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Indirect determination of the energy spectra of particles precipitated in the lower ionosphere associated with solar proton events

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RESUMEN

Los perfiles de densidad electrónica medidos previamente usando la fase y la amplitud de radio señales VLF que se reciben durante los eventos más intensos de protones solares (SPE), junto con el espectro asociado de energías de protones y electrones, los cuales se miden simultáneamente por satélite, nos permiten calcular la razón de producción *q(h)* de los pares electrón-ion, para las regiones sub-Antártica y Sur Atlántica de la Anomalía Geomagnética (SAGA). Se usaron gráficas de *q(h)* junto con los perfiles verticales de la densidad electrónica previamente determinados, para calcular el coeficiente efectivo de recombinación $\psi(h)$ para la región SAGA. Asumiendo que los procesos químicos que se llevan a cabo en la baja ionosfera producidos por el impacto de los constituyentes atmosféricos neutrales son básicamente los mismos, se estiman indirectamente los espectros de las partículas energéticas responsables de la ionización detectada con cierto retraso en la región SAGA. Los parámetros que se obtienen coinciden con los resultados presentados por otros muchos autores para el hemisferio norte, además los espectros deducidos están dentro de los límites impuestos por la rigidez magnética y la profundidad de penetración de las partículas incidentes. Los datos experimentales que se presentan en este trabajo corresponden a las señales en VLF transmitidas desde Australia (NWC-22.3 kHz) y Ω-Trinidad (13.6 kHz) y que se recibieron en Atibaia y Curitiba respectivamente, ambas en Brasil, durante el evento de partículas de agosto 4-7, 1972.

PALABRAS CLAVE: Ionosfera, actividad solar, precipitación de partículas.

ABSTRACT

Electron density profiles previously measured using the phase and amplitude of VLF radio signals during outstanding solar proton events (SPE), together with the associated energy spectra of protons and electrons simultaneously measured by satellite, allowed the calculation of the electron-ion pair production rate *q(h),* for the sub-Antarctic and South Atlantic Geomagnetic Anomaly (SAGA) regions. Plots of *q(h)* together with the predetermined electron density vertical profiles were used to calculate the effective recombination coefficient $\psi(h)$ for the SAGA region. Assuming that the chemical processes in the lower ionosphere due to the impact of neutral atmospheric constituents are basically the same, the spectra of the energetic particles responsible for the delayed ionization detected in the SAGA were estimated indirectly. The parameters obtained are in good agreement with results for the northern hemisphere and the spectra deduced are within the limits imposed by the cutoff rigidity and the penetration depth of the incident particles. The experimental data correspond to VLF signals transmitted from Australia (NWC - 22.3 kHz) and from Ω-Trinidad (13.6 kHz) and received respectively in Atibaia and Curitiba, Brasil, during the SPE of August 4-7, 1972.

KEY WORDS: Ionosphere, solar activity, particle precipitation.

1. INTRODUCTION

Notwithstanding the new and updated techniques employed currently in the determination of the lower ionosphere parameters, the propagation of VLF radio signals through the Earth-ionosphere waveguide is still a simple and useful technique providing reliable information on the behavior of the D-region. During daytime, negative ions dominate the composition of the ionosphere below 70 km (Thomas and Bowman, 1985). During solar flares and solar proton events (SPE), a large increase in the electron density at these altitudes is observed (Mitra, 1981; Wilkinson, 1995). At high latitudes, the precipitation of highly energetic particles causes an abnormal absorption in the polar caps; during very intense events followed by magnetic storms of sudden commencement (Lastoviscka, 1996), these effects can be detected at geomagnetic latitudes as low as 50° .

On the other hand, the South Atlantic Geomagnetic Anomaly (SAGA), considered as a natural sink of energetic particles trapped in the Earth's radiation belts, plays a fundamental role in the study of charged particles interactions in the lower ionosphere. The precipitation of energetic particles in the SAGA region, as well as the mechanisms responsible for such precipitating flux, have been extensively discussed by many authors. Concerning electron precipitation, Pinto Jr. and Gonzalez (1989) presents an excellent review of recent theoretical and experimental work. With regard to proton precipitation at low L-values, Claflin and White (1974) show a temporal stability of the protons trapped in the SAGA during quiet and disturbed periods, although proton fluxes higher than predicted theoretically were measured at L = 1, 15 and L = 1,16 predominantly in the eastside of the Anomaly. Gusev *et al.*, (1987), Kohno *et al.*, (1990), and Mukhtarov and Pancheva, (1996) provided new information on the current morphology of proton and electron trapping regions and on the mechanisms involved, at medium to high latitudes.

