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EXPERIMENTAL INVESTIGATION OF THE EQUATORIAL IONOSPHERIC ANOMALY IN AFRICA IN THE PERIOD OF SOLAR MINIMUM

by

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ABSTRACT

The equatorial ionization anomaly in the F-region has been explored with the help of airborne soundings during March-April and June-July 1965, periods of solar activity minimum. These two periods correspond at longitude observed to opposed symmetrical effects of solar radiation. A three-dimensional representation of the isolines f_0F_2 in latitude, local time and altitude makes apparent several characteristic regions: at the center, an equatorial plateau of high altitudes and low ionization, directed along a narrow ionization trough and propagating from South toward North; on the Northern and Southern edges of this plateau two crests of enhanced ionization, developing unequally in the course of the morning, and widening unevenly across subtropical zones. The warm crest, situated under the ecliptic, evolves slowly and attains a rather weak ionization maximum at about 1700 hours. The cold crest, which is the least exposed to solar radiation, becomes suddenly apparent at about noontime, forming a narrower and much denser tropical ionization maximum. Current theories are unable to provide a satisfactory explanation of this phenomenon. Photoelectron and atmospheric heating are suggested as mechanisms, likely to differentiate the magnetic tubes of force affected by the equatorial F-region anomaly.

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I. INTRODUCTION

The evolution of the ionization of the equatorial F-layer in Africa could up until now be studied only by means of a very loose network of ionospheric stations. With the view of completing the data of this network, two campaigns of airborne soundings were performed; they allowed a description of this evolution, much more detailed than that based upon statistics by Lyon (1963), Thomas (1963 and Vasseur (1965).

(*) 5 Etude expérimentale de l'anomalie ionosphérique équatoriale en Afrique en période de minimum solaire. 6

The zone studied was located between 0 and 5°E in longitude and between 23° N and 4° S in latitude (Fig.1). It was thus possible to cut across the data of the fixed stations in Tamanrasset (Algeria) and Ibadan (Nigeria) and of the provisionally installed Niamey station in the Nigerian Republic, yet taking into account the data of the fixed station of Bangui (Central African Republic), rather remote from the meridian studied; it was possible, moreover, to survey the region comprised between the Northern and Southern tropical ionization crests. In this zone the magnetic equator on the ground is at the latitude 10° N, and the traces on the ground of the magnetic lines of force have a declination of the order of 8°, with a certain asymmetry of lines characterized by a certain entanglement to the South.

The chosen study periods were that of the equinox period from 25 March to 9 April 1965, and a solstice period from 23 June to 9 July 1965. The corresponding solar geometries are indicated in Fig.2. A certain symmetry around the magnetic meridian can be seen, but it is appropriate to recall the previously signaled asymmetry of the magnetic inclination. The times of airborne surveys are indicated in Fig.3. It may be seen that, utilizing an aircraft flying at 300 km/h, it was possible to realize a good exploration of the diurnal structure of ionization during the equinox and solstice periods.

The days of flight were chosen to allow the description of the situation during magnetoquiet days. Table I provides the magnetic parameters for the days of flight, and one may see that the quiet conditions were good in the course of this solar minimum period.

In the course of the examination and morphological description of the results obtained, one will particularly notice new events, at times in contradiction with some of the current theories of the equatorial anomaly. In conclusion we shall briefly consider the processes, to which one may recur for the interpretation of these results.

II. MORPHOLOGY OF THE EQUATORIAL ANOMALY

The ionograms obtained, whether at fixed stations or at flight, were analyzed and converted into ionization profiles. The Budden method (1955) was utilized for the fixed stations, and the Schmerling method (1957) was applied for the airborne observations. Starting from the results thus obtained it was possible to plot a certain number of graphs, striving to account in the best possible way for the continuity of observations, of which the number is at times insufficient. Some of these graphs include data on the magnetic field, whose lines of force were computed after Bitoun (1963).

The principal graphs are those of Figs 4, a and b, which represent the lines of equal ionization as a function of local time and latitude, at F-layer maximum in the equinox or solstice periods; those of Figs 5 (a and b), which represent for certain hours in the equinox period the meridian cross sections of curves of equal ionization as a function of latitude and altitude. Note that the data utilized for drawing the solstice curves are scarcer than those for the equinox. Thus, we were led, for example, to trace in Fig.5b isoaltitude curves more remote than in Fig.5a.

