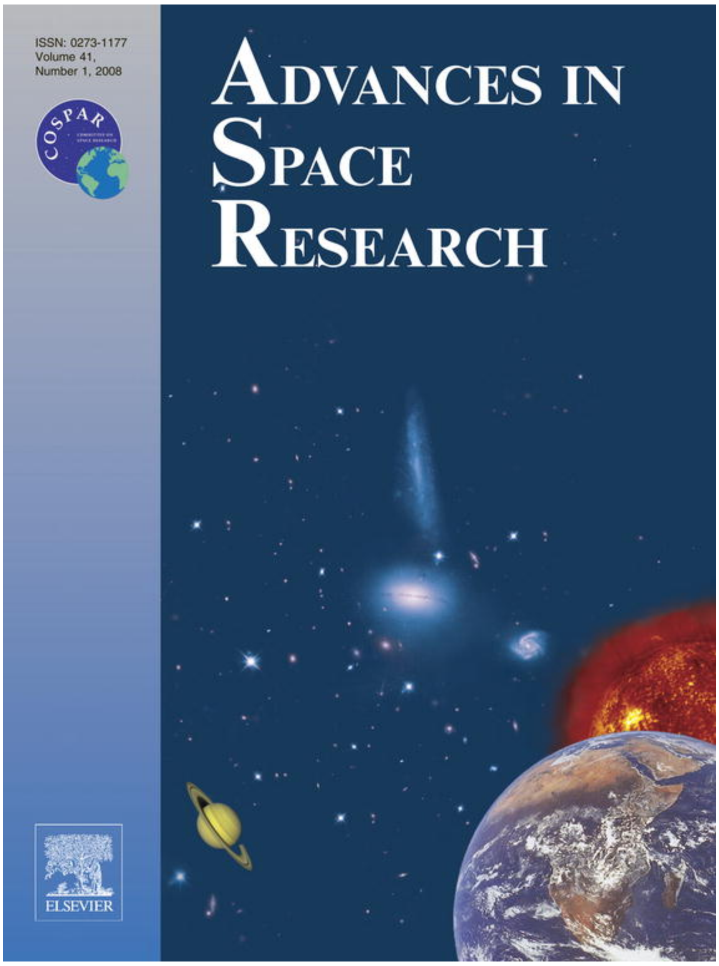
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SAA drift: Experimental results

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Abstract

According to the paleomagnetic analysis there are variations of Earth's magnetic field connected with magnetic moment changing. These variations affect on the South Atlantic Anomaly (SAA) location. Indeed different observations approved the existence of the SAA westward drift rate (0.1–1.0 deg/year) and northward drift rate (approximately 0.1 deg/year).

In this work, we present the analysis of experimental results obtained in Scobeltsyn Institute of Nuclear Physics, Moscow State University (SINP MSU) onboard different Earth's artificial satellites (1972–2003). The fluxes of protons with energy >50 MeV, gamma quanta with energy >500 keV and neutrons with energy 0.1–1.0 MeV in the SAA region have been analyzed. The mentioned above experimental data were obtained onboard the orbital stations Salut-6 (1979), MIR (1991, 1998) and ISS (2003) by the similar experimental equipment. The comparison of the data obtained during these two decades of investigations confirms the fact that the SAA drifts westward. Moreover the analysis of fluxes of electrons with energy about hundreds keV (Cosmos-484 (1972) and Active (Interkosmos-24, 1991) satellites) verified not only the SAA westward drift but northward drift also.

Keywords: SAA drift; Location; Space experiment; Neutral and charged particles

1. Introduction

It is known that LEO (Low Earth Orbit) space vehicles spend a significant part of time in the SAA area. In this region spacecrafts get the greatest radiation dose impact which is associated with intensive fluxes of charged particles (protons and electrons). In order to avoid the prediction of artificially high particle fluxes, the static NASA trapped radiation models AP-8 and AE-8 should only be used with the same geomagnetic field models, for the same epoch, with which they were constructed. It is possible to correct for one aspect of the secular variation of the geomagnetic field, i.e. the secular drift of the local particle flux maximum in the SAA. According to the different definition of the SAA, one can approximate the location of the SAA in three ways as reported by Heynderickx (1996):

- As the mirror point of the center of the eccentric dipole approximation to geomagnetic field,
- As the locus of the local minimum of the geomagnetic field at a fixed altitude in the region of the South Atlantic,
- As the locus of the local particle flux maximum in this region.

