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KeyWords Plus:
ENERGETIC ELECTRON-PRECIPITATION, INNER BELT ELECTRONS, PLASMASPHERIC HISS, PARTICLE-PRECIPITATION, RADIATION BELT, TIME VARIATIONS, VLF-CHORUS, ELF HISS, EMISSIONS, ATMOSPHERE

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X ray microbursts in the South Atlantic magnetic anomaly

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Abstract. Balloon-borne X ray measurements with high time resolution were carried out in the South Atlantic magnetic anomaly to investigate the fine structure of the precipitation in this region. Measurements were obtained on two balloon flights launched from Cachoeira Paulista, São Paulo, Brazil, on January 26 and February 1, 1994, and were supported by onboard electric field and geomagnetic field ground data. In one flight, we have found that rapid changes do occur in times of about 0.05 s during periods of a few seconds. They should be considered as the first evidence of the presence of microbursts in the low *L* value region of the South Atlantic anomaly. These microbursts were not correlated with sferic signatures in the same hemisphere and may be correlated with magnetic fluctuations in the geomagnetic field. Energy-time features of the microbursts are examined in order to identify possible responsible mechanisms.

Introduction

The South Atlantic magnetic anomaly (SAMA) is a prominent feature of the Earth's geomagnetic field, characterized as a region of low magnetic field intensity [*Chapman and Bartels*, 1940; *Pinto et al.*, 1992]. The origin of the SAMA is not well understood; however, it seems that it is associated with a particular reverse flux feature at the core-mantle boundary [*Pinto et al.*, 1991a; *Pinto*, 1993].

In addition to local effects [*Gledhill*, 1976; *Benbrook et al.*, 1983; *Gogoshev et al.*, 1985; *Pinto et al.*, 1990a, b, c], the SAMA has an important role in the dynamics of the energetic electrons of the Earth's radiation belts [*Dessler*, 1959; *Sheldon* et al., 1985; *Pinto and Gonzalez*, 1989a], in particular in the precipitation process (for a review on this subject see work by *Paulikas* [1975]; *Pinto and Gonzalez* [1989b]; *Pinto et al.* [1992]; and *Pinto* [1993]).

The global morphology of the electron precipitation in the SAMA region has been studied in detail both theoretically [*Roederer et al.*, 1967; *Torr et al.*, 1975; *Sheldon*, 1991] and experimentally [*Seward*, 1973; *Vernov et al.*, 1967; *Voss and Smith*, 1980; *Vampola and Gorney*, 1983; *Nagata et al.*, 1987]. The precipitation occurs at all times. During magnetically quiet times, the precipitation is a result of a diffusion process involving electron pitch angle scattering due to wave-particle interactions at higher altitudes [*Vampola and Gorney*, 1983] and coulomb scattering by the atmospheric neutral constituents at lower altitudes [*Roederer et al.*, 1967]. During magnetically disturbed periods, satellite [*Imhof et al.*, 1980; *Allen et al.*, 1989], balloon [*Pinto and Gonzalez*, 1986b; *Pinto et al.*, 1989], and ground [*Trivedi et al.*, 1973; *Abdu et al.*, 1981; *Pinto et al.*, 1989a] measurements have shown that the precipitation is intensified, in particular, during large geomagnetic storms. The intensification is believed to be associated with an increase in the hiss wave intensity through wave-particle interactions during these periods [*Smith et al.*, 1974; *Tsurutani et al.*, 1975; *Larkina and Likhter*, 1982].

The electron precipitation in the SAMA region is also longitude dependent. *Bering et al.* [1988] have summarized the available information, noting that there are significant differences in the amount of longitudinal variation in precipitation that different authors report. *Bering et al.* [1988] suggest that the diffusion process may have a longitude dependence. Such suggestion seems to be supported by ELF/VLF observations made by *Parrot* [1990]. There are also indications that impulsive discrete precipitation processes are longitude dependent [*Bering et al.*, 1988; *Friedel and Hughes*, 1992]. The dependence would be related to the limited amount of scattering during discrete wave-particle interactions in the presence of a strongly longitude-dependent drift loss cone [*Sheldon*, 1991]. The longitudinal dependence of the drift loss cone is such that the precipitation would be larger in the westside of the center of the SAMA. The longitude dependence of the electron precipitation in the SAMA may also reflect the intrinsic longitude dependence of thunderstorm and man-made activity (like VLF transmitter location and power-line distribution), which act as sources to produce wave-particle interactions.

