	357	0·46	135
Mean	1·28	325	1·73	196	1·09	337	0·40	193
				(b) For 1956-66				
00	1·66	362	2·80	176	2·0	352	0·36	112
03	0·89	348	1·07	214	1·08	388	0·14	309
06	3·30	324	2·90	175	1·42	367	0·59	142
09	1·32	244	0·78	150	0·66	357	0·08	170
12	2·29	300	2·92	193	1·55	391	0·37	215
15	3·93	344	1·96	175	1·63	369	0·93	223
18	1·87	317	3·20	185	1·69	348	0·58	152
21	1·24	333	1·42	202	1·33	413	0·29	135
Mean	2·07	334	2·12	184	1·42	329	0·42	182

*Accoring to the equation $L = \sum_{n=1}^{4} C_n \sin \left\{ n\tau + (n-2)\nu + \alpha_n \right\}$

TABLE 2

Coefficients of annual average lunar daily variation over the whole lunation in H at Kodaikanal (1951-60)*, Huancayo (1951-59) and Ibadan (1955-57)

	Period	A_1 (γ)	β_1 (°)	A_2 (γ)	β_2 (°)	A_3 (γ)	β_3 (°)	A_4 (γ)	β_4 (°)
Kodaikanal	1951-55	0·36	285	1·55	189	0·40	315	0·23	342
"	1956-60	0·33	146	2·01	182	0·08	297	0·15	339
"	1951-60	0·12	220	1·8	185	0·24	312	0·19	340
Huancayo	1951-59	0·71	203	4·60	212	0·31	109	0·13	194
Ibadan	1955-57	0·88	351	3·99	234	0·50	202	0·07	34

*According to the equation $L = \sum_{n=1}^{4} A_n \sin (n\tau + \beta_n)$

The eight individual lunar daily oscillation curves can be averaged to give lunar daily oscillation for the whole lunation. These curves are also shown in Fig. 2. The harmonic coefficients of the whole lunation average oscillations for Kodaikanal during 1951-55 and 1956-60 and at Huancayo and Ibadan are given in Table 2. It is seen that for any of the stations the most significant component is the lunar semi-diurnal one (L_2), and the other harmonics including the L_1 are much smaller in magnitude. For example, during 1956-60 at Kodaikanal the L_2 amplitude is $2 \cdot 01\,\gamma$ compared to the L_1 being $0 \cdot 33\,\gamma$. The value of L_1 amplitude on individual days is comparable to the corresponding L_2 amplitude but on averaging the L oscillations over the whole lunation, the diurnal component L_1 is almost cancelled out. Similarly, the L_3 and L_4 component should cancel out on averaging. Thus the amplitudes of all components except L_2 are statistically insignificant. The phase of the L_2 oscillations is found to be 189° during 1951-55 and 182° during 1955-60 and thus the phase of lunar tidal oscillations in H does not change with solar activity. The mean for the entire period 1951-60 is $1 \cdot 8\,\gamma$ with a phase angle of 185°, *i.e.*, the maximum positive deviation would occur at 8·8 hours local lunar time. The phase angles at Ibadan and Huancayo are respectively 234° and 212°, *i.e.*, the maximum positive deviation of H at Ibadan and Huancayo occurs at 7·2 and 7·9 lunar hours respectively and thus the lunar tidal oscillations are delayed by about an hour at Kodaikanal compared to Huancayo. The amplitude of L_2 oscillations is $1 \cdot 8\,\gamma$ at Kodaikanal, about $4 \cdot 0\,\gamma$ at Ibadan, and $4 \cdot 6\,\gamma$ at Huancayo. Thus there is a significant longitudinal effect in the amplitude of lunar tidal oscillations in H at the equatorial stations and this variation is similar to the longitudinal variations of electrojet currents along the magnetic equator.

3. Annual average lunar monthly variations at fixed solar times

Lunar tides can also be estimated by studying lunar monthly M_1 and lunar semi-monthly M_2 variation of ΔH at each fixed solar hour. Fig. 4 shows the annual average curves of H at fixed solar hours, 00, 03, ... 21 as a function of lunar age ν_0 (at Greenwich noon) for both the periods 1951-55 and 1956-60. The coefficients of lunar monthly and semi-monthly oscillations derived from these curves are given in Table 3. In the table the phases of M_1 oscillations are presented in terms of local lunar age ν whereas the phases of M_2 oscillations are presented in terms of local lunar time τ. Proper corrections for the local solar time of the place is applied to compute phase angles.

