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Lunar Tides in the daily range of *H* at Kodaikanal

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ABSTRACT. The diurnal range in H (maximum *minus* minimum instantaneous value) at Kodaikanal is found to be affected by the phase of the moon. The harmonic coefficients of these lunar tidal oscillations have been computed for the period 1950-55. The annual average amplitude is found to be $6\cdot3\pm0\cdot8\ \gamma$ on a mean value of $101\cdot2\ \gamma$ with the maximum occurring at lunar phase μ equal to 9·8 lunar hour. The probable errors in the results for each season separately are found to be too large to ascertain any significant seasonal variation in the lunar tidal coefficients. When the range is defined as the difference between mean of four hourly midday values and mean of two hourly midnight values of H, the annual average oscillation is then found to be $3\cdot1\pm0\cdot5\ \gamma$ with an average value of $56\cdot0\ \gamma$, and the maximum occurs at lunar phase μ equal to 8·7 lunar hour. A similar analysis of the range (midday *minus* midnight) for the high sunspot period 1956-58, the annual average lunar semi-monthly oscillation of the range was $5\cdot9\pm0\cdot9\ \gamma$ with a mean value of $103\cdot6\ \gamma$ and the maximum occurred when μ equals 9·7 lunar hour. These results are consistent with those of almost all other workers except Raja Rao (1962) who found that the range of the instantaneous value of H at Kodaikanal for 1950-55 had an annual average lunar semi-monthly oscillation of $32\cdot6\gamma$ with a mean value of $91\cdot8\ \gamma$, the maximum occurring at lunar phase μ equal to 2·9 lunar hours.

1. Introduction

Lunar tidal oscillations in the hourly values of horizontal intensity of the earth's magnetic field H, have been found to be quite large of the order of 3 to 8γ, at equatorial stations (Bartels 1936, Raja Rao and Sivaraman 1958, Onwumechilli and Alexander 1959, Gouin 1960). The maximum amplitude at all these places is observed to occur at about 07 lunar hour excepting at Kodaikanal where according to Raja Rao and Sivaraman (1958) it was found to occur at 04 lunar hour. The lunar tide in the daily range of H is found to be even larger than the tide in the hourly values of H itself; at Huancayo the amplitude of lunar tidal variation of the diurnal range in the December solstice is $15\cdot4\ \gamma$ in the minimum and $25\cdot1\ \gamma$ in the maximum sunspot period (Bartels and Johnston 1940).

Although L_2 variations are large at places where the daily range $A(H)$ is large, the ratio of $L_2(H)\,/\,A(H)$ is a small fraction, being about 0·15 in December solstice and about 0·07 in the June solstice. This can be seen from Table 1. Thus even at places where the lunar tide in the range of H is abnormally large, its ratio to the range $A(H)$ is less than ·2.

Recently, Raja Rao (1962) has computed the lunar tidal effects in the daily range of H at Kodaikanal for the period January 1950—December 1955; his results are given in Table 2 for different seasons of the year. The amplitudes were found to be about 28 γ in December and 44 γ in June solstice. The ratio of amplitude of L_2 to the average value of the range lay between 0·33 to 0·50 whereas previous determinations by other workers gave the value of this ratio to be less than 0·2 for the equatorial stations. The L_2 amplitudes are much larger than those obtained for Huancayo even during maximum sunspot period. Further, these amplitudes are 3 to 7 times larger than those derived for Kodaikanal for high sunspot period by Rastogi (*Ref.* Table 1). The maximum amplitude according to Raja Rao occurs at 08 to 10 lunar hours in ν*(*i.e.*, 04 to 02 in μ) whereas at all other places including Kodaikanal (1957-58) the maximum occurs at 08 to 11 hours in μ according to Rastogi (*Ref.* Table 1). Since the L_2 amplitudes derived by Raja Rao were abnormally large and opposite in phase to those found at any other place in the world, it was suggested by Prof. Ramanathan that it would be desirable to recalculate the

*In the literature, lunar hour is reckoned in two different ways as μ or ν and $\nu=24-\mu$ (see Sec. 3)

TABLE 1

Coefficients of lunar semi-monthly variation (L_2) in the solar diurnal range of H at some equatorial stations during IGY, IGC (Rastogi 1964)

Station	December solstices				Equinoxes				June solstices			
	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)
Huancayo (1957-59)	158	26·1	·165	7·7	196	22·2	·113	8·8	147	7·6	·052	11·0
Addis Ababa (1958-60)	109	17·3	·159	8·5	132	11·3	·086	8·4	113	5·1	·045	8·5
Trivandrum (1957-59)	108	11·8	·119	7·7	149	13·9	·093	10·5	123	5·9	·048	10·9
Kodaikanal (1957-59)	95	8·9	·094	7·3	120	8·6	·072	9·7	107	3·1	·029	8·6

