1. Publication Nº	2. Version	3. Date	5. Distribution
INPE-3603-PRE/794	*3rd**	*August, 1985*	☐ Internal ☒ External ☐ Restricted

4. Origin *DGA/DIG* Program *MAGNETOSFERA*

6. Key words - selected by the author(s)

ATMOSPHERIC X-RAYS
SOUTH ATLANTIC MAGNETIC ANOMALY

7. U.D.C.: *550.382.7*

8. Title *INPE-3603-PRE/794*

X RAY MEASUREMENTS AT THE SOUTH ATLANTIC MAGNETIC ANOMALY

10. Nº of pages: *21*

11. Last page: *20*

12. Revised by

M. A. Abdu

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Responsible author

13. Authorized by

Marco Antonio Raupp
Director General

14. Abstract/Notes

Balloon-borne experiments using omnidirectional scintillation detectors that measured X ray with energies between 30 and 150 keV in the atmosphere were conducted during 1981 from São José dos Campos-Brazil (geographic coordinates $23^o12'S$, $45^o51'W$ and L ~ 1.13). The measurements detected an intensification in the X ray flux in association with a strong geomagnetic storm. The enhancement in the flux in this energy range, attributed to electron precipitation, was determined to be ~ 7×10^{-3} photons cm^{-2} s^{-1} keV^{-1} at 5 g cm^{-2}. The results are compared to similar ones obtained in the region of the South Atlantic Magnetic Anomaly and their implications are discussed briefly in the context of local energetic electron precipitation.

15. Remarks *This work was partially supported by the "Fundo Nacional de Desenvolvimento Científico e Tecnológico" under contract FINEP 537/CT. This work is being submitted to Journal Geophysical Research.*
**Revised work in April, 1986.*

X RAY MEASUREMENTS AT THE SOUTH ATLANTIC MAGNETIC ANOMALY

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Abstract. Balloon-borne experiments using omnidirectional scintillation detectors that measured X ray with energies between 30 and 150 keV in the atmosphere were conducted during 1981 from São José dos Campos-Brazil (geographic coordinates $23^{o}12'S$, $45^{o}51'W$ and $L \sim 1.13$). The measurements detected an intensification in the X ray flux in association with a strong geomagnetic storm. The enhancement in the flux in this energy range, attributed to electron precipitation, was determined to be $\sim 7 \times 10^{-3}$ photons cm^{-2} s^{-1} keV^{-1} at 5 g cm^{-2}. The results are compared to similar ones obtained in the region of the South Atlantic Magnetic Anomaly and their implications are discussed briefly in the context of local energetic electron precipitation.

Introduction

The South Atlantic Magnetic Anomaly (SAMA) refers to a region characterized by a blogal minimum in the earth's magnetic field total intensity. Dessler [1959] was the first to point out that this anomaly would have important implications in the dynamics of the energetic charged particles trapped in the inner radiation belt, in a way that could cause their precipitation in the anomaly region. The first experimental evidence on the presence of enhanced radiation in the anomaly was provided from measurements carried out on board the Sputnik V satellite [Vernov et al., 1967]. Later on there has been considerable interest in looking for particle precipitation and related processes in the region of SAMA. In particular, ionospheric and aeronomic effects of particle precipitation have received increasing attention [e.g., Paulikas, 1975; Gledhill, 1976, Abdu and Batista, 1977]. However, as printed out by Gledhill [1979], the energy spectra and fluxes of the precipitating electrons are still poorly known, the main reason for this paucity of information being the contamination of the measurements by large fluxes of penetrating trapped protons in the spacecraft detection system and the presence of artificially injected electrons on July 9, 1962, "Starfish" nuclear detonation, whose decay rate caused the return to natural radiation level of the inner belt electrons only by the end of the 1960s [Teague et al., 1979]. In recent years there have been a few attempts to study specifically the particle precipitation in the anomaly region [e.g., Gledhill and Hoffman, 1981; Vampola and Gorney, 1983].

The purpose of this work is to present and discuss the results of X ray measurements carried out in the SAMA region using a scintillation detector on board a stratospheric balloon launched from São José dos Campos-Brazil on April 14 and December 18, 1981. The calculated bremsstrahlung X ray flux, due to electron precipitation, is used to determining the flux and energy spectrum of the corresponding precipitating energetic electrons. The results are compared with similar ones obtained earlier in the anomaly region by Ghielmetti et al. [1964]. But in our analysis we have taken into account the diffuse X ray component which was not originally considered by Ghielmetti et al. [1964] [Hudson et al., 1966]. From our X ray measurements we have also attempted to obtain information about the related energy deposition in the atmosphere over the anomaly.

