Solar daily Geomagnetic Variation in the Low Latitude Region

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ABSTRACT. The solar daily variation in the geomagnetic field at some low latitude stations has been studied from the harmonic analysis of the hourly values of horizontal intensity. The seasonal variations in the amplitudes and phases with geographic, geomagnetic and magnetic latitudes have been examined. It is found that there is no appreciable variation in the amplitude and phase from winter to summer; but the equinoxial amplitudes are highest for the year, while at higher latitudes the summer values are the highest. There is clear indication of geomagnetic control of the *S* variation, dependence on the magnetic latitude being closer than dependence on the geomagnetic latitude.

1. Introduction

Balfour Stewart first put forth the suggestion in 1882 that the observed daily magnetic variations were caused by the electrical currents flowing in the upper regions of the atmosphere, from a discussion of the solar daily variations in the geomagnetic field. Schuster in 1889 developed Stewart's ideas on a mathematical basis. It is now believed that the daily magnetic variations are caused by the movement of the ionospheric layers across the lines of force of the earth's magnetic field. The ionospheric movements are caused by the gravitational and thermal actions of the Sun on the ionosphere. The currents produced by this 'dynamo' action, wherein the ionised air is the armature, and the earth's main field is the permanent magnet, in turn produce the observed daily magnetic variations on the earth's surface.

The solar daily variation *S*, is mainly diurnal. The amplitude of the daily variation is large near the geomagnetic equator and decreases polewards. The seat of the ionospheric currents causing the *S* variations is at the base of the *E* layer about 100 km above the earth's surface.

In the low latitude region the daily magnetic variations show some peculiar features which are not common in higher latitudes. For example, near the geomagnetic equator at Huancayo (geomagnetic latitude $0°\cdot6$ S), the daily range is nearly twice the value expected from a comparison with the ranges elsewhere. In order to study the peculiar features of the *S* field in the low latitude region, the solar daily variation has been studied at four low latitude stations—Kodaikanal, Alibag, Honolulu and San Juan. Such study for Apia has been made by the author with C. T. Thomas and the results are being published in a separate paper in this issue. The results pertaining to Kodaikanal (Raja Rao 1961) and those for Alibag (Raja Rao 1962) have been published. The results of the investigation of the *S* field at Ibadan (Onwumechilli and Alexander 1959) and Huancayo (Chapman and Bartels 1940) made by others are used in order to give a synthetic picture of the *S* field in the low latitude region.

The geographic and geomagnetic coordinates of the stations are given in Table 1.

The location of these observatories together with the disposition of the geomagnetic, the magnetic and the geographic equators is shown in Fig. 1.

2. Harmonic analysis of the *S* field

Periodic variations like *S* can be specified by their sinusoidal components as determined

