THE TRAPPED ANOMALOUS COMPONENT OF THE COSMIC RAYS : THE SHORT OVERVIEW OF EXPERIMENTS

M.I. PANASYUK
Skobeltsyn Institute of Nuclear Physics of Moscow State University
119899, Vorob'ovy Gory, Moscow, Russia, panasyuk@sinp.msu.ru

The experimental data on the chemical composition of galactic cosmic rays (GCR) are analysed in the energy range between ~10 MeV/nucl and ~ PeV. The lower part of the energy range corresponds to the so-called 'anomalous cosmic rays' (ACR). These particles with low charge values can easily penetrate through the Earth's magnetic field and after charge-exchange with neutrals of the Earth's atmosphere increase their charge states to full stripping. As a result of satellite experiments it was shown, that these secondary particles can become trapped in the geomagnetic field and form a radiation belt. Below a short survey of the experimental results which led to this discovery is given.

The term 'anomalous cosmic rays' was first introduced in 1973 after the discovery of a local maximum at $E \sim 10$ MeV/nucl in the energy spectrum of such cosmic ray elements as ^{4}He and ^{16}O [1],[2]. This maximum appeared during solar activity minimum (in 1976-1977) at about 10 MeV/nucl, i.e. at energies between those of particles of solar origin - solar energetic particles (<10 MeV/nucl) and traditional galactic cosmic rays (>100 MeV/nucl).

After the discovery of the GCR anomalous component Fisk, Kozlovsky and Ramaty [3] suggested a theory describing their origin. According to their hypothesis ACR are neutral atoms of the Local Interstellar Medium (LISM) which penetrate inside the heliosphere where they are ionised by solar ultraviolet radiation or due to charge-exchange with ions of the solar wind; then they are picked up by the solar wind and carried away towards the heliopause, where they are accelerated to energies of ~10 MeV/nucl, and finally return back to the Sun. Later it was shown, that this process can be multiple [4]. The charge state of ACR ions can be 1+ or >2+.

The suggested mechanism of ACR origin and acceleration [3] assumes a relative increase of intensity for the elements with a high ionisation potential, whereas for elements with a low ionisation potential (e.g. for Mg, Si, Fe) there should be no 'anomalous' increase of the flux.

Fig.1shows the energy spectra of He, C, N, and O observed by Voyager-2 at the distance of 23 AU during the year of minimum solar activity. The maximum of ACR fluxes is revealed at energies < 50 MeV/nucl. At larger energies GCR particles start to dominate.

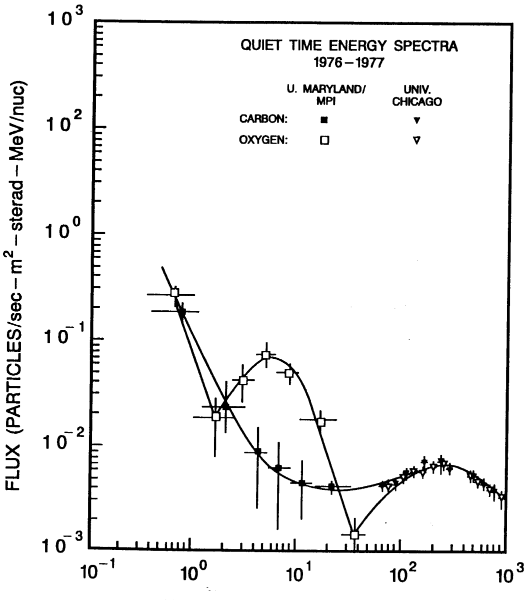

Fig. 1. The ACR energy spectra: He, C, N, O , according to the Voyager-2 observations at ~23 AE in 1987 [1].

It was experimental proof of ACR ions having charge states close to +1, that could serve as the final argument in favour of the above described model of ACR propagation and acceleration in the heliosphere.