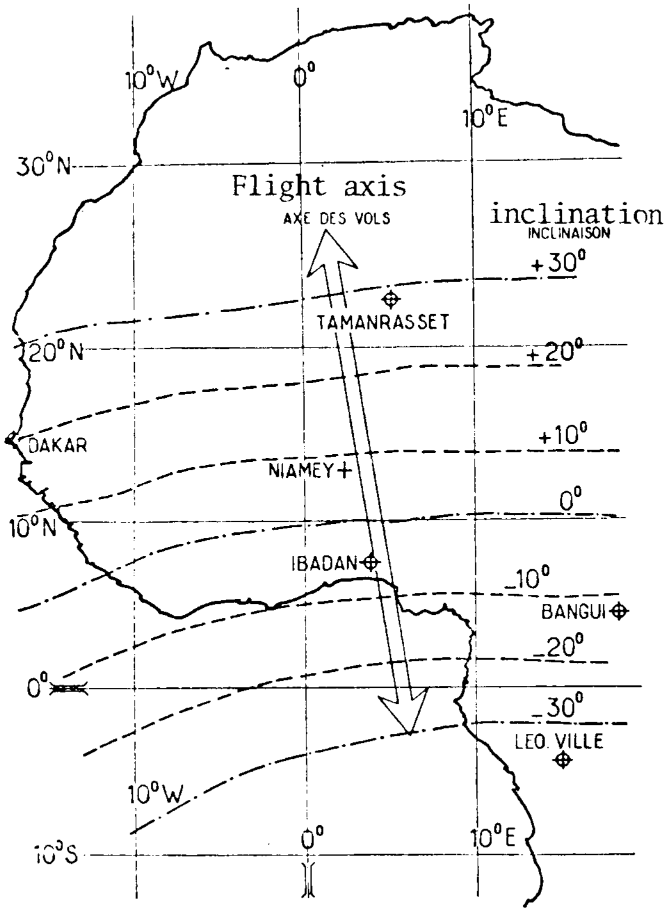


Fig.1. Map of the African region studied

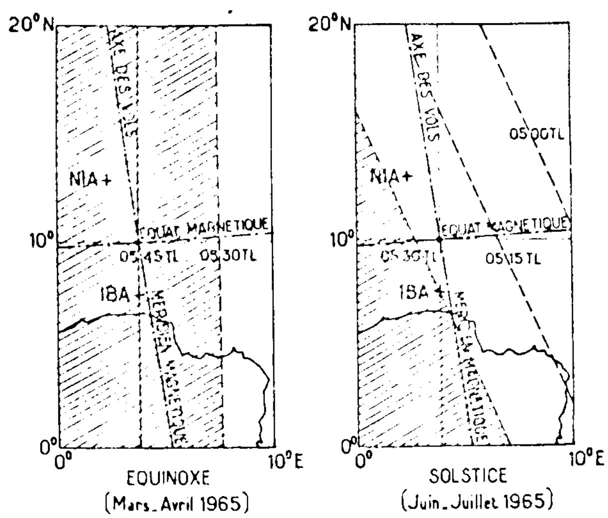


Fig.2. Solar situation in the course of study periods at equinox and solstice (the hatched area is the shadow zine on the ground at 0530 h.L.T. on the 10° N flight meridian