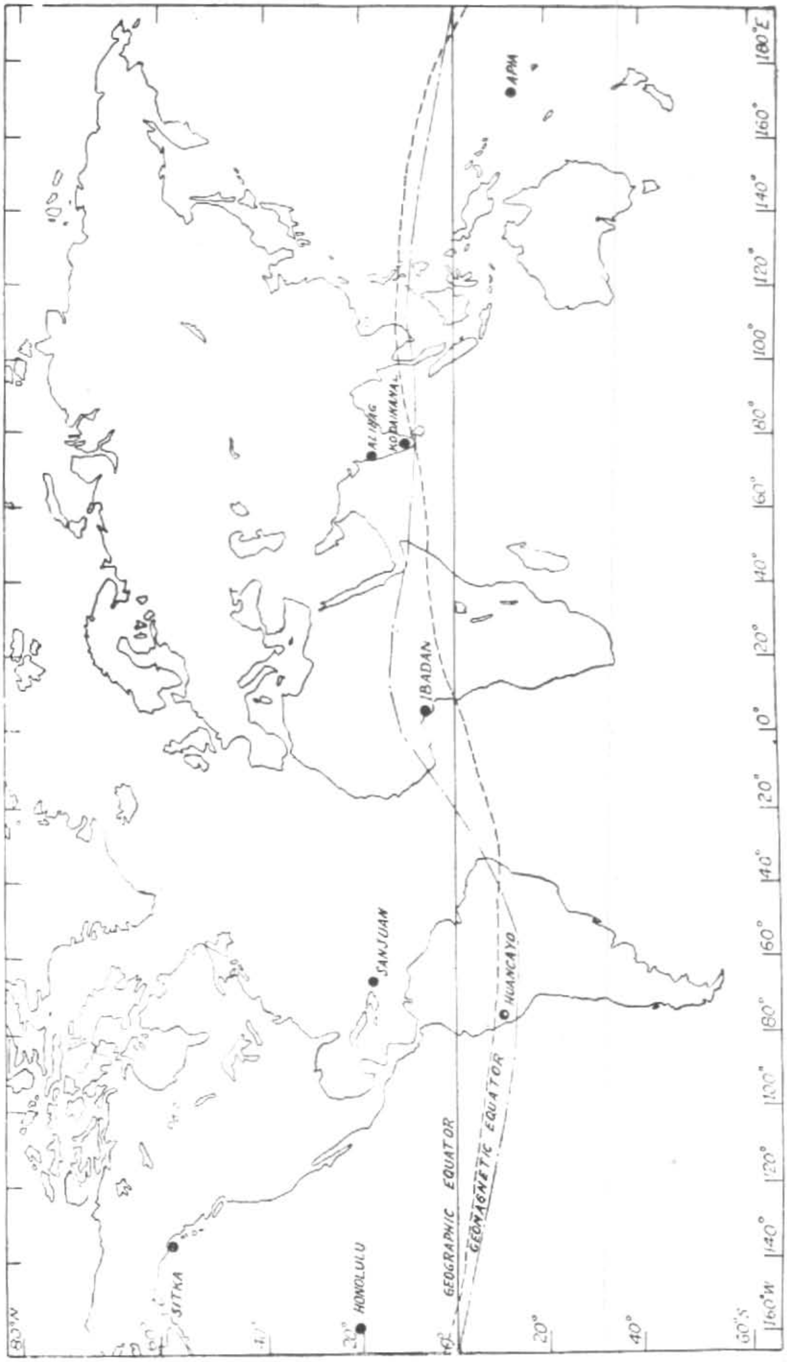

Fig. 1. Location of observatories with respect to the geomagnetic and geographic equators

TABLE 1

Geomagnetic observatories in the low latitude region

Station	Geographic		Geomagnetic		Dip (Mag. Lat.)
	Lat.	Long.	Lat.	Long.	
Apia	13°·8 N	188°·2 E	16°·0 S	260°·2 E	30°·0 S
Huancayo	12°·0 S	75°·3 W	0°·6 S	353°·8 E	2°·5 N
Kodaikanal	10°·2 N	77°·5 E	0°·6 N	147°·1 E	3°·5 N
Alibag	18°·6 N	72°·9 E	9°·5 N	143°·6 E	24°·0 N
Ibadan	7°·5 N	3°·9 E	10°·5 N	74°·7 E	6°·0 S
Honolulu	21°·3 N	158°·1 W	21°·1 N	266°·5 E	39°·5 N
San Juan	18°·4 N	66°·7 W	29°·9 N	3°·2 E	52°·8 N

by harmonic analysis. Such periodic sequences can be represented by the series

$$\sum_n C_n \sin(nt+\epsilon_n) = \sum_n (a_n \cos nt + b_n \sin nt)$$

Here t denotes the local time reckoned in angular measure at the rate of 15° per hour. The curves of daily magnetic variations can be generally represented with sufficient accuracy by using only four harmonics n=1, 2, 3 and 4.