The indirect method is studying of single event upsets (SEU) in the SAA region. This method was presented by Laurients et al. (1995).

But all these SAA center determination methods give different results. Secular drift of the minimum magnetic field point mainly has westward component and does not contain northward or southward components. The maximal flux point drifts mainly westwards and sufficiently slower northwards. The SAA center reconstructed in eccentric dipole approach drifts to the south–west (Heynderickx, 1996). All of three results differ and therefore they did not give us exact SAA center position.

The basic results on the SAA drift research are represented in Table 1.

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Table 1
List of experiments, observed parameters and obtained results

Experiment	Observed parameter	SAA drift rate (deg/year)		References
		Westward	Northward	
Satellites				
Skylab, MIR	Dose	0.28 ± 0.03	0.08 ± 0.03	Badhwar (1997)
Shuttle STS-31	Dose rate	0.32–0.34	–	Konradi et al. (1994)
Shuttle STS-60	Dose rate	0.22 ± 0.02	–	Badhwar et al. (1996)
Shuttle STS-28	Dose rate	0.49	0.12	Golightly et al. (1994)
Topex/Poseidon	SEU	0.29	–	Laurients et al. (1995)
Ground				
Paleomagnetic measurements (last 1400 years)	Reconstructed magnetic field	0.3	–	Yukutake and Tachinaka (1962)
South Atlantic Magnetic Anomaly	Minimum magnetic field	0.27	–	Pinto and Gonzales (1989)

In this paper talking about the long-term variations of the particle fluxes we mean the SAA location shift over the time. One of the first reports devoted to the Earth magnetic field variation is Yukutake and Tachinaka (1962). It has been estimated that there is a longitudinal magnetic variations (westward drift) about 0.3 deg/year during last 1400 years (Yukutake and Tachinaka, 1962). This drift rate is not constant.

In satellite experiments the averaged longitudinal drift rate is ~0.3 deg/year. But in every experiment drift rate varied from 0.1 to 1.0 deg/year (Fig. 1).

In the set of reports has been emphasized that the geomagnetic field drift is accompanied by the SAA drift northward and westward, the westward drift rate is from 0.1 to 1.0 deg/year (Badhwar, 1997; Heynderickx, 1996; Sakaguchi et al., 1999).

The SAA westward drift was experimentally proved in Badhwar (1997), Heynderickx (1996) and Sakaguchi et al. (1999) (Fig. 1).

Main features of the SAA drift:

- Drift rate is different for maximum and minimum solar years,
- Drift rate does not depend (or depending very weak) on the altitude (in altitude range 350–1400 km),

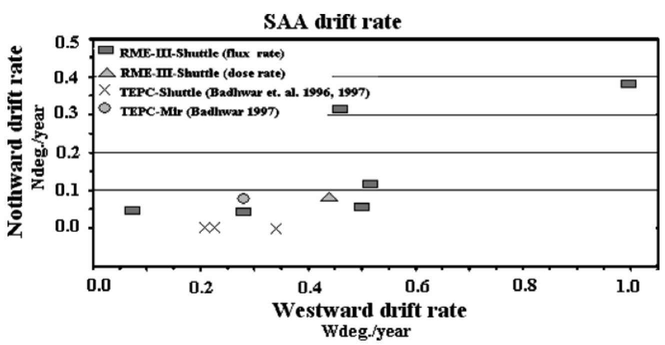

Fig. 1. The SAA drift rate according to Golightly et al. (2001). (http://www.oma.be/WRMISS/workshops/sixth/workshop.html).

- The longitude drift rate is in good agreement with one of the magnetic anomaly feature over the last 1400 years,
- Drift rate determined in maximum particle flux approach doesn't match with one determined in minimum field approach,
- The SAA drift could be related with magnetic field degradation (in fact according to some estimations Earth magnetic dipole reduces with rate 0.05%/year last 150 years, Merill and McElhinny, 1983).

2. Experimental details

To verify the fact of the SAA drift in current work, we used the SAA center determination as a charged and neutral particles flux maximum. Information about the fluxes was collected in Russian experiments carried out in 1960–2003. The dates of the experiments, orbit parameters and registered parameters are shown in Table 2.