X Ray Measurements

The detector used in both of our flights consisted of a Harshaw NaI(Tℓ) crystal with dimensions of 3" x 1/2", set up to look upward to an approximately 2π steradian solid angle. The effective area was 30.4 cm^2, and the efficiency was taken equal to unity for the energy range of interest, namely, 30-150 keV. For the April flight, three differential energy range discriminators were selected (namely, 30-50 keV, 50-70 keV, and 70-150 keV), their outputs were scaled by 64, and the most significant bits of the scaler were fed to three subcarrier oscillators, in a way similar to that used by Ghielmetti et al. [1964]. For the December flight, a 64-channel pulse height analyzer (PHA) that covered the energy range of 30-150 keV was used. A differential discriminator for the whole energy range, scaled by 16, was also available. The data from the PHA were telemetered serially on a pulse code modulation channel. For both flights the data along with assorted payload housekeeping information were telemetered using an FM/FM telemetry system. The duration of the flights was defined by the telemetry range as well as by the payload recovery facilities.

The April 14 and December 18 flights covered local time intervals of 0248-0704 and 0310-0843 with corresponding ceiling altitudes of 4 g cm^{-2} and 5.5 g cm^{-2}, respectively. During both flights the balloons drifted toward the west, staying at approximately the latitude of São José dos Campos ($L \sim 1.13$) and covering a longitudinal interval $\leq 4^{\circ}$.

Balloon-borne X ray measurements for determining the precipitating electron flux in the anomaly region had, in fact, started in the early 1960s. Some relevant details of such existing measurements including those of our present work are given in Table 1. Also shown, for each case, are two parameters related to geomagnetic activity. $|\mathrm{Dst}|_{max}$ stands for the maximum of the absolute value of the Dst index, taken for the time interval that involves the balloon flight and the preceding 24 hours. ΣKp_m represents the mean for the sum of the Kp values taken for the day of the balloon flight and the preceding day. Both parameters show the occurrence of a strong geomagnetic activity related to the flight of April 14, 1981. On the other hand, these parameters indicate lower geomagnetic activities for the other flights.

X Ray Flux Due to Precipitating Electrons

Figure 1 shows the X ray fluxes measured during the flights of April 14 and December 18, 1981, for the energy interval 30-150 keV (the symbols represent the standard deviation "σ" due to counting statistics). At the ceiling altitudes the measured fluxes varied within $\pm 1\sigma$ with respect to the mean values, for both flights. The measured fluxes were also normalized to a mean value between 70 and 180 g cm^{-2}, since at this depth interval and at the low latitude region of our measurements no variation in the flux with geomagnetic activity is expected [Charakhch'yan et al., 1978]. The small differences (of the order of 5%) from one flight to the other are attributed to intrinsic errors of the measurements (the most important of them in this depth interval arising from uncertainty in the depth values). Figure 1 also shows, in the inset, the Dst index for the flights whose time durations are marked by hatched intervals. We may observe that the flight of April 14 occurred during the recovery phase of a strong geomagnetic storm, whereas the flight of December 18 occurred during a time of weak geomagnetic activity (these magnetic activities are confirmed by local magnetograms).

For the normalized flux values of Figure 1 a fitting to a power law was performed, in the depth range 20-50 g cm^{-2}, in order to determine the atmospheric component (secondary X rays due to cosmic rays) at ceiling altitudes. With respect to the power law extrapolation of the fluxes above the Pfotzer maximum, the observations by Peterson [1963], Bleeker and Deerenberg [1970], and Damle et al. [1971], as well as the theoretical calculation by Danjo [1972], provide sufficient strength to justify its adoption for that purpose. The 20-50 g cm^{-2} depth range was selected to avoid the influence of other sources of X rays, for atmospheric depths less than

20 g cm^{-2}, as well as that of the different behavior of the atmospheric component around the Pfotzer maximum. More details on the fitting procedure and on the justification for selecting the depth range 20-50 g cm^{-2} are given by Pinto [1984] and Pinto and Gonzalez [1985]. The fitting is given by $(2.76 \pm 0.06) \times 10^{-3} Z^{-0.682 \pm 0.005}$ photons cm^{-2} s^{-1} keV^{-1}, for the energy interval 30-150 keV, and also shown in Figure 1. A similar procedure was also adopted for the fluxes measured by Ghielmetti et al. [1964], reported in IAFE [1972].