The hourly values of the horizontal intensity of the earth's magnetic field at the four stations have been used in the analysis. The period 1950—54 which is the minimum part of the solar cycle has been taken. For Honolulu and San Juan, the data have been extracted from their annual volumes. In the case of San Juan, only two years' data, *viz*, 1950 and 1952, have been used as data for other years were not available. However, great care has been taken to exclude the disturbance field by rejecting all the daily sequences for days with international character figure exceeding 1·1. The method of calculating the amplitudes and phases of the harmonics has been described by the author in an earlier paper (Raja Rao and Sivaraman 1958).

In this study all the disturbed days have been omitted; but the selection of quiet days only, has not been made. Therefore, the solar daily variation considered is not S_q but $S = S_q + S_D$, where S_D is the disturbance daily variation.

3. Discussion

Results of Analysis—The amplitudes and phases of the first four harmonics for the three seasons—December solstice, Equinox and June solstice—for the low latitude stations, are given in Table 2(a and b).

The prominent harmonic in the S variation is the first harmonic. The second harmonic constitutes 75 to 80 per cent of the first, and the third harmonic 25 to 15 per cent of the first. The ratios of $S_2(H)$ to $S_1(H)$ and $S_3(H)$ to $S_1(H)$ are given in Table 3.

The amplitude of the fourth harmonic is very much less than the first, but still accounts for about 10 per cent of the total variation.

The solar daily variation at each of the low latitude observatories, has been synthesised from the curves corresponding to the first four harmonics and shown in Figs. 2 to 5.

TABLE 2

		Kodaikanal	Alibag	Honolulu	San Juan
(a) Showing the amplitudes in γ of the first four harmonics of solar daily variation					
D-Season	S_1	19·1	12·80	8·02	6·10
	S_2	14·6	6·8	2·10	2·6
	S_3	7·8	2·0	1·22	1·6
	S_4	2·20	0·70	0·71	0·22
E-Season	S_1	24·5	17·0	11·1	8·0
	S_2	18·9	9·0	2·68	2·8
	S_3	10·0	2·9	1·22	1·4
	S_4	4·30	0·80	0·54	0·14
J-Season	S_1	22·6	12·3	6·2	5·5
	S_2	14·8	7·1	2·1	3·0
	S_3	5·6	2·3	1·2	1·6
	S_4	4·20	0·80	0·71	0·21
(b) Showing phases of the above harmonics					
D-Season	σ_1	—69°30′	—69°32′	335°21′	340°16′
	σ_2	—64°34′	—77°14′	159°24′	163°29′
	σ_3	208°27′	—196°06′	304°21′	49°24′
	σ_4	124°00′	—217°06′	85°38′	268°06′
E-Season	σ_1	—73°47′	—70°40′	336°03′	338°54′
	σ_2	118°48′	—102°31′	85°14′	154°45′
	σ_3	134°41′	—209°18′	284°21′	97°20′
	σ_4	113°17′	—275°08′	104°02′	234°42′
J-Season	σ_1	—75°00′	—67°51′	330°01′	322°18′
	σ_2	—67°12′	—80°00′	142°21′	116°57′
	σ_3	218°24′	—183°54′	192°17′	70°46′
	σ_4	63°18′	—275°49′	63°44′	196°52′

