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Investigation of radiation environment and Light Flash phenomenon on board manned space stations with silicon detector telescopes

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Summary. — In this work we review measurements on cosmic-ray abundances and radiation environment on board Mir (1995-2000) and International (2002-2008) Space Stations with active silicon detector telescopes. Additional scientific topics goals involve the investigation of the Light Flash Phenomenon and its relation with nuclear fluence. Characteristics of the detectors employed (Sileye-1, Sileye-2, Sileye-3/Alteino, Altea) and some results are presented.

PACS `96.50.S-` – Cosmic rays.
PACS `95.55.-n` – Astronomical and space-research instrumentation.
PACS `87.50.up` – Dosimetry/exposure assessment.

1. – Introduction

A detailed study and understanding of the radiation environment in space and its effects on human physiology has a growing importance in light of work on the International Space Station (ISS) and of future missions to the Moon or Mars. Radiation in orbit comes from cosmic rays of different energies and origins. In addition to the galactic component—which is modulated by the solar activity at low energies—there are also solar energetic particles associated with transient phenomena such as solar flares and coronal mass ejections. Inside Earth's magnetosphere there is also the significant contribution of trapped particles encountered in low Earth orbit in the Brazilian region. This complex and time-varying environment requires a number of various detectors, of active and passive nature, to characterize the environment and quantify the dose and ultimately the risk associated to manned permanence in space. In this context a number of devices has been realized since 1995 and put on Mir and International Space Stations. These active silicon detectors have been developed with the technology used for study of cosmic rays on board satellite and are particularly suited to the characterization of the nuclear radiation field. Their single particle counting in real time makes them complemental to passive dosimeters or TEPC (Tissue equivalent proportional counters) used

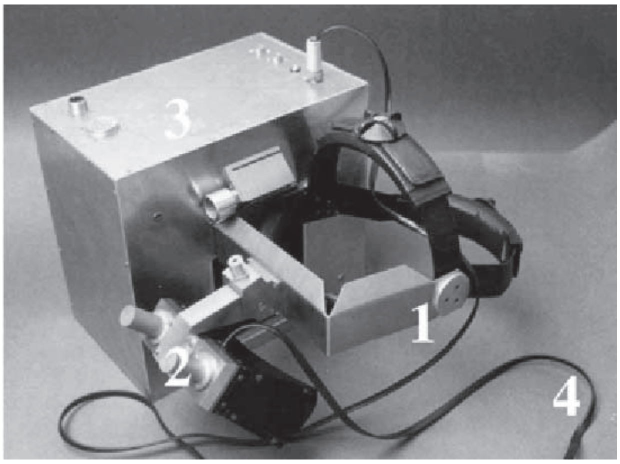

Fig. 1. – Photo of the SilEye-2 helmet and detector case: 1. Head Mounting. 2. Eye mask with internal LEDs. 3. Detector Box. 4. Connection cable for the LEDs used for dark adaptation tests.

in space. In this work we briefly describe the detector characteristics developed by the Wizard collaboration and present some of the results obtained.

2. – Sileye-1 and -2

Sileye-1 was placed on Mir Space Station in 1995 to perform Light Flash (LF) observations and correlations with the incoming cosmic-ray particle flux [1]. The detector allowed real time correlation of particle fluence with LF perception recorded by the cosmonaut. It was employed by various crewmembers until replacement with Sileye-2 in 1998. Sileye-2 was also capable to perform particle identification from H to Fe, thus allowing real time correlation of LF observations with cosmic-ray nuclei.

2˙1. *Sileye-2 description.* – Sileye-2 consists of a silicon detector telescope, shown in fig. 1, housed in an aluminum box, coupled to an "helmet" with an eye mask, and worn by the cosmonaut. The device is connected to a laptop computer equipped with a data acquisition card and a joystick. The detector is small (maximum dimension: 26.4 cm, mass 5.5 kg), robust and easy to handle. A computer-based control software performs data handling and storage. To carry out LF observations, the astronaut wears the helmet which holds the detector box and presses the joystick button when he observes LF. Data come, therefore, from two independent sources: the particle track recorded by the silicon detector and the observation of the LF by the astronaut. The helmet has a mask that shields the astronaut's eyes from light; three internal LEDs allow to cross-check the correct position of the detector, verify the dark adaptation of the observer and measure his reaction time to normalize measurements performed by different astronauts.

The device can also be operated as a stand-alone cosmic-ray detector without the presence of the cosmonaut; in this acquisition mode a monitoring of the environmental radiation inside Mir is performed. Each event (cosmic ray or LF observation) has a time stamp to correlate it with the orbital position of Mir.

