Pergamon

www.elsevier.com/locate/asr

Available online at www.sciencedirect.com

SCIENCE DIRECT•

PII: S0273-1177(02)00880-3

STUDY OF THE RADIATION ENVIRONMENT ON MIR SPACE STATION WITH SILEYE-2 EXPERIMENT

M. Casolino[1], V. Bidoli[1], E. De Grandis [1], M.P. De Pascale[1], G. Furano[1], A. Morselli[1], L. Narici[1], P. Picozza[1], E. Reali[1], R. Sparvoli[1], A. Galper[2], M. Korotkov[2], Y. Ozerov[2]†, A. Popov[2], G. Mazzenga[3], M. Ricci[3], G. Castellini[4], S. Avdeev[5], M. Boezio[6], W. Bonvicini[5], A. Vacchi[5], N. Zampa[5], P. Spillantini[7], P. Carlson[8], C. Fuglesang[9]

[1]*University of Roma, Tor Vergata and INFN Roma 2, Rome, Italy*
[2]*Moscow Engineering and Physics Institute, Moscow, Russia*
[3]*L.N.F. - INFN, Frascati (Rome), Italy*
[4]*IROE of CNR, Florence, Italy*
[5]*Russian Space Corporation "Energia", Korolev, Moscow region, Russia*
[6]*Dipartimento di Fisica, University of Trieste and INFN Sezione Trieste, Italy.*
[7]*Dipartimento di Fisica, University of Firenze and INFN Sezione Firenze*
[8]*Royal Institute of technoloy, Stockholm, Sweden*
[9]*European Astronaut Centre, ESA, Cologne, Germany*
† *Deceased.*

ABSTRACT

In this work we present preliminary results of nuclear composition measurements on board space station MIR obtained with SILEYE-2 particle telescope. SILEYE-2 was placed on MIR in 1997 and has been working since then. It consists of an array of 6 active silicon strip detectors which allow nuclear and energetic identification of cosmic rays in the energy range between $\sim$ 30 and 200 MeV/n. The device is attached to an helmet and connected to an eye mask which shields the cosmonaut eyes from light and allow studies of the Light Flashes (LF) phenomenon. In addition to the study of the causes of LF, the device is used to perform real time long term radiation environment monitoring inside the MIR, performing measurements in solar quiet and active days.

INTRODUCTION: RADIATION ENVIRONMENT ON BOARD MIR AND THE LIGHT FLASHES PHENOMENON

The study of radiation environment in space and an assessment of the related risks in manned missions represents a growing concern for long term manned missions such as those on the International Space Station (ISS) and future missions to 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 to transient phenomena such as solar flares and coronal mass ejections. Particles are also trapped by the geomagnetic field: in addition to the well-known proton and electron belts, recent studies have shown a much more complex dynamics and nuclear composition, for instance, with trapped components of anomalous cosmic rays (Selesnick, 1995). Although $Z \geq 3$ cosmic ray flux is low if compared to protons and heliums, its high quality factor and the interaction with the spacecraft shielding is such to make a significant contribution to the total dose absorbed.

In addition to effects due to radiation there are also other processes that have to be studied in order to have a more complete study of the human response to space environment. One of these phenomena is the "Light Flashes" (LF) effect, originally predicted by Tobias (1952) and reported for the first time almost 30 years ago. LF consist of stimula caused by the passage of charged particles in the cosmonauts' visual system. Studies of the cause-effect relationship of LF were carried out with dedicated observation programs