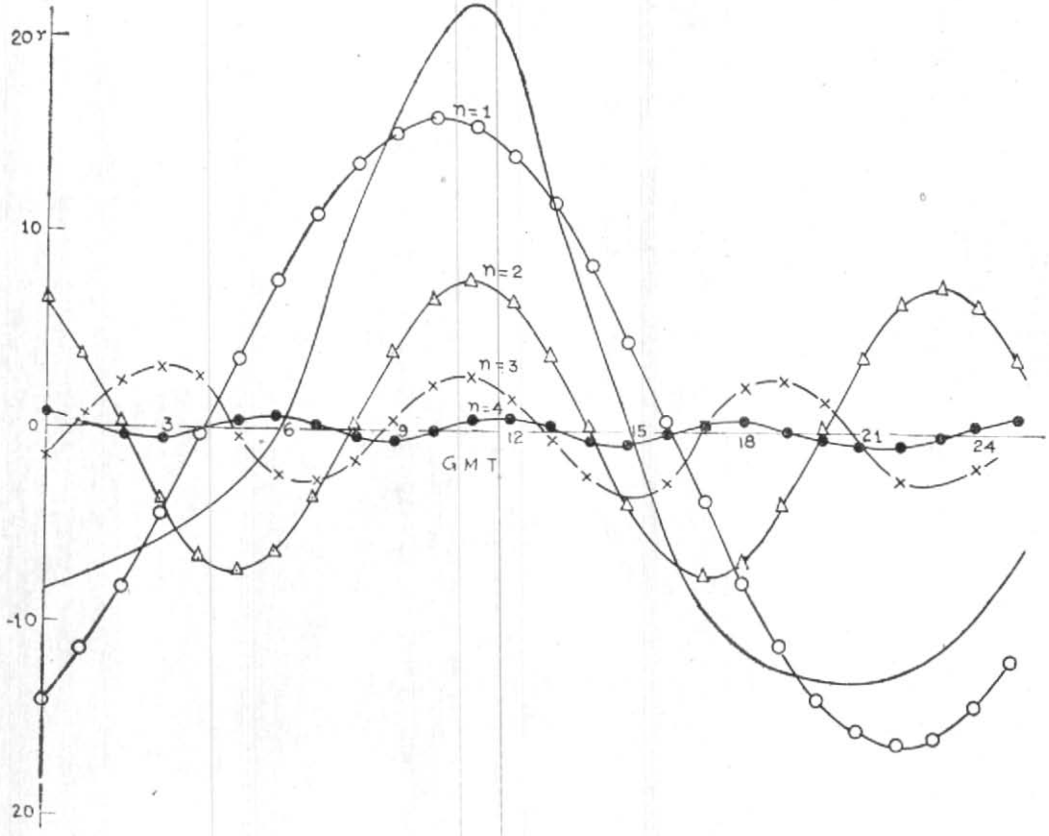

Fig. 2. Solar variation of Honolulu (Heavy curve) synthesised from first four harmonics (n=1, 2, 3, 4)

The discussion of the nature of S variation is confined to the first two harmonics only, although the third and fourth harmonics have been included in the tables and graphs for the sake of completeness.

Seasonal variation—Unlike the $L(H)$, the $S(H)$ does not show any appreciable change from winter to summer, in amplitude as well as in phase. But the amplitudes of $S_1(H)$ and $S_2(H)$ are slightly greater in the equinox than in the solstices. The equinoctial maximum has been noticed in Kodaikanal Alibag, San Juan and Honolulu, as also at Ibadan & Huancayo, the only exception being S_2 at San Juan which is greatest in summer and least in winter. But in Apia, the maximum amplitude occurs in December (southern summer) and the minimum in June (southern winter) the equinoctial value being intermediate between the summer and winter values. The occurrence of equinoctial maximum is entirely a low latitude phenomenon, in contrast with the seasonal variation in the higher latitudes (say, Sitka) where amplitudes are greatest in local summer and least in local winter.

The phase angles are greater in winter than in summer for the two harmonics with the sole exception of Alibag in which case the phase of S_1 is greater in summer than

