



Neutron spectra measurements in the south Atlantic anomaly region

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ARTICLE INFO

Article history:

Received 15 November 2009

Received in revised form

5 May 2010

Accepted 14 June 2010

Keywords:

Cosmic radiation

Neutron spectrum

Unfolding

ABSTRACT

In this work we present the results of measurements of the cosmic-ray neutron induced flux and spectra from the ground level up to the altitude of 2400 m, in the region between 22° S and 45° W, which is under the influence of the South Atlantic Anomaly (SAA). The measurements of neutron spectra induced by cosmic rays were carried out using a Bonner multi-sphere neutron spectrometer with a scintillation crystal of ⁶LiI(Eu) and the data obtained by a modified Hanson and McKibben long-counter directed to the zenith were used to normalize the spectra.

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1. Introduction

The Earth is continuously exposed to solar and cosmic radiations, consisting mainly of protons, helium ions and heavy nuclei. These primary radiations interact with the atmospheric constituents producing secondary radiations consisting of charged particles, neutrons, gammas, X-rays, hadrons and muons, with a wide energy range (Heinrich et al., 1999). One of the most important barriers against this type of radiation is the geomagnetic field, which deflects the incident radiations that have magnetic rigidity less than the cut-off rigidity of the field at the point of incidence.

Many studies have been done about these phenomena and researchers made measurements of the flux and dose of these radiations in the Earth ambient. Parts of these studies are made for neutron fluxes at the ground level, where the main motivation is public exposure (Kowatari et al., 2005; Florek et al., 1996), with most of these studies made in the Northern hemisphere.

A large part of Brazil and South America are under the influence of a magnetic anomaly called South Atlantic Anomaly (SAA), as shown in Fig. 1, that modifies the cosmic radiations' altitude and the form of penetration. In this area the geomagnetic field is approximately 30% less than one would expect at similar latitudes and

altitudes around the globe. Very few measurements have been made in this region, in comparison to the other regions of the world. The presence of the SAA justifies an effort to detail experimentally the cosmic radiation spectra in this region, as carried out in other investigations at other locations (Kowatari et al., 2005; Vega-Carrillo and Manzanares-Acuna, 2004), in order to allow comparisons with the theoretical predictions.

In this investigation the energy distribution and the total fluency rate for the neutron component at ground level as a function of altitude are evaluated. The measurements have been carried during 2009, in four different locations between 22° S and 45° W. Data for these locations are presented in Table 1. The cut-off rigidity and the solar modulation potential were computed with the EXPACS version 2.15 program (Sato and Niita, 2006; Sato et al., 2008). The measured data are also compared with the EXPACS simulated results.

2. Experimental procedure

A Bonner spheres spectrometer, with a ⁶LiI(Eu) thermal neutrons detector was used for this experiment. Several measurements have been made using bare detectors (no Bonner spheres) and Bonner spheres of polyethylene with diameters of 5.08, 7.62, 12.7, 20.32, 25.4, and 30.48 cm, allowing the registration of seven different counts of neutrons with different thermalization.

The detector was connected to a set of NIM modules: a high voltage power supply (ORTEC model 456), a pre-amplifier (ORTEC model 113), a linear amplifier (ORTEC model 571), a single-channel

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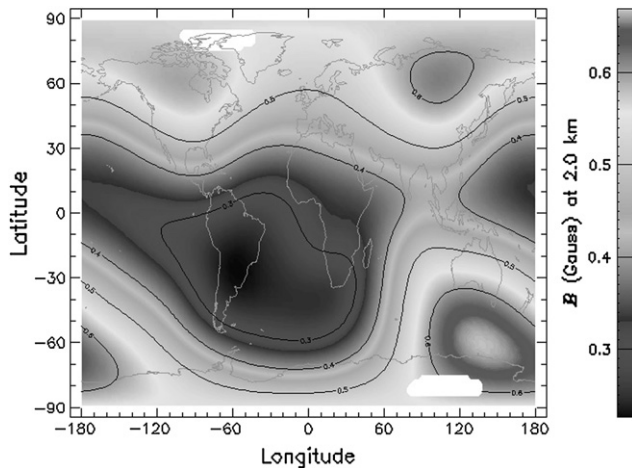


Fig. 1. World map of magnetic field at 2 km altitude, obtained from SPENVIS system (Heynderickx et al., 2004).

analyzer (ORTEC model 552) and a counter (ORTEC model 775). The pre-calibration of NIM modules was made by using a multi-channel analyzer for the correct discrimination between the neutron signal and other spurious signals in the pulse-amplitude spectrum.