The most convincing proof that ACR have charge states close to 1+ were the results of a series of experiments which used the effect of ion separation by the Earth's magnetic field. (see e.g. [5,6,7]). This technique was based on the comparison of ^{16}O fluxes, observed by the IMP-8 satellite in the interplanetary medium and simultaneous measurements at low altitudes (below 350 km) on satellites of the 'Cosmos' series. Detailed analysis of these results is given in [5]. Unambiguous determining of the charge state of ^{16}O was the key result of these experiments and proof of the validity of the Fisk, Kozlovsky and Ramaty hypothesis. Fig.2 [3] shows the results of comparison of the ^{16}O ion data (measured on 'Cosmos' and 'IMP-8' satellites) and model calculations, based on the penetration ^{16}O ions with charge values Q=+1 and Q=+ into the inner magnetosphere. The mean charge state for ^{16}O was found to be $Q = 0.9 \pm^{0.3}_{0.2}$.

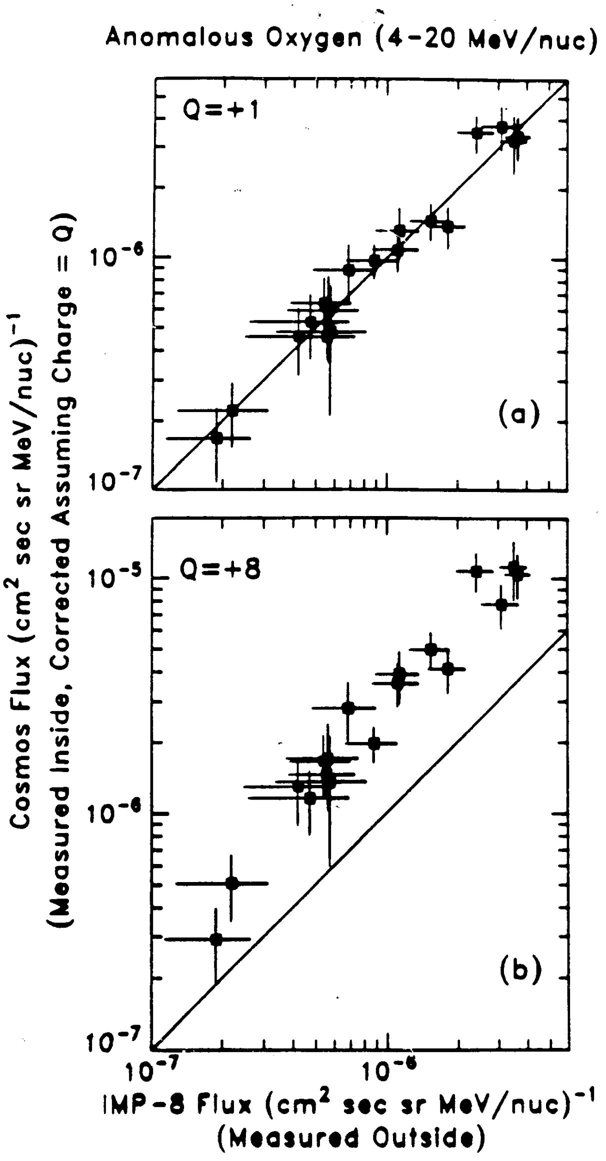

Fig. 2. Comparison of anomalous oxygen intensities measured inside the magnetosphere ('Cosmos' data) and outside the magnetosphere (IMP-8 data) for supposed ^{16}O charged states of +1 and +8 [5].

Studies of ACR are very important for cosmic ray physics. It is known that while propagating through the interstellar medium cosmic rays (ions with energies above ~10 MeV/nucl) soon become fully stripped. In order to lose their orbital electrons the ions need to travel through just several tens of mg/cm^2 of matter. Therefore, the presence of orbital electrons in the low energy cosmic ray component atoms can serve as evidence that their source is located in the direct vicinity of the solar system. Losses of O$^+$ ions associated with charge-exchange processes ($O^+ \rightarrow O^{n+}$), which impose limitations on the life times of these particles in the process of their propagation, were studied in [8]. The authors showed, that for density of H neutrals $n_H = 0.1$ cm^{-3} and upper limit of the mean charge state of O$^+$ ions $<Q>$=1.6, their maximum propagation distance should not exceed 0.2pc for O$^+$ at energies of ~10 MeV/nucl. I.e., this actually means, that the sources of ACR are located somewhere in the near-by regions of the Universe - the LISM. Propagating inside the solar system ACR ions (which have significant momentum) due to their small charge state, can reach the vicinities of planets, which have magnetic fields.