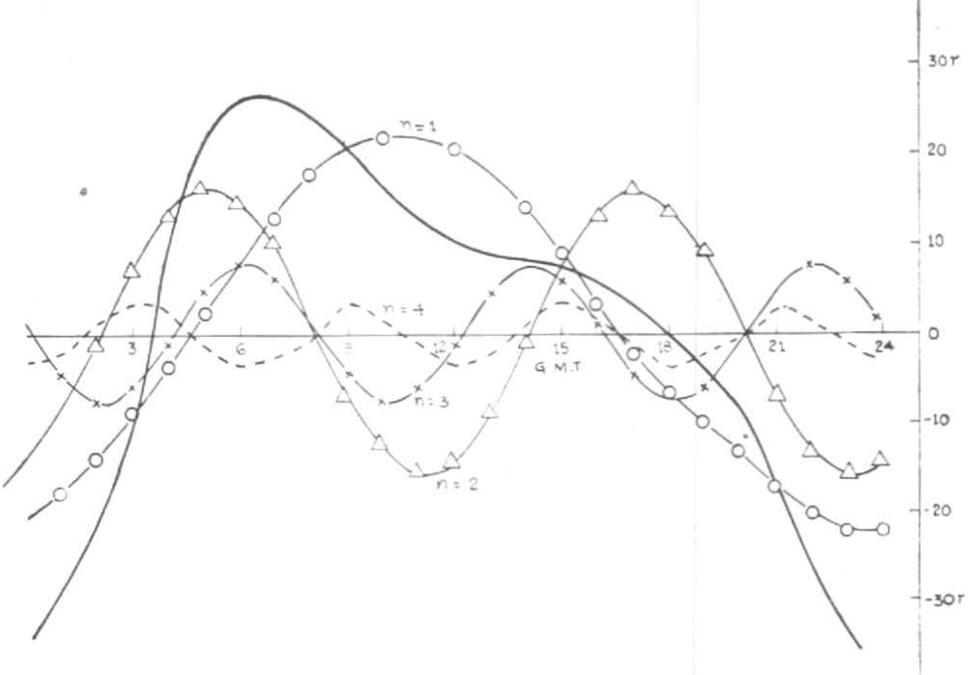

Fig. 3. Solar daily variation of horizontal intensity at Kodaikanal (Thick curve) synthesised from the first four harmonics (n = 1, 2, 3, 4) for 1950-54

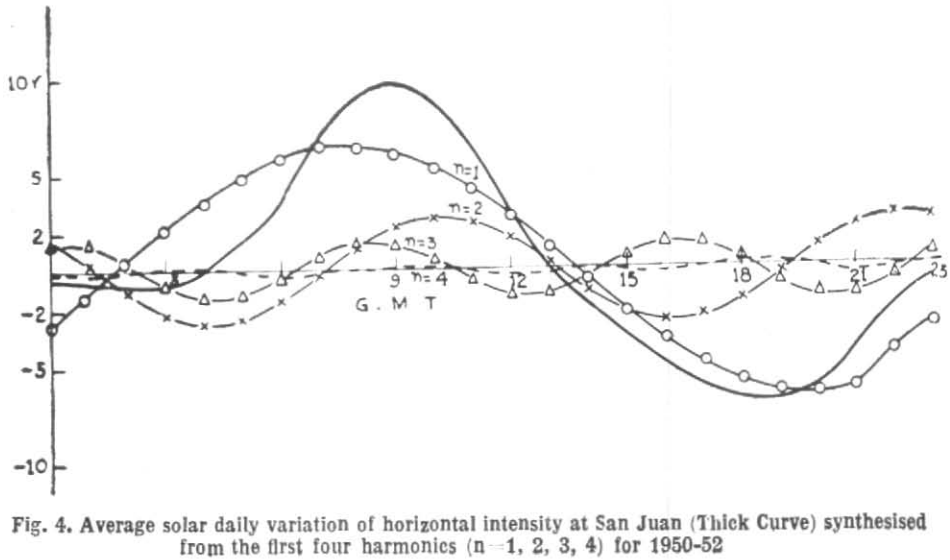

Fig. 4. Average solar daily variation of horizontal intensity at San Juan (Thick Curve) synthesised from the first four harmonics (n = 1, 2, 3, 4) for 1950-52