2.1. Instruments

1. *Space vehicle II*. Registration of the proton and electron ($E_P > 60$ MeV and $E_e > 8$ MeV) fluxes was performed by telescope consisted of two layers of gas-discharged counters (geometric factor 2.5 cm^2 sr).
2. *Cosmos-484*. Detection of the electron (>30 and >300 keV) fluxes was made by the discharge counter (Ø4 mm, geometric factor $2 * 10^{-2}$ cm^2 sr).
3. *Ryabina*. Neutrons (0.04 eV to 4–6 MeV) were registered by scintillation detector Li^6I with the 40 mm * Ø10 mm dimensions.
4. The *Ryabina-2* neutron detecting module was installed inside the station. It consists of 12 slow neutron helium discharge counters separated into four groups of three parallel-connected counters. The dimensions of each counter were 22 cm * Ø3 cm. The detectors were surrounded by a 15 cm-coating of organic moderator. Neutrons with energy from 0.25 eV to 1.9 MeV after slowing

Table 2
List of the experiments, orbit parameters and registered parameters used in this paper

Experiment	Spacecraft	Year	Orbit parameters		Registered parameters
			Altitude (km)	Inclination (deg)	
–	Space vehicle II	1960	307–339	65	$E_p > 60$ MeV, $E_e > 8$ MeV
–	Cosmos-484	1972	220	81.6	$E_e > 300$ keV
Ryabina	OS Salyut-6	1979	400	51.6	$E_n = 0.04$ eV to 4–6 MeV
SPE-1	Intercosmos-24 (Active)	1989–1991	500–2500	81.3	$E_e = 20$–540 keV
Ryabina-2	OS MIR	1991, 1998, 1999	400	51.6	$E_p > 50$ MeV, $E_n = 0.25$ eV–1.9 MeV, $E_\gamma > 0.5$ MeV
Scorpion-1	ISS	2003	450	51.6	$E_p > 50$ MeV, $E_n = 0.1$ eV–1 MeV, $E_\gamma > 0.5$ MeV

down to thermal energy could reach the detector. The thermal neutron registration efficiency reaches 80%. The total area of the setup was ~310 cm^2. Detecting of the charged particles was made by the cylindrical gas-discharge counter (the cylinder's diameter was 10 and 75 mm long, geometric factor 6.3 cm^2). The detector registered fluxes of protons with energy $E_p > 50$ MeV and electrons with energy $E_e > 5$ MeV. Gamma-quanta were detected by the cylindrical scintillation detector (the size of counter is 30 mm * Ø16 mm), made of monocrystal NaI (Tl). Fluxes of the electrons generated by bremsstrahlung in the body of station corresponds to energy >0.3 and >1.5 MeV. The geometric factor was 4.8 cm^2. It also detects proton induced prompt gammas and delayed radioactivity but this influence is not essential. Discriminators cutoff the energy deposition in scintillator corresponding to 100 and 500 keV (Ip2 and Ipl parameters) which corresponds to bremsstrahlung generating electrons with energy >0.3 and >1.5 MeV.The maximal particle flux locations observed by the scintillator and discharge detectors are the same. The simultaneous registration of gamma, protons (>50 MeV) and neutrons (from thermal to several MeV) was realized. The comparison of these measurements shows that peaks of proton or neutron were not registered where the gamma-quanta enhancements were observed. The same technique was used in (Savenko et al., 1962) earlier.

5. Experiment *Scorpion* was installed onboard the International Space Station. The Scorpion-1 neutron module consisted of two parallel-connected counters and was mounted inside the station. These detectors had no moderator and detected neutrons with energies ranging from 0.1 eV to 1 MeV. The effective area of device is ~100 cm^2.
6. *SPE-1*. Experiment on board satellite Active (Intercosmos-24). The electrons with energies from 20 to 500 keV were registered by single Si-surface barrier semiconductor detectors (300 μm thickness, Ø 8 mm, $3 * 10^{-2}$ cm^2 sr geometric factor). There were three detectors measured electron fluxes at different angles (99°, 69°, 39°) with respect to zenith axis of the satellite. All detectors were protected by Maylar foil to stop protons with energy $E_p < 500$ keV.

3. Experimental data

3.1. Variation of charged and neutral particle fluxes in the SAA region

3.1.1. Variations of proton fluxes with energy >50 MeV

In this work we collected the information about maximum particle flux location in the SAA region during the period from 1960 to 2003.