The particle detector telescope is made of a series of six silicon active wafers, originally developed in the construction of NINA-1 and 2 cosmic-ray space telescopes [2,3]. Each of

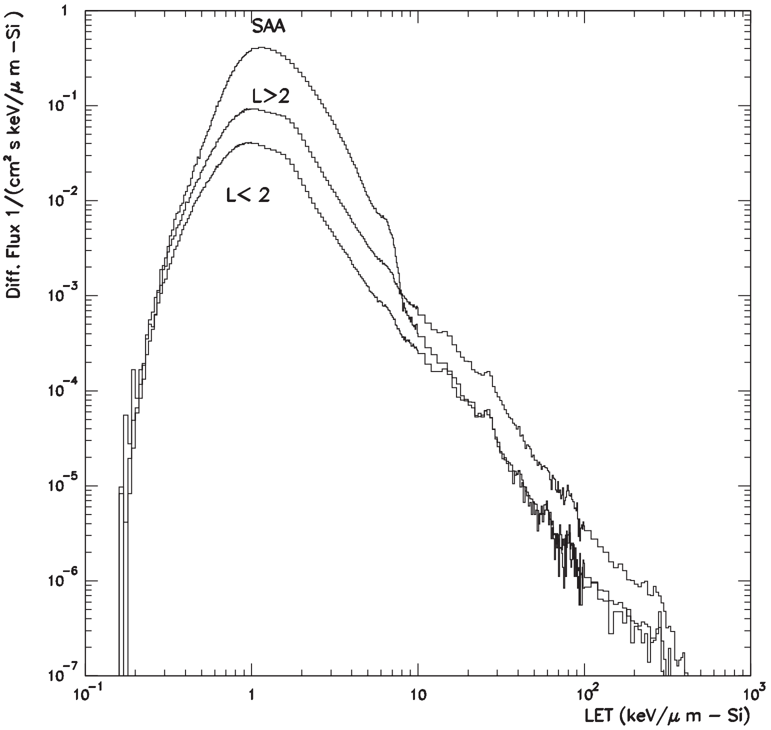

Fig. 2. – Linear energy transfer in silicon for solar quiet period measured with SilEye-2 (solar quiet sessions between August 1998 and August 1999). Top: SAA region. Center: galactic high-latitude ($L > 2$) region. Bottom: galactic low latitude ($L < 2$, outside the SAA.)

the six silicon wafers has an active area of $60 \times 60\,\text{mm}^2$, divided in 16 strips 3.6 mm wide; the thickness is $380 \pm 15\,\mu\text{m}$. Two wafers, orthogonally glued back to back, constitute a plane. Three planes are used together, for a total number of 96 strips and an active thickness of 2.28 mm. The distance between the silicon planes is 15 mm; the geometrical factor is $85\,\text{cm}^2$ sr if particles hitting the detector from both sides are considered. SilEye-2 can measure particle energy losses per strip from 0.25 MeV ($0.69\,\text{keV}/\mu\text{m}$) to about 300 MeV ($830\,\text{keV}/\mu\text{m}$) and then determine nuclear species. Data from the FIFO are then sent—through an interface board—to a PCMCIA Digital Acquisition Board housed in the laptop. The interface board also handles data coming from the cosmonaut joystick and the LEDs used for eye adaptation. Data storage is performed on PCMCIA hard disks; data transfer to Earth is performed by the crew who brings the hard disks to Earth when returning from Mir.

During Light Flash observation sessions the detector is positioned on the temple of the cosmonaut in order to cover the maximum angle for cosmic rays impinging on the eye. In stand-alone mode for cosmic-ray measurements it is placed in a specific location on Mir. The position of the device is recorded each session in order to reconstruct its orientation in respect to the station.

2˙2. *Results.* – In fig. 2 is shown the Linear Energy Transfer (LET) in silicon for solar quiet period data for high-latitude regions, equatorial region and the South Atlantic Anomaly (SAA). The topmost curve shows the SAA, where trapped protons are the

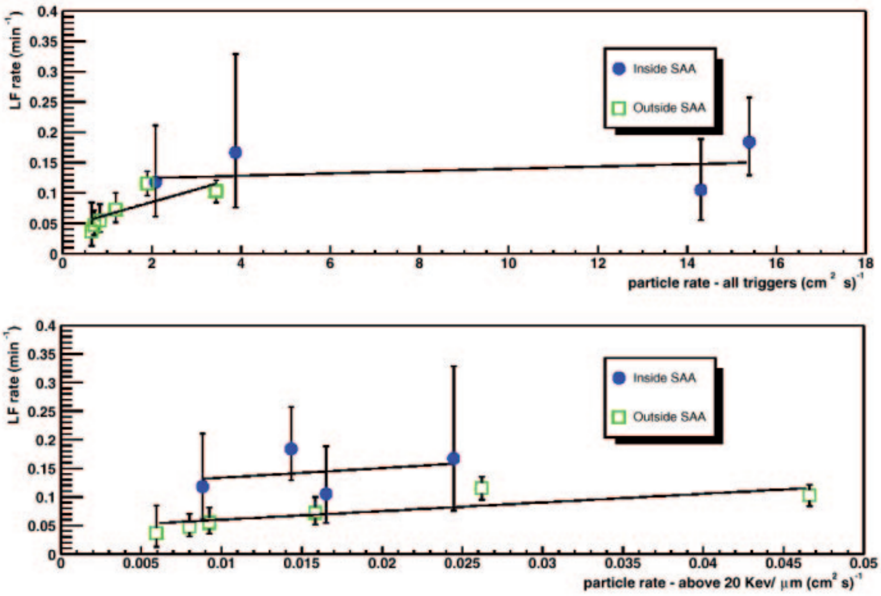

Fig. 3. – Top panel: LF rate *vs.* proton rate. Bottom panel: LF rate *vs.* particle rate with LET 20 keV/mm. Open squares, outside the SAA; full circles, inside the SAA. Continuous lines represent linear fits for each region and are meant to guide the eye.

