Time variations of proton flux in Earth inner radiation belt during 23/24 solar cycles based on the PAMELA and the ARINA data.

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Abstract. The PAMELA and the ARINA experiments are carried out on the board of satellite RESURS-DK1 since 2006 up to now. Main goal of the PAMELA instrument is measurements of high energy antiparticles in cosmic rays while the ARINA instrument is intended studying high energy charged particle bursts in the magnetosphere. Both of these experiments have a possibility to study trapped particles in the inner radiation belt. Complex of these two instruments covers proton energy range from 30 MeV up to trapping limit (E= ~2 GeV). Continuous measurements with the PAMELA and the ARINA spectrometers include falling and rising phases of 23/24 solar cycles and maximum of 24th one. In this report we present temporal profiles of proton flux in the inner zone of the radiation belt (1.11 < L < 1.18, 0.18 < B < 0.22G). Dependence of proton fluxes on a magnitude of the solar activity was studied for various phases of 23/24 solar cycles. At that it was shown that proton fluxes at the solar minimum are several times greater than at the solar maximum.

1. Introduction

Measurements of trapped and quasi-trapped radiation of high energy (E>30 MeV) at the low altitudes (h<1000km) have a great importance as well for theoretical models as for engineering purposes. These altitudes are heavily populated with spacecrafts including ISS and manned spacecrafts. It is known that high energy particles (greater than 30 MeV) in radiation belt have negative impact on electronics [1-4]. For example in [3] and [4] a correlation between passing through the inner radiation belt area and a degradation of solar cells was shown. Moreover interactions of particles with residual atmosphere cause difficulties for theoretical prediction of trapped fluxes due to variations of its density. New data measured on a boundary of particle trapping could help in better understanding of particle loss mechanisms. At low L-shells fluxes of trapped particles vary with time, as it is shown for example in [5]. In this paper also an anticorrelation between fluxes and radio flux at wave length 10.7 cm characterizing the solar activity was shown. Usually this anti correlation is explained by variations in residual atmosphere density in the near Earth space [6]. Today we have a lack of long period accurate measurements of high energy (E>100 MeV) particle fluxes at low altitudes (h<1000 km) continuing at least one full solar cycle. Widely known POES-program lasts several solar cycles but it has a problem with systematic uncertainties [7]. And though methods for taking into account factor of degradation of detectors were developed [8] new measurements are necessary for independent checking of those results. Now de-facto standard models for calculation in radiation belt AP8 max and AP8 min [9] have known restrictions for lower edge of inner belt. They have been discussed many times, see [10] – [18]. The most important ones are that it is based on measurements of 60-70th years and not considering changing Earth's magnetic field. Magnetic dipole moment is decreasing and magnetic shells sink into atmosphere causing more extensive particle lost. There are also other empirical models such as PBS97 [19], Low Altitude Trapped Radiation (LATR) [20], Trapped Proton Model (TPM-1) [21], Combined Release and Radiation Effect Satellite Proton Model (CRESSPRO) [22], NOAAPRO model (more detailed survey see in [23]) But all of them are static and do not cover full solar cycle. There are also theoretical models [24],[25], which include the solar activity variations, but their applicability for nowadays should be confirmed by modern measurements. Detailed analysis of trapped proton flux time variation based on POES (NOAA-10, NOAA-15) data for 21st-23rd solar cycles has been made in work [26]. A strong anti correlation between atmosphere density, which in turn depends on solar activity, and proton fluxes at near Earth L-shells were obtained. At present the PAMELA and the ARINA instruments have been operating on the orbit for more than 8 years. They collected great amount of data at different periods of solar activity from the minimum of 23rd cycle to maximum of 24rd cycle. Main goal of this work is to present variations of trapped proton fluxes at the lower edge of the inner radiation belt with the PAMELA and the ARINA spectrometers along with the solar activity changes.

2. Experiments and instruments

2.1. The RESURS-DK1 satellite

The Resurs-DK1 satellite which carries the PAMELA and the ARINA instruments was launched on 15th June 2006 into an elliptical orbit with altitudes of 350-610 km and an inclination of 70.4 degrees. The orbit was circularised on 10 Sep 2010 to constant 573 km altitude. At these altitudes the instrument crosses the radiation belt in the South Atlantic Anomaly zone 6-8 times a day, so it allows collecting enough data in this region to study trapped particle fluxes with high statistical accuracy.

