EQUATORIAL NIGHTTIME E — REGION IONIZATION SOURCES

by

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Conselho Nacional de Pesquisas

Comissão Nacional de Atividades Espaciais

Laboratório de Física Espacial

São José dos Campos

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To be presented at the 7th Cospar Meeting
Vienna, Austria — May 1966

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Two Nike-Apache rockets were launched from a new site (5.6° S and 35.2° W) close to the magnetic equator in the vicinity of Natal, Brazil. The first launching took place at 19.19UT and the second one at 04.59UT, on December 15 and 18, 1965. This note presents some of the results obtained by means of measurements of H Lyman lines and positive ion profiles. It is shown that the nighttime E region is produced in two levels separated by a deep valley. The lower part in the range 95-130Km is maintained by ionization produced by the flux of scattered H Ly-α and -β which have production peaks at about 104 and 110Km respectively. The higher part of the nighttime E region, merging with the F region, has the contribution of the ionization due to H Ly-δ and -ϵ.

The contents of this note are to be presented at the 7th. COSPAR Symposium in Vienna, Austria, on May 1966 and will be submitted for publication as a Letter to the Editor to the Journal of Geophysical Research .

EQUATORIAL NIGHTTIME E REGION IONIZATION SOURCES

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Comissão Nacional de Atividades Espaciais
São José dos Campos - São Paulo, Brasil

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This letter will present preliminary results of the first two sounding rockets launched from a new site Barreira do Inferno close to the magnetic equator at the Brazilian coast in vicinity of Natal (5,6°S, 35.2°W). The first launch took place at 19:19 UT (solar zenith angle χ = 75°) on 15 December and the second one at 04:59 UT (χ = 130°) on 18 December 1965 ; both periods were very quiet with $k_p < 1$. Both flights were successful and measurements between heights of 60 and 180 km were made of energy radiation fluxes in the EUV with a photoelectron retarting potential analyzer, H Lyman- α with an ionization chamber, electron current and positive and negative ions with modified Gerdian condensers . The payloads were rather similar to the one described by Bourdeau et al. [1966] . A VLF experiment which was included for determining electron densities did not work too well in either flight.

Although all the data has been reduced, we will present here mostly the results concerning the nighttime E region ion densities and its formation by scattered hydrogen Lyman lines. A full paper in preparation , including all the results in detailed form will be submitted in a near future for publication in this Journal. Also a report [Meira et al., 1966] describing the payload and data reduction is available through request to the authors.

Many theoretical and experimental papers have been published about the existence of the nighttime E region, most of them considering either mid or high latitudes. Although our results are obtained from an equatorial station they apply in many respects to the E region behavior at zones other than auroral .

Quite a number of sources and schemes have been suggested for the existence of the nighttime E region, such as transfer of ionization from above, temperature dependence of loss rates , metallic ions , meteors , etc.. More recently evidence has been indicating that the presence of H Lyman- α (λ = 1215.7 Å) at night which was first detected in 1955 by Kupperian et al. [1959] could provide another source . The presence of H Lyman- α and H Balmer- α (λ 6562.8) in the night sky also suggests a possible contribution to ionization due to H Lyman- β (λ 1025.7). For more details on these consideration refer for instance to a recent paper by Swider [1965] and references therein . A completely adequate and well developed explanation for the observed H Ly- α flux in the night sky has not been reached yet . For discussions concerning the generation and interpretation of the H Ly- α glow, whether it is produced by the unlikely scattering of solar radiation by interplanetary hydrogen, or by single scattering in a distant geocoma or by transport of resonance radiation by multiple scattering in geocoronas of varied shapes, or a combination of these processes, see for instance the works of Donahue [1962] , Thomas [1963], Donahue and Thomas [1963], Donahue and Fastie [1964] , Tousey et al. [1964] .