Electron density exponential fits were calculated for the outstanding SPE of August 3-11, 1972, for different L-values (Mendes da Costa and Rizzo Piazza, 1992; Mendes da Costa and Rizzo Piazza,1995). The electron-ion production rate, $q(h)$ was given by Driatsky *et al*. (1970). This allowed the determination of the effective recombination coefficient $\psi(h)$ for high latitudes and indirectly for the SAGA region. As $\psi(h)$ varies only slightly with latitude and altitude in the D-region, (Gledhill, 1986), it may be assumed to be constant for quiet or disturbed conditions. The availability of VLF phase and amplitude data recorded at five different propagation paths, during the SPE of August 1972, led to the calculation of characteristic parameters of the lower ionosphere, in magnetically disturbed regions, such as the sub Antarctic and the SAGA regions.

The purpose of the present work is to estimate indirectly the energy spectra of precipitating particles at different L-values consistent with the phase and amplitude deviations observed on VLF propagation paths passing through the SAGA during an abnormal SPE event.

2. EFFECTIVE RECOMBINATION RATE COEFFICIENT AND ELECTRON-ION PAIR PRODUCTION RATE

For a photochemical equilibrium of the ionosphere, we assume a steady state condition in which the electron-ion production rate, $q(h)$ and the free electrons concentration, $N(h)$ are related to the effective recombination rate coefficient $\psi(h)$, by the expression,

$$q(h) = \Psi(h)N^2(h) \quad . \tag{1}$$

For a known particle spectrum, the electron-ion pair production rate is immediately found from the equation,

$$q(h) = \frac{\rho(P)}{W}\int_{E_k \min}^{E_k \max} D(E_k)\varepsilon(E_k,P)dE_k \quad , \tag{2}$$

where $\rho(P)$ is the air density at a height with a pressure P, $D(E_k) = kE^{-\gamma}$ is the spectrum of primary particles measured by satellite outside the magnetosphere, $\varepsilon(E_k,P)$ is the energy loss through ionization at the level with a pressure P, W is the energy required for a single ion-pair production (35 eV) and E_{kmin} and E_{kmax} are the lower an upper energy limits of particles responsible for absorption (Driatsky, 1970). These limits were chosen to be respectively, 300 keV and 3 MeV for electrons and 10 MeV and 100 MeV for protons according to the efficiency of these energy ranges in ionizing the lowest part of the D-region during daytime (Sellers *et al*., 1977). In Eq. 2, the air density profiles were corrected for latitudinal and seasonal variations.

3. EXPERIMENTAL RESULTS

Experimental data used in this analysis were the phase and amplitude records of VLF radio signals transmitted in the frequency of 22.3 kHz from NWC- Australia (21°40’S, 114°10’E) to Atibaia(AT) - Brasil (23°11’S, 46°33’W) and from Ω-Trinidad-Caribbean Sea (10°42’N, 61°38’W) to Curitiba (CT) - Brasil (25°53’S, 49°16’W), in the frequency of 13.6 kHz. The diurnal reference reflection heights for the High Latitude and the SAGA regions are 60 and 67 km (Mendes da Costa and Rizzo Piazza, 1992). By converting the amplitude changes into relative changes of the electric field we may calculate the attenuation factor and the conductivity parameter and gradient, after Kaufmann and Mendes (1968). The measured phase advances led to diurnal reference height lowering by 14.0 km on August 4, and 3.6 km on August 7 for the HL and LA regions respectively.

Adopting the collision frequency profile given by Friedrich and Torkar (1983) for undisturbed conditions in August, the electron density profile was determined at a given disturbed height by means of the equation

$$N(h) = \frac{W_r(h)\upsilon(h)}{3.18x10^9}(cm^{-3}) \tag{3}$$

where $W_r(h)$ is the calculated conductivity parameter and $\upsilon(h)$ is the assumed collision frequency profile. $N(h)$ profiles were labelled with the corresponding L-values as High Latitude (HL) for L greater than 4, and Low Anomaly (LA) from L = 1.08 to the center of the Anomaly (L = 1.15 in 1970).