2.2. The PAMELA spectrometer

The PAMELA instrument was designed for study of antiparticles in cosmic rays, but it also has possibilities to measure trapped particle flux of energies greater than ~80 MeV. The PAMELA apparatus, as shown in figure 1, compounds of following subdetectors: a time of flight system (ToF), a magnetic spectrometer, an electromagnetic calorimeter, an anticoincidence system (CAS, CAT, CARD), a shower bottom scintillator and a neutron detector. In this analysis ToF and anticoincidence system was used. ToF produces a trigger signal if all of its planes are hit (i.e. it mainly registers protons with energy more than 80 MeV) and determines particle velocity and direction. For more detailed information see [27].

2.3. The ARINA spectrometer

The ARINA spectrometer originally was designed to study high-energy charged particle bursts in the magnetosphere. It consists of 10 scintillator plates and has capability to identify electrons and protons and to measure energy of particles by its range in a multilayer detector. Scheme of the ARINA instrument is shown in figure 2. Energy range of ARINA is 30 – 110 MeV. For more detailed information see in [28].

Characteristics of both instruments are shown in table 1. It is seen that they complement each other by energy range. Different orientation of their axes also allows enhancing angular cover. That fact that both apparatuses are installed onto the same satellite and have the same external conditions and overlapping energy ranges gives an opportunity to crosscheck results on its boundaries of sensitivity.

Table 1. Characteristics of Instruments.

	PAMELA	ARINA
Orientation on the board	Pointing to zenith	Perpendicular to orbit plane
Field of view	16° *19°	20°*20°
Geometrical factor	25 cm^{2}Sr	10 cm^{2}Sr
Angular resolution	±2°	±7°
Available trapped protons energies	80 MeV – trapping limit	30 – 110 MeV

3. Experimental data

For analysis data for period from June 2006 till November 2014 were used. For both apparatuses trapped particles were considered. For the PAMELA spectrometer downgoing particles producing signals in S1, S2 and S3 detectors of ToF (it corresponds to protons with E>80 MeV) were taken into analysis. In the ARINA spectrometer protons stopped in 8th or 9th layers and producing no signal in C10 plane have been considered. That corresponds to proton energy of 80 – 110 MeV. For both spectrometers the same geomagnetic areas and pitch-angles of their main axis equal to 85 – 95° were chosen. The South Atlantic Anomaly region was selected by L<1.20 and B<0.23G criterion, where L is McIlwain parameter describing set of the Earth magnetic field lines and B is intensity of the Earth magnetic field, for their calculation the IGRF11 model was used [28]. Because fluxes strongly depend on L and B parameters, the L,B space was divided into small bins and for each of them proton fluxes depending on time were obtained. L interval was divided into bins dL=0.005 and B into dB=0.001 for PAMELA and dL=0.02 and dB=0.005 for ARINA. To separate equatorial fluxes a parameter B/B0 also was calculated with the IGRF11 model. Contamination of galactic cosmic ray component is minimal for PAMELA as the geomagnetic area selected is below cutoff rigidity 10 GeV and populated mostly with secondary low energy particles. That part of galactic cosmic rays, which is still included in the flux, is not affected by solar modulation and thereby contributes in the radiation belt rate evenly over whole observation period and does not influence the time profile. For ARINA there is no contamination by galactic cosmic rays at all since it has upper energy limit about 110 MeV.