Our measurements conclusively show that production of ionization by the scattered hydrogen lines plays a major role in maintaining the nighttime equatorial E region. As far as we are concerned , nighttime measurements of the hydrogen lines are available only for the Ly- α and Hα and conjectures are made about the Ly- β , since the observed H α could be produced by this line through fluorescence scattering, i. e. , absorption of Ly- β raises a hydrogen atom to quantum 3 state from which it may radiate Ly- α and Hα . Besides Ly- α and β lines we have detected an additional energy flux above 130 km , which must be a contribution from the H Ly- δ (λ 949.7) and H Ly- ε (λ 937.8) lines . The H Ly- γ (λ 972.5) is highly absorbed by molecular nitrogen well above 200 km in the daytime ionosphere and it is expected that is should have similar behavior at night .

Figure 1 shows the nighttime energy flux measurements obtained from the two sensors during the rocket ascent (the descending leg reproduced similar measurements). The sensors ' current presented a modulation of about 20% due to rocket spin (8.5 rps) and 7% due to precession (2.1 rpm) ; the curves have been smoothed through the points of maxima. No integration for the total sky has been performed for the curves shown in Fig. 1. A correction was applied to the leakage current (1.40×10^{-12}a) from the EUV sensor and the values thus obtained have been divided by a constant factor to compensate for the difference in sensitivity to H Ly- α of this sensor with respect to the ionization chamber which was filled with nitric oxide and had a lithium fluoride window. The large increase observed between 80 and 105 km clearly identifies the region where H Ly- α is absorbed; similary the increase between 105 and 125 shows the region where H Ly- β is absorbed . The absence of O^+ below 170 km in the nighttime ionosphere [Holmes et al. , 1965] precludes the possibility of the presence of energy fluxes in the H Lyman continuum (λ 840-911) at the 105-125 km height interval even without considering scattering processes. We suspect that the increase above 135 km is due to the combined effect of the H Ly- δ and - ε lines. This assumption can be justified in view of the measured ion densities to be discussed later and because the solar radiation of