dominant contribution; the galactic nuclear flux (middle curve) is dominant at LET above 8 keV/μm [4]. The bottom curve represents LET at $L < 2$ and outside the SAA: the proton component is below the previous two regions, and the high LET component is—as expected—equal to the SAA region. In these two regions the nuclear component is lower than in the $L > 2$ zone due to the higher geomagnetic cutoff.

In fig. 3 is shown the LF observation rate (for Sileye-1 and -2) *vs.* the incident cosmic-ray particle rate. It is possible to see that the increase of LF observed with latitude is not proportional to the one observed in the South Atlantic Anomaly, suggesting the presence of two LF causing mechanisms, one direct involving direct ionization of the retina and one indirect, involving hadronic interaction of the trapped protons in the astronauts' visual system [5].

3. – Sileye-3/Alteino

Sileye-3 was placed on board of the International Space Station on April 27th 2002 during the Soyuz-34 taxi flight mission. The cosmic-ray detector was placed in the Pirs module in the corner between panels 301 and 201, with longitudinal axis parallel to panel 201 (and silicon planes parallel to panel 301) and was active for the whole duration of the mission. Six Light Flash and EEG sessions were performed by the Italian cosmonaut Roberto Vittori—part of the Soyuz-34 crew—resulting in the first controlled observations of Light Flashes on board the International Space Station. The PCMCIA cards with data were returned to ground with the Soyuz at the end of the mission. The whole dataset amounts to 131 hours, covering 87 station revolutions from 27/4/2002 to 2/5/2002. For this mission three 660 Mbyte cards were used.

Fig. 4. – Photo of Lazio-Sirad (right, in front of the picture) and Sileye-3/Alteino (left) detector performing joint acquisition in the Pirs module of the ISS.

3·1. *Sileye-3 detector description.* – Sileye-3 is composed of 8 silicon strip detector planes, each divided in 32 strips, with 2.5 mm pitch [6-9]. The device has a dynamic range capable of detecting particles from He to above iron. Also non-relativistic protons releasing a signal above 1 mip can trigger the apparatus. Geometrical factor is $23.78\,\mathrm{cm}^2\,\mathrm{sr}$, considering that particles from both sides can trigger the detector. Data are stored on standard PCMCIA cards. Their contents can be downloaded to the ground via telemetry, although usually only data samples relating to one day of acquisition are transferred using this procedure. The used cards are sent to the ground with the Soyuz and the ISS crew at the end of each increment. New cards are uploaded with Soyuz or Progress launches.

4. – Lazio-Sirad

The experiment Lazio-Sirad was placed on board the International Space Station (ISS) with a Progress cargo on the beginning of March 2005. It was operational as part of the "Eneide" mission in the Pirs module for 10 days from April 17th 2005 (fig. 4). Aim of the experiment was to study and correlate measurements of cosmic ray and magnetic environment on board the ISS with the use of two devices: the LAZIO detector [10], built for the mission and the Sileye-3/Alteino telescope [7]—already present on the station—fitted with special multimaterial shielding tiles. A technological test of Russian $1 \times 1\,\mathrm{mm}^2$ Silicon Photomultiplier (Si-PM) [11] was also performed successfully (fig. 5).

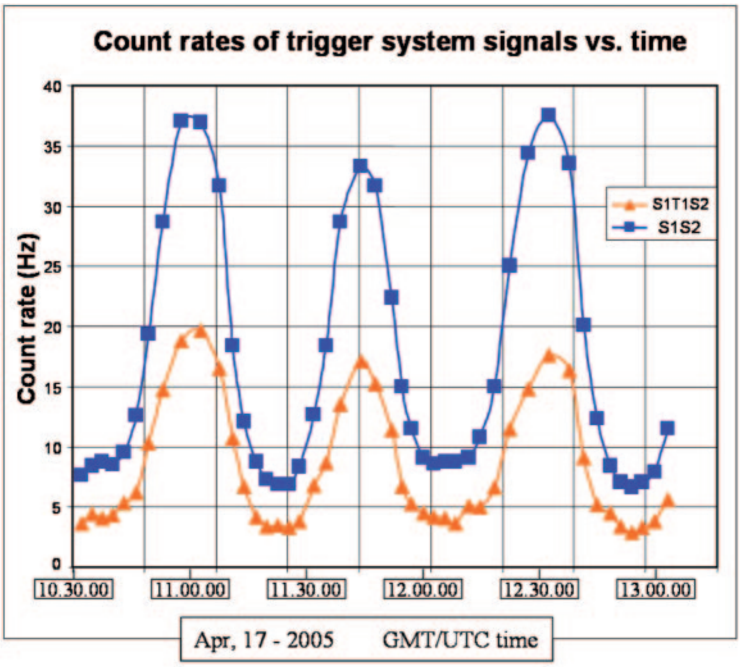

Fig. 5. – Left: scintillator trigger (S1×S2 squares) and SiPM rate (S1×T1×S2) *vs.* time of Lazio-Sirad detector. The lower rate for SiPM is due to the smaller geometrical coverage of the acceptance window of the SiPM tiles (T1) and the inefficiency of some tiles.

