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The SilEye nuclei cosmic ray and eye light flash experiment onboard the Mir space station

S. Avdeev[1], V. Bidoli[2], M. Boezio[3], W. Bonvicini[4], P. Carlson[3], M. Casolino[2], G. Castellini[5], C. Fuglesang[3,6], G. Furano[2], A. Galper[7], A. Khodarovich[7], M. Korotkov[7], G. Mazzenga[8], A. Morselli[2], L. Narici[2], M. P. De Pascale[2], P. Picozza[2], A. Popov[7], E. Reali[2], M. Ricci[8], W. G. Sannita[9], R. Sparvoli[2], P. Spillantini[10], A. Vacchi[4], N. Vavilov[7], and N. Zampa[4]

[1]Russian Space Corporation "Energia" by name Korolev, Korolev, Moscow region, Russia
[2]Dept. of Physics, Univ. of Rome "Tor Vergata" and INFN Sez. Rome2, Italy
[3]Royal Institute of Technology, Stockholm, Sweden
[4]Univ. of Trieste and INFN sezione di Trieste, Trieste, Italy
[5]IROE of CNR, Florence, Italy
[6]European Astronaut Center, ESA, Cologne, Germany.
[7]Moscow State Engineering Physics Institute (MEPHI), Moscow, Russia
[8]L.N.F. - INFN, Frascati (Rome), Italy
[9]DISM-Univ. of Genova, Genova, Italy and Dept. of Psychiatry, SUNY, Stoony Brook, NY, USA
[10]Dept. of Physics of Univ. and Sez. INFN of Florence, Italy

Abstract. The SilEye-2 particle telescope was placed on Mir in October 1997 and has been working since June 2000. It consists of 6 active silicon strip layers which allow charge and energy identification of cosmic ray particles in the energy range ~ 40 – 200 MeV/n. The detector is attached to a helmet with mask, which prevented light from reaching the cosmonaut's eyes. The phenomenon of Light Flashes (LF) in eyes for people in space has been investigated onboard Mir space station. Data on particles hitting the eye have been collected with the SilEye-2 detector, and correlated with human observations. In the period 98/99, we have 17 sessions with simultaneous SilEye-2 detector and LF observation data. 116 LFs were seen during about 800 minutes of observation. An additional 30 LFs were noted during three observation sessions amounting to 250 minutes without the silicon detector. In all 59414 protons and 479 nuclei passed through eyes were registered with SilEye-2 telescope. It is found, that a nucleus are the main reason caused a LF's in the radiation environment of Mir space station and in microgravitation conditions, the proton probability to cause LF is almost three orders of magnitude less.

1 Introduction

Unexpected visual sensations during space flights were first reported after the Apollo-11 flight to the moon in 1969 (Pinsky et al., 1974). These phenomena which became known as light flashes (LF), were subsequently also reported by astronauts on Apollo-12 and -13. It was found, that on average after about 15-20 minutes of dark adaptation, about one LF per three minutes was seen (Pinsky et al., 1974)]. Three basic types of flashes were reported at the time: 'spots' or 'star-like' flashes, 'streaks' and 'clouds'. At the same time several studies were done with accelerator beams, exposing the human eye and brain to well-defined particle fluxes. It was found that neutrons, with energy of more than about 5 MeV, could cause LF sensations (Fremlin, J.H.,1970; Charman, W.H. et al.,1971; Budinger T.F. et al., 1971), but a beam of π^+ mesons with momentum 1.5 GeV/c did not create any effect (Tobias C.A. et al., 1971) Studies using muons (cosmic (Charman W.N. et al., 1971; D'Arcy F.J. et al., 1962) and a 6 GeV/c beam (McNulty J., 1971) also reported LF effects. During dedicated observations in high-altitude (9-16 km) aircrafts LFs were seen, but they were considered to be partly of a different character than those in space, possibly due to a different particle composition in the radiation environment (Akatov Yu. et al., 1996). Still many questions remained to be answered. Among them, which particles in space cause the LFs in astronaut eyes and their frequency in Earth orbits. Further, it was not completely ruled out that the Cherenkov effect, or some other effect could play a role during space flights. Therefore, experiments were performed on Skylab in 1974 (Pinsky L.S. et al., 1975) and on Apollo during the Apollo–Soyuz project in 1975 (Budinger T.F. et al., 1977). Correlation with particle fluxes was done, suggesting a relation with ions having linear energy transfer (LET) greater than 5 keV/µm in tissue (Budinger T.F. et al., 1977). However, no conclusive results were obtained and some results even seem contradictory. For instance, on Skylab a big increase in the LF rate was seen in the South Atlantic Anomaly (SAA), whereas in Apollo no such increase was observed. A recent discussion on the biological aspects of LFs can be found in ref. (Akatov Yu. et al., 1996).