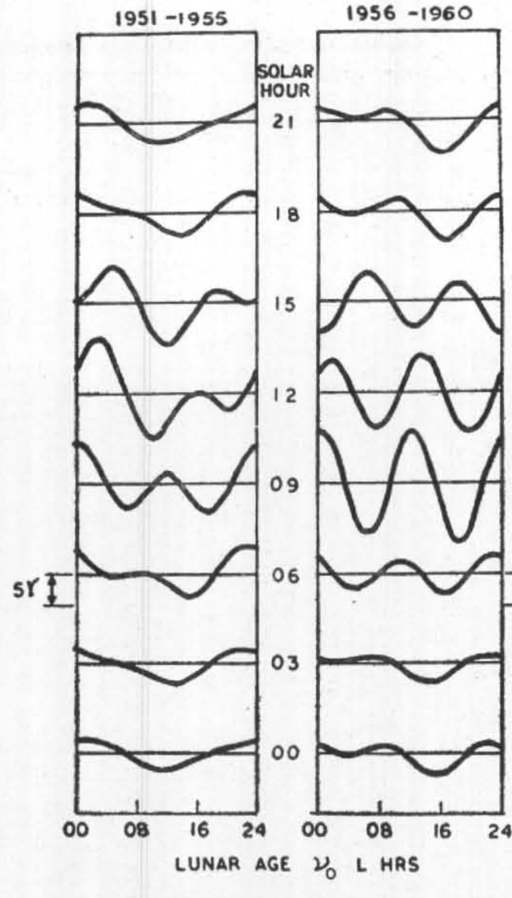


Fig. 4. Lunar monthly variation of H at Kodaikanal for the periods 1951-55 and 1956-60 for different solar times averaged over the whole year

Referring to Fig. 4 one sees similarity between the two sets of curves for the two periods of different solar activity. The tide for both the periods is significantly large during daytime hours and its amplitude reaches maximum value near mid-day. During night-time, the oscillations are small and insignificant, although the phase of the oscillations are roughly the same at the two epochs. The oscillations during the solar daytime have stronger M_2 than M_1 component while the night-time oscillations have stronger M_1 than M_2 wave. Referring to Table 3 the amplitudes of M_1 oscillations (r_1) do not show any dependence on the solar time, its value being between 2 to 5 γ for both the stations.

The amplitudes of M_2 oscillations are plotted as a function of local solar time in Fig. 5 for the stations Kodaikanal and Huancayo. The amplitude r_2 is very small for the night-time hours, it starts increasing with sunrise, has large

TABLE 3

Coefficients of annual average lunar monthly M_1 and lunar semi-monthly M_2 oscillations in H at Kodaikanal

Phases θ_1 and θ_2 are shown as the lunar age and lunar time respectively when the corresponding wave reaches its maximum positive deviation.

Hrs (LMT)	1951-55					1956-60				
	ΔH (γ)	r_1 (γ)	θ_1 (ν) 1-hr	r_2 (γ)	θ_2 (τ) 1-hr	ΔH (γ)	r_1 (γ)	θ_1 (ν) 1-hr	r_2 (γ)	θ_2 (τ) 1-hr
00	427	2·34	0·51	0·47	8·10	497	1·59	2·84	1·95	2·66
01	431	2·15	0·27	0·35	9·57	497	1·95	2·40	1·46	3·8
02	429	2·05	0·44	0·04	7·09	500	2·10	2·97	1·28	4·99
03	431	2·61	0·61	0·64	6·96	500	1·80	2·47	1·05	6·33
04	431	2·69	0·37	0·27	6·16	500	2·07	2·17	1·28	8·00
05	429	3·06	23·65	0·76	8·21	495	0·89	22·64	1·18	7·31
06	430	2·96	23·96	1·98	8·67	499	0·65	0·89	2·84	8·07
07	439	2·77	23·94	3·17	8·84	514	0·53	2·06	5·37	8·74
08	457	1·89	0·62	4·80	9·31	543	0·69	4·69	6·84	8·91
09	477	2·45	0·33	4·31	9·37	578	0·79	6·86	9·26	9·31
10	493	3·14	0·82	3·39	9·47	605	0·84	10·29	9·39	9·81
11	494	3·85	0·86	3·80	8·93	615	0·88	8·20	7·82	10·34
12	487	5·27	1·16	4·60	9·01	606	0·63	10·43	6·28	10·87
13	472	4·04	1·46	4·94	9·58	588	0·57	10·86	3·98	10·31
14	454	4·10	1·70	4·55	9·73	563	0·38	13·90	3·60	9·00
15	440	4·06	1·53	3·54	9·74	542	0·88	8·13	4·47	9·07
16	430	3·58	1·10	2·54	9·20	528	1·12	5·63	3·38	9·03
17	431	3·63	0·80	1·96	8·87	519	1·32	5·46	2·49	8·40
18	430	3·20	0·50	1·07	9·27	510	2·02	4·76	2·48	7·57
19	427	3·15	0·67	0·58	11·83	502	2·44	4·20	2·56	8·23
20	426	3·28	0·50	0·74	4·13	499	2·63	4·10	2·20	9·30
21	425	3·20	0·20	0·82	5·93	497	2·89	4·27	2·14	10·66
22	425	3·07	0·30	0·50	6·60	496	2·52	3·63	2·26	0·43
23	426	2·59	0·93	0·45	8·93	497	1·96	3·53	1·66	1·80

