Journal of Atmospheric and Solar-Terrestrial Physics 179 (2018) 251–260

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

South-Atlantic Anomaly magnetic storms effects as observed outside the International Space Station in 2008–2016

Tsvetan P. Dachev

Space Research and Technology Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Str. Block 1, 1113, Sofia, Bulgaria

ARTICLE INFO

Keywords:
Inner radiation belt
South-Atlantic anomaly
Proton flux
Relativistic electrons
ISS
Space radiation

ABSTRACT

Two Liulin type spectrometers performed measurements of the energetic particles flux outside the International Space Station (ISS) in 3 long-term periods between 2008 and 2016. The linear regression analysis is performed of 1053 averaged per day South-Atlantic anomaly (SAA) proton flux measurements from the daily Dst index. The data reveal that the SAA flux dependence from the Joule heating in the high latitudes and respectively from the neutral atmosphere density, isn't observed only in the time of the magnetic storms. This is a permanent, continues process influencing the SAA fluxes all the time. The data, obtained during the two magnetic storms in 2010 and to powerful storms of March and June 2015, were used to find and classify the following short-term magnetic storm effects: 1) The SAA proton flux maximum and area show strong decrease during the main phase of the magnetic storms. The protons losses can be caused by the collisions with the storm-enhanced neutral oxygen atoms. This hypothesis is proved by a comparison with the prediction by the NRLMSISE-00 model global neutral Oxygen density; 2) Increase of the proton flux, in the presence of solar energetic protons, is observed during the storm sudden commencements (SSC); 3) An enhanced flux of relativistic electrons is recorded in SAA during the recovery phase of the magnetic storms at L-values higher than 1.7. They migrate from the outer radiation belt. Their presence was proved by the analysis of the energy deposition spectra.

1. Introduction

The current paper analyses the short-term geomagnetic storm effects of the inner radiation belt (IRB) in the region of the SAA. Energetic particles fluxes data are obtained with two Liulin type (Dachev et al. (2015a) Bulgarian-German radiation risk radiometers-dosimeters (R3D) (Dachev et al., 2002; Häder and Dachev, 2003; Häder et al., 2009), mounted outside the ISS during 3 European Space Agency (ESA) EXPOSE facility (Dachev et al., 2012a, 2015b; 2017a) missions, as follows:

- R3DE instrument was installed in Expose-E facility (Rabbow et al., 2012) outside ESA Columbus module of the ISS. The flux data covered the time interval between February 22 2008 and September 1, 2009 (Dachev et al., 2012).
- Expose-R facility (Rabbow et al., 2015), hosted the R3DR instrument (Dachev et al., 2015b) in the period from March 11, 2009 to August 20, 2010 outside of the Russian "Zvezda" module.
- R3DR2 instrument measured the flux in the EXPOSE-R2 platform (Rabbow et al., 2017) outside of the Russian "Zvezda" module from October 24, 2014 to January 11, 2016 (Dachev et al., 2017a, 2017b). The R3DR2 instrument is the same as the one that flew in the EXPOSE-R facility from 2009 to 2010. The latter was named R3DR. The instrument in the EXPOSE-R2 platform has the extension R2 to distinguish between the data from the previous mission.

1.1. Long-term IRB variations

The IRB fluxes and dose rates are much stable in comparison with the large and fast dynamics of the ORB fluxes and dose rates (Dachev, 2017). The IRB variations can be split in 2 cases: 1) long-term variations connected with the solar activity and 2) short-term variations, connected with the geomagnetic activity.

The solar cycle variation in the SAA was first observed by Nakano and Heckman (1968). Huston et al. (1998) also found it examining the anticorrelation relationship between the $F_{10.7}$ flux and the SAA proton flux using data from the TIROS/NOAA spacecraft.

Dachev et al. (1999) observed the long-term variations in the "MIR" space station SAA data with LIULIN instrument, too. The peak value of the flux and dose rate in the SAA at L ~ 1.4 increased gradually by a factor of 2 between 1991 and 1994 at an altitude of 410 km. The increase was attributed to the decrease of the atmospheric density during the declining phase of the solar activity, which is due to the lower rate of heating of the upper atmosphere when the solar ultraviolet (UV) and extreme ultraviolet (EUV) radiation diminishes during solar minimum.

E-mail address: tdachev@bas.bg.

https://doi.org/10.1016/j.jastp.2018.08.009
Received 9 May 2018; Received in revised form 6 August 2018; Accepted 14 August 2018
Available online 16 August 2018
1364-6826/

Qin et al. (2014) performed statistical analyses based on reasonable Gaussian fits, using proton flux data measured by NOAA 15 from 1999 through 2009. They found that the variation of the peak proton flux in the SAA anticorrelated with that of $F_{10.7}$ during the solar cycle. They also found it while examining the anticorrelation relationship between the F10.7 radio flux phase lag of 685 days between the solar $F_{10.7}$ flux and the proton flux decrease.

Malakhov et al. (2015) analyzed the proton fluxes with energies E > 80 MeV for L-shells 1.14–1.16 (B/B0 = 1.0–1.07), measured with PAMELA and ARINA instruments of the Resurs-DK1 satellite at a constant 573 km altitude between 2009 and 2014. They found a clear maximum in the proton fluxes in 2009, coinciding with 23th solar activity minimum.

1.2. Short-term IRB variations

A relatively very small number of papers reported IRB proton flux decreases during magnetic storm.

Looper et al. (2005) described that: "after the 29 October 2003, at the approximately 600 km altitude of SAMPEX, the usual belt of the energetic protons (above 19 MeV) around L = 2 almost completely disappeared, recovering only after several months". They also observed the appearance of a new belt of ultrarelativistic (above 10 MeV) electrons, centered on L = 2.