The aim of the SilEye (from Silicon Eye) project, presented here, is to make a systematic study of the Light Flash phenomenon over several space missions and cosmonauts. An active particle detector (Furano G. et al., 1999; Bidoli, V. et al., 2000; Bidoli, V. et al., 1997) has been built, based on

Correspondence to: A.Popov (popov@sileye.mephi.ru)

silicon technology, and sent to the Russian Mir space station. A real time particle-tracking detector, consisting of six silicon layers with 16 strips each, was placed close to the cosmonaut's eye (Figure 1) and detector data as well as the astronaut's reaction to LFs were recorded on computer disks. The energy loss by particles traversing the silicon layers is measured with the amplifier system sensitive from a loss of 0.25 MeV to a maximum of 260 MeV. A trigger signal is given if:

1) Ex1>2.5 MIP(One MIP is the signal given by a high-energy singly charged particle)
2) Ey1>2.5 MIP or Ex2+Ey2>5 MIP
3) Ex3+Ey3>5MIP.

Exi, Eyi - particle energy losses in detectors DXi, Dyi (Fig.1.).

For SilEye-2 a trigger threshold of 2.5 MIP was chosen to exclude high-energy protons, which had saturated the SilEye-1 detector in the SAA in 1995/96. Roughly, the high-energy cut-off value for protons is 200 MeV, but there is no cut-off for particles with charge $Z \geq 2$. The integration time of the signal is about 2 μs.

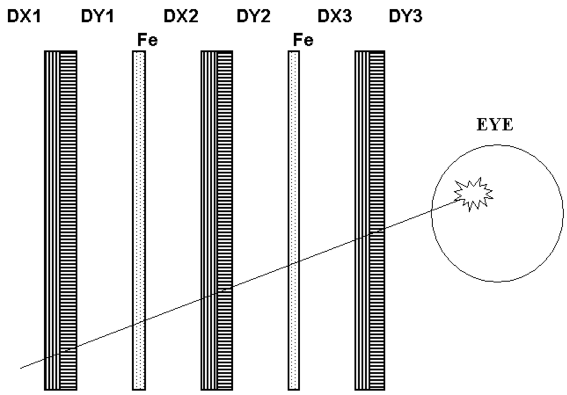

Fig. 1 The SilEye-2 detector. The three planes of double silicon layers are interleaved with two 1-mm iron absorbers.

Between 1997 and 1999 in total 4 astronauts participated in the SilEye project. The SilEye computer disks with data were brought back to Earth for analysis. In this way particles passing through the eye could be identified and correlated in time with LFs.

2. Data collection and analysis

In the period 98/99, we have 17 sessions with simultaneous SilEye-2 detector and LF observation data. 116 LFs were seen during about 800 minutes of observation. An additional 30 LFs were noted during three observation sessions amounting to 250 minutes without silicon detector. Overall, the average time between LFs was about 7 minutes. For particle and radiation studies, the SilEye-2 apparatus has also taken large amounts of data in an autonomous mode, close to 1000 hours of registration. Each observation session begins with 15 minutes of dark adaptation, checked in SilEye-2 with LED pulses. The computer records the reaction time and final pulse length. At the start and end of each data taking session, the detector performs a self-calibration. Noise level, pedestal position and detector linearity is checked and calibration coefficients are calculated.

In this work we are mostly concerned with the discrimination between protons and heavier particles in order to asses the different contributions to the LF phenomena. The energy loss depends on the square of the charge (Z^2) and the energy of the particle, according to the Bethe-Block formula. By combining the amplitude information from the three planes, it is possible to distinguish between various nuclear species in the approximate energy range 40-200 MeV/nucl, somewhat depending on the nuclear charge. Denote the energy deposited in plane i as E_i, the sum of the energies deposited as $\Sigma E = E_1+E_2+E_3$ and the difference between energy deposited in the first and third layer as $\Delta E = |E_1-E_3|$. In a ΣE vs. ΔE scatter diagram particle events fall in bands, each band corresponding to a different nucleus (Figure 2). For fixed ΔE, ΣE increases with the charge. For low-energy particles the stopping power of the detector is large so that also the difference between the energies deposited in the first and third layers is large. Very low-energy particles, however, will not go through the detector, while at high energies all events tend to cluster together at small ΔE values with large tails in the ΣE distribution for individual species, thus considerably decreasing the separation power. For higher energies, nuclear discrimination can be obtained for

