551·510·535 : 523·78

Movements in the *F* region of the Ionosphere during Solar Eclipses

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(*Received 21 March 1960*)

ABSTRACT. *F* layer ionospheric data collected during the partial solar eclipses of 20 June and 14 December 1955 have been analysed. In order to study the effects of the eclipses at several heights, the electron density-height profiles have been obtained from the *h′-f* curves for several levels between 250 and 400 km. Assuming a model of the ionosphere in which electron loss is by an attachment process, the magnitudes of the movement terms of the continuity equation have been derived and discussed for the two eclipses and their respective control days.

1. Introduction

The behaviour of the *F* region of the ionosphere is known to be complex. While the changes in *E* and *F*1 layers are explicable in terms of Chapman layers and changes in the intensity of ionizing radiation during eclipses, the identification of any changes in *F*2 layer associated with the eclipses is not easy. There are unaccounted-for variations from day-to-day in its maximum electron density and height on magnetically quiet days, which make it difficult to derive the 'normal' or 'control day' behaviour for comparison purposes. In equatorial stations such as Kodaikanal where *F* region peak is at about 350 km during day time, the time constant for the life of electrons is large and any decrease in electron density during an eclipse cannot be expected to result from layer response to drop in the intensity of the ionizing radiation. The electron densities are affected differently during eclipses depending upon the season and time of occurrence of the eclipses. Thus, while observations of Minnis (1955) indicate that the electron density of the *F*2 layer remained almost constant during the total solar eclipse of 25 February 1952 at Khartoum, a large reduction in maximum electron density was observed by the present authors (1956) at Kodaikanal during the eclipse of 20 June 1955 of magnitude 0·91. Further the eclipse effects are not confined to simple changes in electron densities. The large vertical drifts caused at low latitudes by the electrostatic polarization field associated with the production of the currents in the dynamo region appear to be considerably modified during eclipses. Evidence of these indirect effects has been found by Thomas and Robbins (1956), who have deduced the magnitudes of the movement term of continuity equation from data of several stations collected during the eclipses.

In the present paper, the *F*2 layer data collected during two partial eclipses of 20 June and 14 December 1955 have been analysed. The temporal variations $N(t)$ of N at a series of heights between 250 and 400 km have been computed from *h′-f* traces for both the eclipse days and their respective control days. Assuming that the Ratcliffe *et al.* (1956) model is correct, the magnitudes of the movement term have been calculated and discussed for the two eclipses.

2. Circumstances of the eclipses

The summer and winter eclipses were both of large magnitudes. The circumstances of the eclipses are given in Table 1.

On both the eclipse days as well as on the respective control days vertical incidence *h′-f* records were obtained at 5-minute intervals using C.R.P.L. type C-3 Ionosonde.

TABLE 1

Eclipse	Beginning h	Beginning m	Middle h	Middle m	End h	End m	Magnitude at ground
	(IST)		(IST)		(IST)		
20-6-1955	07	08·4	08	11·9	09	25·2	0·914
14-12-1955	10	40·4	12	57·6	14	59·3	0·774

The day of the winter eclipse and five out of six control days were classified as magnetically quiet days in the I.A.T.M.E. bulletins with C_p figures between 0·0 and 0·2. For the sixth control day, *i.e.*, on 16 December 1955, the figure was 0·5.

3. Height and maximum electron density variations

For the summer eclipse of 20 June 1955, the features have been described by the present authors in an earlier paper (1956). For the winter eclipse of slightly smaller magnitude the variations in both the height and critical frequency of the $F2$ layer were less marked than those of the summer eclipse. With the progress of the eclipse the virtual height registered an increase till a maximum of about 390 km was reached at about the time of the maximum phase. The 'control day' value of this parameter, for the same time, was 320 km. The critical frequency decreased at the same time, a minimum of 7·5 Mc/sec occurring at about the time of end of the eclipse, the 'control day' value of this parameter being 10·7 Mc/sec for the same time. The standard deviation in $foF2$ for this time of the day being only 1·01 Mc/sec, the drop of 3·20 Mc/sec during the eclipse was, therefore, quite significant.