The results of several authors (e.g., *Vampola and Gorney*, 1983; *Sheldon*, 1991) suggest that basically, there are two types of interaction processes causing electron precipitation in the SAMA region: slow "diffusion" processes and fast processes.

The slow pitch angle diffusion processes causing electron precipitation are driven by coulomb scattering, which occurs all the time, or by wave-particle interactions involving almost continuous waves. The atmospheric scattering process is nearly independent of geomagnetic activity [*Pinto et al.*, 1986]. Two types of waves are supposed to cause slow "diffusion" precipitation: waves produced by VLF transmitters and plasmaspheric hiss. Precipitation of electrons induced by VLF transmitters has been discussed for a long time [*Vampola*, 1977]. The initial studies were later confirmed by simultaneous electron, wave and plasma measurements [*Imhof et al.*, 1981] and by active experiments [*Imhof et al.*, 1983]. *Datlowe and Imhof* [1990] have shown that the

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interaction between VLF whistler mode waves induced by ground-based transmitter signals and electrons can be reasonably explained by assuming a first-order cyclotron resonance at magnetic equator, although there is evidence that off-equatorial interactions may be important as well [*Vampola*, 1987]. The precipitation induced by VLF transmitters is independent of the geomagnetic activity and seems to be important only in a limited region of the SAMA, which depends on the latitudinal position of the transmitters [*Inan et al.*, 1984]. *Imhof et al.* [1984] have found that this region is between L shells 1.6 and 2.2.

Electron diffusion precipitation caused by wave-particle interactions involving plasmaspheric hiss has been identified for a long time. *Thorne et al.* [1973] have attributed the origin of hiss to amplification of the ambient thermal noise by cyclotron instability at the plasmapause. The instability is driven by pitch angle anisotropy of low-energy electrons, due to the presence of a loss cone. After generation, the waves propagate across the magnetic field lines [*Lyons and Thorne*, 1970], filling the entire plasmasphere. In this model the hiss intensity is intensified during magnetically disturbed periods due to the transport of low-energy electrons from the outer magnetosphere to the plasmapause region. Many observations have been consistent with this model (e.g., *Church and Thorne*, 1983]. However, wave growth calculations [*Huang et al.*, 1983] and wave normal angle data [*Sonwalkar and Inan*, 1988; *Storey et al.*, 1991] have shown that the hiss could not be generated directly from a background noise by this model. Recent investigations [*Sonwalkar and Inan*, 1989; *Draganov et al.*, 1992, 1993] seem to indicate that ducted and nonducted whistlers produced by lightning may play an important role in the generation of hiss, producing an enhanced wave background from which hiss could be generated. The ducted and nonducted whistlers may also be responsible for maintaining the experimentally observed levels of hiss during magnetically quiet times. Another point that merits more investigation is related to the hiss observations at low L values. Tsurutani et al. [1975] have found a secondary peak in the hiss intensity around L=1.1, which they attribute to a focusing effect. Also they reported a minimum around L=2, which is difficult to explain by the hypothesis that hiss originates in the vicinity of the plasmapause. In contrast with the region of high L values [*Hayakawa and Sazhin*, 1992], at the low L value region it is possible that hiss can be generated locally by cyclotron instability [*Singh et al.*, 1981], other plasma instabilities [*Prange and Bruston*, 1980], or some sort of nonlinear process [*Etcheto et al.*, 1973]. Such a hypothesis is supported by the observations made by the low satellite AUREOL 3 [*Parrot*, 1990], which indicated that the hiss intensity is weaker in the east side of the SAMA, where small electron fluxes have also been reported. Such observations could explain the evidence reported by *Bering et al.* [1988] that the pitch angle diffusion in the SAMA is longitude dependent. It is worth noting that the characteristic of hiss to propagate over a broad distribution of angles relative to the magnetic field introduces significant wave-particle interactions at higher cyclotron harmonic resonances and at Landau resonance [*Lyons et al.*, 1972; *Pinto and Gonzalez*, 1989c]. Electron precipitation in the SAMA induced by plasmaspheric hiss is believed to be dominant on magnetospheric active periods and longitude dependent.