The calibration of the Bonner multi-sphere neutron spectrometer for the total fluency was previously performed with $^{241}\text{Am}/\text{Be}$, ^{252}Cf and $^{252}\text{Cf} + \text{D}_2\text{O}$ calibrated sources (Lemos Junior, 2004) and was verified with one $^{241}\text{Am}/\text{Be}$ neutron source during field measurements.

The unfolding process to obtain neutron spectra was accomplished by means of the MAXED program (Reginato and Goldhagen, 1999), using SAND4 response functions and the spectrum obtained by Goldhagen et al. (2002) was used as a guess spectrum. The unfolding process was carried out observing two parameters computed by MAXED which helps to indicate the quality of the process: the chi-square parameter and the control value parameter.

The Bonner multi-sphere neutron spectrometer measures were accompanied by measurements made with one modified Hanson and McKibben long-counter directed to the zenith. As the measurements with each Bonner Sphere is sequentially made, typically during one week, possible fluctuations in the ambient cosmic radiation, caused by atmospheric pressure variations and by the solar activity, must be corrected before the unfolding process. So, the measures with the long-counter were used to monitoring and to correct these possible variations between measurements with different Bonner spheres, if necessary.

3. Results

The results of measurements and calculations are summarized in Table 2. The measured fluxes are obtained from the unfolding process discussed above by using each sphere count rate and

Table 1
Measured locations, with altitude, Cut-off rigidity and solar modulation potential.

Location	Coordinates	Altitude (m)	Cut-off rigidity (GV)	Solar modulation potential (MV)
Ilhabela – SP	23.85 S, 45.42 W	20	9.7	228
São José dos Campos – SP	23.15 S, 45.51 W	680	9.9	228
Itajubá – SP	22.50 S, 45.50 W	1840	10	228
Itatiaia – RJ	22.20 S, 44.40 W	2400	10	238

Table 2
Summary of measured and calculated results.

Altitude (m)	Measured flux ($10^{-2} \text{ n/cm}^2 \text{ s}$)	Long-counter count rate (ct/s)	EXPACS calculated flux ($10^{-2} \text{ n/cm}^2 \text{ s}$)		
			Water fraction 0.10	Water fraction 0.15	Water fraction 0.20
20	2.95 ± 0.11	0.0459 ± 0.0111	1.06	0.96	0.89
680	3.53 ± 0.08	0.0501 ± 0.0017	1.83	1.65	1.54
1840	4.52 ± 0.24	0.1156 ± 0.0056	4.38	3.95	3.68
2400	6.39 ± 0.15	0.1580 ± 0.0220	6.42	5.79	5.39

corresponding to the integral unfolded neutron spectra. The long-counter count-rates are the mean values obtained in each location, as we did not observe significant variations during the experimental data acquisition.

The theoretical flux results from EXPACS program considering ground as surrounding environment for three different water contents in the soil: 10, 15 and 20%.

The final neutron flux measured in each altitude from Bonner Sphere spectrometer data are presented in Fig. 2.

A comparison between the EXPACS calculated and the MAXED unfolded neutron spectrum for 2440 m altitude is shown in Fig. 3, where some differences are observed. The most evident of these are in the thermal neutron peak and in the evaporation peak regions. The centroid (peak energy) of measured thermal peak matches with the calculated value, but the integral area is notably much larger. In contrast, in the evaporation peak, the centroid does not match, but the peaks' areas are similar. The possible causes of these differences might be attributed to the poor resolution of the spectrometer and the influence of the soil's water fraction, as the amplitude of these peaks are strongly dependent of this input variable in EXPACS calculation.

The comparison between the measured and calculated total flux as a function of altitude is presented in Fig. 4. The long-counter count-rates had been presented, normalized to the measured total flux at the 2400 m, for comparison purposes. From this figure, it can be seen that there is no good agreement between the Bonner sphere measurements and the EXPACS calculations, particularly at low altitudes.

It can also be noted that the behaviour of the long-counter agrees to a large extent with the EXPACS results.