Once the atmospheric component is determined, one can obtain the additional component from the measurements, defined as the difference between the total flux and the atmospheric component. On the other hand, the additional component can be regarded as the sum of the diffuse component and that related to energetic electron precipitation (if any) in the SAMA. Thus, in order to determine the flux due to precipitation, it is necessary to know the diffuse component at the ceiling altitude. This is accomplished by computing the propagation of the diffuse flux from its known value (primary flux) at the top of the atmosphere down to the balloon ceiling altitude. This calculation was performed by Pinto [1984], taking for the primary diffuse flux $36E^{-2.1}$ photons cm^{-2} s^{-1} keV^{-1} sr^{-1} [Manchanda et al., 1972] and using the Monte Carlo method to compute the X ray photon propagation in the atmosphere (following Horstman and Moretti [1971] and Pilkington and Anger [1971]. Figure 2 shows a comparison between the additional and diffuse components for all flights of Table 1 and for atmospheric depths ≤ 10 g cm^{-2}. The atmospheric component is also shown in this figure. Note that the atmospheric component for the flight of December 13, 1963, is greater than those for the other flights, as expected taking into account the different rigidities associated with the flights. The flight of December 11, 1963, is not shown due to the fact that it does not cover the total 30-150 keV energy range. As pointed out before, the difference between the additional and the diffuse components is assumed to be due to energetic electron precipitation in the SAMA. This flux is shown in Figure 3 for all the flights, together with the diffuse component. In this figure one can observe that the X ray fluxes due to electron precipitation for the flights of December 13, 1963, and April 14, 1981, are of the same order of magnitude as that due to the diffuse component. For the flight of December 18, 1981, only an upper limit for any X ray flux due to electron precipitation could be determined.

Precipitation Electron Flux and Related Energy Deposition in the Atmosphere

Using the X ray flux due to energetic electron precipitation in the SAMA, one can determine the parent flux of precipitating electrons based on some assumptions [see Berger and Seltzer, 1972].

Figure 4 shows the differential precipitating electron spectrum for the flight of April 14, 1981, obtained from the model given by Seltzer et al. [1973]. The spectrum is given by (0.8±0.1) exp (-T/(200±20)) electrons cm^{-2} s^{-1} keV^{-1} sr^{-1}, where T represents the energy in keV (at lower energies, a power law spectrum seems to be more appropriate [Vampola and Gorney, 1983]). Below approximately 100 keV this spectrum is less meaningful, since electrons with those energies contribute less significantly to the $\geq$ 30 keV X ray flux measured at balloon altitudes. For the flight of December 13, 1963, it was not possible to determine one spectrum due to the fact that only two X ray energy ranges were measured. Figure 4 shows the electron precipitating fluxes reported by West and Buck [1976], by Vampola and Gorney [1983] and, at lower energies, by Gledhill and Hoffman [1981]. All these fluxes agree fairly well in representing a common spectrum, at least for energies $\geqq$ 100 keV (as mentioned above), mainly considering that they refer to different conditions of geomagnetic activity. These fluxes are also consistent with those related to the trapped electron population (with the plotted values in Figure 4 divided by 10), as obtained from the model AE-6 [Teague et al., 1976]. The measurements obtained by Imhof et al. [1980] were not included in this figure, since their fluxes were reported only in counts per second.

Finally, Figure 5 shows ionization profiles in the atmosphere of the SAMA for the flight of April 14, 1981, calculated from the precipitating electron flux considering energies $\geq$ 100 keV. The profiles (due to electrons and X rays) were calculated following the method of Berger et al. [1970, 1974] (see also Luhmann [1976, 1977]). Also shown for comparison in Figure 5 are the ionization profiles produced by H Lyman α, galactic cosmic rays, solar X rays and that related to precipitating electrons in the SAMA, as obtained by Vampola and Gorney [1983] for L values between 1.1 and 2.0 and for magnetically quiet times. The profile due to solar X rays, referring to a period of solar maximum and to a zenith angle of 50°, galactic cosmic rays, referring to 5° geomagnetic latitude, and direct and scattered H Lyman α were reproduced from Rosenberg and Lanzerotti [1979]. Ionization caused by precipitating protons was not considered due to the lack of conclusive evidence about its existence, at least at a significant level [Paulikas, 1975; Gledhill, 1979].

Discussion and Conclusions

Results of X ray measurements at balloon altitudes in the SAMA carried out on April 14 and December 18, 1981, are analyzed in order to determine the enhanced X ray flux in the anomaly as well as the spectrum of the energetic electrons responsible for the production of the observed X ray intensities. An extension of the present analyses to similar results reported by Ghielmetti et al. [1964] in December 1963 has been carried out.