Figure 1 shows the quiet and disturbed electron density vertical distributions obtained at 1000 UT on August 4 for the HL region and on August 7 for the LA region, following the procedure given by Mendes da Costa and Rizzo Piazza (1992).

We assume that the additional ionization observed in the lower ionosphere in association with this SPE was mostly produced by solar protons, since these particles dominate the total ionization profile at high latitudes and at altitudes below 70 km (Reagan and Watt, 1976). Figure 2 shows the spectra of protons measured on August 4, (A) at 1326 UT , by the polar orbiting satellite 1971-089A (Reagan and Watt, 1976), (B) at 1102 UT (Reagan *et al.*, 1973), and (C) at 1200 UT, by satellite 1969-046B (Yates *et al*., 1973).

Since the $N(h)$ exponential fits had been obtained at 1000 UT, spectrum (B) was selected for use in Eq. 2 to get

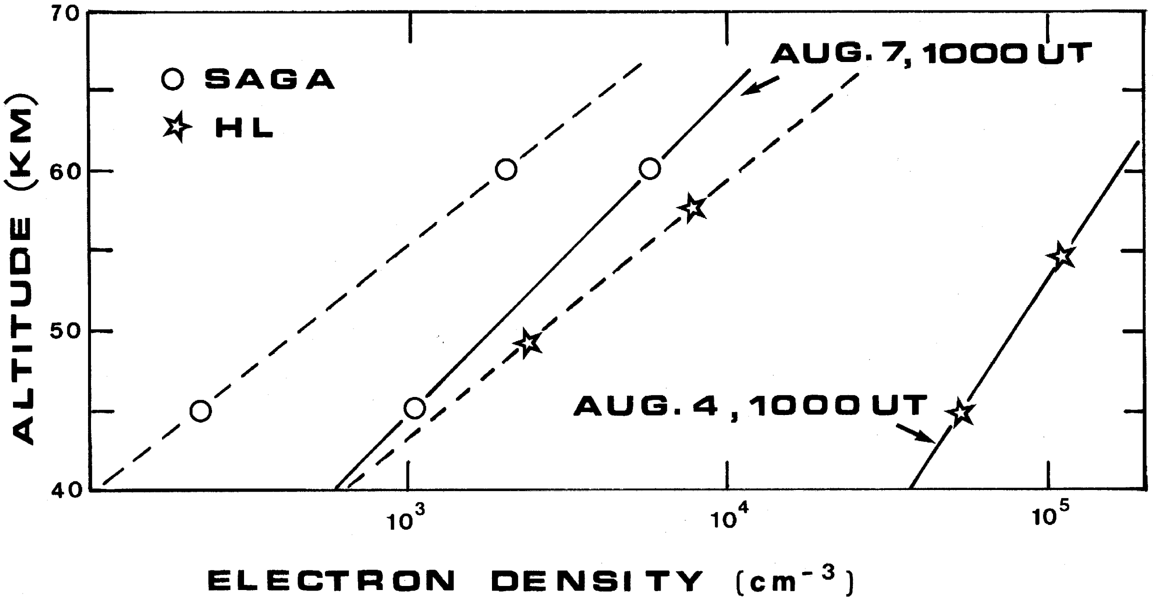

Fig. 1. Electron density disturbed profiles obtained at 1000 UT for the lower ionosphere on August 4, 1972, at High Latitudes and on August 7, 1972, for the Low Anomaly region. The dashed lines represent the corresponding average quiet days profiles (Mendes da Costa and Rizzo Piazza, 1992).