value around mid-day and reduces to a low value by sunset. It is however to be noted that the maximum mid-day value for 1951-55 is about 5γ for Kodaikanal as compared to about $15\ \gamma$ for Huancayo. During 1956-60 the maximum amplitude is $9\cdot4\gamma$ at Kodaikanal and $17\cdot6\gamma$ at Huancayo. Thus the lunar semi-monthly tides in H are smaller at Kodaikanal than at Huancayo, although both the stations are very close to the magnetic equator.

The values of (r_1, θ_1) for different solar hours are plotted on harmonic dials of lunar age and lunar time in Fig. 6. On the harmonic dials of lunar time, the (r_1, θ_1) points for both high and low solar activity periods move progressively around the origin with increasing solar time and form loops during the course of the one complete solar day. For the years 1951-55, the scalar and vector means for the daytime points are respectively $3\cdot5$ and $2\cdot1\gamma$, for the night-time the corresponding values are $2\cdot8\gamma$ and $1\cdot7\gamma$, and for all the hours one gets $3\cdot1\gamma$ and $0\cdot46\gamma$. Similarly, for all hours of the day of 1956-60 the scalar mean is $1\cdot4\gamma$ while vector mean is only $0\cdot57\gamma$. On the lunar age dial the points (r_1, ν_1) corresponding to different solar hours group themselves in a rather narrow sector and thus the vector average value of the amplitude is not different from the individual value of the amplitude. Its vectorial mean for Kodaikanal 1956-60 is $1\cdot17\gamma$ and arithmetic mean is $1\cdot42\ \gamma$ and similar figures for the period 1951-55 are $3\cdot11$ and $3\cdot13\ \gamma$. This suggests that lunar monthly oscillations in H at equatorial stations are controlled more by the age of the moon than by the lunar time.

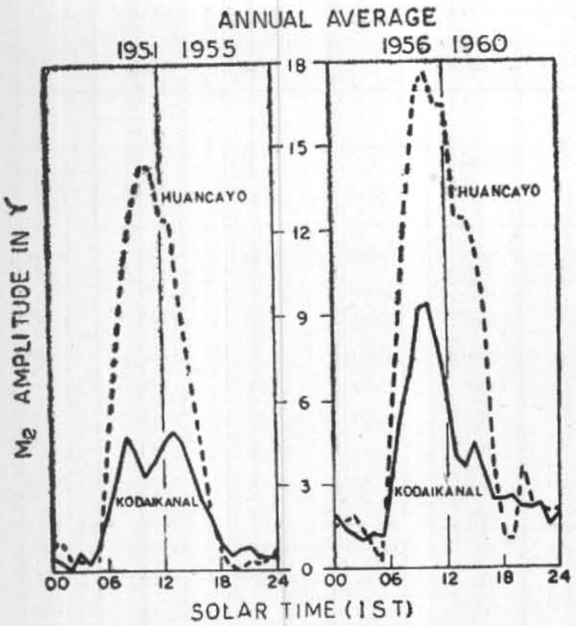


Fig. 5. Semi-monthly and lunar tide $M_2(H)$ amplitudes at Huancayo and Kodaikanal