The fast processes causing electron precipitation are driven by wave-particle interactions involving impulsive discrete waves. There are two main types of such waves: chorus emissions and lightning-generated whistlers. Chorus emissions have been observed in almost all L values [*Oliven and Gurnett*, 1968; *Singh et al.*, 1981]. The origin of the chorus is not well understood. The most probable candidate is electron cyclotron instability [*Sazhin and Hayakawa*, 1992], although the chorus emissions also may be triggered (from a background hiss) by external signals such as lightning or artificial waves [*Sonwalkar and Inan*, 1989]. Electron precipitation caused by the chorus has been reported by several authors [*Oliven and Gurnett*, 1968; *Foster and Rosenberg*, 1976; *Roeder et al.*, 1985; *Imhof et al.*, 1986]. The precipitation takes the form of microbursts, with duration of 100-200 ms and tends to occur in quasi-periodic groups. *Imhof et al.* [1986] found that the daytime electron precipitation bursts in the slot region are predominantly associated with the chorus. Electron precipitation induced by chorus emissions has been observed for all magnetic conditions and at all longitudes. Considering the possible origin of the chorus, we expect chorus-related precipitation to occur predominantly in the west side of the center of the SAMA.

Electron precipitation induced by whistlers generated by lightning has been reported by several authors [*Bering et al.*, 1980; *Voss et al.*, 1984; *Goldberg et al.*, 1986, 1987; *Inan et al.*, 1988a, b, c]. The wave-particle interaction is fundamentally nonlinear. Also the transient nature of the wave indicates that a diffusion process does not contribute significantly to the main precipitation [*Inan et al.*, 1988c]. The precipitation consists typically of large pulses with rise times less than 200 ms, and a duration around 1 s, and which extend in a region of tens [*Sheldon et al.*, 1988] to 100 km [*Inan et al.*, 1988a] around the lightning location. The electron precipitation induced by lightning is independent of the magnetic activity and expected to occur mainly during nighttime and in the west side of the SAMA.

The electron precipitation in the SAMA region may also be influenced by impulsive radial injection of electrons from higher L shells during intense geomagnetic storms. In the low L value region of the SAMA, electrons become quasi-trapped, precipitating in the west side of the SAMA as they drift eastward. Evidence supporting such a process has been reported [*Gusev et al.*, 1987; *Kikushi and Evans*, 1989; *Voss*, 1992]. Also reported have been the occurrence of multiple peaks in the spectrum of electrons in the SAMA [*Cladis*, 1966; *Datlowe et al.*, 1985]. The peaks occur for all levels of magnetic activity. The origin of the peaks remains unknown [*Pinto et al.*, 1991b].

In this paper the results of the analysis of high time resolution X ray balloon measurements obtained during two flights in 1994 in the low L value region of the SAMA are presented and discussed in terms of the energetic electron precipitation in this region. For the first time we have found evidence of the occurrence of microbursts in this region. The origin of the microbursts is investigated in terms of the prevailing physical processes which are believed to occur in subauroral and auroral latitudes.

Experimental Results

Measurements of bremsstrahlung X rays and vertical quasi-DC electric field were carried out by two balloons launched from Cachoeira Paulista, São Paulo, Brazil (geographic

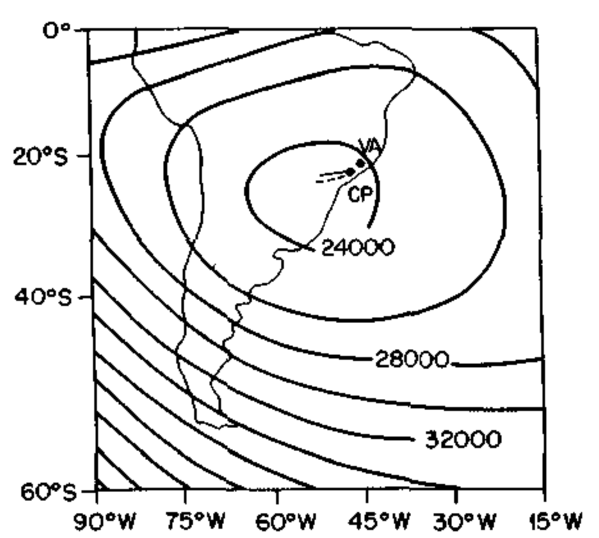

Figure 1. The total intensity of the Earth's magnetic field at the surface (in nT) using the IGRF model for 1980 [*Fabiano et al.*, 1983] in the SAMA region. The trajectories of the flights are indicated by a broken line (January 26) and a solid line (February 1). The launching city, Cachoeira Paulista (CP), and the location of the geomagnetic observatory of Vassouras (VA) are also indicated.

coordinates 22°39'S, 45°01'W, $L \sim$ 1,13), at 1030 UT on January 26 and at 1325 UT on February 1, 1994. Figure 1 shows the trajectories of the balloons in the SAMA region. Geomagnetic field data were also obtained from the low latitude observatory of Vassouras (geographic coordinates 22° 24'S, 43°39'W). The geomagnetic data indicate that the first flight occurred during a geomagnetically moderate period, while the second flight occurred during a quiet time period.