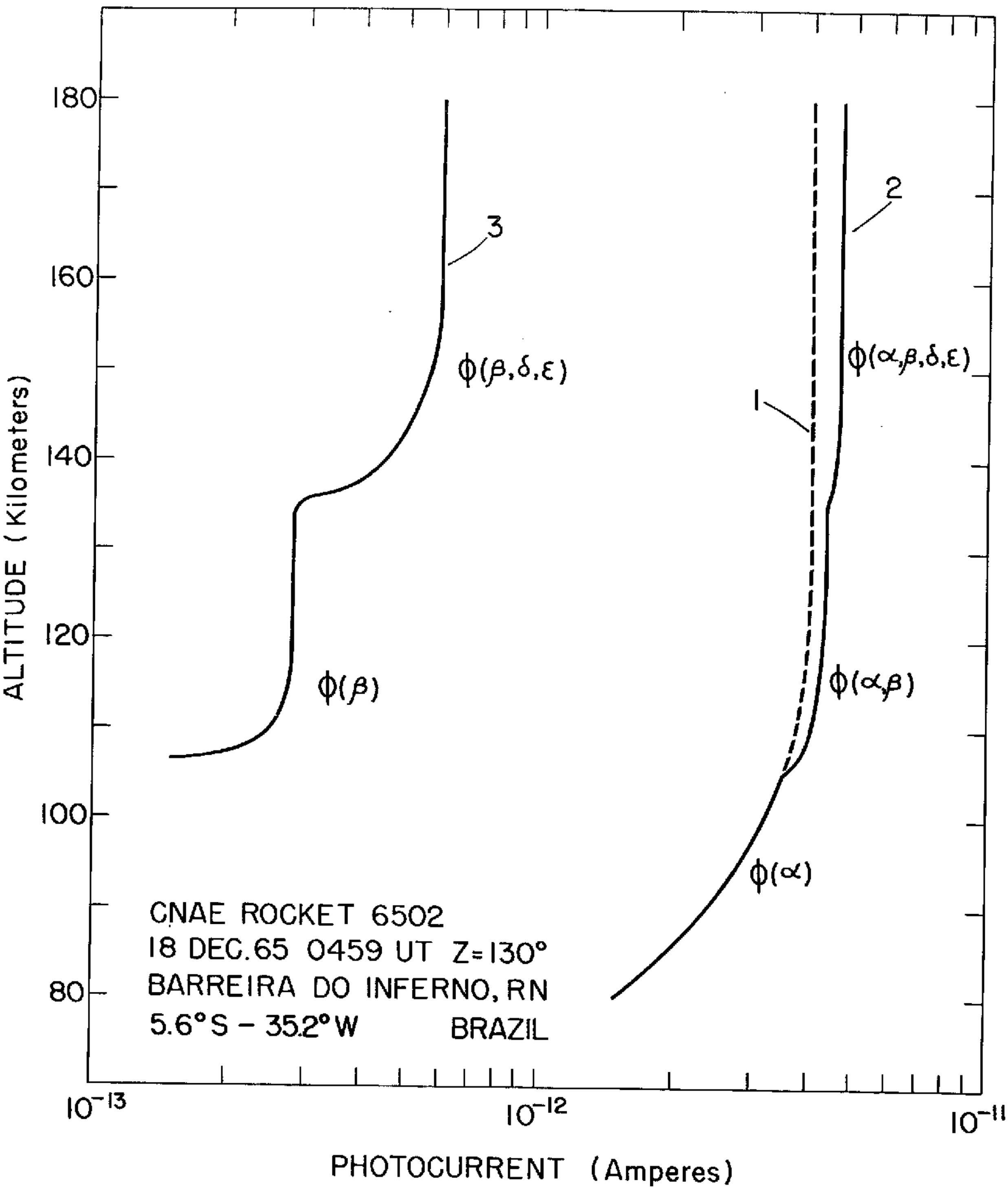

Fig: 1 — Extreme Ultra Violet flux measurements; curve 1 shows the Lyman-α flux measured with the ionization chamber, normalized to the sensitivity of the retarding potential analyser; curve 2 shows the total EUV flux from the tungsten target; curve 3 is the statistical difference between curves 2 and 1.

these lines are of approximately the same intensity [Hinteregger et al. 1965] ; they have also very close values of :(a) absorption cross sections for O_2 and N_2 , (b) ionization cross sections for O_2 and (c) heights of unit optical depth in the daytime ionosphere.

The photoemission yield of our EUV detector [Bourdeau et al. ,1966] was such that it was 8 times more sensitive to Ly-δ and -ϵ and 4 times more sensitive to Ly-β , all with respect to photo emission yield to Ly-α radiation. Thus one should take these ratios into consideration when comparing the curves of Fig. 1 .

Preflight measurements showed that the ionization chamber used at night was 65% more efficient than the one used during the day flight. Assuming a solid viewing angle of 0.85 sr for the chamber used at night and the averages of the H Ly-α intensities rather than the maxima, we integrated the flux for a hemisphere disregarding the albedo and obtained the ratios of the nighttime $\phi(\alpha)N$ to daytime $\phi(\alpha)$ D fluxes of H Ly-α radiations as displayed in Fig. 2 . The daytime flight was performed with a solar zenith angle of approximately 75^{o} ; had it been with a smaller angle the slope of the curve in Fig. 2 would possibly be smaller below 120 km . Since we do not have yet the values of the fluxes above the ionosphere at the time of the launching we will assume for this preliminary note the values given by Hinteregger et al. [1965] to hold under the conditions of our daytime flight, namely , the ratios of the daytime fluxes $\phi(\beta)$D and $\phi(\delta, \epsilon)$D with respect to $\phi(\alpha)$D are 1% and 0.2% respectively . From our measurements these same ratios at night at 170 km are 2.7% and 2.1% . We also find that the night to day ratios $\phi N/\phi D$ at the given height to be 0.6% for Ly-α , 1.5% for Ly-β and 6.1% for Ly-δ, ϵ .These results indicate that percentage-wise the scattered fluxes increase for shorter wavelengths. The H lines profiles have an important bearing on the strength of the airglow produced by resonance scattering of the solar radiation. It is known [Tousey et al., 1964] that both Ly-α and Ly-β are strongly self-reversed lines with peak to peak separation of approximately 2/3 as great for Ly-β as for Ly-α . Thus it should not be improper to assume that Ly-δ and Ly-ϵ are also self-reversed . The increases in the airglow mentioned above could be explained if the central reversals were shallower for the shorter wavelength lines because the scattering cross-sections of the cold telluric hydrogen are small except for the very center of the lines;in other words, if the Lyman lines are once scattered by neutral hydrogen atoms they are monochromatized to the wavelength of the core of the original solar line. Absorption by telluric hydrogen is also less important for the shorter wavelength lines. With the expression for the absorption coefficient per atom at the center of the line [Chamberlain, 1961] and the oscillator strengths [Bethe and Salpeter, 1957] for the H Lyman series it can be shown that absorption by telluric hydrogen decreases with wavelength of the radiation in such a way that the ratios between the absorption coef-