5. – Altcriss

The Altcriss (Alteino Long Term Monitoring of Cosmic Rays on the International Space Station) project aims to perform a long-term survey of the radiation and cosmic-ray environment on board the ISS. It was submitted to ESA in response to the AO in Life and Physical Science of 2004 with observations beginning at the end of 2005 (increment 12) and have been continuing up to the time of writing (see table I). The main goals of this project are:

TABLE I. – *Summary table of launch/return and exposure activities of the Altcriss experiment.*

Expedition	Launch	Return	Location
12	Progress M-55 (ISS-20P) 21-12-2005	Soyuz 11S (TMA-7) 8-04-2006	Pirs Service Module
13	Progress M-56 (ISS-21P) 24-4-2006	Soyuz 12S (TMA-8) 28-9-2006	Service Module Crew Cabins
14	Soyuz TMA-9 (13S) 18-9-2006	Soyuz TMA-9 (13S) 21-4-2007	Service Module
15	Progress M-60 (ISS-25P) 12-5-2007	Soyuz TMA-10 (14S) 21-10-2007	Pirs Module
16	Soyuz TMA-11 (15S) 10-10-2007	Soyuz TMA-11 (15S) 19-4-2008 (exp.)	Pirs / FGB

1) *Monitoring of long- and short-term solar modulation of cosmic rays.* The active nature of the device allows to identify particles of galactic, trapped and solar origin according to their position and temporal profile. Observations are currently being carried at solar minimum, going toward solar maximum.

2) *Observations of solar particle events.* We expect in three years about 10 events with an energy and fluence high enough to reach the interior of the station and trigger our detector. For these events we plan to observe the temporal profile and the nuclear abundances.

3) *Survey of different locations of the ISS modules.* By relocating and rotating the instrument it is possible to study the differences in flux and nature of cosmic rays due to the different shielding of the station material (hull, racks, instruments, etc.). Flux is also dependent on station attitude and orientation: currently several locations in the Pirs (Russian docking) and in the Service Modules (Central area, crew cabins) have been studied. In the future it is planned to make measurements in the Columbus module and in the US section of the station.

4) *Study of the effectiveness of shielding materials.* Different materials are being considered to reduce the dose to the astronauts: the current approach in weight effective shielding in space is to use low-Z materials for their higher stopping power and fragmentation cross-section of the projectile. In this way it is possible to reduce the LET (Linear Energy Transfer) and the quality factor of the radiation, thus reducing the equivalent dose to the astronauts. Although several steps are being taken in this direction (such as putting water reserves in the crew quarters) the best materials from this standpoint are often not practical. For instance, liquid hydrogen would be the best shielding material but cannot be used for the dangers involved in handling such a material. In the Altcriss project we are currently employing two set of tiles to study the effect of shielding on the nuclear radiation field:

    a) *Polyethylene tiles.* These are similar to what currently is used in the crew cabin of the US section of the ISS. These tiles are located on top and bottom of the bidirectional acceptance window of the detector to evaluate the effect of this material (for a thickness of $\simeq 5\,\mathrm{g/cm^2}$) on the radiation and the nuclear abundances. Passive dosimeters are interposed between the detector and the shielding tile to compare the dose measured with TLD and CR-39 with active data coming from Sileye-3/Alteino.

    b) *Multimaterial tiles.* These tiles are divided into four sections, each composed of a different material: Polyethylene, Kevlar, Nextel/Capton Composite and one section left empty as a reference. These tiles were used in 2005 in the framework of the second Italian Soyuz Mission. In the Altcriss project they have until now been used with passive dosimeters interposed between the shielding tiles to measure the radiation dose.

5) *Comparison with other detectors.* Given the complexity of the radiation field in space, in order to build a comprehensive picture of the cosmic-ray environment on board the ISS it is necessary to correlate the measurements obtained with Sileye-3/Alteino with other detectors on board the station. To this purpose the device was located in the starboard cabin close to the Matroska-R spherical phantom. Furthermore a cross-comparison measurement campaign with the ESA Matroska [12]

facility was carried forth during expedition 15: in this case Sileye-3 will be placed at the same locations as the human phantom (but not at the same time) to have the exact comparison of the cosmic-ray flux. Comparison of the nuclear abundances measured with NASA IV-CPDS will also be performed. To study the propagation of cosmic rays in the Earth's magnetosphere and from the exterior to the interior of the station the data coming from the Pamela experiment [13], a satellite-borne cosmic-ray detector placed in a $350 \times 650\,\mathrm{km}$, 70° inclination will be used.