The X ray detector was a 1.27-cm-thick NaI(Tl) scintillation counter with a 7.62-cm diameter. The geometric factor of the instrument was 191.01 cm^2.sr over the upper hemisphere. X ray counts were accumulated in 47-ms intervals (corresponding to one data frame) in three differential energy ranges from 30 keV to 150 keV. The vertical electric field consisted of one aquadag-coated spherical sensor (22 cm in diameter) mounted on a high-impedance vertical boom 1.5 cm up to the payload, which was used as a ground plane.

Figure 2a shows the counting rate in the 30-50 keV, 50-70 keV, and 70-150 keV energy channels during one burst event around 1400 UT on January 26. The balloon altitude at that time was 29 km. The low-energy channel is shown with maximum time resolution in Figure 2b. In this channel can be seen a group of six bursts during a period of about 3 s. The individual bursts have widths less than or equal to one frame (except in one case), and the average time between bursts is 0.6 s. The bursts were not present in the higher energy channels. Two other cases of similar bursts are shown on Figures 3 and 4. In Figure 4 there is also a small event which was discarded by the statistical criteria adopted in this work (see below). Even though the amplitude of the bursts in all events seems to be modulated differently from the event shown in Figure 2, the events shown in Figures 3 and 4 apparently have a double-peak feature. All events occurred in the absence of lightning strokes, as indicated by the onboard electric field data.

In order to distinguish microbursts from any other counting rate fluctuations, the following statistical criteria to select the

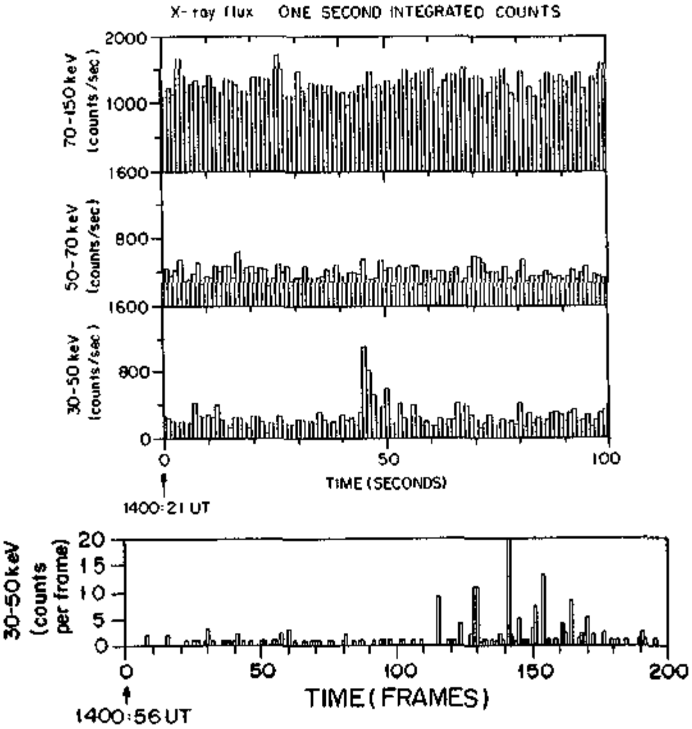

Figure 2. (a) A 100-s segment of 1-s integrated X ray counting rates in three differential energy channels measured on January 26, 1994, starting at 1400:21 UT; (b) high time resolution 30-50 keV X ray counting rates (in counts per frame) during the event shown in Figure 2a. Each frame corresponds to 47 ms.