(a) Average range A in γ, (b) Amplitude L_2 in γ, (c) Ratio L_2/A, (d) Phase of maximum in lunar hour

TABLE 2

The coefficients of lunar semi-monthly variation in the daily range of the instantaneous value of H at Kodaikanal during January 1950 to December 1955 according to Raja Rao (1962)

	Average range A_i (γ)	Amplitude of L_2 (γ)	Ratio L_2/A	Phase of maximum lunar hours	
				ν	μ
December solstices (Winter)	85·5	27·9	·326	8·2	3·8
Equinoxes	102·7	35·1	·342	10·1	1·9
June solstices (Summer)	87·3	43·7	·501	8·8	3·2
Annual average	91·8	32·6	·355	9·1	2·9

lunar tidal effects in the solar diurnal range of H at Kodaikanal. The present article summarises the results of these studies. The geographic co-ordinates of Kodaikanal are 10·2°N, 77·5°E and magnetic dip is 3·5°N.

2. Choice of ranges in the solar daily variation of H

Different definitions of the daily range have been used by different workers. Following Bartels and Johnston (1940), the range will be denoted by A with a subscript defining the way it is derived. The Kodaikanal Observatory publishes, besides the hourly mean values of H, the maximum and minimum values of H on each Greenwich day together with the times of these occurrences. The difference between the highest and lowest *instantaneous* values are referred to as 'Range' in these bulletins. In the present article it will be referred to as the range of the instantaneous value of H and denoted as A_i. Some authors (Onwumechilli and Alexander 1959, Rastogi 1962) have defined the range as the difference between the maximum and minimum hourly mean value of H within a day. Bartels and Johnston (1940) defined the range as the average value of H between 9 hour to 14 hour *minus* the average value from 0 hour to 05 hour L.S.T. The noncyclic changes were eliminated by them by evaluating the range from the straight line connecting consecutive averages for 00 to 05 hr. Forbush and Casaverde (1961) defined the range as the value of H averaged over 10 to 13 hour *minus* the value of H averaged over two intervals 00—01 hour and 23—24 hour. This takes care of the changes in the value of H on consecutive nights. Rastogi (1963a, 1963b), in his analysis of the geomagnetic lunar tide at equatorial magnetic observatories in Peru defined the range as the average value of H between 10 to

TABLE 3

Daily ranges of the instantaneous values (A_i) and of the average values (A_a) of H for the three classes of days with increasing magnetic disturbances

	Range A_i on days			Range A_a on days			Ratios A_i/A_a on days		
	(a)	(b)	(c)	(a)	(b)	(c)	Quiet	Undis-turbed	Dis-turbed
Equinoxes	108·8	112·5	154·0	66·1	67·7	57·9	1·65	1·66	2·66
Winter	84·5	86·0	132·0	53·6	50·4	46·9	1·58	1·70	2·82
Summer	87·3	89·5	133·5	57·4	54·2	45·9	1·52	1·65	2·91
Annual	93·5	96·0	139·8	59·0	57·4	50·2			

(a), (b) and (c) give range (in γ) on quiet, undisturbed and disturbed days

14 hour *minus* the average of two intervals 00—01 hour and 23—24 hour. The ranges so defined are referred to in the present article as the range in a time-average value of H and denoted by A_a .

From the definition itself, A_i would be larger than A_a . In Fig. 1 are plotted the solar times of occurrence of maximum and minimum values of H and the time interval between these two instants for each day in the period November 1953 to February 1954. On about two-thirds of the days the maximum occurred between 05 and 07 hour U.T. (10—12 hr L.S.T.) and the minimum at any time between 15 to 06 hour L.S.T. The interval between the times of maximum and minimum varied from 03 to 16 hour. On some occasions, the minimum occurred in the early morning hours. Thus A_i does not refer to the difference in H between any two fixed periods of the day and so is less associated with the regular movement of the sun.