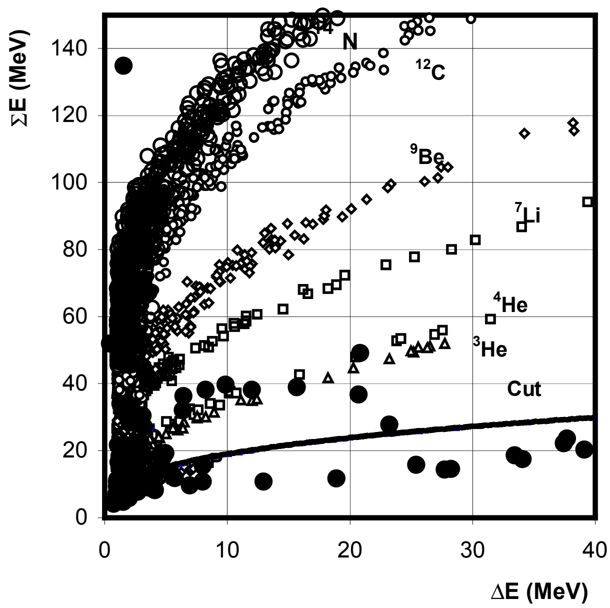

Fig. 2. *ΣE* vs. *ΔE* scatter plot from a SilEye-2 detector simulation.

The points show the simulated values for various nuclei. The continuous line shows the cut used to distinguish between protons and nuclei.

heavier nuclei (Z>4) by requiring a single track and imposing that the energy deposited in the first and third planes differ with less than 20%, and then looking at the total energy loss, ΣE (Furano G. et al., 1999).

The detector covers a geometrical solid angle of only some 6-7% of the two eyes. For showers, we make the assumption that there is always at least one particle going through the eye.

Next we look into a reaction time window preceding the recorded LF time. From the reaction time distribution we chose a window between 1.2 s and 0.2 s before the joystick signal notifying a LF by the astronauts. Any particle registered by the detector in that time frame is a candidate for causing the LF.

3. Results and discussion

The cosmonauts describe five different types of visual sensations:

- a continuous line
- a line with gaps
- a shapeless spot
- a spot with a bright nucleus
- concentric circles.

The two first types make up about 90% of all LFs. This is similar to the Skylab report (Pinsky L.S. et al., 1975), but different to the Apollo flights (to the moon (Pinsky et al., 1974) as well as during Apollo-Soyuz (Budinger T.F. et al., 1977) where "spots" or "star-like" flashes dominated and only about one quarter of the events were described as "streaks".

We compared rates of LFs with different types of events (protons, nuclei, and showers), including and excluding South Atlantic Anomaly (SAA) data, as a function of geomagnetic rigidity. The general trends of the LF-distribution are similar to those of protons and nuclei but direct comparisons with either particle distribution does not show any significant correlation.

The SilEye-2 detector only triggers on protons with energy 40 - 200 MeV, and in this range the proton rate is 22 times larger inside than outside SAA. The LF rate, on the other hand, is only two times larger in the SAA than outside. We conclude that protons are not the main source of LFs, but we can not exclude a contribution. Comparing rates of LFs, protons and nuclei inside and outside the SAA, we deduced that the probability that a nuclei passing through an eye causing a LF is around 1%. The same probability for a proton with energy less than around 200 MeV, is roughly 750 times smaller than the nuclei probability. Higher energy protons are even less likely to make a LF. Probably there is a threshold at LF's occurrence, since ionization losses of helium nucleus only in 4 times exceeds proton losses.

The integration time of the eye is about 50 ms and during this time in the SAA we get on the average 6.7 protons through the eyes. But there is no significant growth of LF's rate in the SAA. Therefore allocation of energy is necessary in spatial area, essentially smaller than volume of an eye for occurrence LF. (Avdeev, S. et al, 2001)

The strongest evidence for nuclei as main source of LFs comes from analysing the particle tracks through an eye. We compared the proton and nucleus rates, between the 'All data' and the 'time window before LF'. The proton rate increases with about a factor of 2, while the nucleus rate is about 7 times larger.

Eight particles that most likely had caused a LF were found. Two of these were helium, but we ca not estimate the kinetic energy and direction of movement for them. Parameters of the remaining 6 nuclei are given in Table 1.

Table 1. Parameters of the 6 nucleuses that most likely had caused a LF.