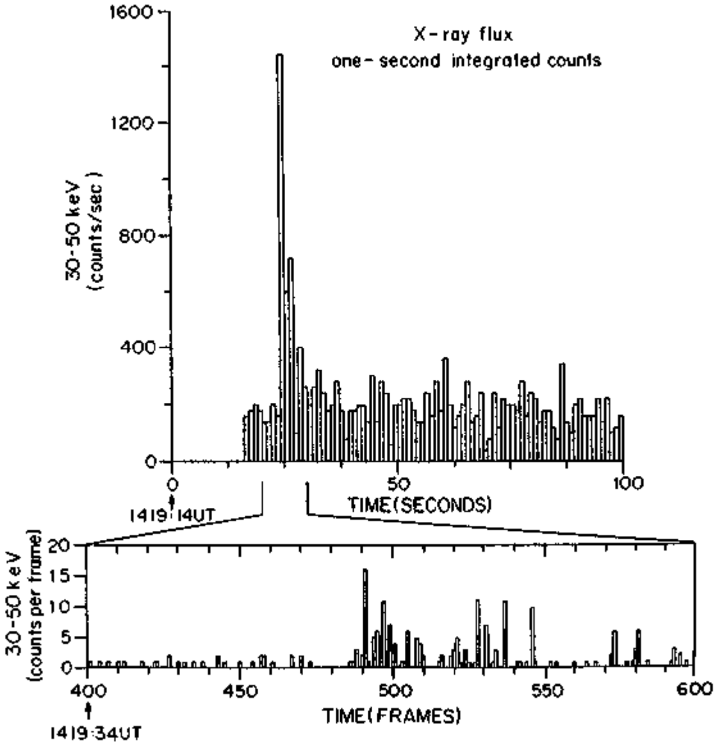

Figure 3. A 100-s segment of 1-s integrated counting rates in the 30-50 keV energy range measured on January 26, 1994, starting at 1419:14 UT. In the lower part of the figure is shown in details the counting rates (in counts per frame) during a microburst event which occurred during this period.

events was adopted: first, to search 1-s, 30-50 keV integrated count events with a counting rate exceeding 800 counts/s (about five times the background value); second, to select from among the candidate events only those in which the peak counting per frame exceed 25 times the square root of the mean counting per frame in a time interval of 20 s around the peak. Similar criteria were adopted by *Rosenberg et al.* [1990]. The three microburst events shown in Figures 2

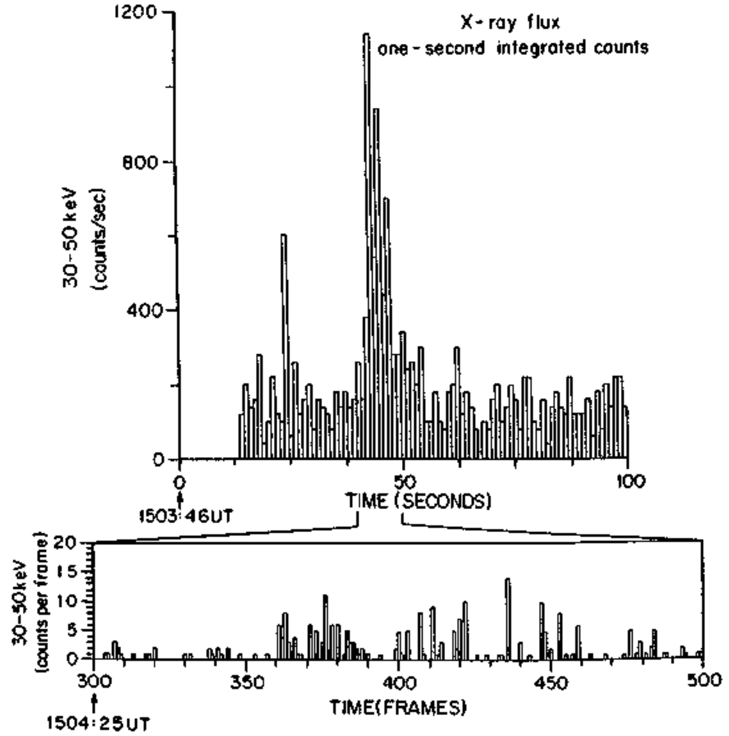

Figure 4. Same as in Figure 3, but starting at 1503:46 UT.

through 4 were obtained on January 26 and were the only ones to satisfy the above criteria. No microburst events were found in the measurements obtained on February 1. Also, the background flux in the flight on January 26 was about 10-20% larger than that on February 1.