The last one hour of this eclipse was characterised by the appearance of a 'spur' in the lower F region. This was followed by substantial changes in the shape of the layer and the development of a ledge or stratification.

4. Distribution of electron desnity as a function of true height

In order to examine the variation of electron density with time at several selected heights during the eclipses, the h'-f records were reduced to N-h profiles using data at 20-minute intervals for both the eclipse days and their control days. For obtaining these profiles Schmerling (1958) has recently published sampling ratios with the earth's magnetic field taken into account. Schmerling and Ventrice (1959) have given tables of coefficients which enable the reduction of h'-f records of any station, whose magnetic dip is not greater than 80° to electron density-height profiles. Using appropriate coefficients for the dip at Kodaikanal the values of N were determined at 20-minute intervals and N-t curves for several heights obtained from these data. For the summer eclipse which occurred immediately after sunrise when the layer height was comparatively low, these data could be obtained for 250 and 300-km levels only for the whole duration of the eclipse and for 350 km during the later part. The variation of N with time at these heights is shown in Fig. 1. For the winter eclipse, the variation of N with the time could be determined upto 400-km level and these for heights of 250, 300, 350 and 400 km are shown in Fig. 2. The values $N(t)$ for the same heights for 'control days' are also plotted in the respective figures.

It will be seen from the curves that the electron densities decreased at all levels following the eclipse. At the lowest level considered here, *i.e.*, 250 km the minimum in electron densities occurred at about the time of maximum phase for both the eclipses. For 300-km level the electron density approached minimum value of about 25 minutes (summer eclipse) and 10 minutes (winter eclipse) after the maximum phase. The time

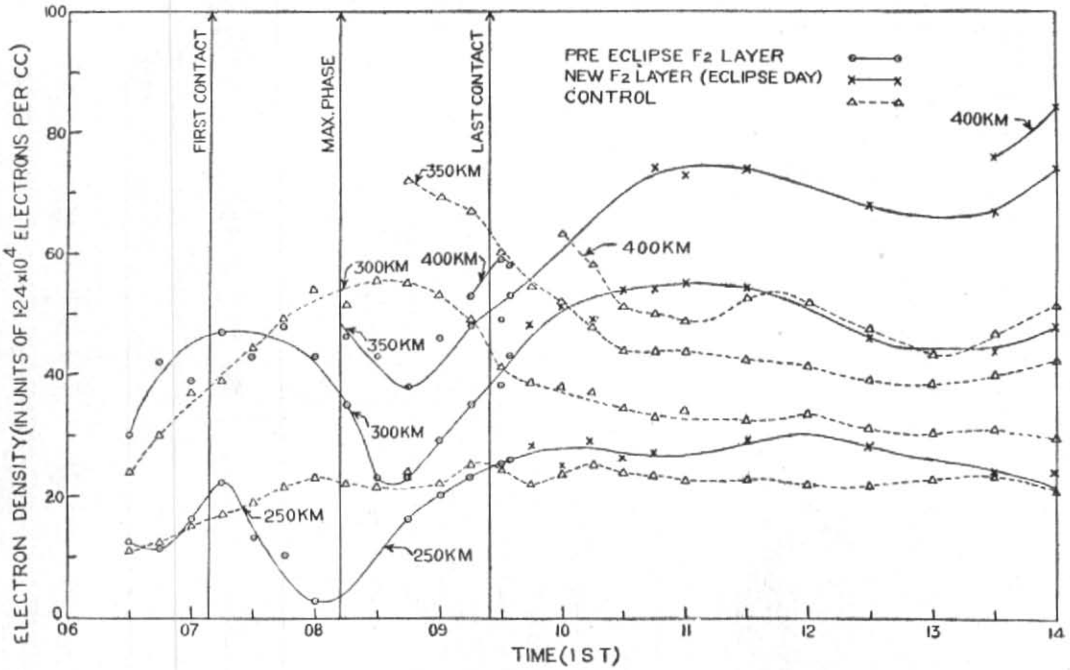

Fig. 1. Observed electron density for several true heights during the eclipse of 20 June 1955