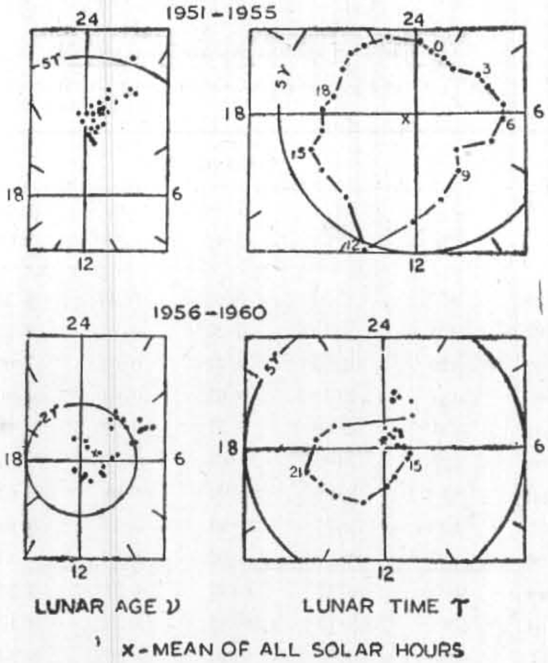


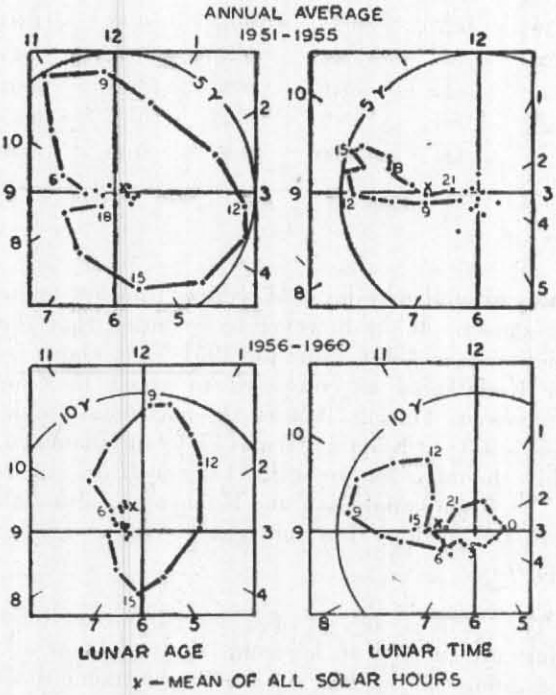
Fig. 6. Lunar monthly oscillations

The amplitude and phase of lunar semi-monthly oscillations (r_2, θ_2) for different solar hours are plotted on the harmonic dials of lunar age and lunar time in Fig. 7. On the lunar age dial the points for different hours of the day move around the origin giving rise to a very small value of the vector average from all the hours. On the lunar time dial the points for various hours of the daytime do not move around the origin but lie within a narrow sector and solar hour average and vector average of the M_2 amplitudes are comparable. During 1951-55 for daytime the scalar mean is $3 \cdot 6\ \gamma$ while the vector mean is $0 \cdot 7$ on lunar age dial and $3 \cdot 6\ \gamma$ on lunar time dial. The corresponding values for 1946-60 are $5 \cdot 47\gamma$ (scalar), $5 \cdot 0\gamma$ (vector on τ dial) and $0 \cdot 8\gamma$ (vector on ν dial). Thus it may be suggested that the lunar semi-diurnal oscillation in H during the daytime hours is controlled by lunar time than by lunar age.

The phase of maximum deviation of M_2 on the lunar time dial is $9 \cdot 4$ 1-hr for the peroid 1951-55 and $9 \cdot 20$ 1-hr for the period 1956-60. For Huancayo the maximum positive deviation of annual average M_2 oscillation in H occurs at $8 \cdot 3$ 1-hr for the years 1951-55 (Rastogi 1968a) and at $8 \cdot 0$ 1-hr for the years 1957-59 (Rastogi 1968b).