From all sets of data we selected ones belonging to the SAA region or a rectangular area with latitudinal coordinates from −50 to −10 deg and longitudinal coor-

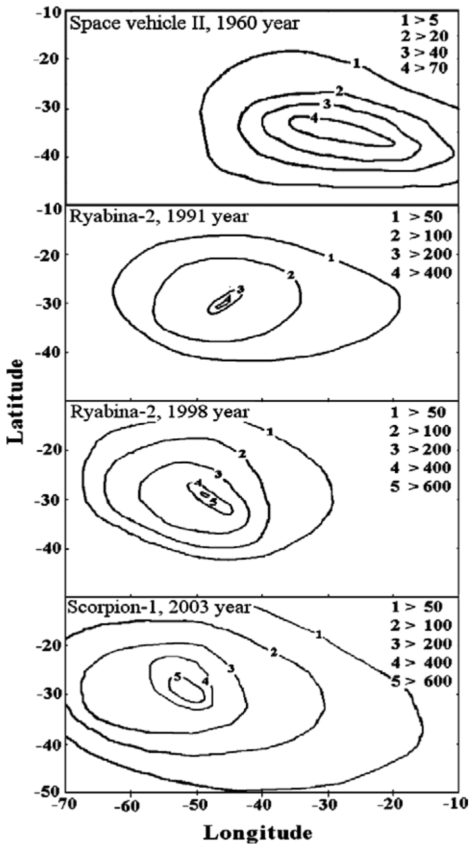

Fig. 2. Proton fluxes intensity isolines reconstructed from the observations of setups Space vehicle II in 1960 (the flux is given in relative units), Ryabina-2 in 1991, 1998 and Scorpion-1 in 2003 (count rate levels are shown, s^{-1}).

dinates from −70 to −10 deg and built sets of particle flux intensity contour lines. The same procedure we applied to the data obtained in 1991, 1998 and 2003. In further analysis the center of the anomaly was marked out as a maximum particle flux area. So several sets of maps for different years were derived and that allows us to compare the SAA locations in different time moments.

The comparison of anomaly location in 1960, 1991, 1998 and 2003 determined via fluxes of protons with energy >50 MeV is shown in Fig. 2. As it seen from the figure the maximum proton flux area in anomaly region shifted westward on several degrees and that allows us to assume the existence of the SAA westward drift from 1960 to 2003.

The effect of solar cycle is the variation of charged particle fluxes but the location does not change essentially. We compared data obtained in different phases of solar cycle (and in different cycles) and found the monotonous drift. The reverse drift was not found in no one phase of solar cycle.

3.1.2. Variations of neutron fluxes with energy 0.1 eV–2.0 MeV

The same way as the proton fluxes data the neutron fluxes data were processed. In Fig. 3 the results of the neutron fluxes with energy 0.25–1.9 MeV consideration are presented. The fluxes were detected by Ryabina-2 in 1991, 1998 and Scorpion-1 in 2003. At the same figure the neutron fluxes intensity contour lines in the SAA region in 1979 (Salyut-6) and 1999 (MIR) are presented according the Shavrin et al. (2002).

3.1.3. Variations of gamma quantum fluxes with energy >0.5 MeV

The results of the gamma quantum (>0.5 MeV) fluxes analysis are presented in Fig. 4. Gamma fluxes intensity contour lines presented are reconstructed from the data sets observed by setup Ryabina-2 (MIR), Scorpion-1 (ISS). As it seen from the figure the maximum location is shifting over the time to the west.

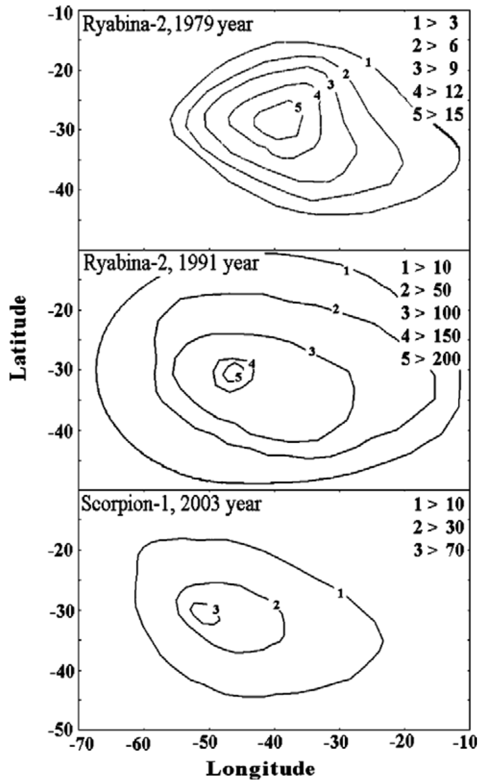

Fig. 3. Neutron fluxes intensity isolines reconstructed from the observations of setups Ryabina-2 in 1991 (s^{-1}), Scorpion-1, 2003 (count rate, s^{-1}) and from observations (Shavrin et al., 2002) onboard Salut-6 in 1979 ($cm^{-2}\,s^{-1}$).