5·1. *Passive dosimeters.* – A number of passive dosimeters is used to measure the dose absorbed in space in the shielded and unshielded configuration and complement the active data coming from Sileye-3. These dosimeters come from JAXA, DLR and Napoli Federico II University and consist of different types of TLD and CR39 detectors. They are placed in four different pouches:

1) two pouches with all dosimeters are interposed between the two polyethylene shielding tiles and the acceptance windows of Sileye-3 when performing measurements in the shielded configuration (and thus are shielded by roughly 2π polyethylene). When the silicon detector is performing unshielded measurements the tiles and pouches are packed close one to the other and placed near the device (and the dosimeters are behind 4π polyethylene shielding).

2) One pouch with four Federico II University dosimeters is placed behind the multimaterial tile. Four samples of TLDs and CR39 are present in the unpackaged configuration and are located behind each material to facilitate the alignment between different materials and maximize the shielding geometrical factor.

3) A control pouch with all dosimeters. This pouch is kept with data cards close to the detectors and moves to the different locations of the station.

4) A ground control pouch follows the others in all phases up to launch in Baikonur.

The pouches are rotated every 6 months, with each taxi flight; for the first set of material that was launched at the end of December and returned in April the duration was shorter.

5·2. *Survey of the radiation environment in the ISS.* – Data cards, dosimeters and polyethylene shielding necessary for the experiment were first sent on board ISS on 21-12-05 with a Progress craft. The detector was switched on 24-12-05 in the Pirs module in the unshielded configuration (fig. 6), with two long-term sessions with and without shielding material (respectively 11 and 15 days). In January 2006 the measurement campaign in the Russian Service module started: up to now the device has been located in both cabins and in several locations of the main area. For each position it has been tried (keeping into account all constraints of logistics and observational time) to have a shielded and an unshielded measurement; acquisitions with different orientations at the same location have also been performed to assess the differences in flux and nuclear abundances due to different shielding materials.

5·3. *Flight data and nuclear identification capabilities.* – Flux modulation is due to the geomagnetic shielding, with higher rate at the poles, where the cut-off is lower and lower rate at the equator where the shielding is higher. The highest peaks occur during passage in the South Atlantic Anomaly (SAA), where particle rate increases due to the trapped proton component. It is possible to build an all particle map (see fig. 7)

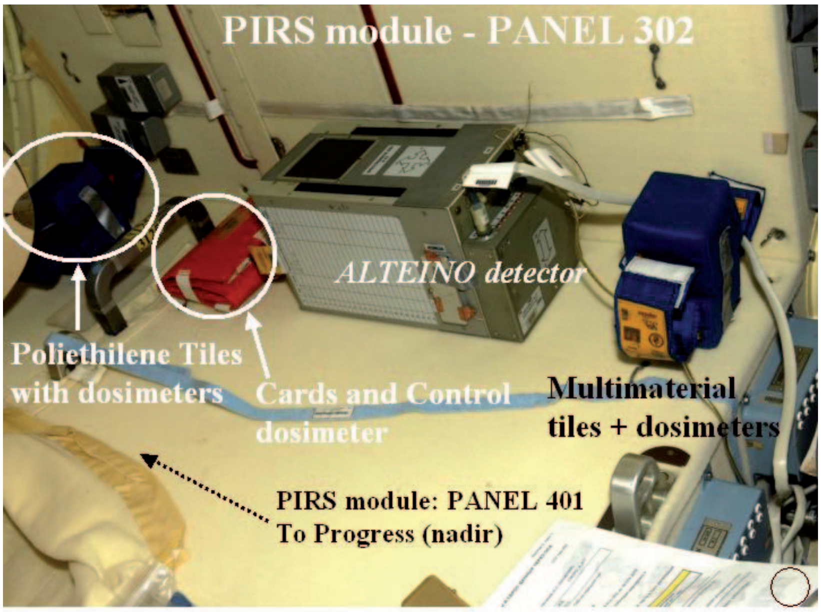

Fig. 6. – Sileye-3 in the Pirs module (Panel 302) of the ISS in its first operational position on of the Altcriss Survey (24-12-2005). The device is in its unshielded configuration, with the polyethylene shielding tiles on the left of the picture (in the Soyuz/nadir direction) and the multimaterial tiles on the right of the picture (in the direction of the station). The dosimeters are placed between shielding elements and in the control pouch.

which shows the latitude increase at high latitude due to galactic particles and the SAA peak due to trapped protons. To derive the spectrum for nuclei up to and above iron, shown in fig. 8 (unshielded configuration in the Pirs Module) relativistic particles in the