It was expected that the magnetic disturbances would cause greater variations in A_i than in A_a. To show the relative effects of magnetic activity on A_i and A_a , the days were divided into three groups according to the degree of magnetic activity, *viz.*, (*i*) quiet days consisting of five international quiet days of each month, (*ii*) undisturbed days consisting of the remaining days from ten international quiet days and (*iii*) disturbed days consisting of five international disturbed days. The average value of A_i and A_a on such groups of days of each season are given in Table 3. As expected, A_i is always greater than the corresponding A_a . There is distinct increase in A_i with increasing magnetic activity. The mean values on the disturbed days are about 1·5 times that on quiet days. The value of A_a seems to decrease slightly with increasing magnetic activity. This is expected because with increasing magnetic activity, disturbance daily variation S_D may become appreciable and decrease the mean daily range of H. During some strong magnetic storms, the diurnal range A_a was found to become negative, because of very large component of S_D or D_{st} variation. The mean value of the range A_a on disturbed days was about 0·85 times that on quiet days. Thus the disturbance effects are much smaller on A_a than on A_i and this makes A_a more suitable for computing the rather small and regular variations like the lunar tides.

3. Method of computation of lunar semi-monthly wave in the solar daily ranges of H

The method used is almost identical with that of Bartels and Johnston (1940). To exclude the effects of magnetic disturbances, only the ranges on the days with the international character index $C_p<1·2$ were used in the analysis. In this paper the *phase* of the moon for a particular day is characterised by the value of μ at Greenwich noon and these are available in tables given by Bartels and Fanselau (1937). It may be noted that the *age* of the moon at Greenwich mean noon, ν, used by some other authors is related to