Discussion

X ray balloon measurements in the low L value region of the SAMA are quite scarce [*Ghielmetti et al.*, 1964; *Pinto and Gonzalez*, 1986a, b; *Pinto et al.*, 1989]. *Pinto and Gonzalez* [1986b] have shown that the X ray flux in the 30-150 keV energy range increased by about a factor of 5 at 35 km altitude during a large geomagnetic storm. The time variation of the enhanced flux showed evidence that a modulation process was operating at that time [*Pinto et al.*, 1989]. Unfortunately, the fine time structure of the X ray flux could not be resolved because the time resolution of the measurements was very poor (30 s). On the other hand, the situation at higher L values of the SAMA is quite different. X ray balloon and rocket measurements at Siple Station, Antarctica (L=4.1), have been reported by several authors [*Rosenberg et al.*, 1971, 1981, 1990; *Foster and Rosenberg*, 1976; *Roeder et al.*, 1985; *Sheldon et al.*, 1988; *Bering et al.*, 1988]. As in the auroral region, X ray microbursts at Siple were found to occur superposed to an enhanced background for all magnetic activity levels. The microbursts were found to be closely associated with the occurrence of VLF chorus, although a one-to-one correspondence between microbursts and VLF emissions does not exist [*Roeder et al.*, 1985]. *Bering et al.* [1988] have shown that the bursts are very common in the west side of the SAMA, being almost absent in the east side. In general, the intensity of the bursts reaches 5 to 10 times the enhanced background caused by continuous electron precipitation, which in turn is about 1.5 to 2 times the cosmic ray background. The spectrum of the precipitated electrons during periods with bursts are characterized by e-folding energies between 25-50 keV, while out of these periods the e-folding is typically 100 keV [*Foster and Rosenberg*, 1976]. There are evidence that the electron spectrum tends to be still softer near the peak of the bursts [*Rosenberg et al.*, 1990].

The X ray microbursts measured at Siple typically occur in groups of three to six, have durations of 0.1-1 s (average of 0.2 s), and have spacings between the bursts of 0.3 to 0.8 s (average of 0.6 s). The characteristics above are very similar to those measured in the auroral zone [*Anderson and Milton*, 1964; *Parks*, 1978]. Measurements in the auroral zone, however, imply other types of microbursts besides those described above. *Parks* et al. [1967] and *Lazutin* [1979] reported the occurrence in the auroral zone of very short X ray bursts (also called micropulses) with durations less than 100 ms and with a very soft spectrum (e-folding around 5 keV). Such micropulses were not observed at Siple.

The X ray data presented above are the first evidence of the presence of microbursts in the low L value region of the SAMA. The spacing and the number of bursts in each group are similar to those at subauroral and auroral latitudes. The duration and the energy spectrum of the bursts, however, are different. They are narrower (widths of 0.05 s or less) and have a much softer energy spectrum than the normal microbursts in the subauroral and auroral latitudes. In fact, the last characteristics are similar to the micropulses reported by *Parks et al.* [1967] and *Lazutin* [1979]. From the counting rates in the two lower energy channels, we have estimated an approximate upper limit to the X ray e-folding energy of the bursts of 12 keV, which corresponds approximately to an electron e-folding of 15 keV [*Berger and Seltzer*, 1972]. This value is lower than the normal value found for microbursts (25-50 keV) and consistent with those attributed to micropulses (~5 keV). The intensity of the bursts in Figure 2 also seems to be modulated. As far as we know, no reference to such modulation exists in the literature.

In the following, we discuss the time-energy characteristics of the bursts measured on January 26 in terms of their possible origin. Nowadays, two mechanisms involving wave-particle interactions are believed to produce X ray microbursts: electron precipitation induced by whistlers generated by lightning and electron precipitation induced by chorus emissions.

All events presented in this paper were obtained during fair weather conditions, as revealed by onboard electric field data, even though during the flight on January 26 several lightning sferics were measured. Figure 5 shows, for example, the vertical electric field (positive downward) and the 30-50 keV X ray counting rate measured during the occurrence of a large sferic (the largest sferic measured during this flight). The sferic has an amplitude of 8 V/m in the upward direction, corresponding to a negative cloud-to-ground lightning with a duration of approximately 0.6 s. The 30-50 keV counting rate did not show any variation in association with the sferic. The same occurred for all events of sferics measured during both flights. The considerations above indicate that the X ray microburst events showed above are not associated with lightning events in the same hemisphere. What about lightning events in the magnetic conjugate points? The region conjugate to that of our measurements is located in the Atlantic Ocean, approximately 10 km north of the coast of Brazil, near French Guiana. No lightning information is available for this region. However, we have good reasons to believed that the X ray microbursts are not associated with lightning events in this region. First, lightning-induced precipitation from the inner radiation belt is expected to produce very (energetic) hard spectra [*Inan et al.*, 1988a] related to MeV electrons, and not the very soft spectra observed. Second, the total duration of the X ray microburst events (about 3 s) is too long to be attributed to a lightning flash, while individual bursts are too short [*Goldberg et al.*, 1987]. It seems that at least during daytime, lightning does not have enough power to produce X ray microbursts in the low L value region of the SAMA.