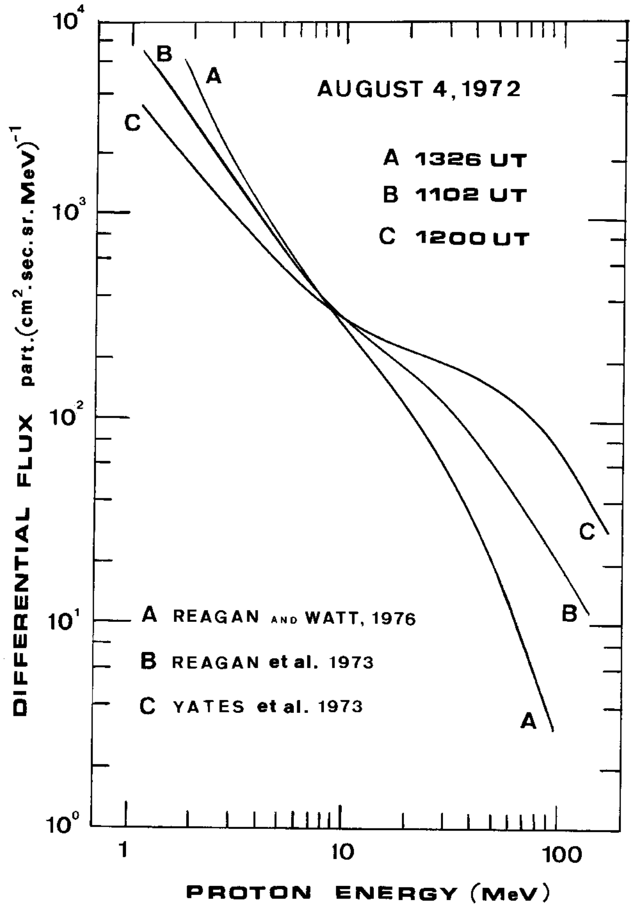

Fig. 2. Spectra of protons measured on August 4, 1972: (A) at 1326 UT by satellite 1971-089A (Reagan and Watt, 1976), (B) at 1102 UT (Reagan *et al.*, 1973) and (C) at 1200 UT, by satellite 1969-46B (Yates *et al.*, 1973).

the corresponding $q(h)$ for the HL region of the propagation path. By introducing $q(h)$ and $N(h)$ in Eq. 1, we derived the effective recombination rate coefficient $\psi(h)$ (Figure 3).

The same procedure was applied to the SAGA region on August 7. Gledhill (1986) reported that the vertical distribution of $\psi(h)$ measured during flares, SPE or quiet conditions varies only slightly in the altitude range considered. Therefore the $\psi(h)$ profile obtained at the HL was reintroduced in Eq.1 together with the electron density exponential fit calculated on August 7 for the SAGA. Then $q(h)$ profiles were inferred for that region. Figure 4 shows the electron-ion production rates calculated for both regions HL and LA. Proton and electron contributions to the total production rate on August 4 as given by Reagan and Watt (1976) are shown for reference.

As to PCA development, the ionization produced by the energetic particles in the initial phase of the PCA over the polar caps spreads out to lower latitudes and the particles trapped by the Van Allen Radiation Belts are slowly precipitated in the SAGA through different processes causing the observed delayed ionization, (Paulikas, 1975; Pinto Jr. and Gonzalez, 1989). Thus, electrons as well as protons must be taken into account in the computation of the total amount of ionization measured. Hence an attempt was made to split the overall electron-ion production rate profile for the SAGA into two distinct components. If the $q(h)$ profile shown in Figure 4 for the SAGA is due to protons only, the estimated spectrum of protons is shown in Figure 5. Experimental curves (dashed) given by Paulikas (1975), and theoretical predictions (full lines) by Claflin and White (1974) are shown for comparison.