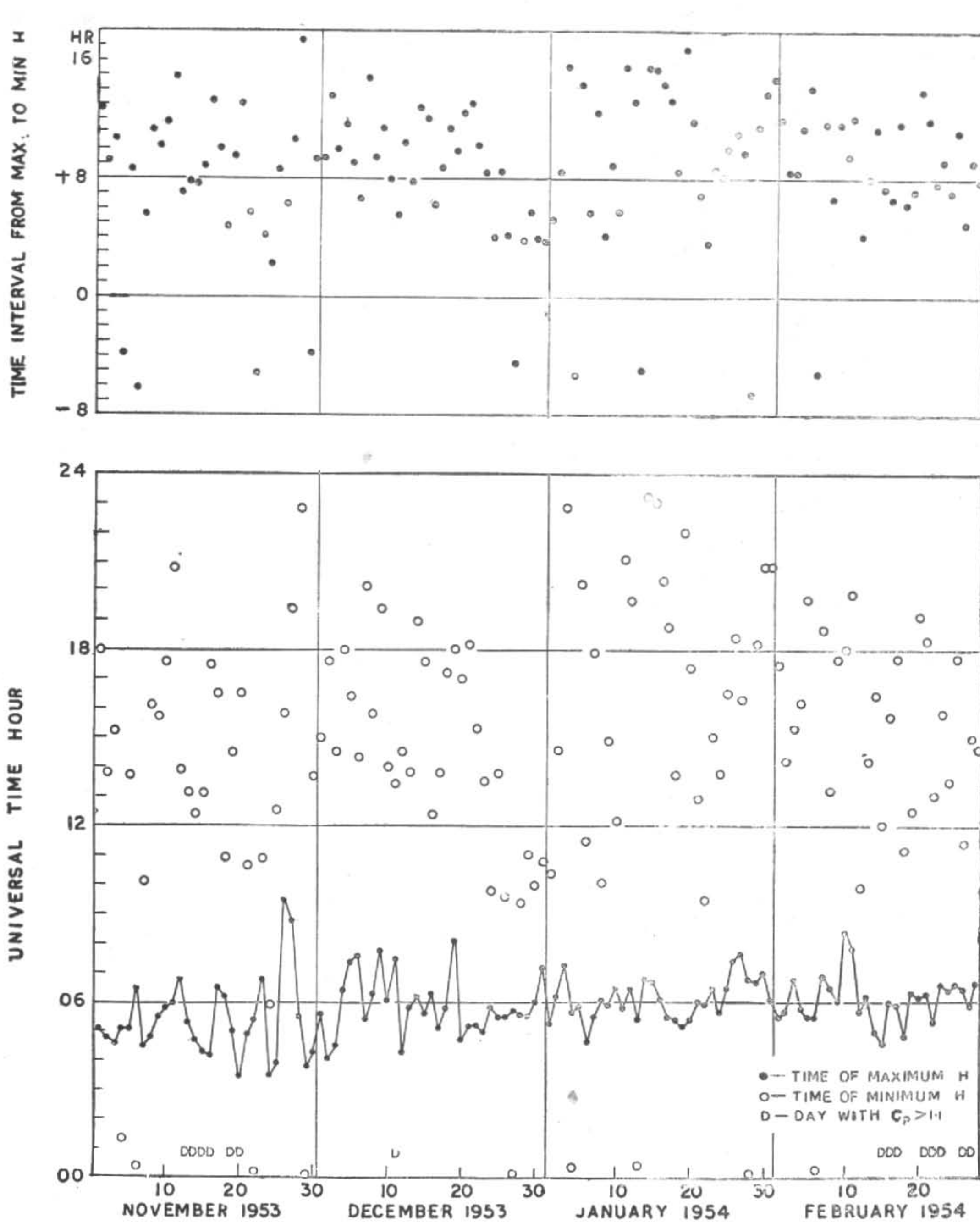

Fig. 1. The times of the occurrence of daily maximum and minimum instantaneous values of H at Kodaikanal during Nov 1953 - Feb 1954

TABLE 4

Computation of lunar semi-monthly wave in daily ranges of the instantaneous values of H at Kodaikanal during the month of June

June in the year	Lunar Phase μ in lunar hour 24 / 12	23 / 11	22 / 10	21 / 9	20 / 8	19 / 7	18 / 6	17 / 5	16 / 4	15 / 3	14 / 2	13 / 1	Mean	Average range of all days (γ)
1950	89	93	—	—	70	104	132	163	122	83	104	88		
	(137)	146	155	69	109	(130)	82	(135)	103	—	—	(187)		
		91		108			91	(128)			90	106	112	
1951	118	82	110	96	115	114	97	232	92	(158)	131	(243)		
	(115)	(227)	—	101	92	(215)	165	78	106	130	(201)	62		
		109	145				95	89		96	107		124	
1952	(139)	(136)	(121)	112	77	72	70	82	67	72	78	67		
	59	(136)	101	88	75	66	(233)	81	67	65	109	81		
		(116)	102			(158)	105		61	65			95	
1953	84	64	68	58	68	52	88	100	96	100	56	82		97·5
	128	80	(212)	56	84	(76)	60	68	64	78	96	68		
	68	68	(84)	(202)					92	74			86	
1954	92	76	70	112	106	71	44	59	80	70	66	93		
	68	86	92	64	67	36	68	108	94	51	61	52		
	72			98	62			46	64				73	
	48													
1955	78	76	84	114	120	58	64	64	48	96	80	95		
	96	125	117	107	127	90	98	146	103	64	85	86	95	
			120	122				114	63	104		92		
Mean	83·3	91·3	105·8	93·2	90·2	73·6	89·9	102·1	82·6	82·0	88·6	81·0		

Average range on undisturbed days = 88·6γ, Lunar semi-monthly way = $3 \cdot 94\ \gamma \sin(2\mu + 177°)$

(All values are given in $\gamma = 10^{-5}$ gauss)

Dashes indicate absence of reading due to instrumental defect

Bracketted values indicate disturbed days with $C_p > 1 \cdot 1$

μ by the relation $\nu = (24 - \mu)$ hours. The daily ranges on quiet days were arranged in 12 groups for μ or $\mu - 12$ is equal to 12, 11, 10 ...... 01 as shown in the sample Table 4 for A_i during months of June. The blank spaces in the table are due to missing values in the original data bulletins, while the bracketted values refer to days with $C_p > 1 \cdot 1$ and are not used in deriving the mean. The averages for the twelve columns is harmonically analysed to give the semi-monthly wave.

$$a \cos 2\mu + b \sin 2\mu = C \sin (2\mu + \alpha)$$

The harmonic analysis of the average lunar variation of A_i in Table 4 gives the following wave —

$$A_i = 88 \cdot 6 + 3 \cdot 94 \sin (2\mu + 177°),$$

i.e., the amplitude of lunar oscillation is $3 \cdot 94\ \gamma$ on an average value of $88 \cdot 6\ \gamma$, the maximum occurring at lunar phase $\mu = 9 \cdot 1$ lunar hour. The corresponding wave derived by Raja Rao is

$$A_i = 83 \cdot 3 + 60 \cdot 4 \sin (2\nu + 172°)$$

It is seen that the average values of A_i in the two analyses are not very different but the amplitude of oscillation is very large in Raja Rao's expression. The two waves are exactly opposite in phase, because although the apparent phase angles are the same, the lunar phase is expressed differently (in μ and ν).