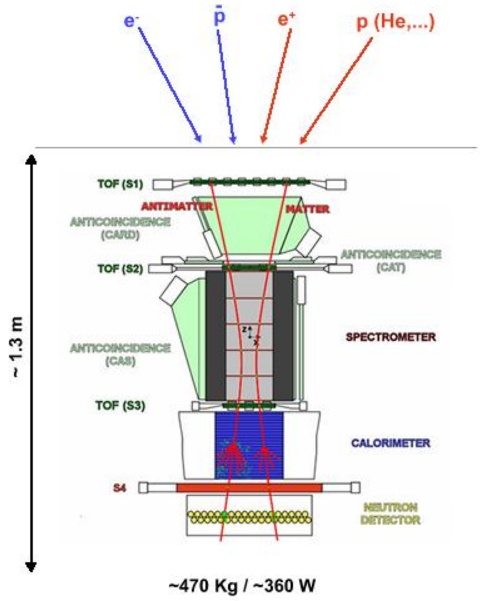

Figure 1. Layout of the PAMELA spectrometer

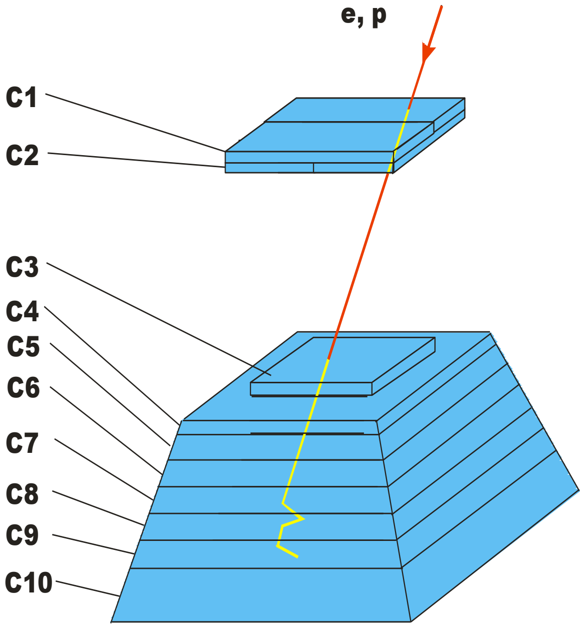

Figure 2. Layout of the ARINA spectrometer

4. Results and discussion

In this article proton fluxes of the PAMELA and the ARINA instruments are shown for period from June 2006 to November 2014 including solar minimum of 23/24 cycle and current solar maximum of 24th cycle. This time span is very interesting because solar activity of current maximum of the 24th solar cycle is relatively low and characterised by 2 years time delay from expected one. In figure 3 as example time profiles of proton flux on L=1.14-1.16 and B/B0=1.00-1.07 i.e. equatorial flux are shown, the same results were obtained for each cell in LB space described above. Green line presents smoothed f10.7 cm wave length flux intensity characterising solar activity level. It is seen that the PAMELA and the ARINA data are in agreement and both of them anti correlate with f10.7 flux intensity. Different spread in fluxes values between solar minimum and maximum measured by the PAMELA and the ARINA spectrometers can be explained by different mean energy of particles taken into analysis. In figures 4 and 5 proton fluxes of ARINA, PAMELA, count rates of NOAA-15(MEPED) and AP8-MIN and AP8-MAX model calculation are shown depending on the Earth magnetic field B (corresponding B/B0 interval is 1.0 – 1.07) for the solar minimum and the solar maximum respectively. The NOAA-15 data were normalized on the ARINA fluxes. In these figures a good agreement also is seen. Moreover the PAMELA and the ARINA data go to the lower B, where AP8 does not give any results.

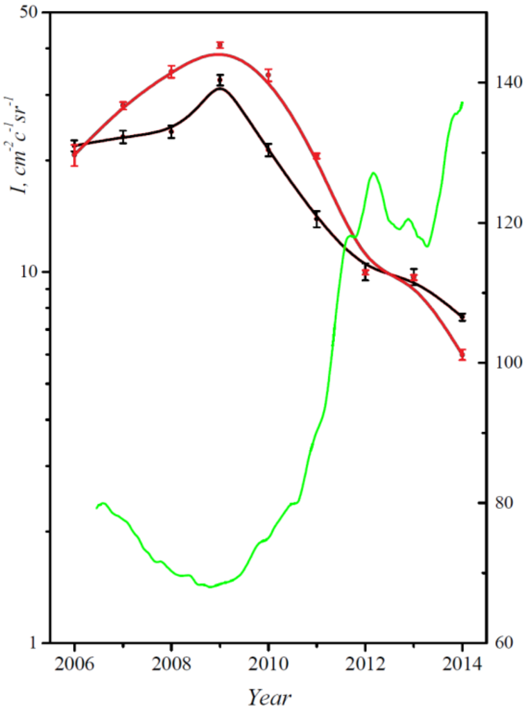

Figure 3. Proton flux time variations measured by PAMELA (black curve) and ARINA (red curve) for L-shells 1.14 – 1.16 (B/B0=1.0-1.07, i.e. equatorial flux) and f10.7 cm wavelength solar radio flux (green line)