4. Lunar daily variation of H during different seasons of the year

To study the seasonal effect in the lunar tide the whole data are divided into three groups of



Figs. 7. Lunar semi-monthly oscillations

Figs. 6 & 7. The coefficients of annual average lunar monthly and semi-monthly oscillations in H at Kodaikanal at different solar hours on the harmonic dials of lunar age ν and lunar time τ

TABLE 4

Coefficients of lunar daily oscillations in H averaged over the whole lunation during different seasons (1951-60)*

Season	Year	A_1 (γ)	β_1 (°)	A_2 (γ)	β_2 (°)	A_3 (γ)	β_3 (°)	A_4 (γ)	β_4 (°)
D — Months	1951—55	0·52	345	1·36	225	0·65	327	0·35	334
	1956—60	1·14	153	2·71	208	0·65	325	0·45	318
	1951—60	0·32	144	2·0	214	0·65	326	0·40	325
	1951—55	0·18	220	1·96	195	0·33	303	0·15	312
E — Months	1956—60	0·78	297	2·60	157	0·17	258	0·19	270
	1951—60	0·42	285	2·15	173	0·23	288	0·15	293
	1951—55	0·94	280	1·80	171	0·14	303	0·18	382
J — Months	1956—60	0·59	125	1·43	189	0·34	165	0·18	382
	1951—60	0·24	248	1·6	178	0·13	187	0·18	382

*According to equation $L=A_n \sin (n\tau + \beta_n)$

TABLE 5

Amplitudes of lunar semi-diurnal (L_2) and solar semi-diurnal (S_2) wave in H at Huancayo and other equatorial stations

	Period	D - months			E - months			J - months			Reference
		L_2 (γ)	S_2 (γ)	L_2/S_2	L_2 (γ)	S_2 (γ)	L_2/S_2	L_2 (γ)	S_2 (γ)	L_2/S_2	
Kodaikanal	1951—55	1·36	12·54	0·108	1·96	18·92	0·103	1·80	15·84	0·113	Present paper
	1956—60	2·71	20·52	0·132	2·60	28·68	0·09	1·43	26·32	0·05	
Huancayo	1951—55	6·1	21·4	0·285	5·2	25·4	0·205	2·2	19·3	0·114	Rastogi (1968a)
	1956—59	8·73	35·6	0·245	6·5	42·7	0·152	1·8	32·9	0·055	Rastogi (1968b)
badan	1955—57	4·7	16·9	0·278	3·8	21·9	0·174	3·4	19·0	0·179	Onwumechilli *et al.* (1959)
Kodaikanal	1950—55	3·32	14·6	0·227	2·28	18·9	0·121	1·43	14·8	0·097	Raja Rao (1961)
Bombay	—	1·35	7·9	0·170	0·63	10·7	0·059	0·53	10·7	0·050	Schmidt (1926) Chambers (1887)

months denoted as (i) D-months (November, December, January and February), (ii) E-months (March, April, September and October) & (iii) J-months (May, June, July and August). For Kodaikanal, the D-months refer to Winter while the J-months refer to Summer months. Lunar daily variation at the lunar age groups were computed separately for each season. For any particular season, the whole lunation average curves were also derived by averaging eight individual curves. Similar to the annual average curves, it is found that during any individual season also, the major deviations occur during the daytime hours and the peak deviations occur during the daytime hours and the peak occurs earlier in lunar time with increasing age of the moon . During any of the seasons the variation of the phase of a particular harmonic with the lunar age was found as expected of Chapman's phase law. The whole lunation average curves for individual seasons were harmonically analysed and the amplitude (A_n) and phases (β_n) are given in Table 4.

It is seen from Table 4 that the most predominant component in L oscillation during any of the seasons being the lunar semi-diurnal one. Averaging over 1951 to 1960 the L_1 amplitude is of the order of $0 \cdot 3\gamma$ while L_2 amplitude is about $2 \cdot 0\ \gamma$. The higher order components are still smaller. The L_2 amplitude for the D and E-months is larger during the period 1956-60 than 1951-55 while that during J-months is slightly larger during 1951-55 than during 1956-60. The seasonal variation of L_2 amplitude for the epoch 1951-55 shows a maximum during E-months ($2 \cdot 0\ \gamma$) and a minimum during D-months ($1 \cdot 4\ \gamma$). For the epoch 1956-60, maximum amplitude occur during D-months ($2 \cdot 7\gamma$) and minimum during J-months ($1 \cdot 4\gamma$). Similar seasonal effects have been found in the lunar tides in the range of H at Kodaikanal during the two epochs (Rastogi 1965b).