From the results of this analysis, an X ray flux of the order of 7×10^{-3} photons cm^{-2} s^{-1} keV^{-1}, between 30 and 150 keV and at ~ 5 g cm^{-2} atmospheric depth, is consistent with the measurements of April 14, 1981, and December 13, 1963, whereas for the flight of December 18, 1981, only an upper limit of the order of 10^{-3} photons cm^{-2} s^{-1} keV^{-1} could be determined. The fact that the fluxes measured on December 13, 1963, and April 14, 1981, are of the same order of magnitude, even under different conditions of geomagnetic activity (see Table 1), has to be interpreted with care, since they correspond to different locations within the SAMA and since the measurements of December 13, 1963, occurred during an epoch characterized by the presence of strong artificial inner belt energetic electron population (related to the "Starfish" nuclear detonation). On the other hand, a comparison between the measurements obtained on April 14 and December 18, 1981, at the same location within the SAMA, suggests an intensification of the X ray flux with geomagnetic activity. This type of intensification is in accordance with similar direct evidence [Paulikas, 1975; Voss and Smith, 1980; Imhof et al., 1980], as well as with indirect evidence [Trivedi et al., 1973; Abdu et al., 1973, 1981] concerning increases in the flux of precipitating electrons in the SAMA region during periods of enhanced geomagnetic activity.

Thus, the results presented in this work concerning the X ray flux intensification at balloon altitudes could be considered as the first evidence on the precipitation of inner belt natural electron population associated with geomagnetic activity inside the anomaly region. Similar evidence on gamma rays has been claimed by Martin et al. [1974].

From the measured X ray flux due to precipitating electrons on April 14, 1981, which was a magnetically disturbed period, a precipitating electron flux of ~ 0.8 exp (-T/200) electrons

$cm^{-2}\ s^{-1}\ keV^{-1}\ sr^{-1}$ was obtained. This corresponds to an integrated energy flux of ~ 2.7×10^{-4} ergs $cm^{-2}\ s^{-1}$, in the energy range between 100 keV and 1 MeV. This flux is comparable to that reported by West and Buck [1976] and by Vampola and Gorney [1983] (of about 6.71×10^{-4} ergs $cm^{-2}\ s^{-1}$ for the same energy range), both for geomagnetically quiet conditions. Since their measurements occurred at higher L values (see Figure 4) than ours, and since it is known that a maximum of precipitation is expected at about L = 1.4 [Voss and Smith, 1980], one is inclined to attribute this coincidence in the fluxes (referring to quite different conditions of magnetic activity) as due to the flux differences arising from the different L values being partially compensated for by the higher magnetic activity that was present during our measurements.

From the atmospheric ionization profile computed for the flight of April 14, 1981, one observes that it dominates all other ionization sources by almost two orders of magnitudes at atmospheric altitudes around 60 km. Thus, during magnetically disturbed periods, this ionization source can be regarded as the dominant one at ~ 60 km height and at L ~ 1.13, mainly at night. In fact, Gonzalez et al. [1982] claimed to have observed an effect of this type of middle atmosphere ionization in the fair-weather electric field.

Finally, it is well known that during geomagnetically calm periods the main physical mechanism responsible for the electron precipitation process is multiple Coulomb scattering [Roederer et al., 1967]. On the other hand, during geomagnetically disturbed periods, additional physical mechanisms could be present as well. One important mechanism could involve wave-particle interactions [Paulikas, 1975]. Examples of such interactions at low L values are electromagnetic hiss [Tsurutani et al., 1975], local ionospheric fluctuations [Imhof and Smith, 1966], and geomagnetic micropulsations (Pc5) [Trivedi et al., 1973]. Furthermore, even an intensification of the Coulomb scattering itself, during geomagnetically active periods, should not be disregarded. However, only with more measurements of the precipitating electrons, mainly during disturbed periods, will a major understanding of the precipitation process in the SAMA be achieved.

Acknowledgments. This work was partially supported by the Fundo Nacional de Desenvolvimento Científico e Tecnológico FNDCT, under contract FINEP 537/CT. We appreciate the support given by the Director of INPE, Marco Antonio Raupp. The magnetograms were kindly provided by the Observatório Nacional of Rio de Janeiro-Brazil. The authors also appreciate the comments by I.J. Kantor and A.L. de Moura Fernandes and the critical review of the manuscript by M.A. Abdu.

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(Received August 5, 1985;
revised November 18, 1985;
accepted December 16, 1985.)

Paper number 5A8812.
0148-0227/86/005A-8812$05.00

Pinto and Gonzalez: X Ray Measurements

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Fig. 1. X ray fluxes between 30 and 150 keV and the Dst index for the flights of April 14 and December 18, 1981. The symbols represent the standard deviation due to counting statistics. The flight times are indicated by hatched intervals.