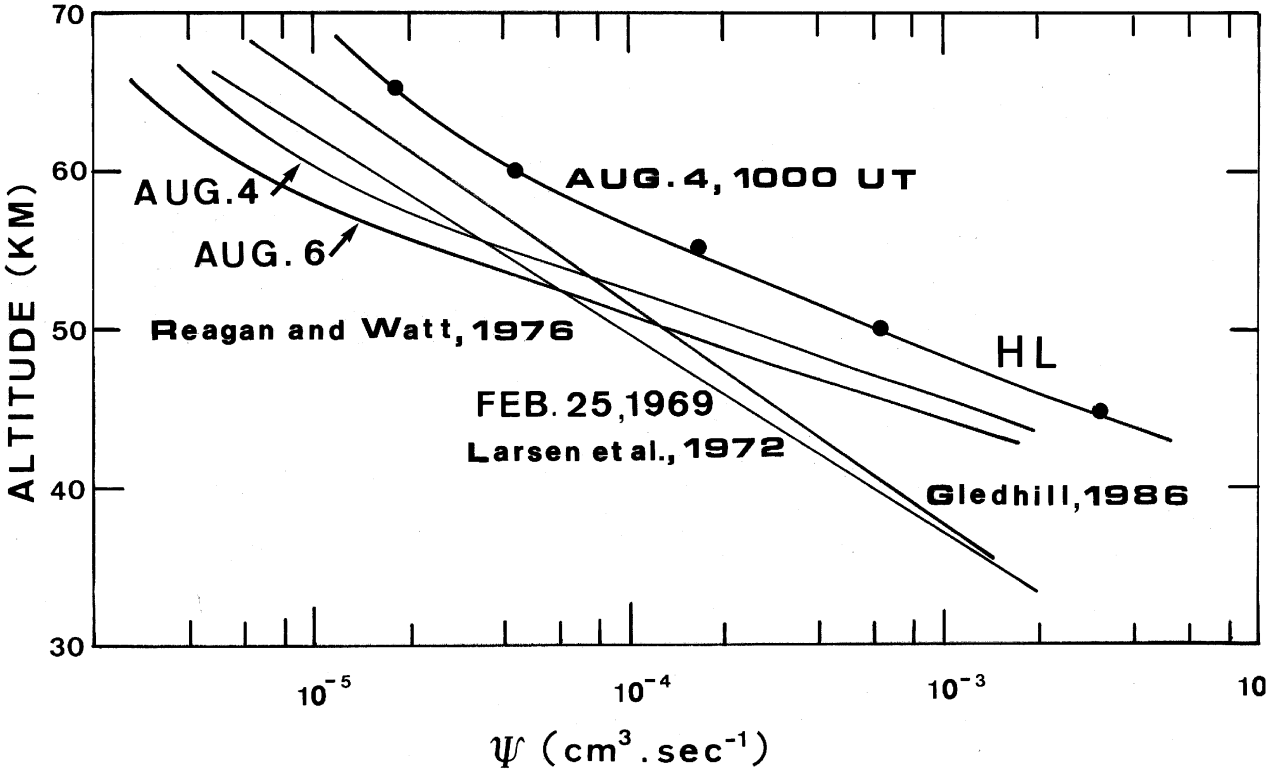

Fig. 3. Effective recombination rate coefficient calculated on August 4, at 1000 UT, for High Latitude, compared to results given by Reagan and Watt (1976), for the same day at 1326 UT and on August 6, at 0235 UT. The average disturbed values given by Gledhill (1986) and the disturbed profile presented by Larsen *et al*., (1972) for the PCA of February 25, 1969 are also included for comparison.