difference was about 34 minutes (summer eclipse) and 42 minutes (winter eclipse) at 350 km height. The time thus increased with increasing heights but the magnitudes of the delay were far short of time constants of the electrons at all levels. From the Ratcliffe *et al.* (1956) model, the loss coefficient β varies with height according to the following expression—

$$\beta = 10^{-4} \exp \left\{ \frac{300 - h \text{ (km)}}{50} \right\} \text{ sec}^{-1}.$$

The time constant for the life of electrons at heights of 250, 300 and 350 km from the above expression are 1 hour, 3 hours and 7·5 hours respectively. The intervals between the times of maximum phase and minimum in electron density for both the eclipses were thus much shorter than the time constants of electrons at all heights. It, therefore, follows that the effects of the eclipses were not simple reduction of N following a decrease in ionizing radiation but that there were indirect effects apparently associated with additional movements set up in the region and subsequent redistribution of ionisation. The magnitudes of the movements at several heights for the two eclipses are derived in the following section.

5. Movements in the *F* region

The equation of continuity of electron density N at a fixed height may be written,

$$\frac{dN}{dt} = I\,(t) f\,(X,\, h) - \beta(h)\, N + M\,(h,t)$$

where I (t) is the intensity of ionizing radiation and is a function of time during an eclipse, $f(X, h)$ represents the way in which the rate of electron production depends upon the solar zenith angle X and the height h in the inosphere, β (h) is the attachment coefficient for the rate of electron loss and is a function of height, M (h, t) is the movement term $\frac{d(N.w)}{dh}$, w being the vertical drift