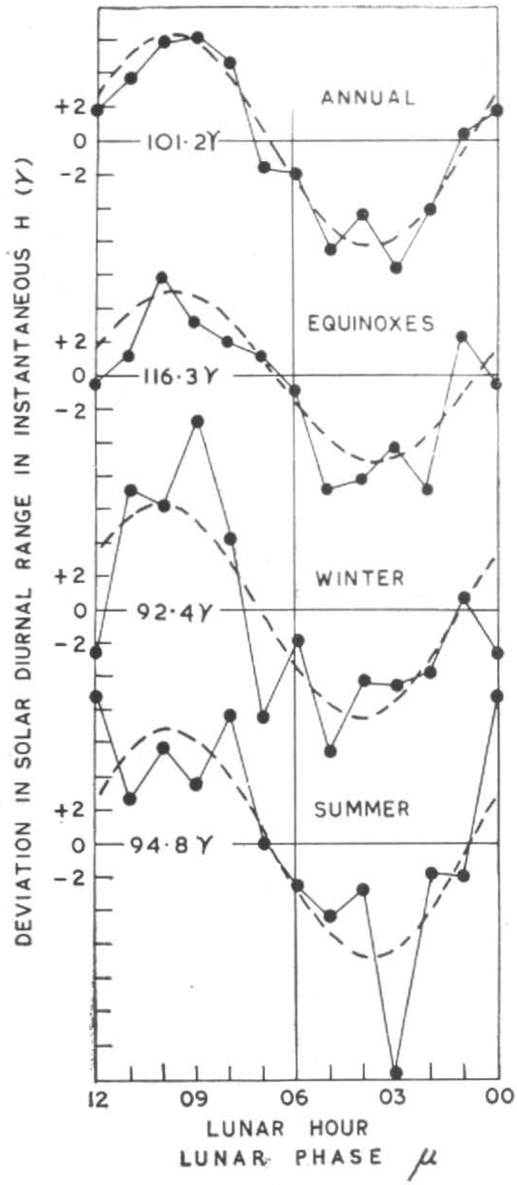

Fig. 2. The lunar variation of the range of instantaneous value of H at Kodaikanal averaged for different seasons of 1950-1955

The probable error has been calculated for each of the amplitude P_2. In June (Table 4) the probable error in amplitude is $2{\cdot}0\gamma$. Chapman (1951) has expressed the view that any determination of amplitude should be considered as statistically significant only if it is at least three times its probable error.

The coefficients of L_2 oscillation are first evaluated for each calendar month and are then combined into seasonal groups, *viz.*, December solstice or winter consisting of November, December, January, February, June solstice or summer consisting of May, June, July, August and equinoctial months consisting of March, April, September and October.

4. Lunar tidal oscillations in the range of instantaneous value of $H(A_i)$ at Kodaikanal for 1950—55

First of all, analysis was done to evaluate the coefficients of lunar semi-monthly variation in the *range of instantaneous values* of H separately for each calendar month. The results are given in Table 5. The amplitudes for different months vary from about 4γ to 10γ and the probable error ranges between 2γ to 4γ. The ratios of the amplitudes to their probable errors are in general less than 3 excepting for February, May and November, the mean value of the ratio for all months is $2{\cdot}46$. Thus according to Chapman's criterion the determinations of the amplitude for individual months are not statistically significant. The maximum of the oscillation for different months occurs at lunar phase μ between 8 to 11 lunar hours, the majority of points being close to 09 hours.

In Fig. 2 are shown the lunar variation of A_i averaged for different seasons and for the whole year separately. The lunar semi-monthly wave derived from the harmonic analysis is shown as the dashed curve. The amplitude and phase μ in lunar hour when the wave attains its maximum positive deviation are given in Table 6. The coefficients together with their probable error circles are shown in the harmonic dial in Fig. 3.

The ratio of the amplitude to its probable error for any season is greater than 3 and thus the coefficients may be considered significant statistically. The amplitude ranges between 5 to 7 γ, the annual average value being equal to $6{\cdot}25$ γ. The amplitude of lunar

TABLE 5

Coefficients of lunar semi-monthly variation in the range of instantaneous values of H at Kodaikanal during different months of the year (1950—1955)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Amplitude (γ)	6·27	9·98	5·12	5·40	9·40	4·07	4·59	7·82	6·76	6·88	7·60	7·30
Probable error (γ)	3·38	3·03	2·65	3·01	2·55	2·00	2·00	3·60	3·17	3·13	2·14	2·81
Amplitude/Probable error	1·86	3·29	1·93	1·79	3·69	2·04	2·25	2·17	2·13	2·20	3·55	2·60
Phase μ of maximum L_2 in lunar hour	8·9	9·3	10·8	8·2	9·1	9·2	9·3	9·6	9·0	9·4	11·2	8·5
Average range (γ)	103·8	102·1	115·8	123·5	105·2	88·6	87·8	94·8	115·9	110·0	82·3	82·3