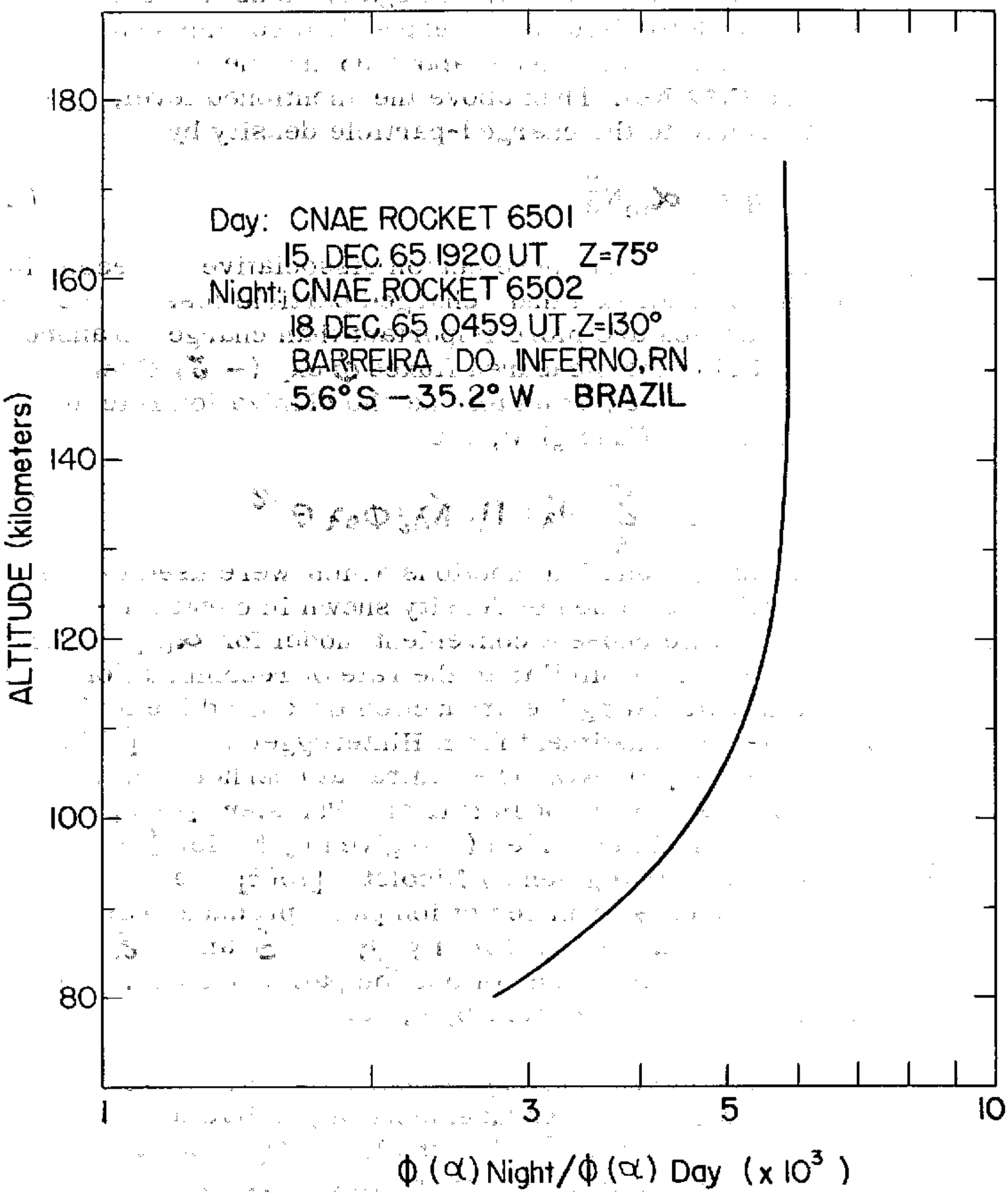

Fig: 2 — Ratio between integrated nighttime and daytime Lyman-α fluxes as measured by the ionization chambers and corrected for their difference in sensitivities.