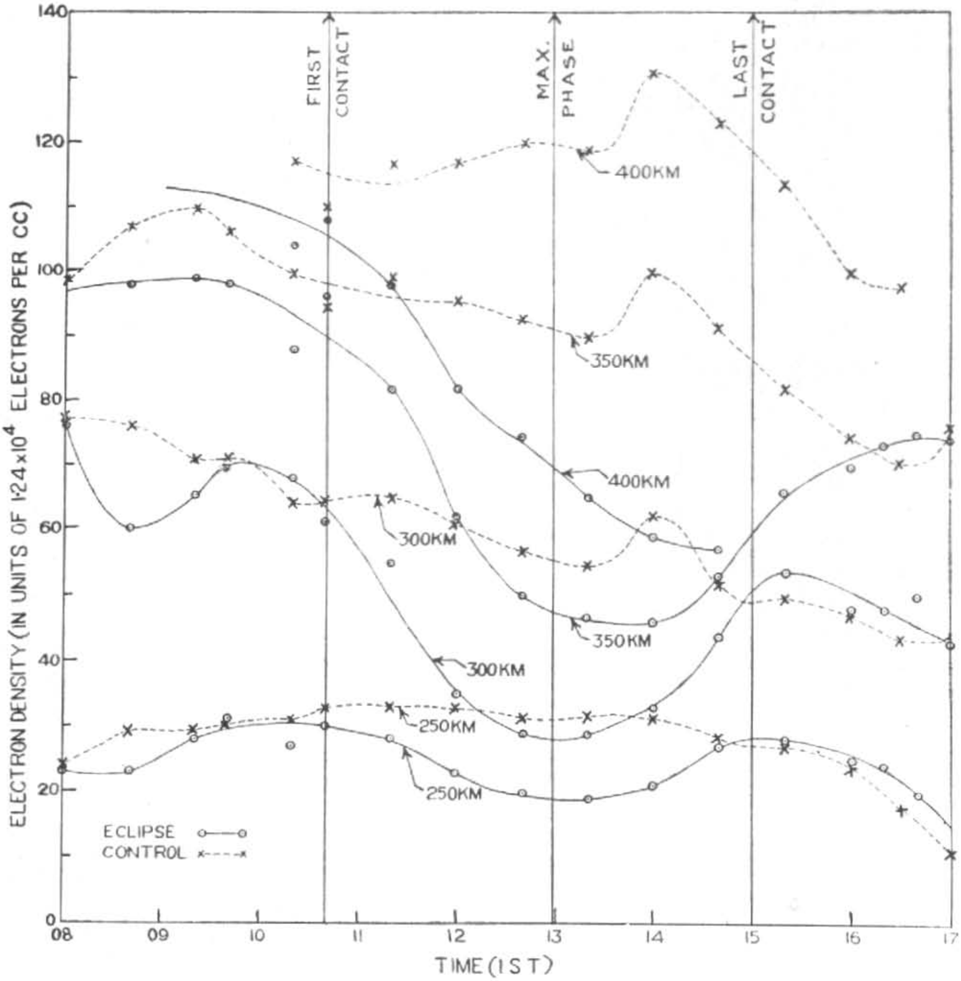

Fig. 2. Observed electron density for several true heights during the eclipse of 14 December 1955

velocity measured positive downward.

Chapman has shown that in a plane stratified isothermal atmosphere, $f(\chi, h)$ is given by:

$$f(\chi, h) = \exp\,(1 - z - e^{-z} \sec\,\chi)$$

where, $z = \dfrac{h-h_0}{H}$, the reduced height; H=the scale height kT/mg of the atmosphere constituent ionized; h=the height of peak of electron production when $\chi=0$.

$I(t)$ is given by—

$$I(t) = 280\,(1 + 1{\cdot}4 \times 10^{-2}\,\bar{R})\ \text{cm}^{-3}\,\text{sec}^{-1}\,,$$

$\bar{R}$ being the average Zurich sunspot number for the month. For computation of $f(\chi, h)$ the values of h_o and H were taken as 180 km and 45 km respectively. For the eclipses, the values of visible fractions of the solar disc were computed at suitable intervals and these were plotted. The values of fraction of the disc unobscured at 20-minute intervals were obtained from these plots.

The equation for the loss coefficient β given in Section 4 was determined by Ratcliffe *et al.* (1956) by using true height profiles of electron density for three stations and by a method of analysis in which the effects of drifts were minimum. This equation was, therefore, used for obtaining the numerical values of ρ for the desired heights. N and dN/dt for the desired instants were obtained from the N-t curves of Figs. 1 and 2. Assuming that the ionizing radiation originated uniformly from the sun's disc, and substituting the values of N, dN/dt, $I(t)$, $f(\lambda, h)$, the fraction of solar disc unobscured and ρ (h), the magnitudes of the movement term $M(h, t)$ were calculated. These together with the control day values of M (h, t) are shown in Figs. 3 and 4 for the summer and winter eclipses respectively.

Confining our attention to 250-and 300-km levels at which the N-t curves and therefore the magnitudes of movement could be computed for the summer eclipse of 20 June, it is seen from Fig. 3 that the normal movements as represented by the 'control day' curves are absent on the eclipse day and are replaced by modified movements. For the winter eclipse, for 300-, 350-and 400-km levels, the nature of movements is similar to those of the summer eclipse. The magnitude of the movement term increases during the first half of the eclipse and decreases after the maximum phase. These characteristic variations are similar to those derived by Thomas and Robbins (1956) for several low latitude stations. It, therefore, appears that in so far as low latitudes are concerned, additional vertical transport of ions, more or less identical in nature, occur following all eclipses.