Fig. 2. The additional, atmospheric, and diffuse components for atmospheric depths $\leq$ 10 g cm^{-2} and for the flights of December 13, 1963, and April 14 and December 18, 1981.

Fig. 3. X ray fluxes due to electron precipitation at SAMA for the flights of December 13, 1963, and April 14 and December 18, 1981. The flux due to the diffuse component is also shown. The arrow at the bottom indicates that for the flight of December 18, 1981, only an upper limit could be determined.

Fig. 4. Precipitating electron spectrum in the SAMA for the flight of April 14, 1981, compared with those obtained by other authors.

Fig. 5. Comparisons of the atmospheric ionization profiles due to precipitated electrons and associated X rays for the flight of April 14, 1981 with those due to solar X rays, H Lyman α and galactic cosmic rays. Also shown is the ionization profile related to electron precipitation as obtained by Vampola and Gorney [1983].

TABLE 1. Balloon Flights for X Ray Measurements at the SAMA

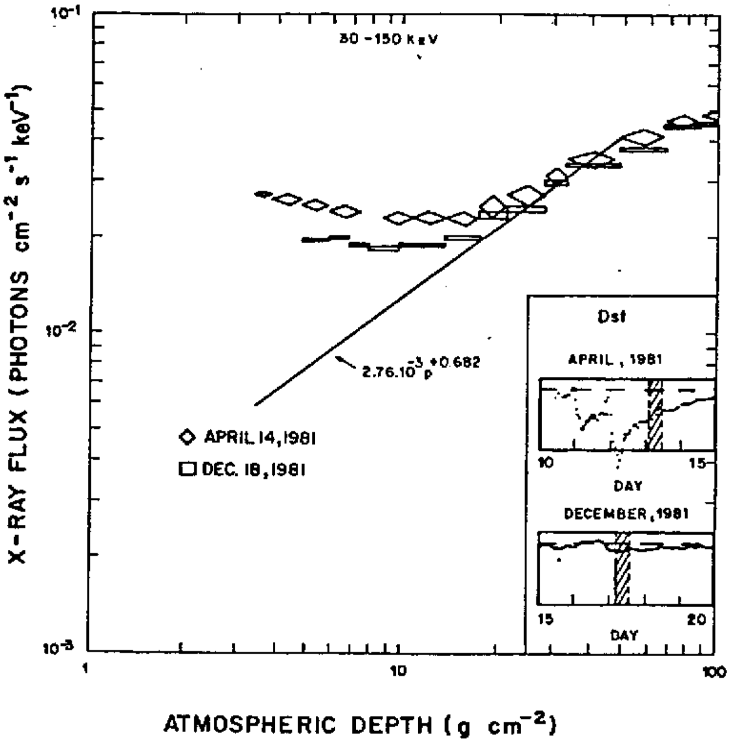
30 -150 keV
10^{-1}
10^{-2}
10^{-3}
X-RAY FLUX (PHOTONS cm^{-2} s^{-1} keV^{-1})
1
10
100
ATMOSPHERIC DEPTH (g cm^{-2})
2.76.10^{-3} p$^{+0.682}$
◇ APRIL 14,1981
☐ DEC. 18,1981
Dst
APRIL , 1981
10
15
DAY
DECEMBER , 1981
15
20
DAY