TABLE 6

Coefficients of lunar semi-monthly variation in the range of instantaneous values of H at Kodaikanal for different seasons of the year (1950—1955)

	December solstice	Equinoxes	June solstice	Annual
Amplitude (γ)	6·38	5·13	6·79	6·25
Probable error (γ)	1·46	1·00	1.11	0·78
Amplitude/Probable error	4·37	5·13	6·12	8·01
Phase μ of maximum L_2 in lunar hour	10·06	9·63	9·78	9·81
Average range (γ)	92·4	116·3	94·8	101·2
Amplitude/Average range	6·9%	4·4%	7·2%	6·2%

TABLE 7

Coefficients of lunar semi-monthly variation in the range of average values of H at Kodaikanal during different months of the year (1950—1955)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Amplitude (γ)	3·38	3·67	4·64	4·10	6·26	4·30	5·50	5·66	8·34	5·50	2·52	3·00
Probable error (γ)	1·85	1·90	2·28	2·34	1·98	1·43	1·29	1·84	1·62	1·60	1·29	1·43
Amplitude/Probable error	1·83	1·93	2·04	1·75	3·16	3·01	4·26	3·08	5·15	3·44	1·95	2·10
Phase μ of maximum L_2 in lunar hour	9·6	9·4	10·2	7·3	9·6	9·5	8·3	7·8	8·8	8·6	10·1	10·4
Average range (γ)	59·4	59·2	70·7	64·6	61·2	50·7	46·3	52·2	62·6	63·8	44·7	45·8

oscillation is only about 6 per cent of the mean value and is consistent with the earlier results that the lunar variation is much smaller than the solar variation.

According to Raja Rao (1962) the amplitudes of lunar semi-monthly wave in A_i are 27·9 γ for December solstice, 35·1 γ for Equinoxes and 43·7 γ for June solstice. These values are about six times as large as those from the present analysis. Further his conclusion that the lunar tide in range of H at Kodaikanal is maximum in June and minimum in December does not give the due regard to the probable errors in the determination of the amplitudes.

According to the present analysis, the maximum positive deviation occurs at lunar phase μ between 9·6 to 10·1 lunar hour, which is in conformity with the results for Huancayo by Bartels and Johnston (1940) who obtained the phase to be 8·5 μ for December and 10·5 μ for June solstices,

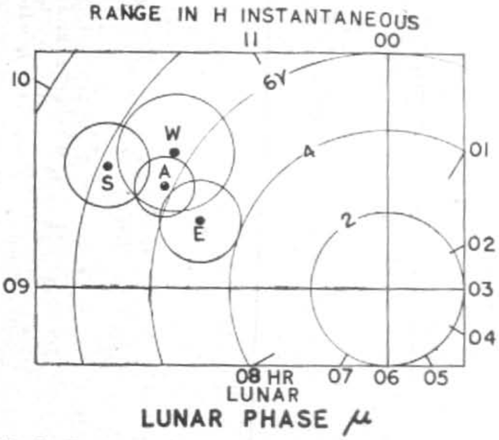

Fig. 3. Harmonic dial showing coefficients of lunar semi-monthly variations in the range of instantaneous value of H at Kodaikanal during winter (W), summer (S), equinoxes (E) and for the whole year (A) for 1950-1955

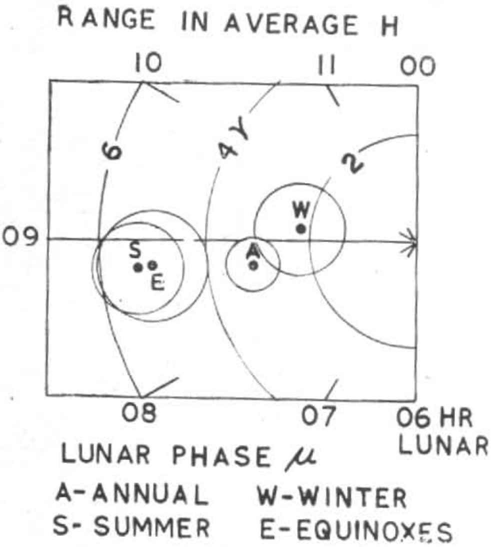

Fig. 5. Harmonic dial showing coefficients of lunar semi-monthly variations in the range of average value of H at Kodaikanal during winter (W), Summer (S), equinoxes (E) and the whole year (A), 1950-1955