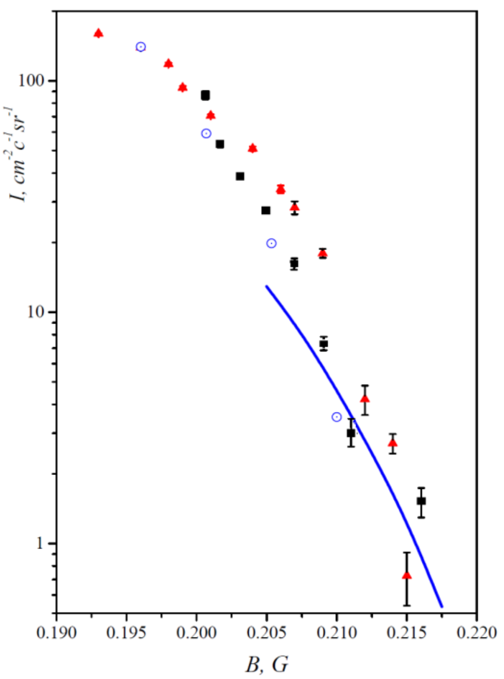

Figure 4. Proton flux vs B dependence measured by the ARINA (red triangles), the PAMELA (black squares), MERED on NOAA-15 (blue circles)[26], and AP8MIN calculations (blue curve), for solar minimum and L=1.14 – 1.16

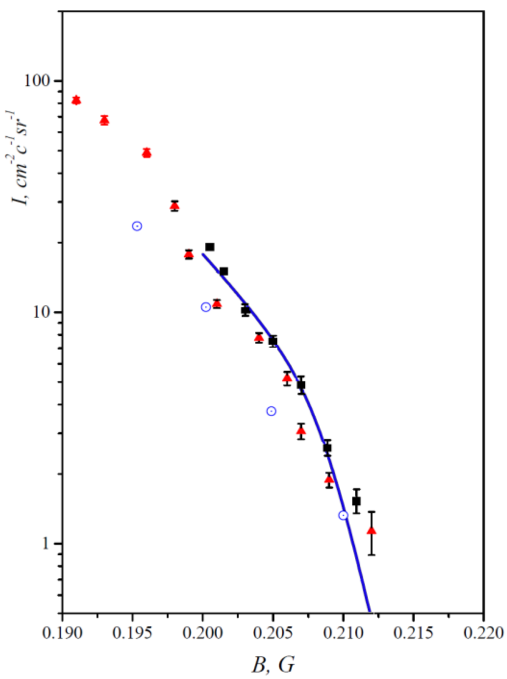

Figure 5. Proton flux vs B dependence measured by the ARINA (red triangles), the PAMELA (black squares), MERED on NOAA-15 (blue circles)[26], and AP8MIN calculations (blue curve), for solar maximum and L=1.14 – 1.16

5. Conclusion

In this work time variations of proton fluxes with energies E>80 MeV at the low edge of the inner radiation belt with PAMELA and ARINA instrument were obtained. An anti correlation between flux and level of the solar activity was shown. Flux dependence on B for different L-shells in interval 1.12 - 1.20 has been obtained. Good agreement between PAMELA and ARINA data is seen.