Adv. Space Res. Vol. 31, No. 1, pp. 135–140, 2003

0273-1177/03 $22.00 + 0.00

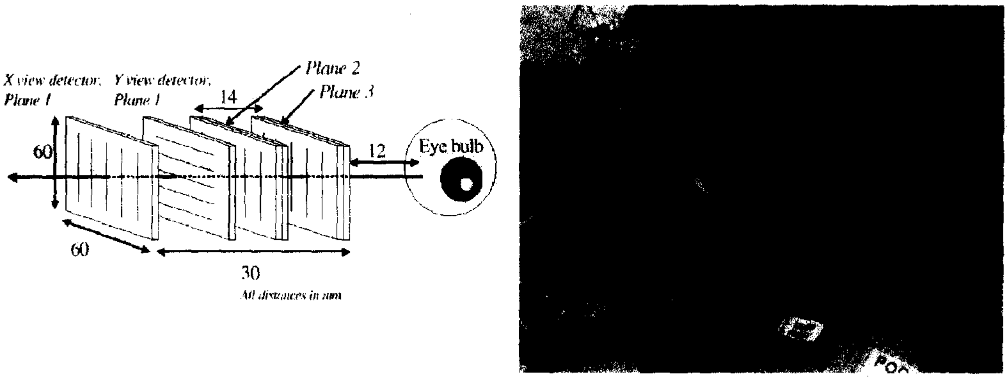

Fig. 1. Left: Scheme of the SilEye detector. Right: Cosmonaut Sergei Avdeev wearing the device before an LF acquisition session.

performed both in space, with the Apollo, Skylab, Apollo-Soyuz (Malachowski, 1978, Tobias, 1981, Horneck, 1992, McNulty, 1996) and MIR programs (Galper et al., 1996, Picozza et al., 1997, Bidoli et al., 2000), and on Earth, with accelerator beams (Budinger, 1971, Tobias, 1975).

The SilEye experiment have contributed to the researches in the field of radiation environment study conducted with active detectors (Reitz, 1996, Sakaguchi, 1999) and of LF processes by using two devices: SilEye-1, operational on MIR between December 1995 and December 1997, and SilEye-2. Sileye-2 was first turned on in August 1998 and systematic observations started in October 1998. It was operational in various periods until August, the 28^{th}, 1999. When the new crew reached again MIR on March 2000, SilEye-2 was turned on again for the duration of the mission (until June 2000); it is also scheduled for operations in the next crew shift.

The space station MIR has a 51.6^o inclination orbit, at an altitude varying between 300 and 400 km. Particle flux on board MIR varies according to its geomagnetic latitude due to the deflection of low energy nuclei by Earth's magnetic field. The geomagnetic field is a complex, time dependent structure which is the result of the interaction between the field generated by Earth with the ionized plasma and the magnetic field carried by the solar wind. At 300 km, however, external effects can be neglected and we can consider only the contribution of internal sources. At the first order the geomagnetic field can be approximated by a dipole tilted about 11^o in respect to Earth's rotation axis. According to their energy and approach direction, incoming particles can be deflected by the geomagnetic field: at the geomagnetic equator the deflection is maximum (and consequently the flux is lowest) and decreases towards the poles (with an increase of the flux), where incoming particles are channeled along the field lines. However, there are anomalies, or higher order terms in the series approximation of the field, which give important contributions. The most important of these is the South Atlantic Anomaly (SAA), where the field is lower and particle flux increases.

This paper reports preliminary analysis on particle composition of radiation on board space station MIR between August 1998 and August 1999. More recent data are currently under analysis. Data have been taken in 93 sessions, 22 of which devoted to Light Flashes observations. 10^7 particle events have been acquired in 1068 hours of observation time: during these observations 7 Solar Particle Events (SEP) were also detected.

THE SILEYE DEVICE

The instrument SilEye was built with the twofold objective to study the radiation environment on board space station MIR and the Light Flash phenomenon. To meet these goals it was necessary to measure in real time the kind and energy of the incoming particles and to correlate them with visual responses coming from the astronaut.

The particle detector telescope consists of a series of silicon active layers, ideal to meet the constrains posed by spaceborne experiments. The structure of the detector is shown in Figure 1 (left). The device is connected to a portable PC equipped with data acquisition card and a joystick. It is small (maximum