ficients of H Ly-α versus H Ly-β, γ, δ and -ϵ are respectively 6, 18, 38, and 70 approximately.

Our measurements of negative ions in the nighttime flight were not good enough to allow us to derive firm conclusions from them; however they indicate that at least above 95 km one may assume equilibrium conditions ($N^+ \approx Ne$). Then above the mentioned level, production and loss can be related to the charged-particle density by

$$q = \alpha_{ie} N_e^2 \tag{1}$$

where α_{ie} is the effective rate for ion-electron dissociative recombination, provided this mode is the dominant charged particle loss mechanism and chemical processes are more important than charge transport.

Using the measured fluxes $\phi \exp(-\tau)$ shown in Fig. 1 and admitting that the equation for the photoionization rate at a given altitude is valid for a diffuse glow, i.e..

$$q = \sum_j \sum_\lambda \sigma'_{\lambda j} n_j K_{\lambda j} \phi_{o\lambda} e^{-\tau} \tag{2}$$

we calculated the ion pair production functions which were used to derive, by means of equation (1), the values of density shown in curves a - d of Fig. 4. For these curves we chose a convenient model for α_{eff} which is shown in Fig. 3 and which is similar to the rate of recombination given, by Friedman [1960]. In calculating the production q we used the ionization cross section σ' for the j^{th} constituent from Hinteregger et al. [1965] for O_2 and from Watanabe [1954] for NO. The neutral atmosphere distribution n_j was adapted from the case S= 70 of Harris and Priester [1962] for O_2. Utilizing the distribution of nitric oxide n(NO) given by Miller [1961] we obtained curve a and from n(NO) given by Nicolet [1965] we obtained curve b of Fig. 4. Values of $K_{\lambda j}$ (number of ion pairs produced per photon), were taken from Norton et al. [1963] for Ly-β, -δ and -ϵ; for Ly-α we used the ionization efficiency of one ion pair per 35 ev. Curve e results from the combination of curves b, c, d.

The curve f on Fig. 4 represents the densities which were obtained from our nighttime measurements of positive ions (N^+) with a modified Gerdien condenser [Meira et al. 1966]. Note that the gross features of curve f are reproduced in curve e in spite of the uncertainties in n(NO), α_{eff} and the assumption of no charge transport. The continuation of curve f above 180 km was obtained from an ionogram taken at the time of the flight. We shall comment on this problem later.

The conspicuous valley in N^+ at 128 km in our measurement is common to practically all densities measurements made with rockets at night [Ivanov-Kholodny, 1965] either for quiet or active sun, whether in equatorial [Blumle et al. 1965] or midlle latitudes [Aono et al. 1961 ; Sagalyn and Smiddy, 1964; Bowhill, 1966; Smith, 1966].
This evidence corroborates our assertion for the importance of the contribution to ionization at night by the H Lyman fluxes, producing an E-