The phase of L_2 wave at Kodaikanal for the entire period 1951-60 is 214° during D-months, 173° during E- and 178° during J-months. Thus the maximum effect of L_2 oscillation in H occurs about $1\frac{1}{2}$ hours later during E- and J-months than during D-months. Similar advance in the time of maximum deviation of $L_2(H)$ wave at Huancayo occurs from D-, E- to J-months.

In Table 5 are collected the amplitudes of lunar semi-diurnal (L_2) and solar semi-diurnal (S_2) waves in H on individual seasons at Kodaikanal and other equatorial stations analysed by earlier workers; the ratio of L_2/S_2 are also given to compare the lunar and solar waves in H. The solar wave S_2 is seen to be larger during high than during the low sunspot year, indicating the increase of electrojet currents with the increase of solar activity. At Kodaikanal, the L_2 wave during the D- and E-months is larger during 1956-60 than during 1951-55, still the ratio of L_2/S_2 for any of the seasons is smaller in 1956-60 than during 1951-55. Similar results are seen for Huancayo. Thus with the increase of solar activity, the lunar tidal wave does not increase in the same proportion as the solar semi-diurnal wave.

The ratio L_2/S_2 at Bombay is in general smaller than that at the equatorial stations indicating that although L_2 is large where S_2 is large but there is additional enhancement of the L_2 near the magnetic equator due to the electrojet effects. The variation with the time of the day of M_2 amplitude in H as well as ΔH for the individual seasons of the two epochs at Kodaikanal are shown in Fig. 8. The full line curves refer to 1951-55 while the dashed curves refer to 1956-60. It is well known that the maximum value of H occurs about an hour before noon at most of the low latitude stations. The diurnal range is maximum

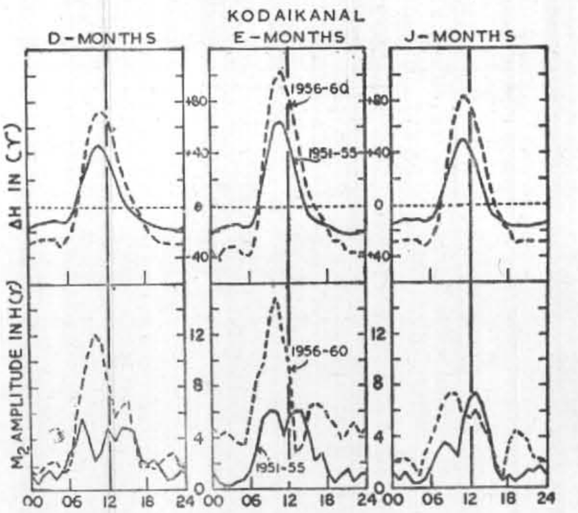


Fig. 8. Solar daily variation of semi-monthly tide M_2 and of H itself in different seasons at Kodaikanal for the period 1951-55 and 1956-60

during E- months than D- or J-months during each of the epochs. The daily variation of M_2 (H) is similar to the daily variation of ΔH, for all the seasons during the high and low sunspot epochs. The amplitudes are low during the night-time start increasing with sunrise, reach the maximum value near noon and reduce to night-time value by sunset.

The maximum value of M_2 (H) during 1951-55 or 1956-60 is largest during E-months. However during 1956-59 maximum amplitude is larger during D- than during J-months while during 1951-55 the midday value is slightly larger during J- than D-months.

5. Lunar monthly oscillations in H at fixed solar time during different seasons of the year

The lunar monthly M_1 and lunar semi-monthly M_2 oscillations in H together with probable errors for each of the solar hours were computed separately for different seasons of the year. The coefficients M_1, as mentioned earlier, were found to be small and not statistically significant. Accordingly only the amplitudes and the phases of maximum deviation of M_2 oscillations are given in Table 6 (a) and (b) respectively for the epochs 1951-55 and 1956-60. These coefficients are plotted in harmonic dials of lunar time in Fig. 9. Similar harmonic dial for the Huancayo H during the IGY/IGC are included for comparison.