6. Electric conductivity during eclipses

The daily variations in horizontal force at Kodaikanal (magnetic latitude 1·75°N) are comparatively large. Such variations according to Egedal (1947) are caused by the enhanced east—west current system (the electrojet), flowing at a height of about 100 km and are restricted to a narrow zone centred around the magnetic equator. Singer, Maple and Bowen (1952) have confirmed the existence of enhanced conductivity in the region of about 100 km. According to Baker and Martyn (1953) the enhanced conductivity is due to inhibition of Hall current under the influence of electrostatic (polarization) field. At Kodaikanal, ionospheric and geomagnetic characteristics indicate considerable influence of the 'electrojet' such as occurrence of intense equatorial E_s and large diurnal range in H.

Considering the ionosphere as isotropic the variation in horizontal field $\triangle H$ can be expressed by

$$\triangle H = 2\pi I = 2\pi K \; \triangle E$$

where I is the total electric current in region E, K is the effective conductivity and $\triangle E$ is the variation in the electric field. The daily magnetic variations in equatorial regions consist of normal (S_q) variation and an electrojet effect. In these regions the shadow of the moon will considerably reduce the strength of the electrojet which is a line current or band of line currents and whose width may be smaller than the shadow. The relaxation time T $(=1/2\alpha N)$ in the 100 km region being of the order of only a few minutes, the conductivity in the region will reduce quickly during an eclipse and a departure in daily variation in horizontal force should occur shortly following the eclipse.

In order to examine these effects the horizontal force magnetograms were analysed and values of horizontal force at 10-minute intervals were plotted beginning about 150 minutes before to 120 minutes after the eclipse. The resulting curve, together with a 'control day' curve, is shown in Fig. 5. It will be seen that a decrease in the horizontal force began about half an hour after the commencement of the eclipse. The departures in daily variation in H at 3-minute intervals are given in Table 2 and these show that the maximum departure of about 16γ occurred about 17 minutes after the maximum phase of the eclipse thereby indicating a considerable reduction of the E region conductivity. The drift velocity w is related to the eastward component of the electric field E by,