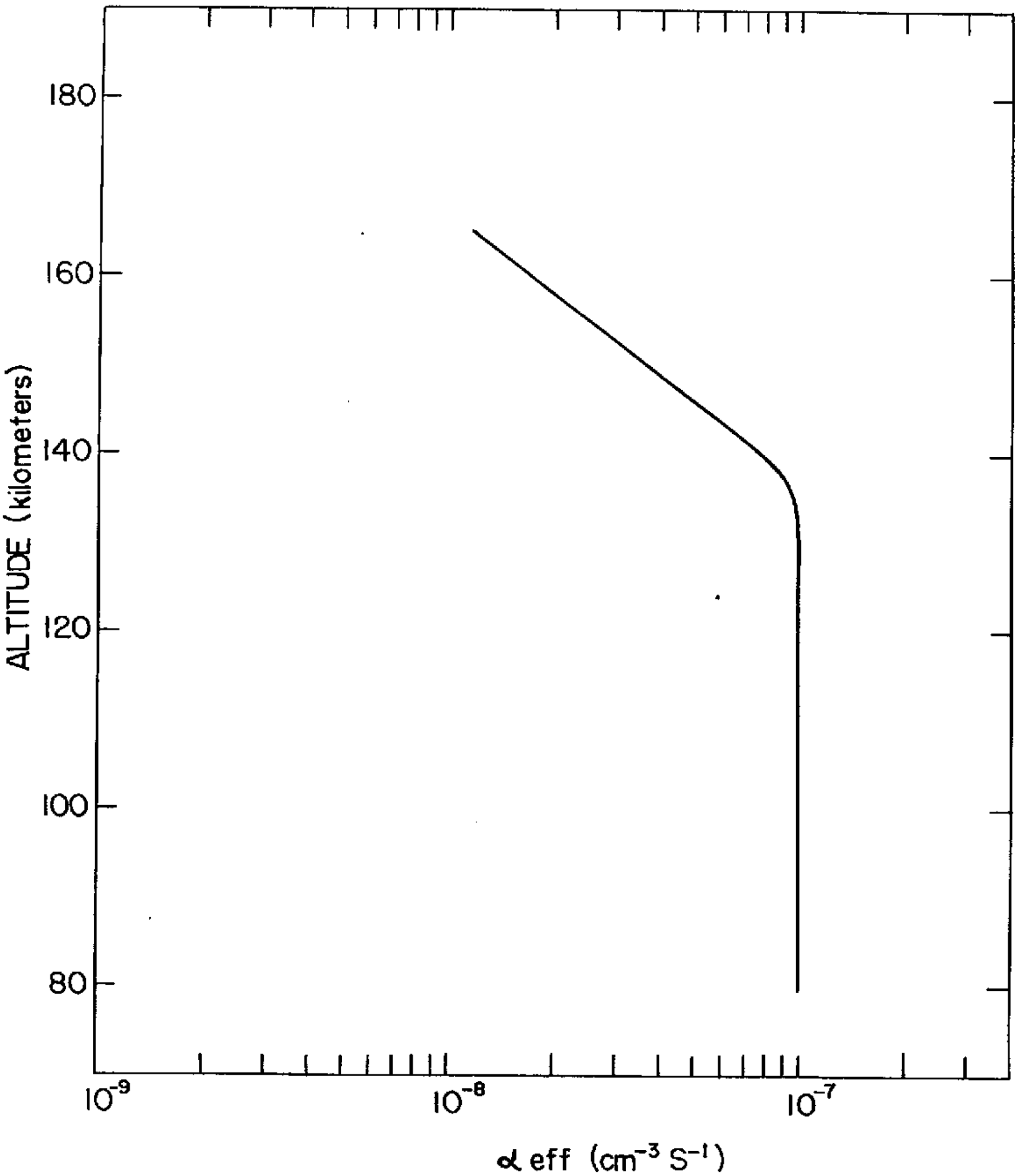

Fig. 3 — Values of α eff used in computing the curves of Fig. 4.