Fig. 1

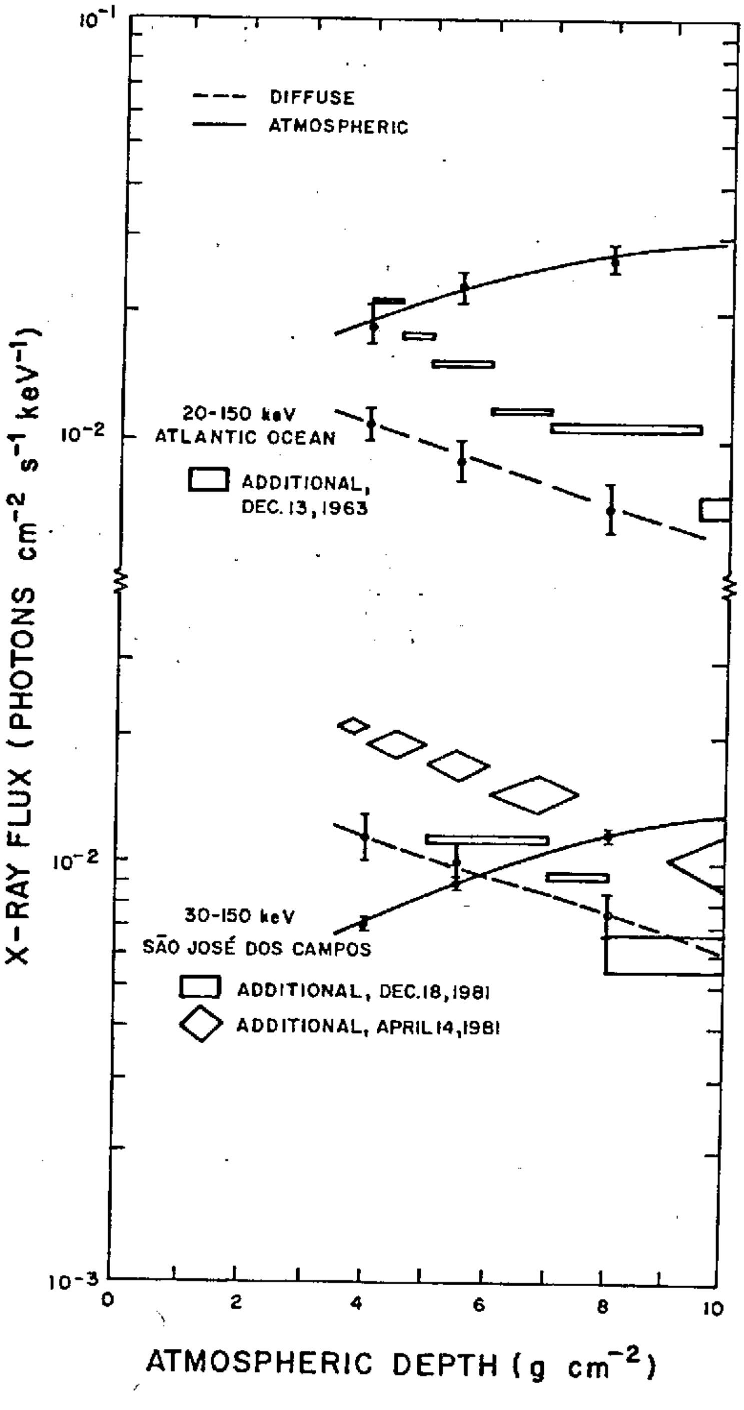
DIFFUSE
ATMOSPHERIC
20-150 keV
ATLANTIC OCEAN
ADDITIONAL, DEC. 13, 1963
30-150 keV
SÃO JOSÉ DOS CAMPOS
ADDITIONAL, DEC.18, 1981
ADDITIONAL, APRIL 14, 1981
10^{-1}
10^{-2}
10^{-2}
10^{-3}
0
2
4
6
8
10
X-RAY FLUX (PHOTONS cm^{-2} s^{-1} keV^{-1})
ATMOSPHERIC DEPTH (g cm^{-2})

Fig. 2

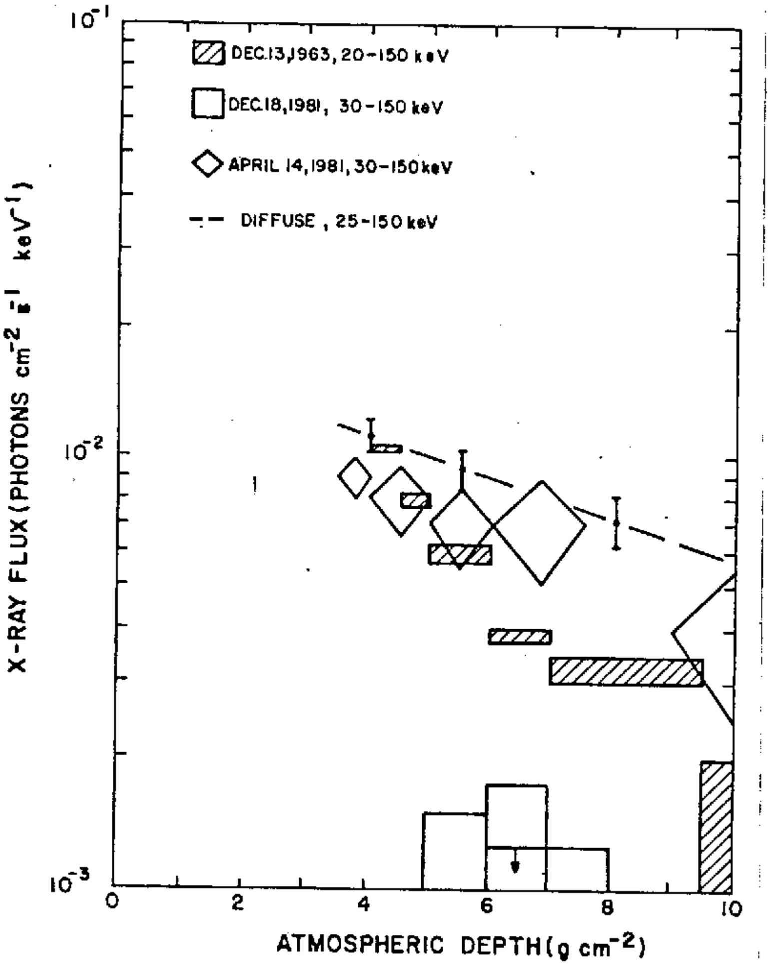
10⁻¹
10⁻²
10⁻³
▨ DEC.13,1963, 20-150 keV
☐ DEC.18,1981, 30-150 keV
◇ APRIL 14,1981, 30-150 keV
- - DIFFUSE, 25-150 keV
X-RAY FLUX (PHOTONS cm⁻² s⁻¹ keV⁻¹)
0
2
4
6
8
10
ATMOSPHERIC DEPTH (g cm⁻²)