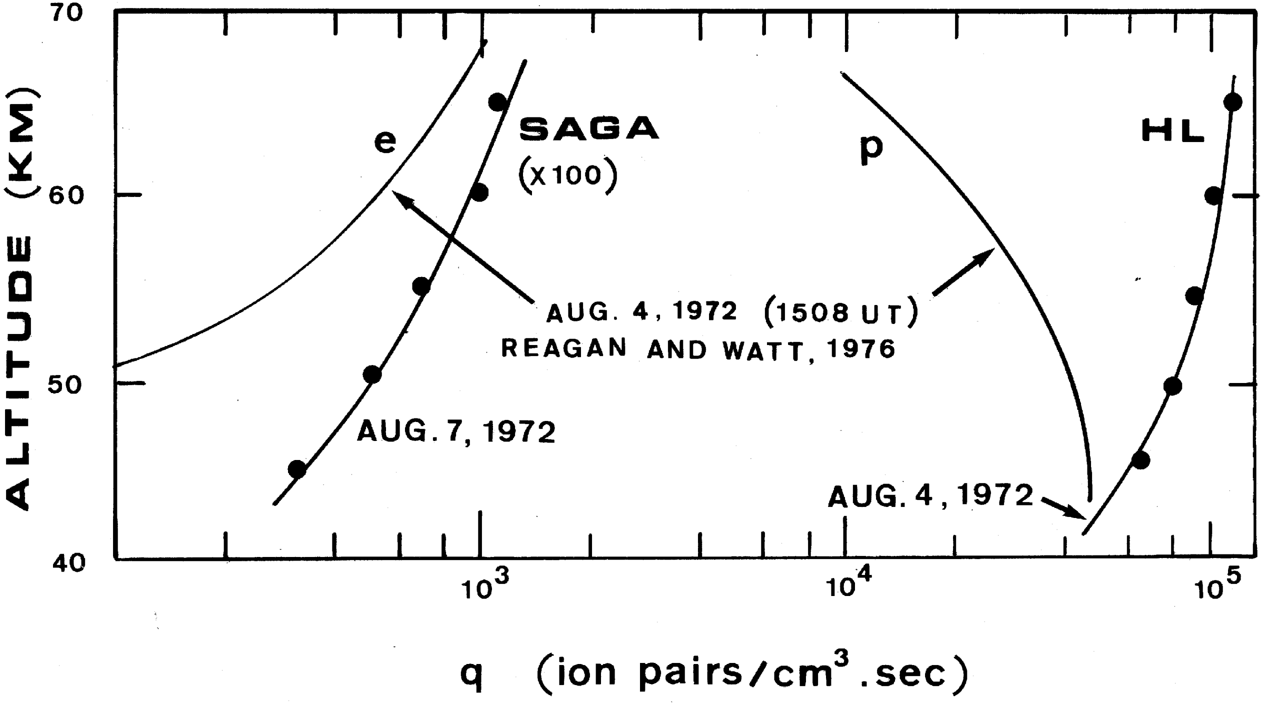

Fig. 4. Total electron-ion pair production rates calculated on August 4, 1972, for High Latitudes and the profile deduced for the SAGA on August 7, 1972, at 1000 UT. The contribution of the electrons (e) and the protons (p) to the total production rate on August 4 at 1508 UT are also included (Reagan and Watt, 1976).

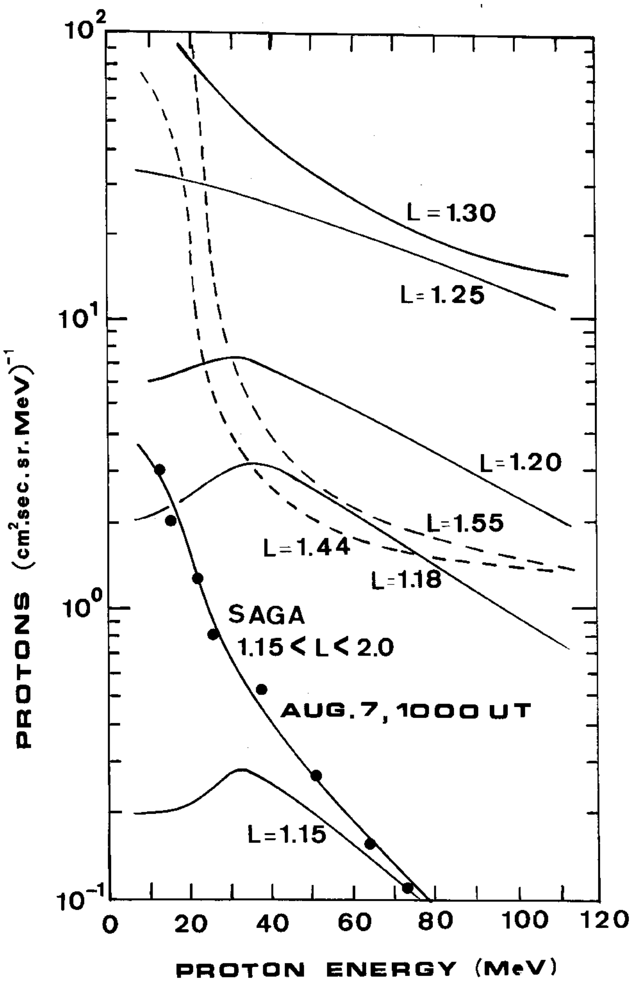

Fig. 5. Precipitating particle spectrum inferred for the SAGA region on August 7, 1972 (experimental points) assuming a production rate totally produced by protons and compared to the experimental results given by Paulikas (1975) (dashed lines) and the theoretical results by Claflin and White (1974) (solid lines).

Similarly, the spectrum of electrons is shown in Figure 6. Theoretical values predicted by Claflin and White (1974), and experimental results by Pinto Jr. and Gonzalez (1989) for the magnetically disturbed period of April 14, 1981 at L = 1,13 are shown for comparison.

4. DISCUSSION

The electron density profiles calculated for the SAGA on August 7 account for the ionization produced by electrons and eventually by protons. The surplus energy in the lowest part of the ionosphere caused a delayed ionization detected on August 7 and 8 as a lowering of the diurnal reference reflection height of 3.6 km.

In Eq. 2, the term representing the spectrum of primary protons was replaced by a sum of three terms with the proper exponent to account for the different slopes shown by protons spectrum (B) in Figure 2.