$$w = \frac{E_y}{H} \cos \phi,$$

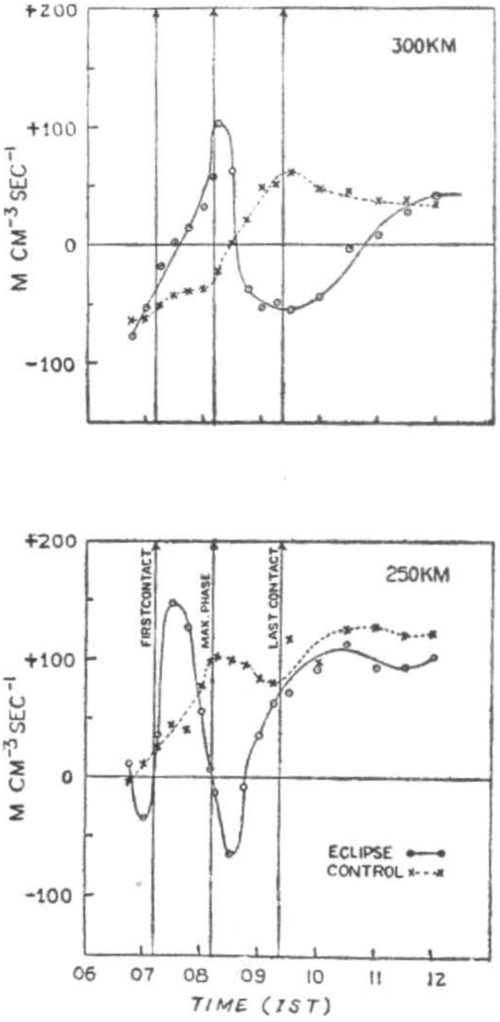

Fig. 3. Eclipse of 20 June 1955

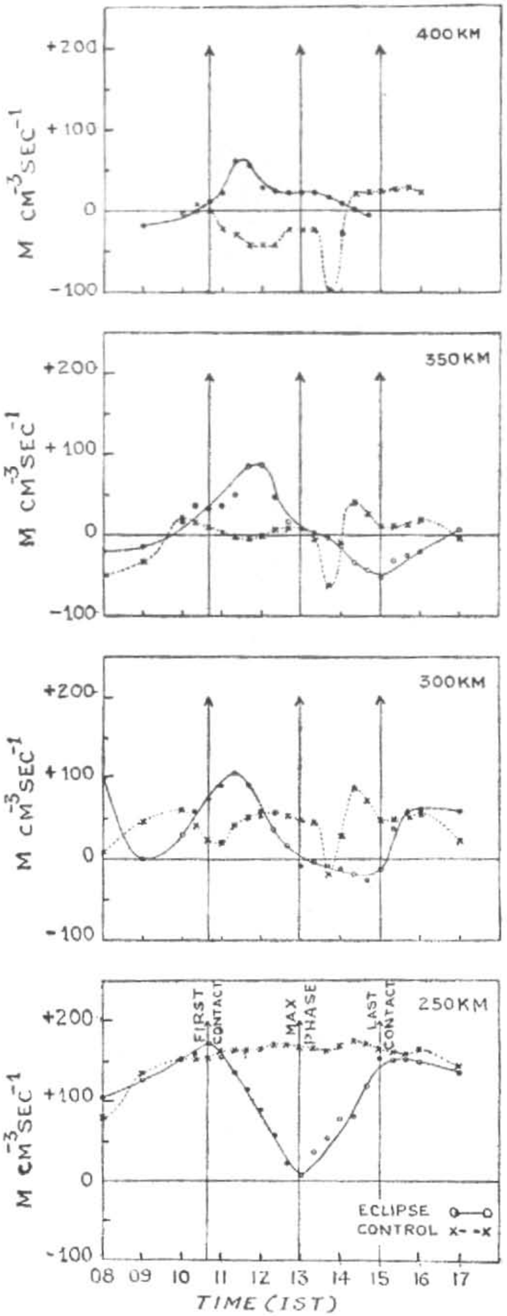

Fig. 4. Eclipse of 14 December 1955

Figs. 3 and 4. Variation of vertical ionic transport term $M[=d(N.w)/dh]$ of the continuity equation with time during the two eclipses