Figures 6 and 7 show 1-min averages of the geomagnetic field at Vassouras corresponding to the days of the flights and the preceding days. The numbers in the ordinate represent the H component of the field minus the previous year annual mean (21,352 nT). The time interval corresponding to the X ray observations are indicated for January 26 and February 1, as well as (indicated by arrows) the January 26 time of occurrence of the X ray microbursts showed on Figures 2 to 4. With exception of January 26, the other days have a typical daily variation expected for a low-latitude observatory. On January 26, however, the H field was characterized by large fluctuations. The fluctuations have amplitudes in excess of 100 nT and a timescale around 30 min. In particular, just before the X ray microburst events, the field dropped by almost 500 nT in approximately 1 hour. Similar magnetic fluctuations in the horizontal component of the geomagnetic

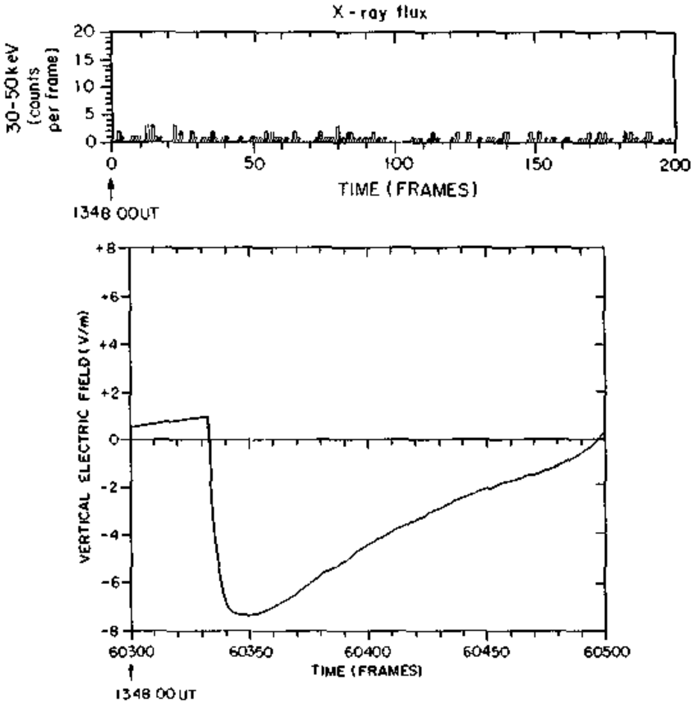

Figure 5. (a) X ray counting rates in the 30-50 keV energy range (in counts per frame) measured during a large sferic signature on January 26, 1994; (b) the vertical quasi-DC electric field due to the large sferic.

field are commonly measured at low latitudes. *Cladis* [1966] was the first to suggest that such fluctuations may cause acceleration and inward radial drift of the electrons of the inner belt. Later on, *Kikushi and Evans* [1989] also reported apparently unusual enhancement of energetic electrons at low latitudes in association with magnetic fluctuations which occurred at the time of a large geomagnetic storm. The magnetic fluctuations seem to occur independent of the magnetic (storm) activity and to be related to variations in the solar wind pressure [*Pinto et al.*, 1991b]. Although no direct relationship can be established between magnetic fluctuations and the X ray microbursts, it is reasonable to assume that the effect of the magnetic fluctuations on the inner belt electrons is such that they can trigger some discrete emissions like the chorus, so as to produce the X ray microbursts observed. Past observations of chorus at low latitudes [*Singh et al.*, 1981] have suggested that the emissions were generated by local cyclotron instability driven by an enhanced electron flux. A comparison between the X ray background flux measured in the two flights showed that during the first flight the flux was about 10-20% larger than that during the second flight. Such difference seems to be very small to support the idea that the emissions would be generated locally by this process.

Conclusions

High time resolution X ray measurements at low latitudes of the SAMA have identified for the first time the occurrence of