TABLE 6

Coefficients of lunar semi-monthly M_2 oscillations in H at Kodaikanal averaged over different seasons for (a) 1951-55 and (b) 1956-60

Hrs (LMT)	D—Months				E—Months				J—Months			
	39000+ $\triangle H$ (γ)	r_2 (γ)	Probable error (γ)	Phase τ_2 lunar time	39000+ $\triangle H$ (γ)	r_2 (γ)	Probable error (γ)	Phase τ_2 lunar time	39000+ $\triangle H$ (γ)	r_2 (γ)	Probable error (γ)	Phase τ_2 lunar time
(a) 1951 — 55												
00	413	1·20	1·6	131	428	1·20	2·0	255	439	1·2	1·2	291
01	415	0·4	1·7	196	431	0·54	2·1	300	440	0·6	1·2	312
02	416	1·2	1·8	183	432	0·36	2·0	261	442	1·2	1·3	346
03	417	1·4	1·9	206	434	0·31	1·9	207	441	0·3	1·2	245
04	418	0·8	1·7	199	434	0·52	1·8	81	442	0·4	1·1	256
05	416	1·5	1·6	246	432	0·70	1·7	183	439	0·7	1·1	294
06	417	2·8	1·3	263	432	1·56	1·6	252	442	1·6	1·0	266
07	426	3·6	1·1	262	442	3·28	2·6	261	449	2·8	0·9	276
08	443	5·6	1·0	274	465	5·53	1·5	276	464	3·5	0·8	293
09	459	3·9	1·0	267	492	6·14	1·6	285	483	3·2	0·8	287
10	472	2·4	1·0	256	511	6·00	1·6	300	497	2·5	0·7	272
11	474	3·0	1·0	219	513	4·96	1·6	297	502	5·3	0·7	266
12	467	4·9	0·9	203	501	5·70	1·6	294	496	7·0	0·8	286
13	455	3·9	0·9	226	479	6·09	1·6	297	483	7·4	1·0	306
14	440	5·0	0·9	231	457	6·03	1·7	300	466	6·6	0·6	325
15	429	4·9	0·9	242	443	4·46	1·5	306	450	4·2	0·6	331
16	424	4·6	0·8	259	437	2·24	1·5	282	444	1·5	1·0	324
17	421	2·4	0·8	273	435	2·84	1·5	255	441	0·8	0·6	272
18	417	2·1	0·9	317	433	1·23	1·5	246	437	1·0	0·6	225
19	414	2·4	0·8	13	430	0·48	1·5	255	437	0·5	0·6	114
20	412	1·5	0·9	69	428	1·07	1·5	171	436	0·8	0·7	153
21	411	0·8	0·9	80	426	1·47	1·5	204	436	1·3	0·8	172
22	411	0·8	1·3	·103	427	0·52	1·7	243	437	1·3	0·9	220
23	411	1·5	1·2	114	428	1·13	1·9	261	437	1·7	1·0	293
(b) 1956 — 60												
00	500	1·4	1·1	86	490	4·8	1·2	102	502	2·0	1·0	289
01	501	1·2	1·1	172	487	4·4	1·1	129	502	2·2	0·9	11
02	503	1·9	1·1	216	494	4·6	1·1	150	503	2·3	0·9	19
03	503	2·1	1·0	263	495	4·0	1·0	181	503	2·0	0·8	55
04	503	2·2	1·0	288	495	3·6	1·0	216	502	0·9	0·9	70
05	497	1·2	1·2	341	489	3·5	1·3	246	499	2·8	1·0	151
06	504	1·8	1·2	233	489	5·8	1·3	280	503	3·9	1·1	185
07	519	5·4	1·3	228	508	8·7	1·4	299	515	5·4	1·2	233
08	543	8·4	1·6	233	544	9·9	1·6	307	542	7·0	1·4	249
09	571	10·7	1·8	245	589	13·4	2·0	308	575	7·4	1·6	275
10	593	12·1	2·0	254	622	14·9	2·1	331	601	7·2	1·7	284
11	601	11·4	2·1	274	631	11·3	2·2	350	614	5·6	1·7	303
12	596	8·3	2·0	295	611	8·9	2·1	7	610	5·4	1·7	309
13	581	5·7	1·9	272	588	2·8	2·0	7	594	6·0	1·7	318
14	561	6·4	1·7	241	558	3·5	1·8	252	571	4·6	1·5	335
15	544	6·9	1·5	245	537	6·3	1·6	263	546	4·0	1·4	345
16	532	3·9	1·4	254	525	6·6	1·3	263	526	1·8	1·2	361
17	523	1·7	1·3	248	518	6·4	1·3	258	515	0·8	1·2	127
18	512	1·9	1·3	186	508	5·5	1·4	271	511	3·4	1·2	177
19	505	1·7	1·3	226	499	4·9	1·4	296	501	4·4	1·1	198
20	501	2,1	1·3	320	495	3·8	1·4	350	503	4·0	1·1	222
21	499	2·7	1·3	320	491	4·5	1·3	11	502	3·6	1·0	244
22	498	2·9	1·3	358	490	5·1	1·3	46	501	2·3	1·1	279
23	499	1·9	1·2	55	490	4·3	1·3	79	501	2·0	1·0	303
		3·24		260°		2·93		305°		2·05		280°