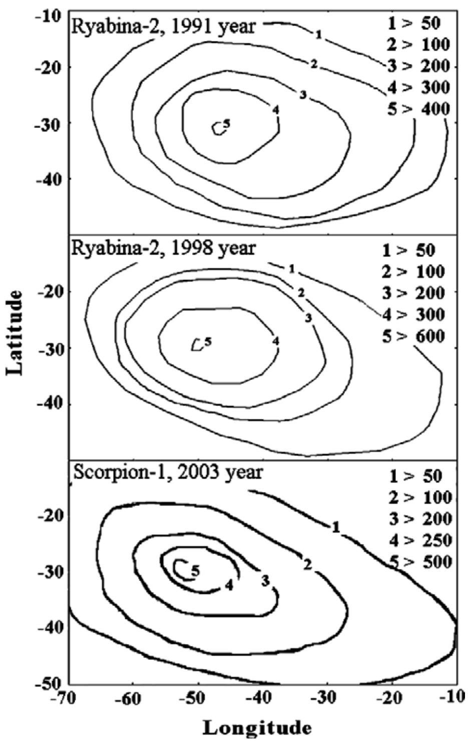

Fig. 4. Gamma radiation fluxes intensity isolines reconstructed from the observations of setups Ryabina-2 in 1991 and Scorpion-1 in 2003.

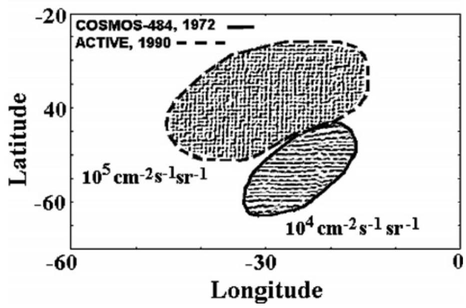

Fig. 5. Electron fluxes intensity isolines reconstructed from the observations onboard satellites (Cosmos-484, 1972, solid line) and (Active, 1990, dashed line).

3.1.4. Variations of electron fluxes with energy >300 keV

To analyze the long-term variations of electron fluxes with energy of hundreds keV the data observed onboard Earth's artificial satellite Cosmos-484 in 1972 was used. These data were compared with ones observed onboard satellite Active (Intercosmos-24) in 1990.

Two electron fluxes intensity contour lines are shown in Fig. 5. Solid line corresponds to the flux intensity of $1.5 * 10^4\ cm^{-2}\ s^{-1}\ sr^{-1}$ (Cosmos-484, 1972) and dashed one corresponds to the flux intensity of $10^5\ cm^{-2}\ s^{-1}\ sr^{-1}$ (Active, 1990).

Fig. 5 shows the ACTIVE satellite data corresponding to 500 km altitude (perigee). The COSMOS-484 data are given for 220 km (the orbit was near-circular). Due to losses in upper atmosphere the fluxes at 200 km are less than fluxes at 500 km so the region of fluxes $\sim 10^4$ $(cm^2 s\ sr)^{-1}$ according ACTIVE satellite is wider than the same region according COSMOS-484. In this work, we compare the regions with maximal flux. So the thresholds were different.

It is clear that after approximately 20 years the electron flux maximum location is shifted not westward only but northward also.

4. Conclusions

1. As a result of the experimental data analysis including proton (>50 MeV), neutron (0.1 eV–2.0 MeV), gamma quantum (>0.5 MeV) and electron (>0.3 MeV) fluxes consideration and summarizing the observations onboard various satellites (Cosmos-484, 1972, Intercosmos-24, 1990) and orbital stations (Salut-6, 1979, MIR, 1991 and 1998, ISS, 2003) we can formulate the following conclusions:
   - There are long-term variations of charged and neutral (neutral particles are not part of the SAA but are secondary reflecting proton and electron fluxes) particle fluxes maxima locations in the SAA region,
   - There is a tendency to westward drift of the SAA.
2. The comparison of electron fluxes maxima with energies of hundreds keV (1972 and 1990) reveals that there is a northward drift of the SAA at the same time with westward. The northward drift of the SAA for protons is not observed according our data.

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