Zou et al. (2015) observed proton losses at the outer boundary of the inner radiation belt, which can be explained by the field line curvature scattering mechanism. They mention that the decrease of the proton flux and SAA area of the central part of the SAA is probably caused by the enhanced neutral atmospheric density during geomagnetic storms.

2. Material and methods

A total of 14 different space instruments were developed, qualified and used in different space missions between 1988 and 2017 (Dachev et al., 2015a) by the scientist from the Solar-Terrestrial Physics Section, Space Research and Technology Institute, Bulgarian Academy of Sciences (SRTI-BAS). Data from 3 experiments are presented here. These are the R3DE/R/R2 instruments mounted outside ISS in 3 different mission of the ESA EXPOSE facility between 2008 and 2016. More than 600,000 10-s resolution data with SAA flux measurements are analyzed to reveal the geomagnetic storm effects.

Fig. 1 shows the external view of R3D instruments mounted on the 3 EXPOSE facilities. The R3D instruments are small-dimension (76 × 76 × 36 mm), low-mass (0.17 kg) automatic devices that measure solar electromagnetic radiation in four channels and ionizing radiation in 256 channels. In Fig. 1, the small circles on the surface in the central part of the R3D instruments show the four solar visible-and UV-radiation photodiodes. (The data from these diodes are not addressed in this paper.) The ionizing radiation detectors are located below the photodiodes and behind the aluminum wall of the instruments and are therefore not visible.

The R3D instruments are a Liulin type (Dachev et al. 2002, 2015a) deposited energy spectrometers containing: one semiconductor detector (Hamamatsu S2744-08 PIN diode) 2 cm^2 area, 0.3 mm thick), one charge-sensitive preamplifier (AMPTEC, A225F type), 2 microcontrollers and a serial interface of RS422 toward the EXPOSE facility. A pulse analysis technique is applied to obtain of the deposited energy spectrum, which further is used for the calculation of the absorbed dose and the flux in the silicon detector. The two microcontrollers, through specially developed firmware, manage the units.

A system international (SI) determination of the dose is used to calculate the absorbed dose in the silicon detector. The SI dose is the energy in Joules deposited in one kilogram of a matter. The following equation relates the dose to energy loss and detector mass:

$$D(Gy) = \sum_{i=1}^{255} N_i E_i MD^{-1} \tag{1}$$

where *MD* is the mass of the detector in kg, N_i is the number of the pulses registered in channel "i", E_i is the deposited energy (in Joules, known through the calibration of the detector) corresponding to channel "i".

According to the formulae (1) the dose rate is a function of the count rate in the 256 channels or totally a function of the flux. In many of our previous publications, concerning the R3DE/R/R2 data, the dose rates were analyzed, while in this paper the main studied variable is the flux. The linear dependence between the dose and flux rate allow using qualitatively the previously obtained trends in the dose rate to make a consideration for the trends in the flux.

The semiconductor detectors of the R3D instruments was mounted below of 0.3 g cm^2 total shielding from the front side. The calculated required kinetic energy of particles arriving perpendicular to the detector was 0.835 MeV for electrons and 19.5 MeV for protons.

Recently, Dachev (2017) and Dachev et al. (2017a) published a comprehensive description of the R3DR2 instrument and its calibration. Therefore, we will skip those details. R3DE and R3DR instruments are identical to the R3DR2.

3. Results for the geomagnetic storm effects observed with R3D instruments

Our first observation of the flux and the dose rate short-term decrease in the SAA maximum, during magnetic storm, was performed with the LIULIN instrument on "Mir" Space Station during the famous magnetic storm on March 24, 1991. The prestorm SAA flux inside of the station was at the maximal flux level of 25–30 $cm^{-2} s^{-1}$, while the average per day flux level was 10–12 $cm^{-2} s^{-1}$. The SSA average fluxes decrease down to 7-8 $cm^{-2} s^{-1}$ in the period March 25–30, 1991. This coincides with the main and recovery phase of the magnetic storm. On

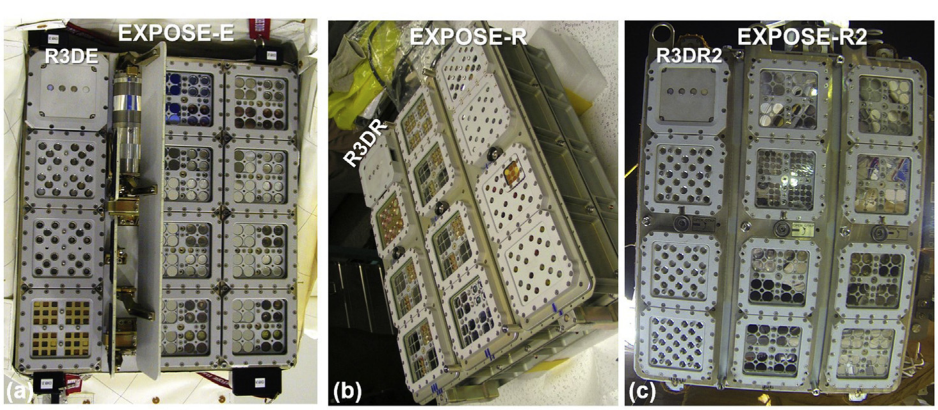

Fig. 1. a/b/c. External view of the R3D instruments (in the upper left corner of the pictures) as mounted on the ESA EXPOSE facilities. (The EXPOSE-R2 picture (Fig. 1c) was taken by the Russian cosmonauts G. Pedalka and M. Kornienko on August 15, 2015 during an examination of the facility outside the Russian "Zvezda" module.) (Picture credit ESA/RKA).