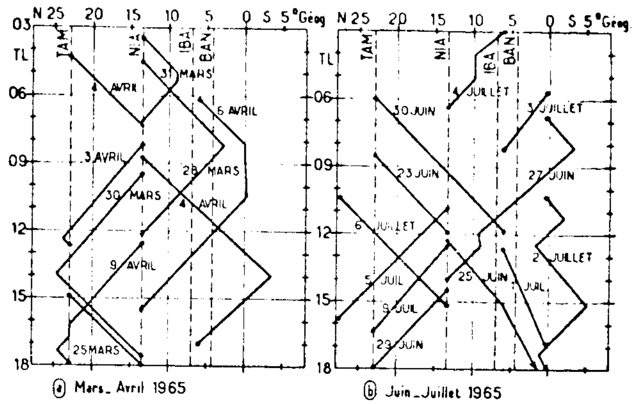


Fig.3. Flight Graphs: a) equinox; b) solstice

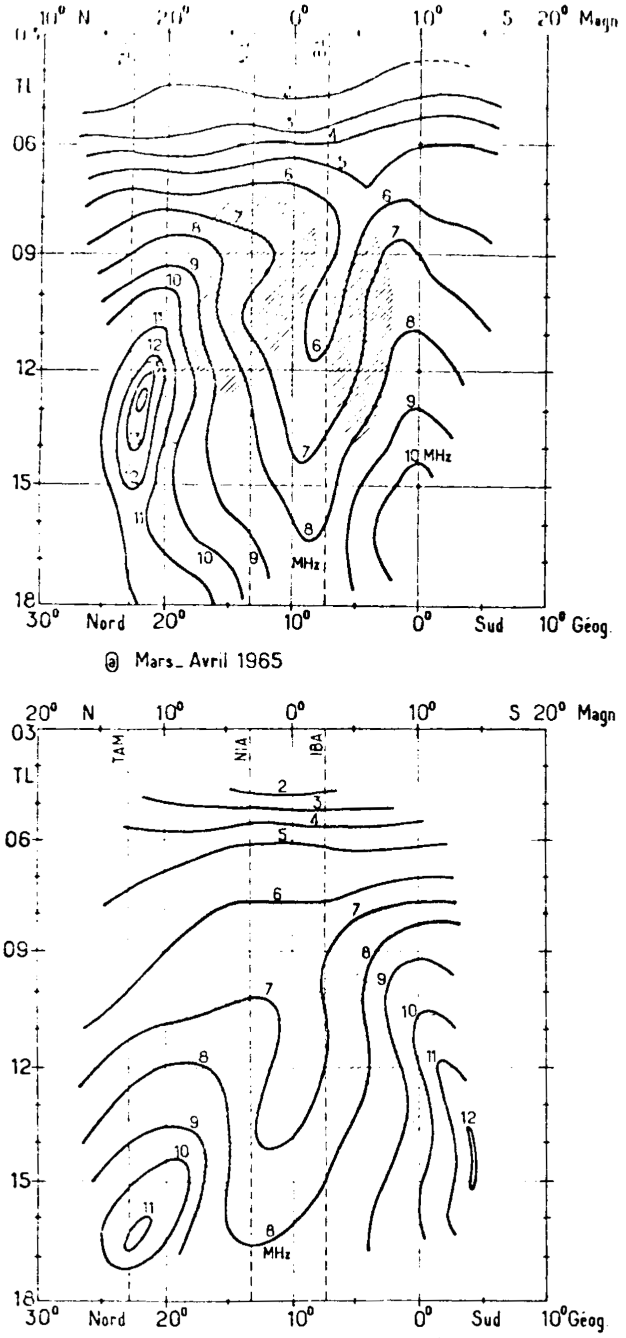
a) March-April b) June-July 1965

The general structure appearing on these graphs is indeed the one anticipated: From the standpoint of the ionization (Fig.4), an equatorial "trough" is formed in the morning, and two "ionization maximum crests" situated on either side of that trough evolve toward a tropical afternoon position. From the standpoint of altitudes (Fig.5) the crest widening phase is attended by a gradual elevation. If we compare the variation in local time to that in longitude, we find a simple dome with two unequal supports in equinox , and a surface with two asymmetric summits in the solstice. In either case the most ionized tropical crest is accompanied by a brutal sinking.

However, certain particular aspects emerge, of which the originality must be stressed relative to other observations carried out in the period of solar activity maximum (Wright, 1962).

1) The Tropical Ionization Maxima are inverted relative to Solar Lighting

There exists between the Northern and Southern crests an assymetry, which may be explained by the ionization ratios between the respective extremes of the N.crest, the equatorial trough