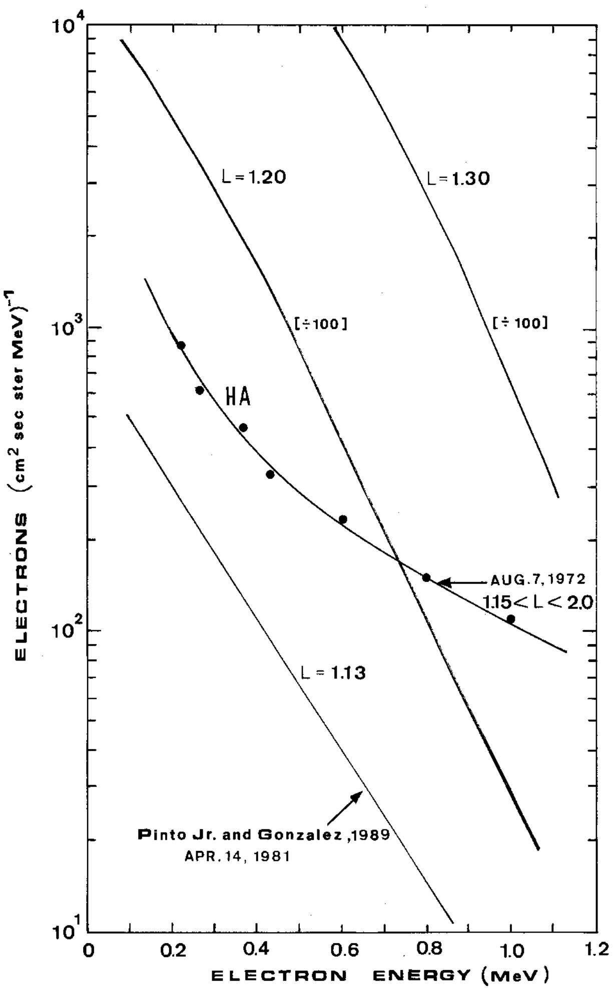

Fig. 6. Precipitating particle spectrum inferred for the SAGA region on August 7, 1972 (experimental points) assuming a production rate totally produced by electrons in comparison with experimental results given by Pinto Jr. and Gonzalez (1989) for the magnetically disturbed period of April 14, 1981.

The spectra shown in Figure 5 and in Figure 6 are limiting approaches, based on the assumption that one hundred percent of the ionization was produced either by protons or by electrons only. However, the results presented in Figure 6 are consistent with the experimental results provided by Pinto Jr. and Gonzalez (1989). The fluxes obtained for the SAGA on August 7 for electrons of energy greater than 0,6 MeV were about one order of magnitude higher than for the magnetically disturbed period of April 14, 1981. For lower energy electrons, a better agreement was achieved.

The results given by Pinto Jr. and Gonzalez(1989) for electrons with energy lower than ~ 500 keV confirm the efficiency of this energy range in ionizing the lower ionosphere during the recovery phase of magnetic storms. This behavior also shows that the obtained spectrum is more important when lower L-values are considered.

The softer part of the spectrum shown in Figure 5 agrees with the empirical curves by Paulikas (1975) for L-values equal to 1.44 and 1.55. On the other hand, for energies greater than 30 MeV good agreement is obtained with the theoretical values by Claflin and White (1974), for L = 1.15. The spectrum, as a whole seems to fit both models with a common point around 30 MeV.

The lag in the maximum lowering of the diurnal reference height of the lower ionosphere at low latitudes ($1.08 < L < 1.15$), observed for the propagation path Ω-Trinidad-Curitiba on August 7, suggests that the global mechanisms involved in particle precipitation and trapping took at least 72 hours.

The spectra of the energetic particles shown in Figures 5 and 6 were obtained from the energy loss profiles and the penetration depth of the particles in the atmosphere given by Maehlum (1973). An isotropic pitch angle distribution is assumed in the calculations.

The accuracy in the profiles of $q(h)$ and $\psi(h)$ is estimated to be around 20% in this altitude range, since the "constancy" of $\psi(h)$ is reliable within a factor of two (Glendhill, (1986). The spectra of Figures 5 and 6 should be considered only as qualitative, since they are based on the hypothesis that all the ionization observed was produced either by protons or by electrons alone.

5. CONCLUSIONS

Our results extend the earlier work of Paulikas (1975). After an abnormally intense SPE, as the one studied in this paper, a loss of energetic protons from the inner radiation belt is confirmed.

The final spectra agree with theoretical or experimental values found by considering electron of protons as the only source of ionization.

In spite of stringent assumptions and restrictions, the analysis is successful in estimating the spectra of energetic particles precipitated in the SAGA in association with very intense solar-proton events.