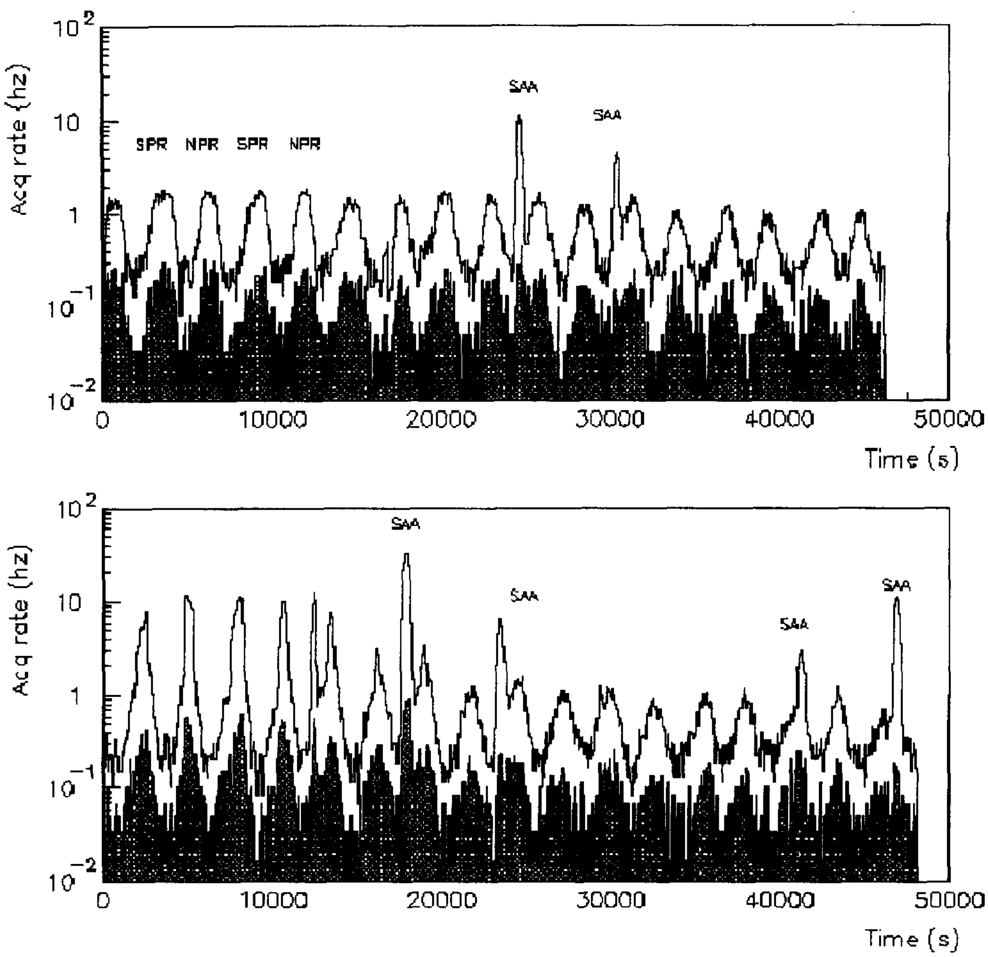

Fig. 2. Particle rate as a function of time for a typical acquisition session (top) and during a Solar Particle Event (bottom). Continuous line: all particles; Filled line: $Z \geq 2$ particles.

dimension: 26.4 cm, mass 5.5 kg), robust and easy to handle, with low power consumption. A PC-based control software performs real time data analysis and, via a user friendly interface, allows the astronauts to control the experiment.

The silicon detector array comes from the technology developed for the construction of NINA-1 and 2 Cosmic Ray space telescopes (Sparvoli et al., 2000) and consists of six silicon wafers, each $60 \times 60 \times 0.38$ mm^3 and divided in 16 strips 3.6 mm wide. Two wafers, orthogonally glued back to back, constitute a plane. Three planes are used together, for a total number of 96 strips and a detector thickness of 2.28 mm. The distance between the silicon planes is 15 mm, corresponding to a geometrical factor of 100 cm^2 sr. Data are read from a multiplexer and converted to digital format by a 12 bit ADC, then sent to an interface board and finally to the PC for storage on PCMCIA hard disks. Data transfer to ground is performed during crew shifts who bring the hard disks to Earth.