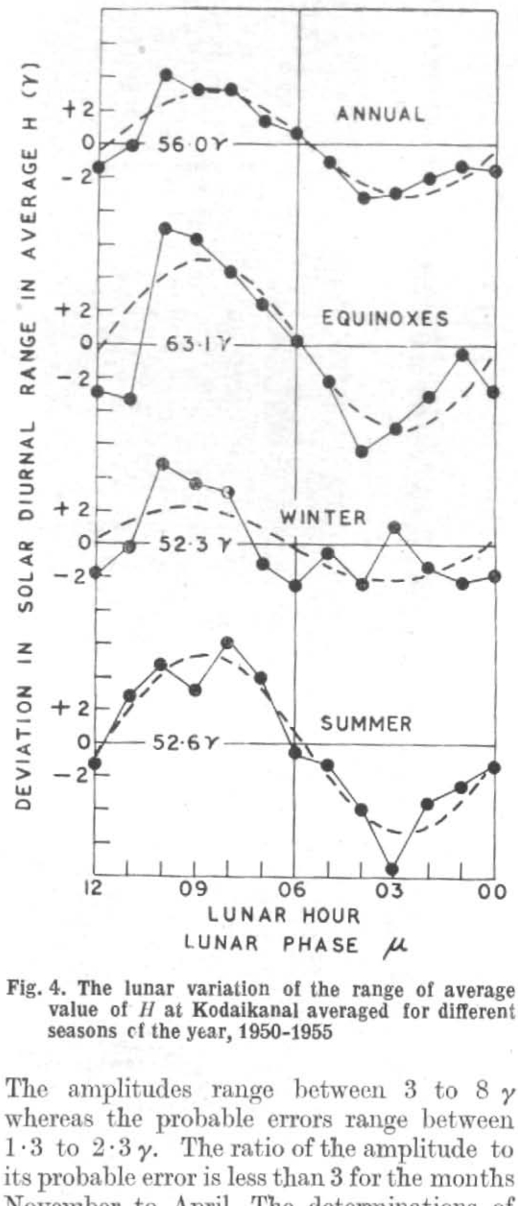

Fig. 4. The lunar variation of the range of average value of H at Kodaikanal averaged for different seasons of the year, 1950-1955

According to Raja Rao the maximum occurs between 8·2 to 10·1 lunar hour in phase ν.

5. Lunar tidal oscillations in the range of average value of $H(A_a)$ at Kodaikanal for 1950–55

A similar analysis was done using the range of average value of H (A_a) as defined in Sec. 2. The coefficients of lunar semi-monthly variation for each month are given in Table 7. The amplitudes range between 3 to 8 γ whereas the probable errors range between 1·3 to 2·3 γ. The ratio of the amplitude to its probable error is less than 3 for the months November to April. The determinations of the amplitude may be taken significant for May to September. The average ratio for all months is 2·8 compared to 2·4 in case of A_i. Thus one gets more significant results using A_a than A_i even for the identical periods. This further indicates large amount of irregular disturbance effects in the range of H when the instantaneous values are utilised

TABLE 8

Coefficients of lunar semi-monthly variations in the range of average values of H at Kodaikanal for different seasons of the year (1950—1955)

	December solstice	Equinoxes	June solstice	Annual
Amplitude(γ)	2·21	5·04	5·33	3·14
Probable error (γ)	0·82	0·99	0·82	0·51
Amplitude/Probable error	2·70	5·09	6·50	6·16
Phase μ of maximum L_2 in lunar hour	9·2	8·8	8·8	8·7
Average range (γ)	52·3	63·1	52·6	56·0
Amplitude/Average range	4·2%	8·0%	10·1%	5·6%

TABLE 9

Coefficients of lunar semi-monthly variations in the range of average value of H at Kodaikanal for different seasons of the year (1956—1958)

	December solstice	Equinoxes	June solstice	Annual
Amplitude (γ)	5·69	8·81	4·40	5·88
Probable error (γ)	1·46	1·71	1·26	0·85
Amplitude/Probable error	3·90	5·15	3·49	6·92
Phase μ of maximum L_2 in lunar hour	8·9	10·3	9·9	9·7
Average range (γ)	88·8	119·8	103·9	103·9
Amplitude/Average range	6·4%	7·4%	4·2%	5·7%

In Fig. 4 are shown the seasonal average curves of the lunar variation in A_a . The coefficients of lunar tidal oscillations are given in Table 8 and are plotted in harmonic dial in Fig. 5. The amplitudes are about 2 γ during December solstice and about 5 γ during June solstice or equinoxes. The low value of amplitude during December solstice makes it rather uncertain due to comparatively large probable error. The annual amplitude was 3·1 γ being maximum at phase μ equal to 8·7 lunar hour. Comparing the analyses of A_i and A_a the average values of the range as well as the amplitude of L_2 oscillations in case of A_a are about half that in A_i. The ratio of the L_2 amplitude to the average range is about 6 per cent in both the cases. The phases of the lunar tide are approximately the same for A_a and A_i.