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BIBLIOGRAPHY

CLAFLIN, E. S. and R. S. WHITE, 1974. A study of operational inner-belt protons from 2 to 200 MeV. *J. Geophys. Res*., *79*, 959-973.

DRIATSKY, V. M., T. M. KRUPITSKAYA and A. V. SHIROCHKOV, 1970. Variations of the loss coefficient in the lower ionosphere during polar cap absorption. *Geom. and Aeronomy*, *10*, 657-663, 1970.

FRIEDRICH, M. and K. M. TORKAR, 1983. Collision frequencies in the high-latitude D-region. *J. atmos. Terr. Phys*., *45*, 267-280.

GLEDHILL, J. A., 1986. The effective recombination coefficient of electrons in the ionosphere between 50 and 150 km. *Radio Science*, *21*, 399-407.

GUSEV, A. A., G. I. PUGACHEVA, L. JUST and K. KUDELA, 1987. On the source of high energy electrons trapped in the inner radiation zone. *Planet. Space Sci*. *35*, 1281-1295.

KAUFMANN, P. and A. T. M. MENDES, 1968. Relative changes on the lower ionosphere conductivity gradients during SID events. *J. Geophys. Res*. *73,* 2487-2496.

KOHNO, T., K. MUNAKAT, K. NAGATA, H. MURAKAMI, A. NAKAMORO, N. HASEBE, J. KIKUCHI and T. DOKE, 1990. Intensity maps of MeV electrons and protons below the radiation belt. *Planet. Space Sci*., *38*, 383-397.

MAEHLUM, B. N., 1973. Particle precipitation Scattering and Absorption. *In:* Cosmical Geophysics. Eds. Egeland A, Holter, O. and Omholt, A., Scandinavian University Books, CH, 15, 211-225.

MENDES DA COSTA, A. and L. RIZZO PIAZZA, 1992. Diurnal lower ionosphere electron density variations observed in the South Atlantic Geomagnetic Anomaly and the sub Antarctic region during the occurrence of the major PCA event of 4 August, 1972. *J. atmos. Terr. Phys*, *54*, 903-999.

MENDES DA COSTA, A. and L. RIZZO PIAZZA, 1995. Night-time D-region electron density variations observed in the South Atlantic Geomagnetic Anomaly in association with solar-proton events. *J. atmos. Terr. Phys*, *57*, 899-904.

MITRA, A. P., 1981. Chemistry of middle atmosphere ionization- A review. *J. Atmos. Terr. Phys.*, *43*, 737-752.

MUKHTAROV, PL. and D. PACHEVA, 1996. Modelling of the electron density profile in the lowest part of ionosphere D-region on the basis of radiowave absorption data: 1. Theoretical model. *J. Atmos. Terr. Phys*, *58*, 1721-1728.

PAULIKAS, G.A., 1975. Precipitation of particles at low and middle latitudes. *Rev. Geophys. Space Phys*., *13*, 709-715.

PINTO, Jr. O. and W. D. GONZALEZ, 1989. Energetic electron precipitation at the South Atlantic Magnetic Anomaly – A review. *J. atmos. Terr. Phys*., *51*, 351-360.

REAGAN, J. B., W. L. IMHOF and V. L. MOUGHAN, 1973. Characteristics of the August 1972 solar particle events as observed over the Earth's polar caps. *Report UAG-28*, 676-680.

REAGAN, J. B. and T. M. WATT, 1976. Simultaneous satellite and radar studies of the D-region ionosphere during the intense solar particle events of August 1972. *J. Geophys. Res*., *25*, 4579-4588.

SELLER, B., F. A. HANSER, M. A. STROCCIO and G. K. YATES, 1977. The night and day relationships between polar cap riometer absorption and solar proton. *Radio Science*, *12*, 779-885.

THOMAS, L. and M. R. BOWMAN, 1985. Model studies of the D-region negative-ion composition during daytime and nighttime. *J. Atmos. Terr. Phys*., *47*, 547-553.

WILKINSON, P. J., 1995. Predicability of ionospheric variations for quiet and disturbed conditions. *J. Atmos. Terr. Phys*., *57*, 1469-1482.

YATES, G. K., L. KATZ, B. SELLER and F. A. HAUSER, 1973. Proton and alpha particle fluxes observed aboard OV5-6 in August 1972. *Report UAG-28*, 348-354.

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