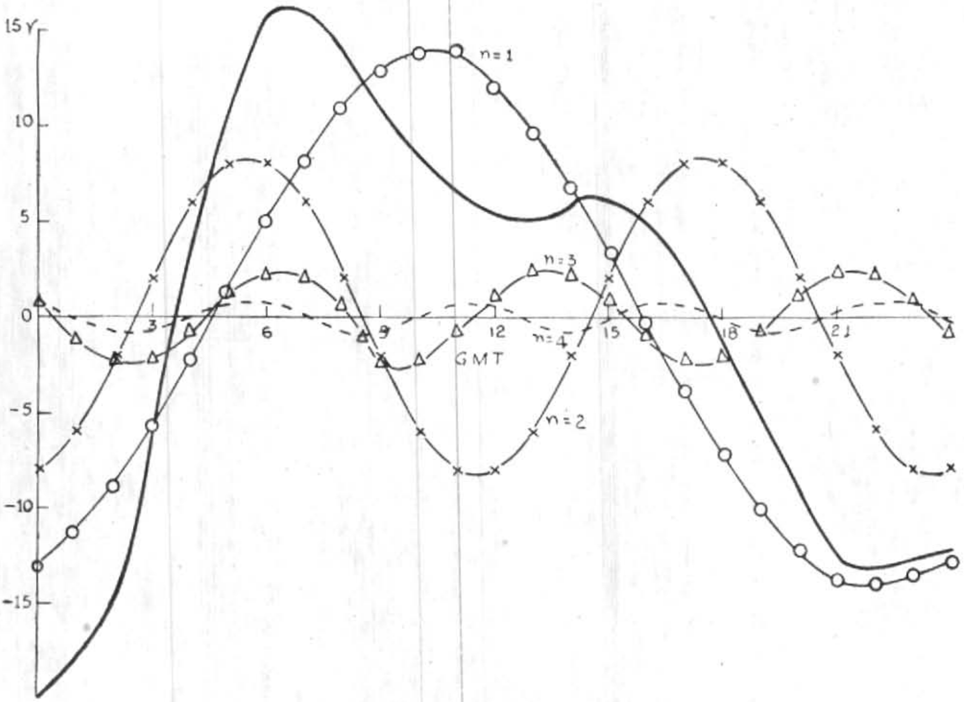

Fig. 5. Average solar daily variation of horizontal intensity at Alibag (Thick curve) synthesised from the first four harmonics (n=1, 2, 3, 4) for 1950-54

in winter by 1°41′. The magnitude of the difference increases with the geomagnetic latitude, except very near the geomagnetic equator. The difference between the winter and summer phases is given in Table 4.

At Sitka (Caine 1957) $\sigma_{\text{winter}} - \sigma_{\text{summer}}$ is 9° for the first harmonic and —26° for the second.

Geomagnetic control of the S field—Study of the amplitudes of $S(H)$ obtained for Kodaikanal, Alibag, Honolulu, San Juan and Apia, together with those for Ibadan and Huancayo reveals some interesting features. Firstly, it has been noticed that Kodaikanal, Huancayo and Ibadan show anomalously large S variations. Although the original theory of Chapman could not explain this anomaly, later investigations of Martyn and Baker (1953), Hirono (1950, 1953) and Fejer (1953, 1954) have shown that the ionospheric conductivity is enhanced in a narrow zone near the magnetic equator. The presence of this 'electrojet' is responsible for the large amplitudes of $S(H)$ at these stations.

Secondly, it is noticed that although Alibag and San Juan are practically on the same geographic latitude, their amplitudes of $S(H)$ are widely different—the $S_1(H)$ at Alibag is 2·1 times the $S_1(H)$ at San Juan and $S_2(H)$ at Alibag 3·2 times the $S_2(H)$ at San Juan. Chakrabarty (1954) had earlier drawn attention to this anomaly. In the present investigation, observations at Honolulu (geomagnetic latitude 21°·1 N and geographic latitude 21°·3 N) are also considered. For Honolulu, whose geomagnetic latitude and dip are intermediate between those for Alibag and for San Juan, the magnitude of $S(H)$ variation is also intermediate between those of Alibag and San Juan. The discrepancy between the Alibag and San Juan amplitudes cannot, therefore, be explained by the simple longitudinal variation, for in that case the amplitude of