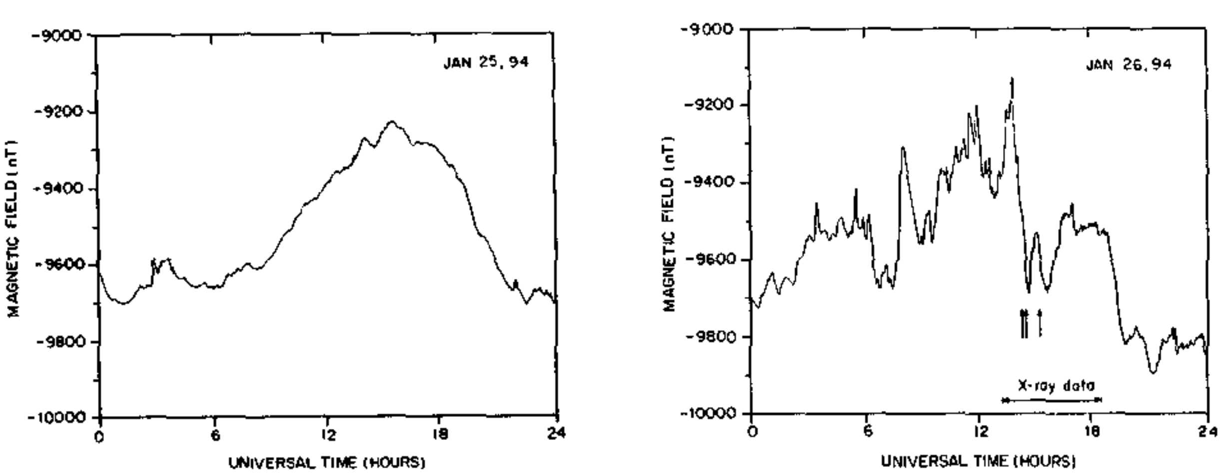

Figure 6. One-minute average of the geomagnetic field for (a) January 25 and (b) January 26, 1994. The number at the ordinate represents the H component of the field minus the previous year's annual mean (21,352 nT). The period corresponding to the X ray observations on January 26 is indicated, as well as the time of occurrence of the three microburst events discussed in the text.

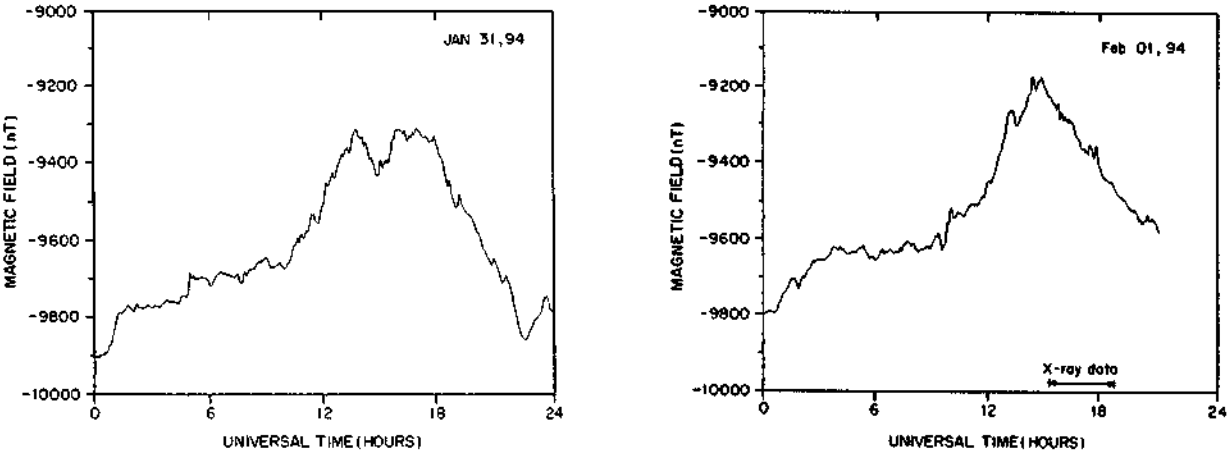

Figure 7. Same as in Figure 6 but for (a) January 31 and (b) February 1, 1994. The period correspondent to the X ray observations on February 1 is indicated.

X ray microbursts in this region. The bursts have shown some characteristics similar to those at subauroral and auroral latitudes, although their duration and spectrum resemble more closely those attributed to a particular type of bursts known as a micropulse. Even though the origin of the bursts is not known yet, the analysis of the stratospheric electric field and the geomagnetic field data suggest that they are not related to lightning flashes and may be related to discrete emissions associated with geomagnetic fluctuations. Also, we believed that as has already been pointed out by *Bering et al.* [1988], the SAMA region probably plays a significant role in the occurrence and the characteristics of the bursts. In the west side of the center of the SAMA where our measurements were done, the electron precipitation can be a combination of several mechanisms acting at different time intervals along the trajectory of the electrons as they drift eastward within the drift loss cone.

The relative importance of the microburst electron precipitation to the whole precipitation in the SAMA remains to be investigated. Clearly, more high time resolution X ray data in the low latitudes of the SAMA need to be accumulated, in particular during nighttime and at different geomagnetic activity levels, so that a comprehensive picture about the electron precipitation in this region of the SAMA can be obtained.

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