June-July 1965

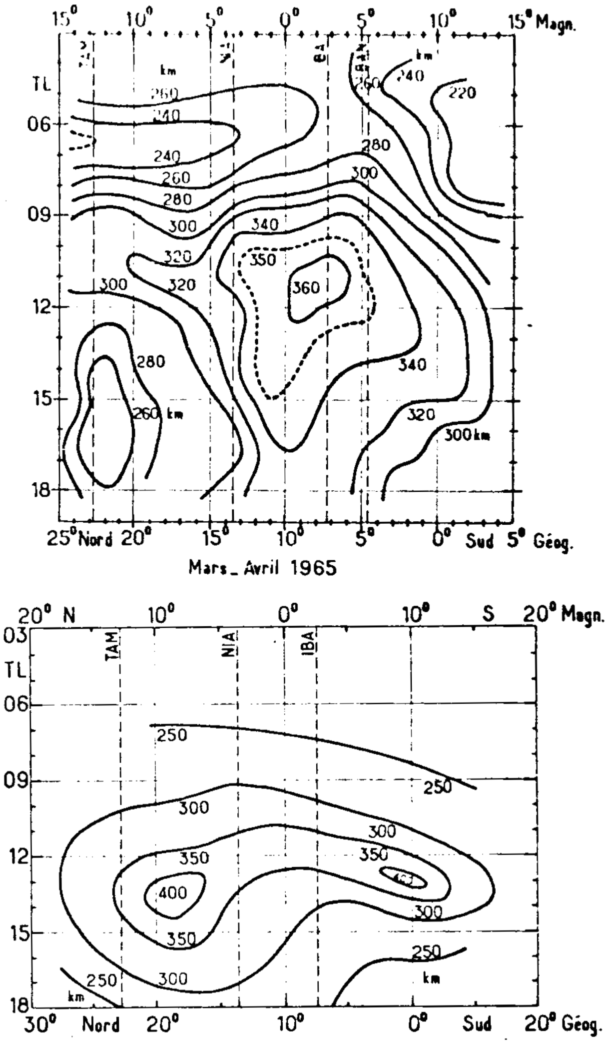


Fig. 5. — Altitude de la couche F : *a)* équinoxe ; *b)* solstice.

Fig.5. Altitude of the F-layer:
a) equinox; b) solstice

← Fig.4. Lines of equal ionization as functions of L.T. and latitude at F-layer maximum for the equinox and solstice periods

and the S.crest. The greatest asymmetries take place in the case of equinox (Fig.4a), in the neighborhood of 1300 h.L.T. At solstice (Fig.4b) the phase maximum of the S.crest, the cold and most ionized one, is reached only at 1600 h.L.T. The ionization ratios may be schematized by the Table I below, where the crest situated on the ecliptic is marked by the symbol ⊙.

One may notice that the cold crest of the equinox is more ionized than that of the solstice. Figs.4 indicate also that the cold crest is always narrower than the warm crest.

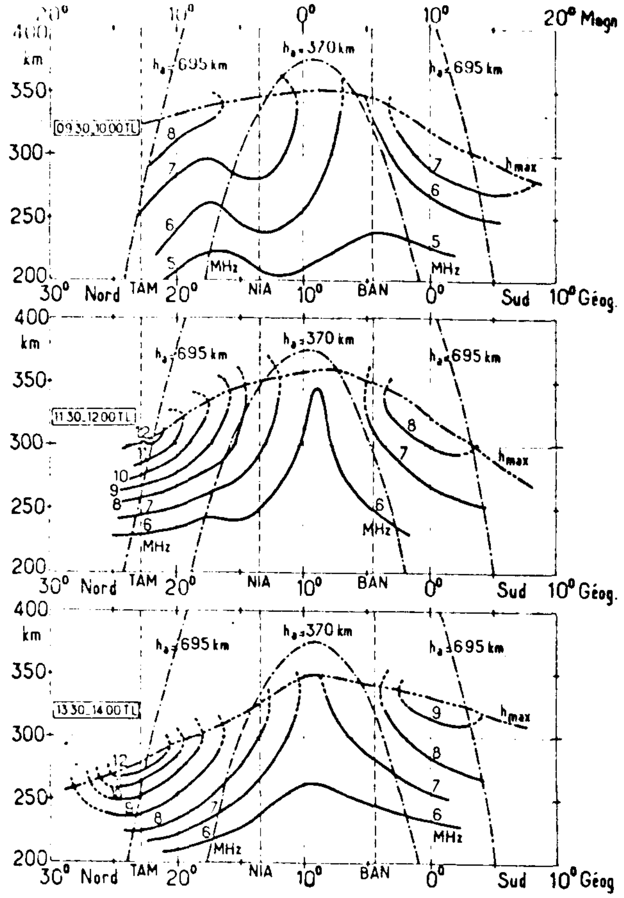


Fig.6. Meridional curves of ionization profiles for certain hours of the equinox period

These various phenomena, and namely the rapid appearance of the maximum of the N.crest at 1300 hours local time in the equinox period, thus on the cold side, seem to be inconsistent with the generally admitted theories for the interpretation of the equatorial anomaly. The narrowness of the cold crest in both cases underscores a very well marked effect of ionization accumulation by diffusion along the magnetic tube of force of this intensely ionized crest.