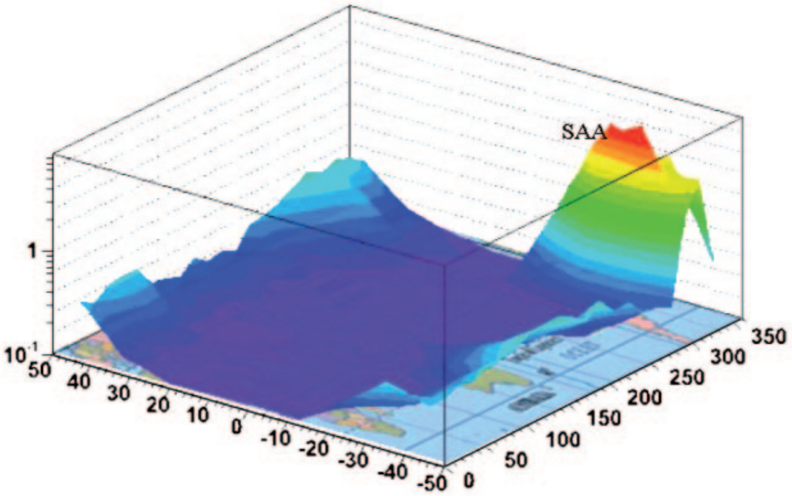

Fig. 7. – All particle rate (arb. units) *vs.* position measured with Sileye-3. It is possible to see the trapped proton peak in the South Atlantic Anomaly and the increase in the high-latitude regions due to galactic nuclei.

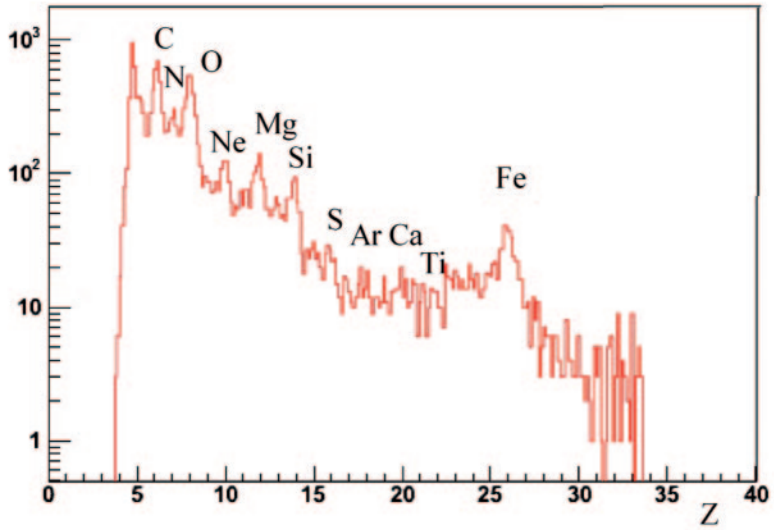

Fig. 8. – Histogram of particle counts showing the nuclear identification capabilities of Sileye-3 from C to Fe in the Pirs module. Note how even numbered nuclei are more abundant than odd numbered ones.

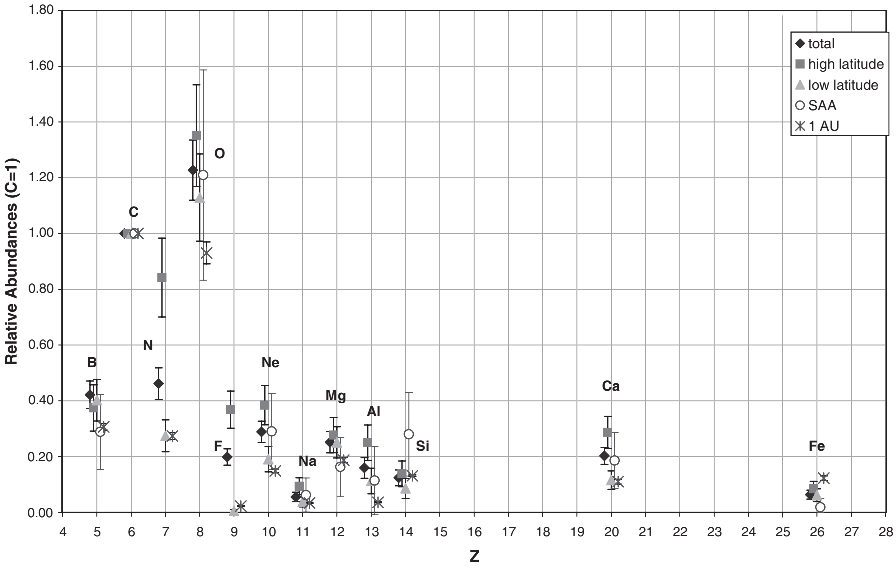

Fig. 9. – Relative nuclear abundances (normalized to C = 1) measured measured with Sileye-3 for the whole orbit and the three regions (see text). 1 AU data are taken from [14]. It is possible to see the O and Ca group enhancement. On the other hand, the Fe group ($23 \leq Z$) is suppressed by a factor 2.