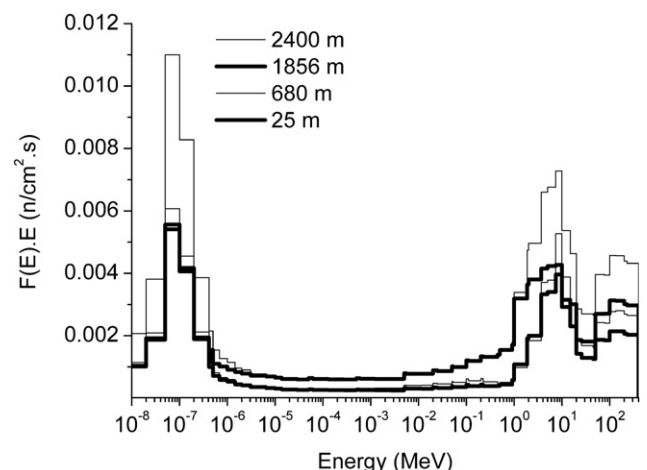


Fig. 2. Neutron spectra measured at various altitudes.

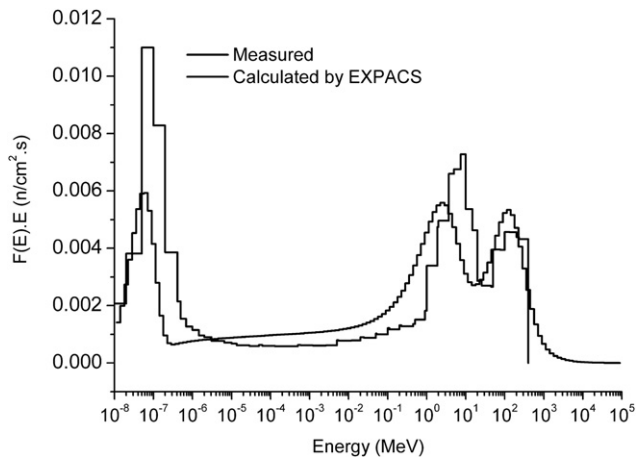


Fig. 3. Neutron spectra measured at 2400 m compared with the calculated results for the same location.

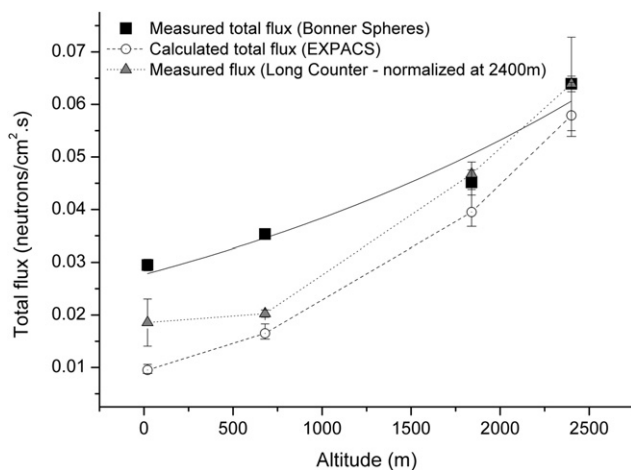


Fig. 4. Total flux measured and calculated as a function of altitude.

The total neutron flux rate ϕ_{total} is clearly altitude dependent. Some references (Kowatari et al., 2005) describe this dependence as an exponential function as follow,

$$\phi_{\text{total}} = \phi_0 \cdot \exp(\alpha \cdot Z), \quad (1)$$

where the ϕ_0 is the neutron flux rate at sea level, while Z is an

altitude parameter. The fitted curve is shown as a solid line in Fig. 4. Parameter values obtained from a fit of our experimental data are $\alpha = 0.00033 \pm 0.00006 \text{ m}^{-1}$ and $\phi_0 = 0.0277 \pm 0.0034 \text{ n/cm}^2 \text{ s}$.

4. Conclusion

Few experimental data exist for the Southern hemisphere and in particular for the SAA region. These results indicate that the shape of the measured spectra do not agree well with the EXPACS calculations, mainly in the low energy region and for low altitudes. This can possibly be explained by thermal neutrons contributing to the total spectrum. Therefore these discrepancies indicate the necessity of more accurate measurements in this energy region. The contribution of thermal neutrons at low altitudes in the SAA region may be investigated in more detail using with better equipment and more controlled experimental conditions.

Acknowledgment

We thank FINEP and CNPQ for partial financial support, as well as the Astrophysics National Laboratory (LNA) for logistic support to execute some of the field survey measurements.

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