6. Lunar tidal oscillations in the range of average value of H (A_a) at Kodaikanal for 1956—1958

In order to determine the effect of solar activity on the lunar tide of H similar analysis of the range A_a was done for the high sunspot period 1956—1958. The seasonal average lunar variations are shown in Fig. 8. The results of harmonic analysis are given in Table 9 and plotted in harmonic dial in Fig. 7. Each of the determinations are significant according to Chapman's (1951) criterion.

With reference to Tables 8 and 9 the tidal amplitudes for the annual average oscillations are found to be greater during high sunspot period similar to the average range itself. The ratio of the annual average L_2 amplitude to the average is 5·6 per cent for 1950—55 and 5·7 per cent for 1956—58. When each of the seasons are considered separately large variations are found in the tidal amplitudes for different solar activity periods. The tidal amplitudes during the December solstice increased from 4·2 per cent during 1950—55 to 6·4 per cent during 1956—58, but during the June solstice the tide had decreased from 10·1 per cent in 1950-55 to

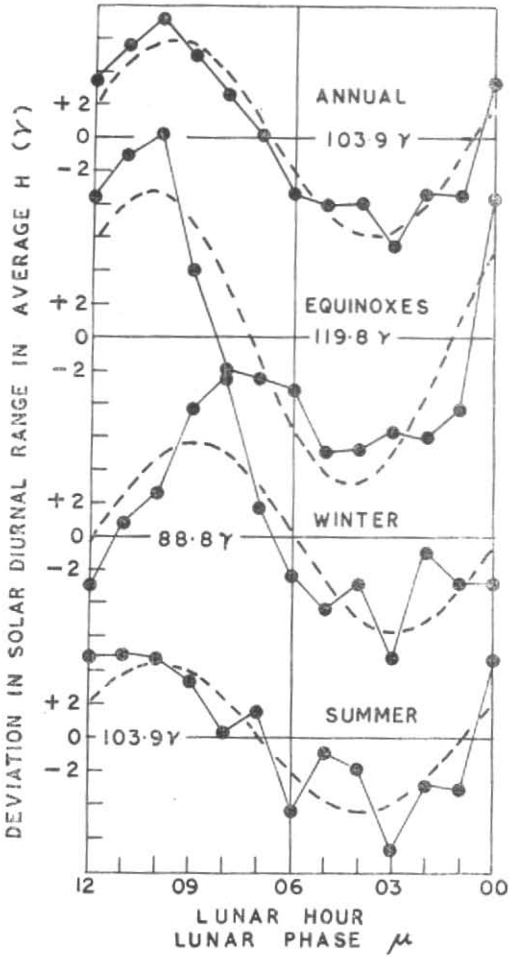

Fig. 6. The lunar variation of the range of average value of *H* at Kodaikanal averaged for different seasons of the year, 1956-1958

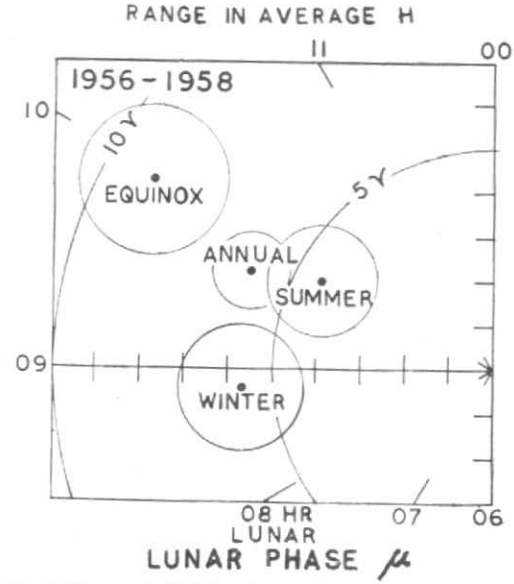

Fig. 7. Harmonic dial showing coefficients of lunar semi-monthly variations in the range of average value of *H* at Kodaikanal during different seasons of 1956-1958

4·2 per cent in 1956—58. Bartels and Johnston (1940) found for Huancayo systematic increase of the L_2 amplitude with sunspots for the Equinoxes and December solstice with rather uncertain decrease in June solstice.

7. Acknowledgements

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