2) The Ionization Crests are displaced unequally and the Trough evolves Northward.

The ionization crests arise between 0700 and 0800 h.L.L. on either side of a narrow trough centered to the South of the magnetic equator on the ground. These crests then spread apart and widen. The N.crest shifts much more rapidly in both cases and in the Northerly direction. In the case of equinox (Fig.4a) a regular and slow growth is observed on both crests in the morning. For example, between 0800 and 1000 h.L.T. the maximum frequencies increase from 7 to Mc on the N.crest, from 4.8. to 7 Mc om the S.crest, and only from 5.2 to 5.7 Mc along the trough; the average rates of ionization crresponding per hour thus are $3.1 \cdot 10^5$ cm^{-3} at the North, $1.1 \cdot 10^5$ $cm^{-3} \cdot h^{-1}$ at the South and $0.3 \cdot 10^5$ $cm^{-3} \cdot h^{-1}$ at the equator. The raised equatorial surface of slowly rising ionizations of the morning then lines up, between 0900 and 1000 hrs L.T. in the vicinity of the summit of a line of force of 360 km apex between o6! and 12° N.latitude. These latitudes coincide with the bases of the subtropical ionization crests. The narrow equatorial trough shifts northward from 05°N at 0800 h.L.T. to 07°N toward 1100 h.L.T. It covers 50 km per hour during the entire growth phase, only to reach the magnetic equator at about 1500 h.L.T. One will also notice that the magnetic synchronization of the crests is always but very approximate, and this is so in the course of their entire evolution.

3) The Widening of the Crests in the Morning is attended by Stratifications, apparent on the Meridional Flank.

We reproduced in Fig.7 a sequence of ionograms taken in flight over the interior flank; it shows a stratification of the F_2-layer)called F_{15}-layer).

TABLE I

IONIZATION RATIOS BETWEEN EXTREMES

	N.Crest	Trough	S.Crest	L.T.
Equinox	3.5	1.0	2.0	⊙ 13.30
Solstice	⊙ 2.0	1.0	2.5	16.00