At the start of each acquisition sequence, a series of detector calibrations are performed: they include the determination of the electronic pedestal (no injected charge) of each strip and the response of each preamplifier to predefined amounts of charge to determine their gain. The detector has been notably stable during all measurements, in accordance with the behaviour of the detectors used in NINA telescopes. Hit strips in separate X and Y views determine the direction and spatial position of incoming particles. A pedestal suppression algorithm selects only the information coming from the strips which have been crossed by particles, in order to reduce data size. SILEYE-2 can measure particle energy losses from 0.25 MeV

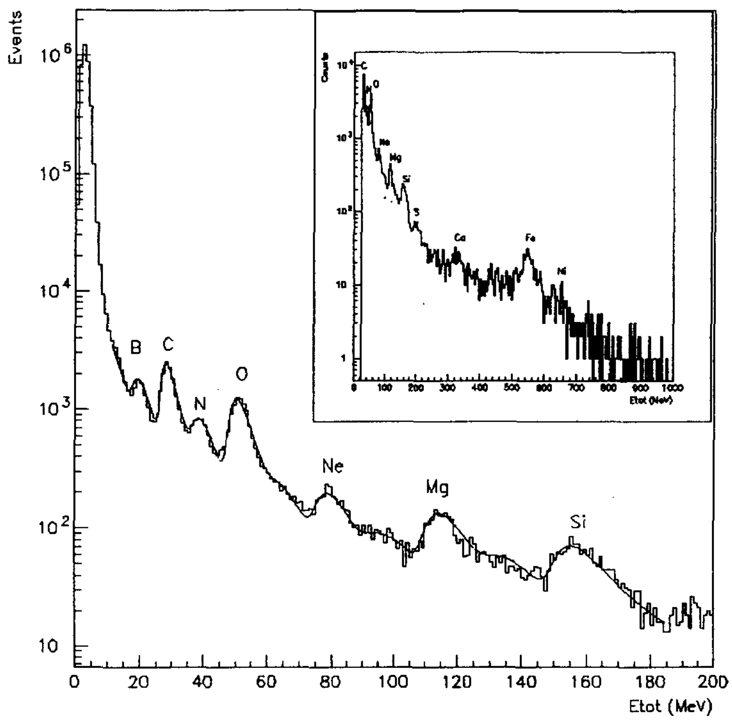

Fig. 3. Nuclear identification capabilities of SilEye-2 for low Z particles. In the inset is shown the contribution of high Z particles.

($6.6 \times 10^{-4} MeV/\mu m$) to more than 250 MeV ($6.6 \times 10^{-1} MeV/\mu m$) and from these determine nuclear species. The particle trajectory is determined with an angular accuracy of 3 degrees. Two passive absorbers (1 mm iron each) are inserted between the position-sensitive detectors to extend the energy range.

Each event has a time stamp (1 s precision) to correlate it with the position of the MIR. An event is defined by the energetic and topological information coming from the strips hit by incoming particle(s). At least one signal from each of the six planes of the telescope is required for a trigger and to record the event. In this way it is possible to acquire particles coming from both sides of the detector: however, the material crossed by particles is different in the two cases since particles cross the 0.2 mm Cu window on one side (closer to the cosmonaut's head) and $\simeq$ 2 cm of electronics on the other. This requires a correction in the energetic spectrum determined for particles coming from this direction, but - aside from nuclear fragmentation in the interposed material - does not affect nuclear composition.

To perform LF observations, the astronaut wears an helmet which holds the detector box, placed on the side of the astronaut's head who presses the joystick button when he observes a 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 when the astronauts are performing other tasks; in this mode of acquisition it is possible to perform long term (many hours) monitoring of the environmental radiation.

DISCUSSION

The study of the radiation environment on board manned spacecraft allows evaluation of the dose absorbed by the astronauts and the risks involved in manned space missions. In this case, one has to take into account the differences in the cosmic ray composition at different geomagnetic cutoffs and the interactions of particles with the spacecraft materials, both contributing to create a peculiar secondary spectrum inside the vehicle. Furthermore, there are also transient effects due to solar activity which have to be considered in order to have a complete picture of the total dose absorbed by astronauts.