Fig. 10. – Photo of the Altea facility. It is possible to see the various detector boxes. The front box has been removed to show the inside of the helmet.

detector were selected. It is possible to distinguish peaks from C to Fe, with the even-Z nuclei more abundant and evident than the odd, as found in cosmic rays. Relative abundances—normalized to carbon—are shown in fig. 9 for the whole orbit and the three regions and compared with data outside the station [14]. It is possible to see how oxygen is more abundant than carbon in all regions; furthermore odd numbered nuclei such as nitrogen and fluorine are enhanced (respectively by a factor 2 and 10) by nuclear fragmentation inside the station. This effect is more evident on these low-abundance nuclei. This phenomenon is more evident at high latitudes, where the low-energy particles are more abundant and have a higher fragmentation cross-section. It is also possible to see how the Ca group ($15 \leq Z < 23$) and Fe group ($23 \leq Z$) are respectively enhanced and suppressed by a factor 2 in their interaction with the station.

6. – Altea

The Altea facility was launched on July 4th 2006 and located in the US laboratory of the International Space Station [15, 16]. A number of Light Flash observation sessions with different crew have been performed. The apparatus (fig. 10) is composed by 6 boxes arranged around the head of the astronaut. Each box, using detectors and front end electronics deriving from Sileye-3 detector holds six planes ($3X$ and $3Y$) of silicon detectors (two detectors per plane for a total active area of 16×8 cm). Other components are the joystick pushbutton and the electroencephalograph, allowing to record in real time brain activity and the observation of LF by the astronaut. In addition to LF observations, the detector has been performing long-term radiation measurement operations inside the ISS. The multidetector nature of the device makes it particularly suited to study spatial anisotropies in cosmic rays, specifically in the trapped region of the South Atlantic Anomaly.

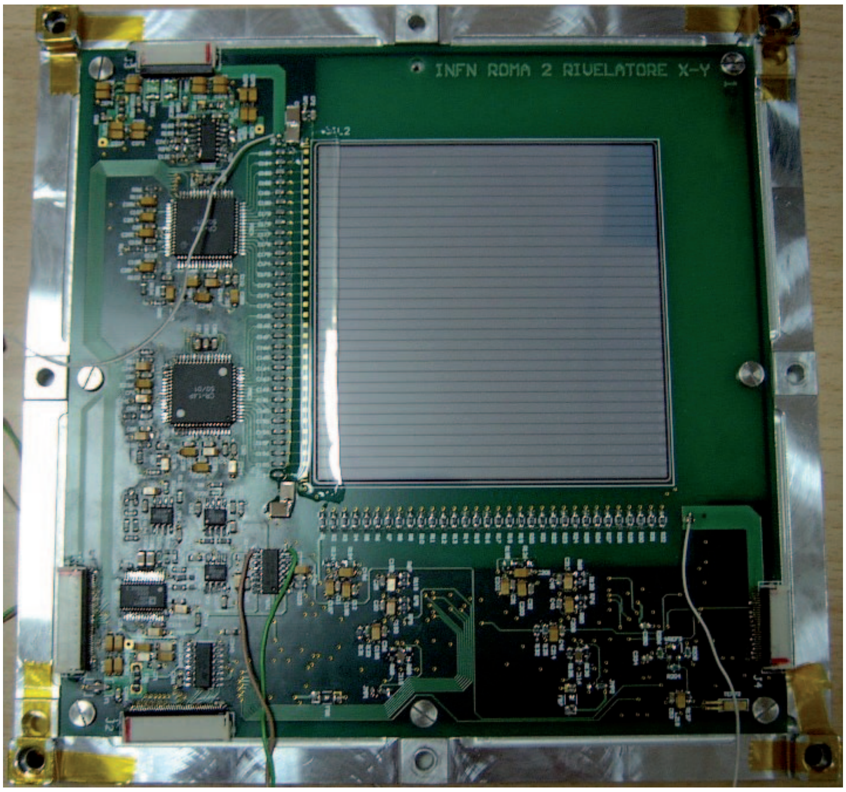

Fig. 11. – The Front End board of the Si-Rad experiment. Each board (160×160 mm) houses two 80×80×0.38 mm 32 strip silicon detectors. The full device is composed by 16 boards for a total of 32 silicon detectors.

7. – Si-Rad

Sirad aims to perform detailed measurements of cosmic rays on the inside and outside of the International Space Station with two identical instruments. The detectors will be capable of detecting nuclei from protons to above iron in the energy range between $\simeq 30\,\mathrm{MeV}$ and $\simeq 5\,\mathrm{GeV}$, recording spatial and temporal variations due to orbit, solar modulation and solar particle events. The device is made of 32 silicon detector planes, each $80 \times 80 \times .380\,\mathrm{mm}$ size and divided in 32 strips (fig. 11). The wafers are located in a stack of 16 front end boards, each housing two silicon planes (one X and one Y). On top and bottom of the silicon tower are two scintillator systems, each read by four Hamamatsu H6780 phototubes for trigger (crossing protons) and analogic information. An additional self-trigger for $Z \geq 6$ nuclei is provided by the silicon detectors. Finally, an intermediate trigger is performed by the "AND" between the top scintillator and a SI-PM (Silicon Photomultiplier) system reading a scintillator located between plane 4 and 5 of the silicon stack (fig. 12). Readout is performed by an FPGA interfaced with a CPU (144 MHz, 280 Mips 2 Mbyte flash, 4 Mbyte RAM, 2 usb port). The detector, located on the outside of the station, linked to an identical CPU on the inside of the ISS. Here data are stored on Flash memory cards. All systems (power supply, DC/DC converters, CPU, FPGA, etc.) are redunded. The silicon detectors are intrinsically redundant, with