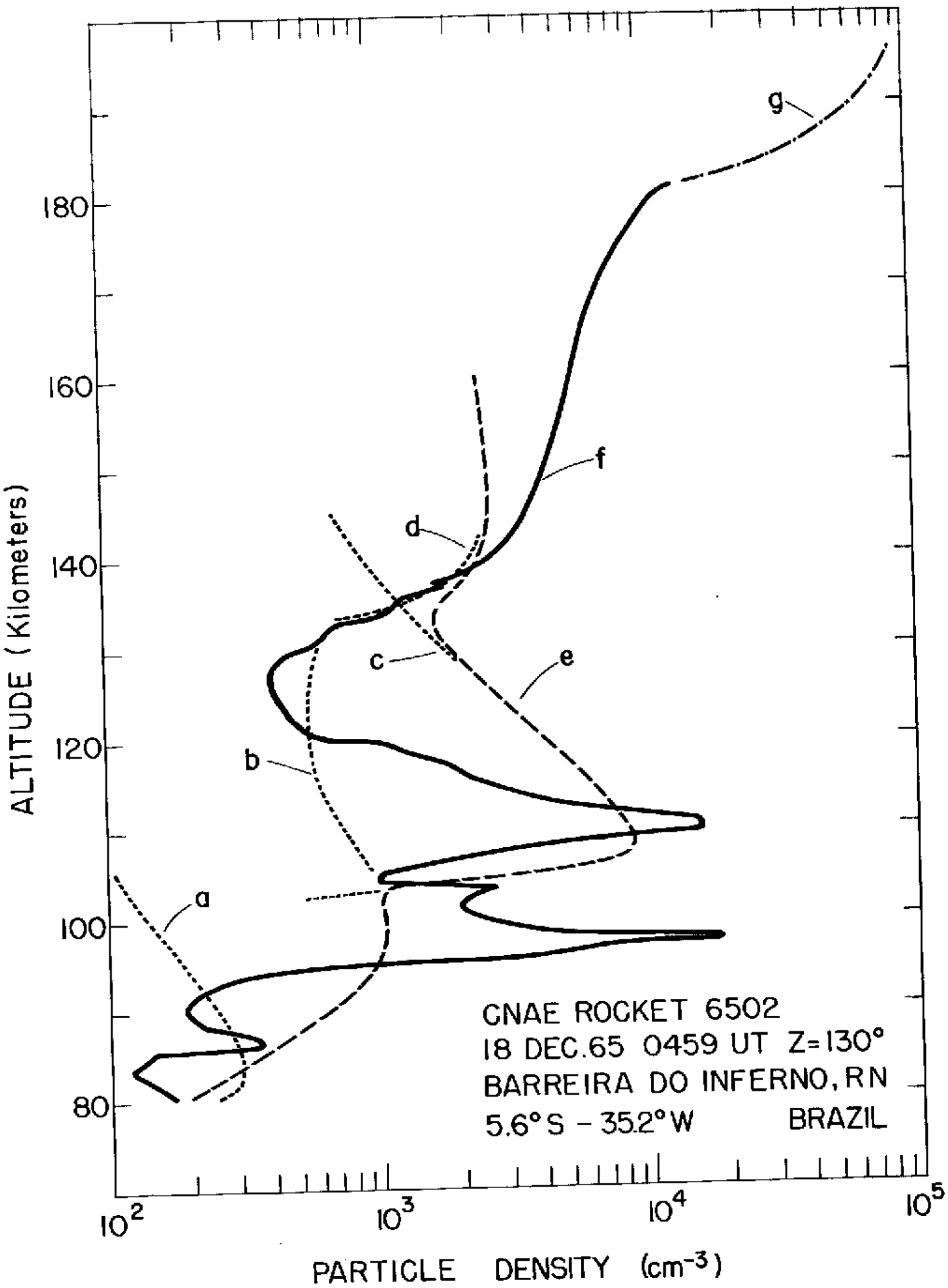

Fig. 4 — Measured and calculated values of ionic distribution
(a) computed with the measured $\phi(\alpha)$ and the model of Miller (1961) for NO;
(b) same for model by Nicolet (1965);
(c) same for $\phi(\beta)$ and O_2 densities from Harris and Priester (1962);
(d) same as (c) for $\phi(\delta,\varepsilon)$;
(e) total densities from (b), (c) and (d);
(f) measured ion densities;
(g) electron densities from ionogram.

region divided in two parts, a lower one (90-130 km) due primarily to Ly- α and Ly- β and a higher part (above 130 km) merging with the F-region due to Ly- δ and Ly- ε radiations .

Our ionogram showed an Es at a height of about 100 km. It is interesting to note the density peaks at 98 and 110 km in curve f of Fig. 4 . This double peak is very common in mid latitude nighttime rocket measurements [Aubry et al. 1966; Smith, 1966; Bowhill, 1966] and has been justified in terms of the wind-shear theory of Es formation which does not apply to equatorial region [Axford and Cunnold , 1966]. To this effect our measurements are puzzling to say the least , and some studying and revaluation of present theories will have to be done before a final conclusion can be reached about the formation of the double peak of ionization close to the equator. It should however be noticed that the heights of the peaks of density N^+ coincide with the heights of the peaks of ionization due to Ly- α and Ly- β radiations as shown in curve b and c of Fig. 4 .