Fig. 3

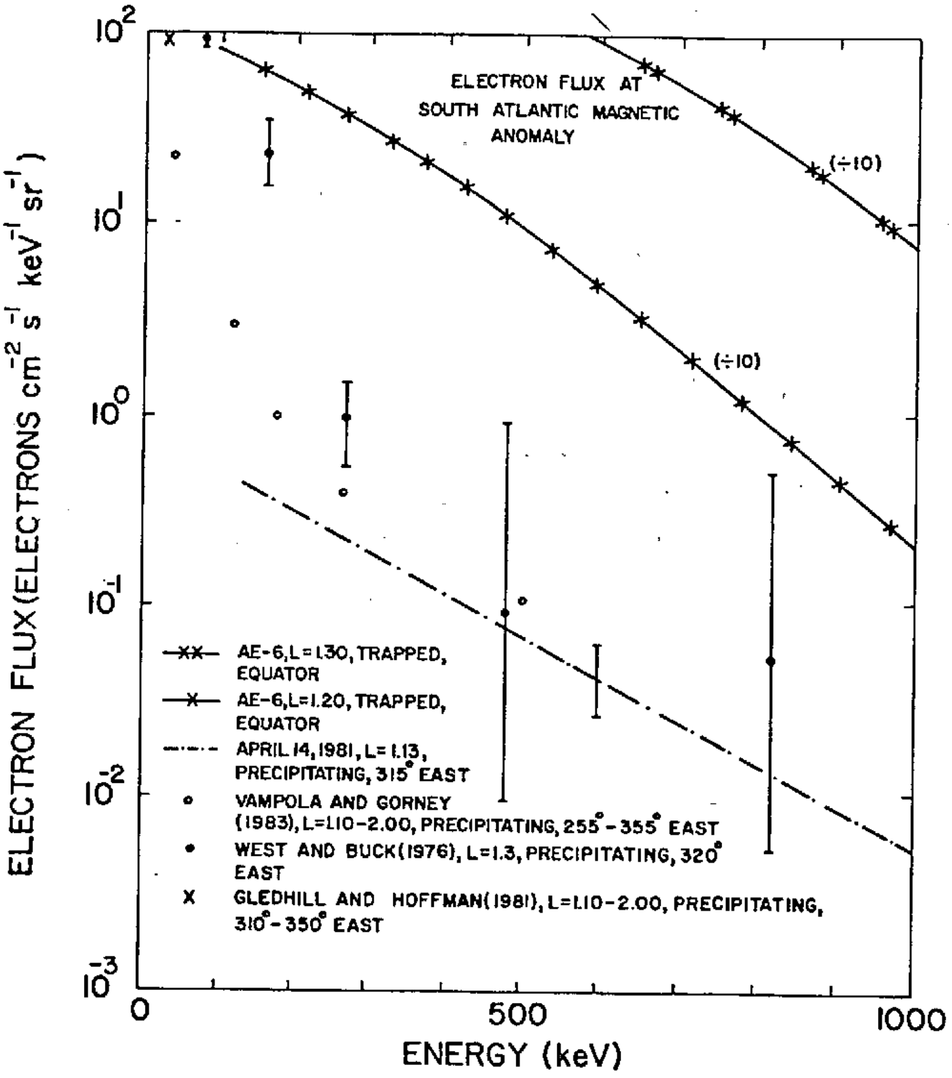
ELECTRON FLUX AT SOUTH ATLANTIC MAGNETIC ANOMALY
(÷10)
(÷10)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
500
1000
ENERGY (keV)
ELECTRON FLUX (ELECTRONS cm^{-2} s^{-1} keV^{-1} sr^{-1})
—XX— AE-6, L=1.30, TRAPPED, EQUATOR
—X— AE-6, L=1.20, TRAPPED, EQUATOR
—·—·— APRIL 14, 1981, L=1.13, PRECIPITATING, 315° EAST
○ VAMPOLA AND GORNEY (1983), L=1.10-2.00, PRECIPITATING, 255°-355° EAST
● WEST AND BUCK (1976), L=1.3, PRECIPITATING, 320° EAST
X GLEDHILL AND HOFFMAN (1981), L=1.10-2.00, PRECIPITATING, 310°-350° EAST