Multiple tracks due to particles showering in the material of the space station can be detected by the experimental set-up. These events are discarded in nuclear analysis (where we consider only single tracks) but contribute to the total dose. Figure 2(top) shows a typical radiation acquisition session with SILEYE-2 detector: a plot of the number of tracks as a function of time displays the oscillatory behaviour typical of the passage between high and low latitude regions. The highest peaks are present during passage in the SAA where it is possible to see that the particle rate increases up to about an order of magnitude. The unhatched curve shows the rate of single tracks crossing the detector. The filed lower curve shows the rate of $Z \geq 2$ nuclei: heavy nuclei component does not increase in the SAA as much as the proton component.

Particle flux in the proximity of the Earth can drastically increase as a result of solar activity: Solar Energetic Particles (SEP) can be emitted in conjunction with solar flares or coronal mass ejections. SEPs represent an hazard to both manned and unmanned space missions as they can damage, temporarily or definitively, the on board electronics of satellites and probes. SEP fluences can easily be 10^2 to 10^3 times higher than quiet time periods and thus contribute heavily to the absorbed dose by astronauts. In Figure 2 (bottom) is shown the observation of the SEP event of November the 14^{th} on board MIR. As already mentioned seven such SEPs were observed, each with its own intensity, composition, and time profile.

The nuclear discrimination capabilities of SILEYE-2 are shown in Figure 3. The events were selected requiring at least one hit per plane, rejecting multiple tracks and imposing a ratio of $R = E_3/E_1$ (with E_i the energy released in plane i) of $0.8 < R < 1.2$. As a result, energy loss variation between planes is reduced, thus selecting particles with incident kinetic energy $E > 40 Mev/n$. The elemental peaks of the most abundant species up to Nickel are easily distinguished, although the proton component currently prevents nuclear identification for nuclei below Boron. A more detailed analysis is currently in progress to improve low Z identification and to evaluate nuclear abundances. For purposes of the present work we have divided nuclear components in low Z (from H to B) and high Z (above B); data were also separated by the L=2 shell parameter in low latitude (including SAA) and high latitude. Results are shown in Table

Table 1. Nuclear Component at Low ($L < 2$) and High ($L > 2$) Latitude for Solar Quiet Days for the 7 SEPs Observed. Particle Rate (in Hz) Refers to Single Events with $E > 40 MeV/nuc$. The Ratio $D = Rate(Z < 6)/Rate(Z \geq 6)$ Shows the Varying Nuclear Component in Different Locations and in Presence of Different SEPs.

Date	R($Z \leq 6, L < 2$)	R($Z \leq 6, L > 2$)	R($Z > 6(L < 2)$	R($Z > 6$ $L > 2$)	D($L < 2$)	D($L > 2$)
Sol. quiet	0.2832 ± 0.0003	0.324 ± 0.0004	(2.05 ± 0.02)·10^{-3}	(0.780 ± 0.006)·10^{-2}	138 ± 1	41± 0.4
8/10/98	0.938 ± 0.003	1.413 ± 0.005	(5.2 ± 0.2) ·10^{-3}	(2.15 ± 0.07) ·10^{-2}	181 ± 7	66± 2
6/11/98	0.896 ± 0.003	1.341 ± 0.005	(7.7 ± 0.3) ·10^{-3}	(3.26 ± 0.08) ·10^{-2}	116 ± 4	41± 1
14/11/98	0.835 ± 0.002	1.466 ± 0.004	(6.4 ± 0.2) ·10^{-3}	(2.71 ± 0.06) ·10^{-2}	131 ± 4	54± 1
1/1/99	1.367 ± 0.004	1.051 ± 0.007	(6.1 ± 0.3) ·10^{-3}	(1.70 ± 0.09) ·10^{-2}	220 ± 10	62± 4
9/6/99	0.649 ± 0.002	1.403 ± 0.003	(7.0 ± 0.2) ·10^{-3}	(3.33 ± 0.05) ·10^{-2}	93 ± 3	42± 1
23/6/99	0.622 ± 0.002	1.073 ± 0.003	(4.7 ± 0.2) ·10^{-3}	(1.95 ± 0.04) ·10^{-2}	132 ± 5	55± 1
15/7/99	0.632 ± 0.003	1.020 ± 0.006	(3.5 ± 0.2) ·10^{-3}	(1.98 ± 0.09) ·10^{-2}	182 ± 11	51± 3