TABLE 3

Ratio of amplitudes

Station	$S_2(H)/S_1(H)$	$S_3(H)/S_1(H)$
Huancayo	0·55	..
Kodaikanal	0·73	0·35
Ibadan	0·45	0·21
Alibag	0·57	0·17
Apia	0·50	0·18
Honolulu	0·27	0·14
San Juan	0·44	0·23

TABLE 4

Winter to Summer difference in phase at low latitude stations

Station	Geomagnetic latitude	$\sigma_{\text{winter}} - \sigma_{\text{summer}}$	
		First harmonic	Second harmonic
Kodaikanal	0°·6 N	5°31′	2°38′
Alibag	9°·5 N	1°41′	2°46′
Ibadan	10°·5 N	1°57′	7°38′
Honolulu	21°·1 N	5°20′	+17°22′
San Juan	29°·9 N	17°58′	46°32′
Apia	16°·0 S	20°00′	−33°01′

σ is the phase angle

Honolulu should have been greater than the amplitude at San Juan.

In a recent communication Matsushita (1960) has stated that the solar geomagnetic variations on quiet days at San Juan are almost identical with those at Teoloyucan (19°45′N, 99°11′ W, and geomagnetic latitude 29°·6N) because both are situated on the same geographic latitude. On the contrary, Matsushita's observation lends further support to the contention stated earlier, *viz.*, geomagnetic rather than geographic dependence of $S(H)$. For, San Juan and Teoloyucan have practically the same geomagnetic latitude—29°·9N and 29°·6 N respectively. If on the other hand the geographic dependence prevailed, Alibag, San Juan, Honolulu and Teoloyucan which are nearly on the same geographic latitude, should have had the same $S(H)$ variation which is not a fact.

In the dynamo theory we have for the current function R, the relation

$$K\left\{\frac{\partial^2 R}{\sin\theta\,\partial\phi^2}+\frac{\partial}{\partial\theta}\left(\sin\theta\,\frac{\partial^2 R}{\partial\theta}\right)\right\}$$

$$-\left\{\frac{\partial K}{\partial\phi}\cdot\frac{\partial R}{\sin\theta\,\partial\phi}+\sin\theta.\,\frac{\partial K}{\partial\theta}\cdot\frac{\partial R}{\partial\theta}\right\}$$

$$=aK^2\left\{\frac{\partial(vH_z)}{\partial\phi}+\frac{\partial}{\partial\theta}(uH_z\sin\theta)\right\}$$

where K is the height integrated electrical conductivity of the ionosphere; H_z is the vertical component of the earth's magnetic field; u and v are the components of horizontal velocity of matter in the ionosphere along north and east directions respectively and θ and ϕ are the co-latitude and longitude of the place.

From this equation, it is clear that θ and K are the only terms connected with magnetic latitude and appearing explicitly. Although H_z is present, only its variation with latitude, $\partial H_z/\partial\theta$ is taken into account. It should be mentioned here that the modern ideas of ionospheric conductivity were not known at the time when the original dynamo theory was propounded, basing on the spherical harmonic analysis of the observed solar daily variation of the geomagnetic field. Therefore, geomagnetic control of the S variation was not contemplated earlier.

According to the modern theory of ionospheric conductivity, the total specific conductivity K is made of K_1, K_2, and K_3,

$$K = K_1+K_2+K_3$$

where K_1 is the transverse or Pedersen conductivity, K_2 is the Hall conductivity and K_3 is the Cowling conductivity; each of these conductivities K_1, K_2 and K_3 contains the factor Ne/F (Ne=number of electrons per c.c. in the ionosphere and F is the geomagnetic field) so that the geomagnetic control of the S variation is contained in the conductivity term. But in the dynamo equation, K, the height integrated conductivity is taken as constant whereas the total conductivity varies with latitude as F is involved in the conductivity.