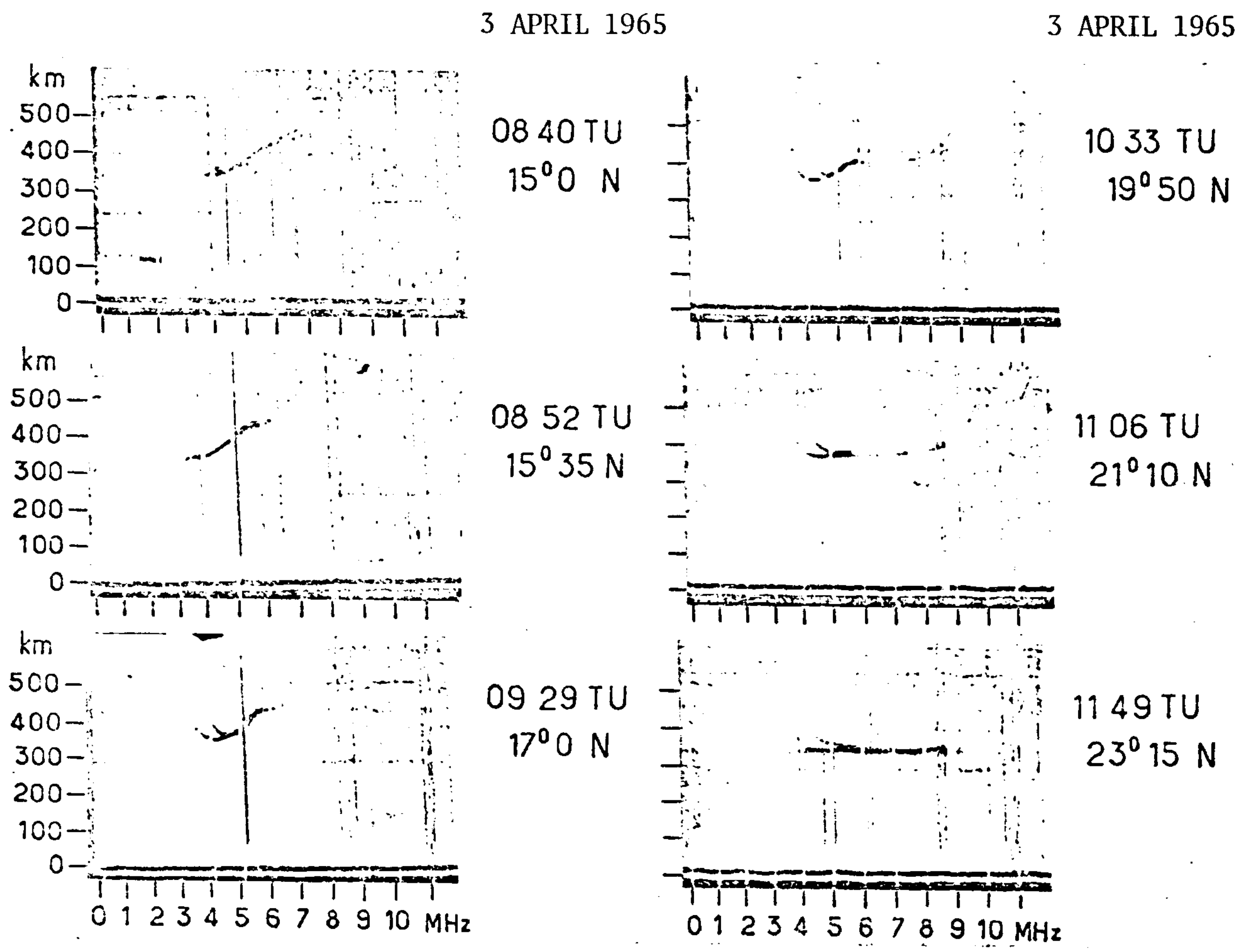


Fig.7. Sequence of Ionograms taken in Flight on 3 April 1965, showing the Stratifications of ($F_{1.5}$)

The zones of appearance of this stratification are hatched in bith Figs.4. It was observed as of 0300 h.L.T. in the entire region concerned with the rise of crests. This structure must correspond to those indicated by Ratcliffe (1965) on the solstice sequences of the Huancayo solar minimum: ascending stratifications were observed above the $f_0F_2$critical frequency in the growth period of morning ionization till the maximum at the end of the morning. The structure of $F_{1.5}$may be continually followed on the flight ionograms of 3 April (Fig.7) from 15°N at 0830 h.L.T., where it breaks off the F_2 maximum level at about 300 km on the 370 km apex line of force, to about 19°N at approximately 1200 h.L.T., where it merges with the stratification F_1 at about 180 km, on the 520 km apex line of force. The negative ionization gradient corresponding to this stratification appears also on the cross section 0930 - 1000 h.L.T. in Fig.6. This structure, aligned over a line of force, shows a gradual enlargement, linked with the tropical crests.

None of these characteristics could be observed during the years of hourly observations of stations, too dispersed in the equatorial zone. The space-time coverage assured by the aircraft allows, to the contrary, to distinguish with certainty itinerant perturbations on these stable levels, characteristic of medium latitudes, and which move with a velocity of 1° to 5° per hour, in sequence of discontinuous fronts.

On the other hand, the meridian cross sections of Fig.6 show ionization structures aligned on the magnetic field only if one considers each crest separately, without making obvious at any moment of time a synchronization of F_2-maximum cells.

4. Itinerant Perturbations appear only outside Crests and Sporadic E-Levels are observed only on Both Sides of Crests.

In the equatorial plane of Fig.5a diffused equatorial type-E_s sporadic levels were very frequently observed, but never on the equatorial trough. The typical E_s q of the observation period thus appear as less related to an evolution of equatorial electrojet's amplitude than to the effect of photoelectron flux on the lines of force of the lower apex.

Numerous sporadic levels are also present on both sides of tropical crests. Finally, itinerant stratifications were observed, either at equinox or solstice, only on the external flanks of tropical crests. They seem very rapid and rather evenly distributed in the course of a day.

III. DISCUSSION

In the morphological study of the preceding chapter we underscored some experimental facts that seem to be in disagreement with the current interpretations of the equatorial anomaly. These theories (Hanson & Moffett (1965); Goldberg & Chandra(1964); Risbeth & Barron (1960) assume generally a ionospheric plasma in diffusion equilibrium under the influence of the gravitational field a uniform distribution in latitude of temperatures and pressures and the presence of a large-scale system of currents. They never consider the temperature as a determinant dynamic factor.