The first measurements of O ions in the vicinity of the Earth were made in 1973-74 on the Skylab orbital station (orbit altitude 435 km) by Biswas et al. (see e.g. survey [9]) using solid state Lexan Poly-carbonate detectors. It was these measurements that permitted to point out that O ion fluxes recorded in the Skylab orbit (exceeding those in the interplanetary medium) could be associated with O ions having a small charge state. However, at that time no proof was obtained, that these are in fact particles trapped in the Earth's magnetic field. The same pioneering works of Biswas et al. presented data on the relative abundance of N; C; Ne. In particular, it was shown that O/C=4.7±0.1, which served as a convincing indication of the close relations of these particles with the ACR fluxes observed in the interplanetary medium.

Important result of ACR studies carried out during the 90-ies was proof that ions can be trapped by the Earth's geomagnetic field. This idea was suggested by Blake and Friesen in 1977 [9]. According to this theory a singly-ionised ACR ion, penetrating inside the geomagnetic field, is stripped by the residual atmosphere at altitudes of ~300 km, becomes multiply-charged and is trapped by the geomagnetic field.

This theory was confirmed in the experiments onboard satellites of the 'Cosmos' series [10]. The trapped ^{16}O were actually recorded using angular distributions of particle tracks in solid state detectors; and their flux exceeded by a factor of hundreds the ^{16}O fluxes in the interplanetary medium. Thus, the possibility of studying ACR in the direct vicinity of the Earth was revealed.

Starting from 1992 large-scale tudies of penetrating and trapped ACR began on 'SAMPEX'. It was confirmed, that besides ^{16}O, and ^{14}N ACR also contain Ne and Ar. The different efficiency of ACR trapping and losses in the geomagnetic field effect their energy spectra: they become softer in comparison to the interplanetary ones [11]. As a consequence, their relative composition also changes. Table 1 shows the relative abundances for the individual components of ACR for trapped and interplanetary ions according to 'SAMPEX' data [5]. The discrepancies are obvious.

Table 1. The relative abundances of ACR according to 'SAMPEX' data [11].

Ratio	Trapped 16-45 MeV/nucl	Interplanetary > 17 MeV/nucl
C/O	~0.0004	0.014±0.009
N/O	0.09±0.01	0.19±0.03
Ne/O	0.04±0.01	0.06±0.02

Measurements of ACR during the last two solar activity cycles show that this GCR component is extremely sensitive to solar modulation. The flux of anomalous ^{16}O with $E \sim$ 10 MeV/nucl in the interplanetary medium varies within a factor of ~100. Temporal variations of trapped ACR were studied for the first time on satellites of the 'Cosmos' series (see Fig.3, [5]) . It turned out, that the behaviour of trapped anomalous ^{16}O is similar. This means, that the life time of the trapped component is relatively small - does not exceed the characteristic times of interplanetary ACR flux variations.

On the basis of 'Cosmos' data a model of the spatial distribution of trapped ACR particles was built. It was revealed, that the ACR belt is localized slightly eastwards of the South-Atlantic Anomaly (see Fig.4.) with maximum intensities at L-shells of about 2.2-2.5. The results of this calculation model [12] were later confirmed by direct observations of trapped ACR particles on the 'SAMPEX' satellite (see Fig.5)