Acknowledgments

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References

[1] Knoll G F 1989 Radiation Detection and Measurement *JohnWilley &Sonic Inc.*
[2] Kazama Y, Goka G, 2008 A new modelling method of solar energetic proton events for ISO specification *Adv. Space Res.* **42** 1293–99
[3] Miyake W, Miyoshi Y, Matsuoka A, 2014 On the spatial of proton radiation belt from solar cell output variation of the Akebono satellite *Adv. Space Res* **53** 1603-9
[4] Ishikawa H, Miyake W, Matsuoka A, 2013 Variation of proton radiation belt deduced from solar cell degradation of Akebono satellite *Earth planets space 65* 121-5
[5] Huston S L, Kuck G A, Pfitzer K A 1997 Low Altitude Trapped Radiation Model Using TIROS/NOAA data *Radiation Belts:Models and Standards*
[6] Miyoshi Y, Morioka A, Misawa H 2000 Long Term Modulation of Low Altitude Proton Radiation Belt by the Earth's Atmosphere *Geophysical Research Letters* **27 14** 2169-72
[7] Galand M, Evans D 2000 Radiation Damage of The Proton MERED Detector on POES (TIROS/NOAA) *Technical report OAR* **456-Sec 42**
[8] Asikainen T 2012 Correction of detector noise and recalibration of MERED/NOAA energetic proton fluxes *Journal of Geophysical Research* **117** A0924
[9] Sawyer D M, Vette J I 1976 AP8 Trapped Proton Environment for Solar Maximum and Solar Minimum *NSSDC/WDC-A-R&S* 76-06, NASA Goddard Space Flight Center, Greenbelt, Maryland
[10] Vette J I, Chan K W, Teague M J 1978 Problems in modelling the Earth's trapped radiation environment *NASA TM-80447*
[11] Abel B, Thorne M, Vampola A L 1994 Solar cyclic behavior of trapped energetic electrons in Earth's inner radiation belt *J.Geophys. Res.* **99** 19,427-19,431
[12] Heynderickx D Comparison between methods to compensate for the secular motion of the south Atlantic anomaly *Rad. Meas.* **26**
[13] Dyer C S 1998 Space radiation environment dosimetry *IEEE **NSREC Short Course Notes,*** Ch. **2,** Newport Beach, CA, USA
[14] Daly E J, Evans H D R 1996 Problems in radiation environment models at low altitudes *Rad. Meas.* **26** 363-8
[15] Blake J B, Kolasinski W A, Fillius R W, Mullen E G 1996, Injection of electrons and protons with energies of tens of MeV into L<3 on Mar. 24, 1991 *Geophys. Res. Letr.* **18** 821
[16] Mazur J 2002 The radiation environment outside and inside a spacecraft, *IEEE NSREC Short Course Notes,* Ch. 2, Phoenix, *AZ,* USA
[17] Armstrong T W, Colburn B L 2000 Evaluation of trapped radiation model uncertainties for spacecraft design *NASNCR-2000-2* 10072
[18] Gussenhoven M S, Mullen E G, Brautigam D H 1994 Near-earth radiation model deficiencies as seen on CRRES, *Adv. Space Res.* **14** 927-41

[19] Heynderickx D, Kruglanski M, Pierrard V, Lemaire J, Looper M D and Blake J B 1999 A low altitude trapped proton model for solar minimum conditions based on SAMPEX/PET data *EEL Tram. Nucl. Sci.* **46**
[20] Huston S L 2002 Space Environments and Effects: Trapped Proton Model, *NASNCR-2002-2 I* 1784
[21] Boscher D M, Bourdarie S A, Friedel R H W, Belian R D 2003 Model for the geostationary electron environment: POLE, *IEEE Trans. Nucl. Sci.* ,**50** 2278-83
[22] Huston S L, Pfitzer K A, 1998 Space Environment Effects: Low-Altitude Trapped Radiation Model, NASNCR-1998-208593
[23] Lauenstein J-M, Barth J L 2005 Radiation Belt Modeling for Spacecraft Design Model Comparisons for Common Orbits" NSREC 2005 Data Workshop Paper # W-16
[24] Selesnick R S, Looper M D, Mewaldt R A, 2007, A theoretical model of the inner proton radiation belt, *Space weather* 5 S04003
[25] Lodhi M A K, Diaz A B, Wilson T L, 2005 Simplified solar model of inner trapped belt proton flux as a function of atmospheric density, *Radiation Measurements*, **39** 391-99
[26] Kuznetsov N V, Nikolaeva N I, Panasyuk, 2010, Variation of the trapped proton flux in the inner radiation belt of the Earth as a function of solar activity, *Cosmic Research*,**48** 80-85
[27] Picozza P, Galper A, Castellini G et al, 2007 PAMELA: Payload for Antimatter Matter Exploration and Light nuclei Astrophysics, *Astropart. Phys.* **27** 296-315
[28] Bakaldin A et al, 2007, Satellite experiment ARINA for studying seismic effects in the high-energy particle fluxes in the Earth's magnetosphere, *Cosmic Research*, **45** 445-8
[29] Finlay C C, Maus S, Beggan C D et al 2010, International Geomagnetic Reference Field: the eleventh generation, *Geophysical Journal International* **183** 1216-30