However, the phenomenon of crest inversion, referred to in the Sec.II, 1, requires the presence of a very selective mechanism that would isolate and maintain between the hours 1100 and 1600 L.T. a cold tropical crest, as ionized and narrow, as the warm crest, in either equinox or solstice. A diffusion mechanism only would not lead to such an inversion.

Per contra, the phenomenon suggests the consideration of the maximum possible ionization capability of magnetic tubes, which isan inverse function of the temperature of electrons. One thus is led to think of heating effects of photoelectrons that depend very selectively on the length of the lines of force, and, therefore, of the latitude.

Likewise, the morning evolution of the crests, noted in Sec.II, 2, shows the difference in the rates of growth of ionization in both hemispheres, as of 0800 hours L.T. But the simple diffusion of electrons, stemming from the ultraviolet and forming at about 180 km altitude, can not enhance as rapidly the ionization till 300 km. Nor is it possible to hope to accelerate the mechanism by making intervene electrodynamic forces. It is indeed sufficient to consider the magnetograms of such stations as Aquila (Italy), M'Bour (Senegal), San Juan, Puerto Rico or Tucson, Arizona to be assured that the variations registered in April-May 1965 are still weaker than those utilized in the classical model of currents of Price and Wilkins (1963). These feeble variations reduced to conditions at the meridian studied, would lead to zero potentials in subtropical regions of the South. The phenomenon rather suggests the consideration of a process involving the temperature.

The other results, mentioned in Sec.II, 3 and 4, do not seem to lend themselves either to interpretations as functions of classical theories. The $F_{1.5}$ stratification on the flank of ionization maximum crests appears to be a phenomenon aligned on the field; the equatorial E_s on both sides of the trough seem to be linked with the lines of force of the lower apex; the itinerant perturbations appear only outside the anomaly. All these results agree for the elimination of the role of high-altitude contribution to ionization and the consideration of the motion of electrons along the magnetic field.

Thus, we are logically led to consider the role of photoelectrons in the general process of the equatorial anomaly. Studies on photoelectron transfer along the lines of force have already been presented by Hanson (1963), Willmore (1964) et Weekes (1964), though applied to other geophysical phenomena, generally at higher altitudes.

Hanson has proposed, in particular, average efficient cross sections that would allow the arrest of photoelectrons in the lower band at 13 eV, at the extremity of a column of $6.6 \cdot 10^{15}$ oxygen atoms per cm^2. A first approximation of the mean trajectories required, effected by rough integration of volumes by equal density cross sections gives an average trajectory of 1100 km along the line of force of 400 km apex. The possibility is thus envisioned of a pro-

TABLE II

MAGNETIC ACTIVITY IN FLIGHT

Equinox (25 March-9April 1965)

	Day	Kp								ΣKp	Ap
March	21	3_-	1_0	1_0	2_-	3_-	2_-	1_+	3_+	15_+	8
	22	1_-	0_+	1_-	0_+	1_-	1_+	3_0	4_0	11_0	8
	23	2_0	4_-	4_+	3_0	3_0	4_+	5_0	4_+	30_-	25
	24	1_+	2_-	3_0	4_0	4_-	2_0	2_0	2_+	20_0	12
	25 (*)	2_0	3_+	5_0	4_+	2_+	2_-	4_0	2_+	25_0	20
	26	4_+	3_0	4_-	2_+	2_-	2_-	2_0	2_+	21_0	18
	27	3_-	2_+	3_-	2_-	1_+	2_0	3_0	1_+	17_0	9
	28 (*)	1_-	2_0	3_-	1_+	1_-	1_+	0_+	0_+	9_+	4
	29	2_0	2_-	1_+	1_-	2_0	2_-	2	1_+	12_+	6
	30 (*)	0_0	0_0	0_+	1_-	1_0	1_0	1_0	0_+	4_+	2
	31 (*)	1_+	2_0	1_+	2_-	0_+	0_+	0_+	1_0	8_+	4
April	1	2_+	2_-	1_+	0_+	1_0	1_-	1_-	0_+	8_+	4
	2	0_+	1_0	1_0	1_-	0_0	0_+	0_+	1_-	4_+	2
	3 (*)	0_0	1_0	1_-	0_+	1_+	1_-	1_-	1_-	5_+	3
	4 (*)	0_+	2_0	3_-	2_-	2_+	2_0	1_0	0_+	12_+	6
	5	0_+	3_-	1_-	0_+	0_+	0_+	0_+	1_0	6_0	4
	6 (*)	1_+	2_0	1_+	1_-	2_+	3_-	2_-	2_+	14_+	7
	7	3_0	3_+	1_+	1_+	3_-	2_-	1_-	1_0	15_0	8
	8	1_0	0_+	0_+	1_-	1_0	1_0	1_-	2_-	7_-	4
	9 (*)	3_0	4_0	3_0	1_-	1_-	2_0	2_-	3_-	18_-	11
	10	3_0	2_0	1_0	2_-	0_+	0_+	1_-	1_-	10_-	5