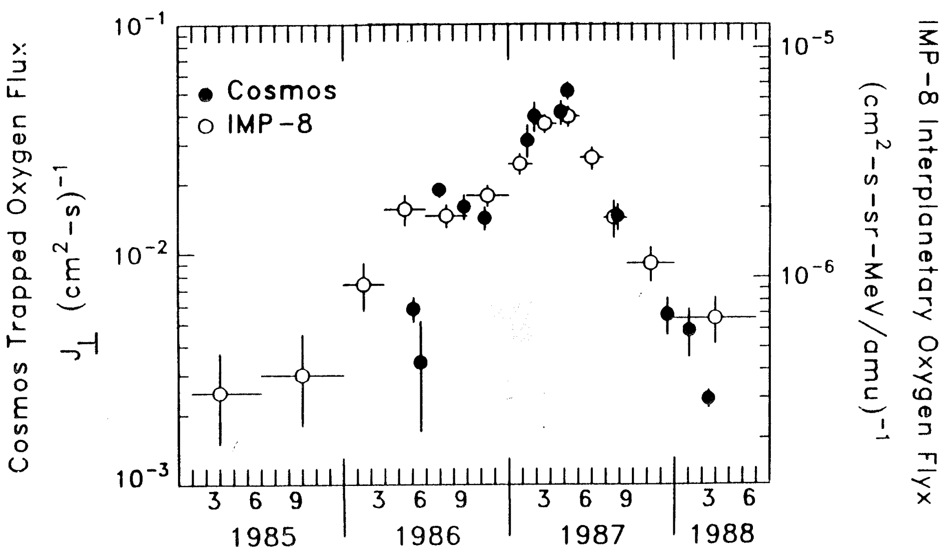

Fig. 3. Time history of the trapped flux (left-hand scale) measured on the Cosmos flights and the quite-time interplanetary 5-11 MeV/nucleon oxygen flux (right-hand scale) measured by the instrument on IMP-8 [10].

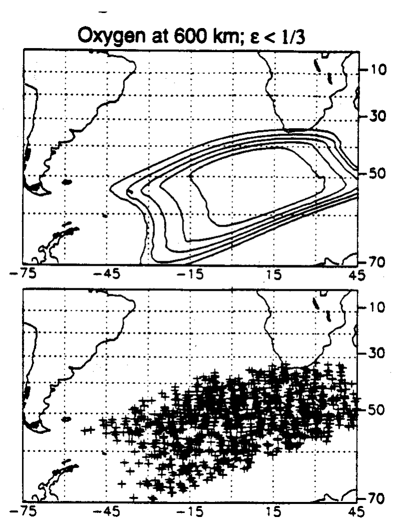

Fig. 4. Isoflux contours of the E > 20 MeV/nucleon oxygen at 600 km (top panel) and Monte-Carlo simulations of the distribution produced by sampling along the SAMPEX satellite orbit [12].

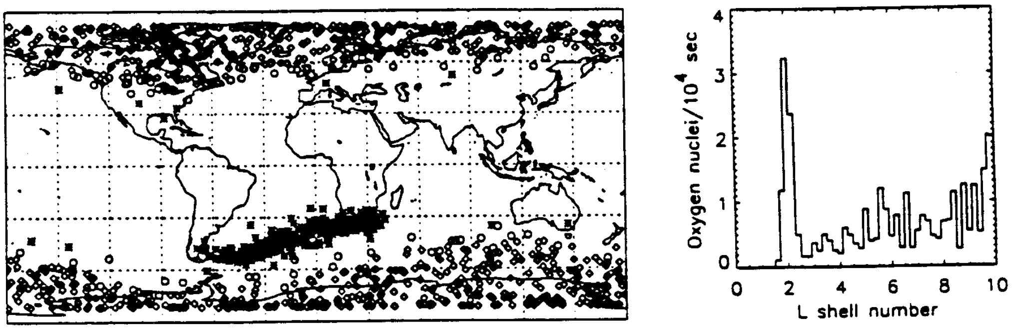

Fig. 5. Observed geographic and L-distributions of the oxygen ions (SAMPEX satellite data) [11].