Vestine and others (1947) discussing the Sq variation remark 'Sq depends about as closely on geographic as on geomagnetic latitude, the difference being negligible in low latitudes and very slight in middle latitudes'. But the present studies show that this difference—which is a factor of 2·1 for the first harmonic and a factor of 3·2 for the second—is not negligible. Also, this difference cannot be attributed to longitude effect, for in that case Honolulu should have shown S variation smaller than San Juan, while it is actually intermediate between Alibag and San Juan.

Nagata, Fukushima and Suguira (1950) have tried to explain the longitudinal inequality of S, by attributing it to the non-coincidence of the geographic and geomagnetic axes. But this phenomenon of non-coincidence of the two axes is accounted for as a natural consequence if geomagnetic latitude somehow appears explicitly in the dynamo equation, for, the expressions for geomagnetic latitude

$$\tan x = \cos (\lambda - \lambda_0) \cot\phi$$

$$\tan \Lambda = -\tan (\lambda - \lambda_0) \sin x \sec (x+\phi_0)$$

$$\tan \phi = -\cos \Lambda \tan (x+\phi_0)$$

take into account the co-ordinates of the geomagnetic pole (λ_0, ϕ_0). Here Λ is the geomagnetic longitude, λ and ϕ are geographic latitude and longitude, of the place; x is an auxiliary angle.

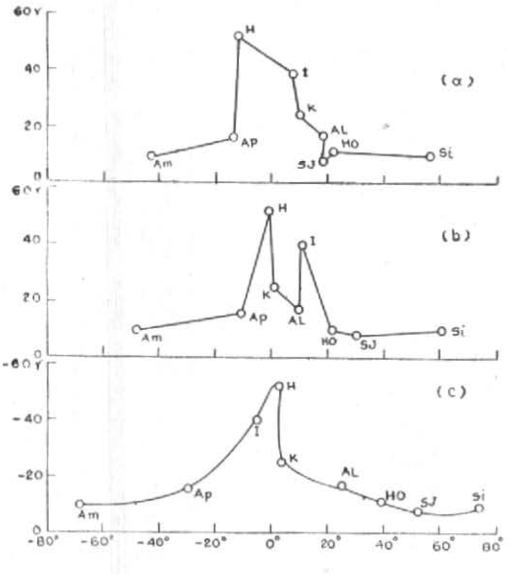

Fig. 6. Variation of main component of solar Geomagnetic tide with (a) Geographic latitude, (b) Geomagnetic latitude and (c) Dip

Am—Amberly, Ap—Apia, AL—Alibag, H—Huancayo, HO—Honolulu, I—Ibadan, K—Kodaikanal, SJ—San Juan, Si—Sitka

Meada (1953) has attacked the problem from a different point of view while trying to eliminate the residuals of Sq variation; he has put forth a suggestion that a new set of co-ordinates may be used in place of the geographic latitudes and longitudes, in the dynamo equations. The new co-ordinates given by Meada are not much different from geomagnetic latitudes and longitudes.

In order to decide whether the magnetic dip or the geomagnetic latitude represents a good geomagnetic control, amplitudes of $S(H)$ have been plotted against magnetic dip, and also against geomagnetic latitude, magnetic latitude and geographic latitude. These plots are given in Fig. 6.

These graphs indicate that the dependence of $S_1(H)$ on magnetic dip explains the geomagnetic control of $S_1(H)$ better than geomagnetic latitudes does. It may be recalled here that Appleton (1946) found that plot of F_2 critical frequency against magnetic dip represents geomagnetic control of the F_2 layer better than the plot against geomagnetic latitude.

4. Conclusion

From these studies, it is seen that equinoctial maximum in the amplitude of $S(H)$ is purely a low latitude phenomenon. The $S(H)$ variation is not dependent on geographic latitude as the dynamo equations imply; but there is a geomagnetic control of $S(H)$. Dependence appears to be better with magnetic latitudes than with geomagnetic latitudes. The dynamo equations need modification in the light of these facts.

5. Acknowledgement

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