Referring to harmonic dials for D-months the phases for the daylight hours are almost constant centering between 8 and 9 lunar hours while for the night-time it varies almost through 360° thereby forming a big loop in about 8-9 lunar-hour sector for the daytime and a small loop centering the origin for the night-time. Similar features are present in E-months. During the J-months of 1951-55 one gets a broad loop between 9 and 10 lunar-hour sector. For the J-months in 1956-60 one finds two loops, one referring to the daytime and one referring to the night-time, both containing the origin. The night-time loop is slightly smaller than the daytime one. Similarly, two loops are seen for Huancayo data. This indicates that while during the D-months the tidal effects in H for the daytime hours occurs at the same lunar time, but during the J-months the time of maximum deviation increases with the increase of solar time or in other words the phase of M_2 for different solar hours happens to be at the same lunar age. Similar control of lunar time during the D-months and lunar age during J-months in the lunar tidal oscillations had been indicated in the earlier tidal analyses (Rastogi 1968b).

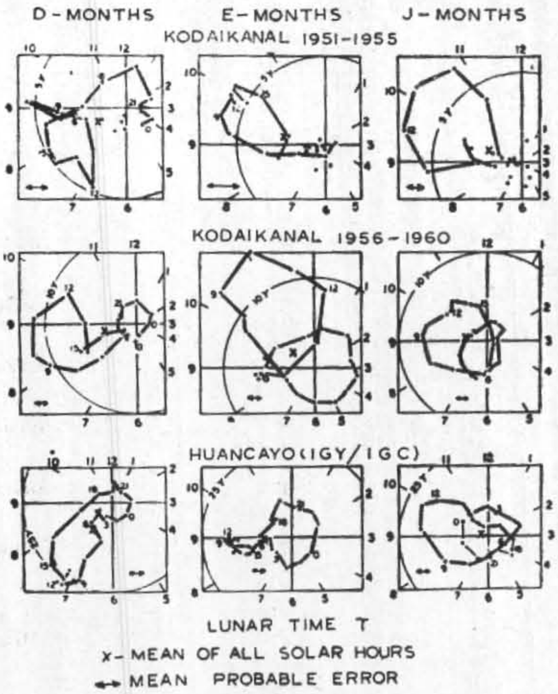


Fig. 9. The coefficients of lunar semi-monthly oscillation in H at Kodaikanal and Huancayo at different solar hours on the harmonic dials of lunar time separately for D-, E- and J-months

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Appendix I

The following symbols are used in the present article —

t	local solar mean time
τ	local lunar mean time
ν_0	lunar age at Greenwich noon
ν	local lunar age
l-hr	lunar hour = 1/24th mean lunar day
s-hr	solar hour = 1/24th mean solar day
$L_1(H)$	lunar diurnal oscillation in H at fixed lunar age ν.
$L_2(H)$	lunar semi-diurnal oscillation in H at fixed lunar age ν.
C_n, ϕ_n, α_n	amplitude, phase angle and phase constant of the n^{th} harmonic of lunar daily variation according to the equation $L = C_n \sin(n\tau + \phi_n)$ $= C_n \sin\{n\tau + (n-2)\nu + \alpha_n\}$
$M_1(H)_t$	lunar monthly oscillation in H at fixed solar time t.
$M_2(H)_t$	lunar semi-monthly oscillation in H at fixed solar time t.
A_n, β_n	amplitude and phase angle of the n^{th} harmonic of lunar daily oscillation averaged over the whole lunation.
(r_1, θ_1), (r_2, θ_2)	amplitude and time of maximum positive deviation of M_1 and M_2 oscillations respectively.