Conclusions

Satellite studies of anomalous cosmic rays carried out during the 70-ies-90-ies led to the understanding that the most low-energy component of GCR, observed in the heliosphere, consists of particles which originate in the LISM - the part of the Galaxy which is located close to us, and the limited time of their propagation and acceleration inside the heliosphere is responsible for their low charge state. These particles can penetrate inside the magnetosphere, and, interacting with the atmosphere, are transformed into ions with larger charge states. In this way the conditions for their trapping inside the magnetic field are created. The radiation belt, formed by ACR particles, is, essentially different from those known previously for the following reasons:

1) The source of these particles is not the Sun and not the Earth's ionosphere, but matter from the LISM;
2) The main mechanism of the new radiation belt formation is trapping of multi-charged ions, produced as a result of charge-exchange of singly charged ions in the ionosphere, not radial diffusion across the magnetic field lines, typical for the radiation belts discovered at the end of the 50-ies.

Acknowledgements

The author sincerely wishes to thank theorganizers of the 2nd International Workshop on Matter, Antimatter and Dark Matter, Trento, Italy and especially Professor RobertoBattiston
for the opportunity to present this tutorial lecture and to publish it in these Proceedings.

References

1. Garcia-Munoz, M., Mason, G.M., Simpson, J.H. (1973) A new test for solar modulation theory: the 1972 May-July low energy galactic cosmic ray proton and helium spectra, *Astrophys. J. (Lett.).* **182**, L81-L84.
2. Hovestadt, D.O., Valmer, O., Gloeckler, G., Fan, C. (1973) Differential energy spectra of low-energy (8.5 MeV per nucleon) heavy cosmic rays during solar quiet times, *Phys. Rev. Lett.* **31**, 650-667.
3. Fisk, L.A., Kozlovskiy, B., Ramaty, R. (1974) An interpretation of the observed oxygen and nitrogen enhancements in low-energy cosmic rays. *Astrophys. J. (Lett.)* **190**, L35-L38.
4. Mewaldt, R.A., Selesnick, R.S., Cummings, J.R., Stone, E.C., Von Rosenvinge, T.T. (1996) Evidence for multiply charged anomalous cosmic rays,*Astrophys. J.* **466**, L43-L46.
5. Adams, J.H., Garcia-Munoz, M., Grigorov, N.L., Klecker, B., Kondratyeva, M.A., Mason, G.M., McGuire, E., Mewaldt, R., Panasyuk, M.I., Tretyakova, Ch.A., Tylka, A.J., Zhuravlev, D.A. (1991) The charge state of the anomalous component of cosmic rays, *Astrophys J.(Lett)* **375**, L45-L48.
6. Panasyuk, M. (1993) Anomalous cosmic ray studies on 'Cosmos' satellites*, Proc. of the 23 Int. Cosmic Ray Conference*. (Invited, rapporteur and highlight papers), 455-463.
7. Klecker, B. (1995). The anomalous component of cosmic rays in the 3-D heliosphere, *Space Science Reviews* **72**, 419-430.
8.Adams, J.,Leising, (1991) *Proc. 22nd Intern. Cosmic Ray Conf. (Dublin)*, **3**, 304..........
9. Biswas,S (1996) The new radiation belt of the earth from trapped anomalous cosmic rays,*Space Science Reviews,***75,** *423-451.*
10. Blake, J.B. and Friesen , L.M. (1977). A technique to determine the charge state of the anomalous low energy cosmic rays., *Proc. of the 15th ICRC* **2**, 341-346.
11. Grigorov, N.L., Kondratyeva, M.A., Panasyuk, M.I., Tretyakova, Ch.A., Adams, J.H., Blake, J.B., Shultz, M., Mewaldt, R.A., Tylka A.J. (1991) Evidence for trapped anomalous cosmic ray oxygen ions in the inner magnetosphere, *Geophys. Res.. Letters* **18**, 1959-1962.
12. Selesnik, R.S., Cummings, A.C., Cummings, J.R., Mewaldt, R.A., Stone, E.C., Von Rosenvinge, T.T. (1995). Geomagnetically trapped anomalous cosmic rays, *J.Geophys. Res.* **100**, 9503-9509.
13. Tylka A.(1993) Theoretical modeling and interpretation of trapped anomalous cosmic rays*, Preprint Cosmic Ray Section E.O.Hulbert Center for Space Research, Naval Research Laboratory, 10 p.p. Proc. of the 23 th Intern. Cosmic Ray Conf.*,**5**.