The results presented in this letter have a bearing in many topics related to the ionosphere. Among them we would like to call attention to and briefly describe some of the implications :

1 - Based on the nighttime observationsof the H Lyman lines it is perfectly plausible to assume that a similar night glow [Brandt, 1961] ought to be observable in the resonance lines of He I (λ 584) and mainly He II (λ 304) which is a rather strong solar line [Hinteregger et al.,1965] . These sources can ionize N_2 , 0_2 and 0 in the F region and it would for instance provide an explanation to the mistery mentioned by Holmes et al. [1965] in observing ions with mass 28 in the night sky above 200 km. It would also justify the sharp increase with height of the density of 0^+ above 200 km and 0_2^+ above 190 in their measurements . The line H Ly- γ which has a daytime flux comparable to the sum of the fluxes of H Ly- δ and H Ly- ε , probably also contributes to the nighttime F region 0_2^+ densities .

2 - We have yet to determine if the general direction of the observed minimum flux intensity, which caused modulation in our measurements , is toward the anti solar direction as reported by Kupperian et al. [1959] . This would enhance the contribution to ionization of the winter polar nighttime ionosphere by the energy fluxes cited in item (1) above in view of smaller solar zenith angle ($\chi < 114^o$) at the pole .

3 - The horizon brightening implied in the previous item could possibly provide an explanation to the pre sunrise and post sunset enhancements of slab thickness ($\int$ Ndh/Nmax) as deduced by Garriott et al. [1965] from satellite measurements and a Chapman model ionosphere .

4 - The night glow [OI] $_{32}$ green line at λ 5577 Å is known [McCaulley and Hough , 1959 , Chamberlain , 1961] to arise predominantly from the 100 km neighborhood and can be related with the mechanism for 0_2^+ which is energetically capable of exciting this line . Thus our measurements of Ly - β have obvious implications as an indirected contributing

source . Also in view of the ionization considerations (N_2 , 0_2 , 0) of item (1) above concerning the F-region , ion-atom interchanges and dissociative recombinations [Nicolet , 1965] could contribute to other night glow lines such as $[OI]_{21}$ for instance .

5 - The ionogram obtained at the time of the flight was reduced to true height profiles by means of several different and usual procedures [Thomas, 1959 ; Piggott and Rawer , 1961 ; Titheridge , 1963] . In all cases it presented a discrepancy in height of about 80 km for the density measured at 180 km with the rocket. Working the inverse problem, i. e. finding the virtual height from the N (h) profile measured with the rocket we could reproduce very closely the virtual height at the given point in the ionogram. Obviously this comes about due to the contribution to the retardation caused by lower nighttime E region ionization which is just below the threshold density (1.25×10^4 cm^{-3}) of the sounder . This result should make one be cautious about drawing conclusions based on observations of very high values for nighttime hm F2 [Yonezawa , 1965; Olatunji, 1959] .

In view of our measurements we conclude that the H Lyman glows play a major role in the maintenance of nighttime lower ionosphere and we intend to make similar additional simultaneous rocket soundings from three locations(equatorial, middle and high latitudes) up to 400 km in order to measure the possible glow in the helium lines.

Acknowledgments - It is a pleasure to acknowledge the fruitful discussions with S. Bauer , A. C. Aikin and J. L. Donley of GSFC. This work resulted from the first sounding rocket cooperational program performed under a Memorandum of Understanding between NASA in the United States and CNAE in Brazil . The payloads were instrumented by P. I. Seixas and one of us (L. G. Meira, Jr.) under the direction of G. Spaid and R. Hagemeyer of GSFC . The launchings were performed under the direction of M. del Tedesco . Programming and computations by S. Casali, and reduction of N (h) ionosonde profiles by O. G. Almeida and L. C. Barata were done at the Space Physics Laboratory of CNAE and are here also gratefully acknowledge.

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