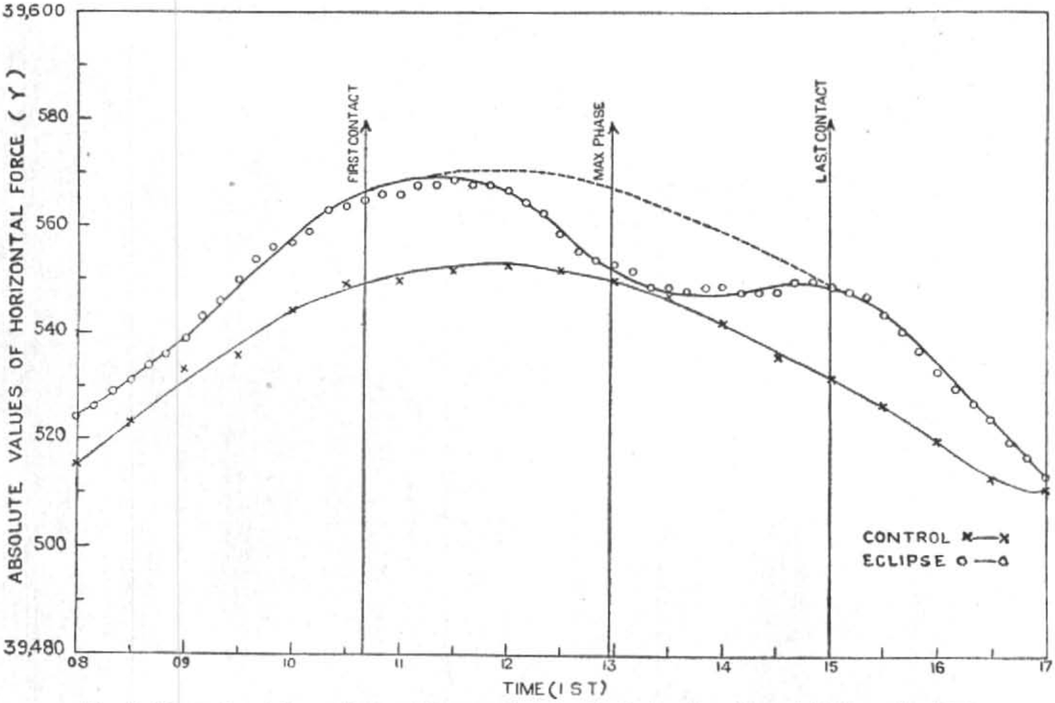

Fig. 5. Observed variation of horizontal magnetic intensity during the eclipse of 14 December 1955

TABLE 2

Time (IST)	Dep. of horizontal force	Time (IST)	Dep. of horizontal force	Time (IST)	Dep. of horizontal force	Time (IST)	Dep. of horizontal force
1115	0	1212	—6·9	1309	—15·5	1406	—10·6
1118	—0·5	1215	—7·3	1312	—15·6	1409	—10·0
1121	—0·7	1218	—7·9	1315	—16·0	1412	—9·7
1124	—0·9	1221	—8·5	1318	—15·8	1415	—8·7
1127	—1·0	1224	—9·3	1321	—15·8	1418	—8·1
1130	—1·1	1227	—9·9	1324	—15·7	1421	—7·5
1133	—1·3	1230	—10·6	1327	—15·5	1424	—6·5
1136	—1·6	1233	—11·0	1330	—15·5	1427	—5·9
1139	—1·8	1236	—11·5	1333	—15·3	1430	—5·1
1142	—2·0	1239	—12·0	1336	—14·9	1433	—4·7
1145	—2·4	1242	—12·8	1339	—14·5	1436	—4·0
1148	—2·8	1245	—13·1	1342	—14·4	1439	—3·5
1151	—3·2	1248	—14·0	1345	—14·0	1442	—3·0
1154	—3·6	1251	—14·1	1348	—13·5	1445	—2·8
1157	—4·0	1254	—14·4	1351	—13·0	1448	—2·5
1200	—4·6	1257	—14·2	1354	—12·7	1451	—1·9
1203	—5·0	1300	—15·0	1357	—12·5	1454	—1·1
1206	—5·6	1303	—15·2	1400	—11·9	1457	—0·2
1209	—6·2	1306	—15·3	1403	—11·3	1500	0

H being the magnitude of the earth's main field and ϕ the dip. Changes in E_y caused by a reduction in the strength of the electrojet should, therefore, modify the drift velocity w and result in a modification of magnitude of the drift shown in Figs. 3 and 4.

7. Bifurcation of the F region during the eclipse

Like other low latitude stations, the daytime F region at Kodaikanal remains thick and high under the influence of electrodynamic forces. As usual for winter, there was no bifurcation of the region during December 1955. However, on the eclipse day the bifurcation of the region developed during the later half of the eclipse. According to Bradbury's hypotheiss (1938) the $F1$ and $F2$ regions are both produced by the same ionizing process and the higher region is distinguished because of a lower electron loss rate.

It would appear that during the eclipse favourable conditions developed for the occurrence of bifurcation and that these were caused by vertical movements. While the semi-thickness $YmF2$, which according to Chatterjee (1955) is proportional to scale height H which in turn is a linear function of the intensity of solar ionizing radiation, decreased during the eclipse, $hmF2$ registered an increase. The condition for bifurcation, namely,

$$hmF2 - hmF1 \geqslant YmF2 - x$$

(where x is the point of intersection of the two parabolae corresponding to the two layers) was satisfied resulting in the appearance of bifurcation in the F region on the eclipse day.

8. Acknowledgements

We wish to thank Mr. P. V. Sanker Narayan for the analysis of magnetic data and Mr. J. V. Narayana for the computation of visible fraction of the solar disc.

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