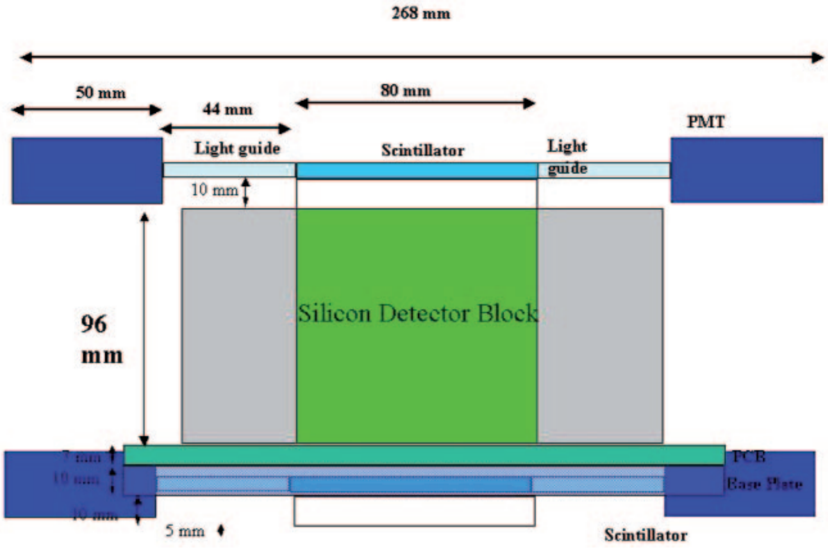

Fig. 12. – Section of the Sirad detector. On top and bottom of the silicon detector block is located an array of scintillators. The scintillators are used to provide trigger and energy information for crossing particles.

the loss of one or more planes degrading the performances of the device. Likewise, the scintillator and trigger system has been designed in order to withstand failure to one ore more tubes; even the loss of one trigger system would allow the experiment to continue using the others.

8. – Conclusions

In this work we have resumed recent activities devoted to the measurement of cosmic rays on board manned space stations (Mir and ISS). The ongoing effort has resulted in the realization of a number of increasingly complex detectors aimed to the characterization of the radiation environment and the study of the Light Flash Phenomenon. Data acquisition is currently in progress in the Russian section of the ISS. Data analysis and new detector realization are also ongoing.

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REFERENCES

[1] Avdeev S. *et al.*, *Acta Astronaut.*, **50** (2002) 511.
[2] Bidoli V., Canestro A., Casolino M. *et al.*, *Astrophys. J. Suppl.*, **132** (2001) 365.
[3] Sparvoli R., Bidoli B., Canestro A. and Casolino M., *Nucl. Phys. B (Proc. Suppl.)*, **85** (2000) 28.
[4] Bidoli V., Casolino M., De Grandis E. *et al.*, *J. Phys. G*, **27** (2001) 2051.

[5] Casolino M., Bidoli V., Morselli A. *et al.*, *Nature*, **422** (2003) 680.
[6] Casolino M. *et al.*, *Nucl. Phys. B*, **113** (2002) 71.
[7] Bidoli V., Casolino M. *et al.*, *J. Radiat. Res.*, **43** (2002) S47.
[8] Casolino M. *et al.*, *Adv. Space Res.*, **37, 9** (2006) 1691.
[9] Casolino M. *et al.*, *Adv. Space Res.*, **40** (2007) 1746.
[10] Altamura F. *et al.*, *Preliminary results from the LAZIO-Sirad experiment on board of the ISS, Proceedings of the XXIX ICRC, August 3-10, 2005, Pune, India*, Vol. **2**, p. 343.
[11] Bencardino R. *et al.*, *Response of the LAZIO-SiRad detector to low energy electrons, Proceedings of the XXIX ICRC, August 3-10, 2005, Pune, India*, Vol. **2**, p. 449.
[12] Reitz G. and Berger T., The MATROSHKA Facility - Dose determination during an EVA. *Radiat. Prot. Dosimetry*, **120** (2006) 442.
[13] Picozza P. *et al.*, *Astropart. Phys.*, **27** (2007) 296.
[14] Simpson J. A., *Annu. Rev. Nucl. Part. Sci.*, **33** (1983) 323.
[15] Zaconte V. *et al.*, *Adv. Space Res.*, **37** (2006) 1704.
[16] Di Fino L. *et al.*, *Adv. Space Res.*, **37** (2006) 1710.