Solstice (23 June- 9 July 1965)

	Day	Kp								ΣKp	Ap
June	21	0_+	0_+	0_0	0_+	0_+	0_+	0_0	0_+	2_0	2
	22	1_-	1_0	1_-	1_+	1_0	1_-	1_-	1_+	7_+	4
	23 (*)	2_-	0_+	0_+	1_-	1_-	1_0	1_-	0_0	5_+	3
	24	1_-	0_+	0_+	0_+	1_-	1_+	1_0	0_+	5_0	3
	25 (*)	0_+	1_0	1_-	1_0	3_+	4_0	3_+	2_+	16_0	11
	26	3_0	3_-	2_0	2_0	1_-	1_0	3_0	3_+	18_-	10
	27 (*)	3_0	2_0	2_-	2_-	2_-	1_0	1_-	1_-	12_+	6
	28	0_+	1_+	1_-	1_0	1_0	1_-	1_-	1_-	6_+	3
	29 (*)	2_0	2_+	3_+	3_-	2_+	3_-	2_+	3_-	20_+	11
	30 (*)	2_-	2_+	3_0	3_-	3_0	2_0	3_0	4_+	22_0	14
July	1 (*)	3_+	2_0	3_0	3_0	2_+	2_-	3_+	3_0	22_-	13
	2 (*)	2_-	2_-	2_0	1_+	2	1_0	1_0	1_+	12_-	5
	3 (*)	2_+	1_+	1_+	1_-	1_-	1_-	2_0	2_0	11_0	5
	4 (*)	1_0	1_-	1_0	0_+	0_+	1_-	1	1_+	6_+	3
	5 (*)	1_0	1_-	1_-	1_0	0_+	0_+	1_-	1_0	6_-	3
	6 (*)	2_-	5_-	4_-	4_0	4_0	3_+	2_-	2_-	25_-	19
	7	2_+	2_0	2_-	2_-	1_0	1_+	2_+	3_0	15_+	8
	8	4_0	4_0	2_-	2_0	3_-	4_+	4_0	4_+	27_0	21
	9 (*)	4_-	4_-	1_0	2_0	2_0	2_+	3_-	3_0	20_+	12
	10	3_0	5_-	3_+	3_0	3_0	1_+	1_-	1_0	20_0	14

(*) The days indicated are those when measurement flights took place process in which, depending upon their energy and the line of force considered, the photoelectrons would play a role, sometimes by creating a heating by direct action originating from the underlying levels and sometimes by contributing electrons to the lower F_2 -levels, where the recombination, already reduced, will allow them to play the role of contributor for the constitution of the F_2-ionization maximum.

It is important to make this possibility more precise by a more detailed calculation of the photoelectron flux, and the role of photoelectrons. Such a calculation can be successfully performed starting from a plausible model of unperturbed ionization and of energy distribution of photoelectrons, such as those presented by Delgarno ET AL (1963), although the author considers essentially a middle-latitude model. Following the path of photoele trons along the lines of force, it is possible to compute the contribution of local heat consecutive to collisions. In order to evaluate the role of this contribution of heat upon the organization of ionization, one should then examine the various phenomena that could intervene and namely, the diffusion along the magnetic field.

The results of such a calculation will be presented subsequently and we shall consider which aspects of the equatorial anomaly may lend themselves to interpertation in a process involving photoelectrons. The possibility of completing the data presented here on the lower ionosphere by the observations with the help of AES Alouette, registered at Kano (NIGERIA) on the upper ionosphere, will, moreover, allow us a more complete viewing of the phenomenon.

Follow votes of thanks.

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