Fig. 4

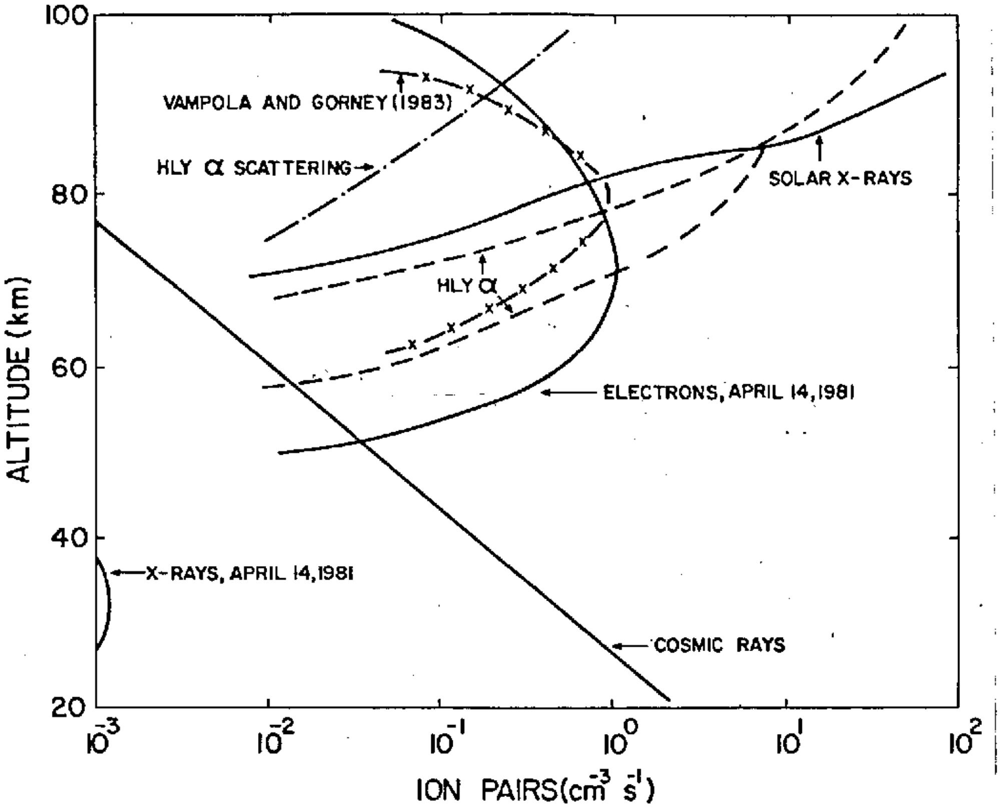
100
80
60
40
20
ALTITUDE (km)
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
ION PAIRS($cm^{-3}\ s^{-1}$)
VAMPOLA AND GORNEY (1983)
HLY α SCATTERING
SOLAR X-RAYS
HLY α
ELECTRONS, APRIL 14, 1981
X-RAYS, APRIL 14, 1981
COSMIC RAYS

Fig. 5

Table 1

Date	Launch Time, UT	Site	Rigidity, GV	McIlwain Parameter, L	Detector NaI (Tℓ)	Differential Energy Range, keV	Ceiling, $g\ cm^{-2}$	Ceiling Time, min	$\|Dst\|_{max}$	$\sum Kp_m$	Author
Dec. 11, 1963	1919	Atlantic Ocean 35.5° S 323.3° E	10.4	1.32	1 1/4" x 1/2"	20 - 60	4.5	11	6	3	Ghielmetti et al. [1964]
Dec. 13, 1963	1624	Atlantic Ocean 37.7° S 313.0° E	10.5	1.28	1 1/4" x 1/2"	20 - 60 60 -150	4.0	160	15	10	Ghielmetti et al. [1964]
April 14, 1981	0548	Brazil 23.1° S 314.5° E	12.1	1.13	3" x 1/2"	30 - 50 50 - 70 70 -150	4.0	105	291	41	Present work
Dec. 18, 1981	0610	Brazil 23.1° S 314.5° E	12.1	1.13	3" x 1/2"	64 Channel PHA	5.5	210	36	17	Present work