The different SEPs components, corresponding to a particle rate increase with respect to solar quiet days should also be noted. This effect is more evident if we calculate the ratio $D = Rate(Z < 6)/Rate(Z \geq 6)$ for the different cases. As expected, the value of D is higher at low latitudes where heavy nuclei have a lower flux. Furthermore it is possible to see how $D(L < 2)$ decreases (up to 30%) or increases (up to 60%);

at higher latitudes $D(L > 2)$ this rate increases (again, up to 60%) in respect to solar quiet days. This preliminary and simple analysis reflects a complex and varying nature of the SEPs and of the interplanetary environment. Analysis is currently in progress to improve the identification capabilities of the device and produce elemental spectra, particularly at low Z. This will result in the calculation of relative and absolute fluxes for solar quiet and active days taking into account the different position and orientation of the detector in the MIR space station.

REFERENCES

Bakaldin, A. *et al.* , Experiment NINA: investigation of low energy nuclear fluxes in the near-Earth space, *Astropart. Phys.*, **8**, 109 (1997).

Bidoli, V., *et al.*, Experimental beam test of the SilEye2 apparatus, *NIM A*, **399**, 477 (1997).

Bidoli, *et al.*, Study of cosmic rays and light flashes on board space station MIR: The Sileye experiment, *Adv. Space Res.*, **10**, 2075 (2000).

Budinger, T.F., H. Bichsel and C. A. Tobias, Visual phenomena noted by human subjects on exposure to neutrons of energies less than 25 million electron volts, *Science* , **172**, 858 (1971).

Casolino, M., *et al.*, Light Flash observation in space: Experiment ELFO, *Il Nuovo Cimento*, **19 D**, N.10 (1997).

Galper, A., *et al.*, Sileye on MIR – First active detector for the study of light flashes in space, Proc. of the Sixth European Symposium on Life Sciences Research in Space 17-21 June, Trondheim, Norway, (1996).

Horneck, G., Radiobiological experiments in space: a review, *Nucl. Tracks Radiat. Meas.*, **20 1**, 185, (1992).

Malachowski, M. J., The effects of ionizing radiation on the light sensing elements of the retina, LBL Report LBL-5683, National Technical Information Service, Springfield, Virginia (1978).

McNulty, P.J., Single-Events Effects Experienced by Astronauts and Microelectronic Circuits flown in space, *IEEE Trans. on Nucl. Sci.*, **43 n.2**, 475, (1996).

Morselli, A., *et al.* , Cosmic ray studies on the MIR space station, *Proc. of the XXV ICRC*, OG 10.2.8, Vol.5, p. 45 (1997).

Reitz, G., *et al., Radiat. Meas.*, **26**, Nr.6, 679 (1996).

Simpson, J.A., *Ann. Rev. Nucl. Part. Sci.*, **33**, 323 (1983).

Sparvoli R., et al., Launch in orbit of the telescope NINA for cosmic ray observations: preliminary results - *Nuclear Physics B (Proc. Suppl.)* **85** 28-33 (2000).

Selesnick, R.S., Cumming, A.C., et al., *J. Geophys Res.*, **100** (A6), 9503-9518 (1995).

Sakaguchi, T., *et al.*, LET distribution measurement with a new real-time radiation monitoring device-III onboard the Space Shuttle STS-84, *NIM A*, **437**, 75 (1999).

Tobias, C.A., Radiation hazards in high altitude radiation, *J. Aviat. Med.*, **23**, 345, (1952).

Tobias, C.A., Y. G. Grigoriev, Ionizing Radiation, in *Foundation of Space Biology and Medicine*, edited by M. Calvin and O.G. Gazenko, NASA, Washington (1975).

Tobias, C.A., T. F. Budinger and J. T. Lyman, Radiation induced light flashes observed by human subjects in fast neutron, x-ray, and positive pion beams, *Nature*, **230**, 596 (1981).