Z	**E**kin in Mev/Nucl.	Direction
22±2	566±47	From eye
9±1	425±31	To eye
9±1	218±22	To eye
$3\pm^{1}_{0}$	44±3	From eye
$2\pm^{1}_{0}$	53±6	To eye
$2\pm^{1}_{0}$	50±5	To eye

We have studied the likelihood of a particle causing a LF as a function of its ionization, expressed in LET (Linear Energy Transfer in water) as usually used in biological contexts. The LET for all tracks that passed through an eye was calculated. The fraction of tracks that occurred in the 116 LF-window (1.2-0.2 s before a registered LF signal, as used above) as a function of LET is shown in figure 3. For comparison an "anti-LF" window was defined, being 0.2-1.2 s after the LFs. The corresponding fraction of tracks in the "anti-window" is also shown in Figure 3. In the first sample (tracks falling in the LF-windows) we expect to find particles, which could have made a LF, whereas no particle from the second sample (the "anti-windows") could have caused a LF.

The fraction of tracks in the LF-window increases for LET-values larger than about 10 keV/μm, whereas the "anti-window" distribution is more or less flat. Actually, we do not find any particle with LET > 10 keV/μm in the "anti-window" distribution. The statistics is admittedly not large at high LET values, with only five events in the LF-window sample above 30 keV/μm, but it shows an increasing probability to create LFs with increasing LET. This probability is about 8% around 90 keV/μm. Not surprisingly, all the five highest LET events are found among the 8 "strong candidates" for causing a LF, as described above.

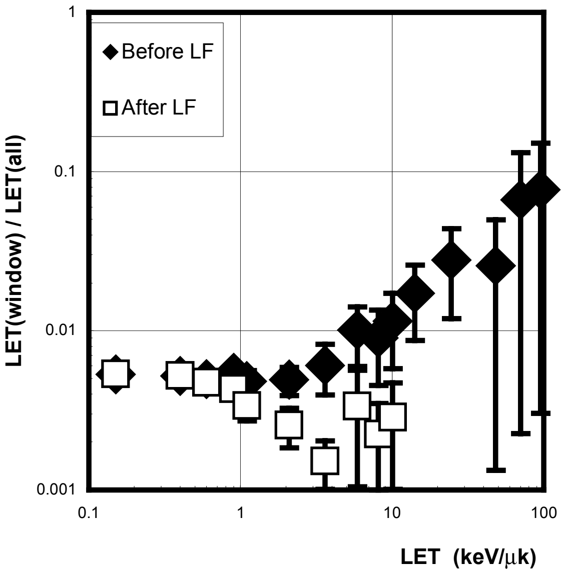

Fig. 3. Fraction of tracks through eye, in LF-window (◆), and in "anti-LF" window (□), as a function of LET.

4. Conclusions

Data on 116 Light Flashes (LFs) in human eyes have been collected on board the Russian space station Mir between 1998 and 1999 for the SilEye experiment Particle data, taken by the SilEye-2 detector and concurrent with the observations, have been used to correlate LFs with particles passing through the eyes.

Eight events with identified particles which most likely had caused a LF were found. The analysis of these events indicates that four of them were helium, one - lithium nuclei, two were fluorine (or more probably oxygen) nuclei and one was a heavy nucleus with charge Z around 22.

The rate of LFs inside the SAA was found to be about twice as large as outside, however the proton rate is many times higher inside than outside. Comparing rates of LFs, protons and nuclei inside and outside the SAA, we deduced that the probability that a nuclei passing through an eye to cause a LF is about 1%. The same probability for a proton with energy less than around 200 MeV, is roughly 750 times smaller than the nuclei probability.

As a function of ionization, expressed as LET (Linear Energy Transfer in water), there is a clear increase in probability that particles give rise to LFs for LET more than 10 keV/μm, reaching about 8% around 90 keV/μm.

No correlation with solar activity, as measured by the number of sunspots, was found.

About 90% of the LFs were described as looking like a continuous line or a line with gaps. This is similar to results from Skylab, whereas from Apollo flights "spots" or "star-like" shapes were reported to dominate.

Dark adaptation and reaction time were measured at the start of each observation session, for control purposes. However, no difference was found for these physiological functions between ground and space, nor was any change over time in space noticed.

It has been shown that nuclei and largely ionizing particles are the dominant, if not exclusive, source of Light Flashes in space (at least in a space station orbiting the Earth). From this, the Cherenkov effect can be excluded as one of the candidates for creating the light in the eye. Local energy deposition by ionization seems the most likely candidate. It still needs to be explained, though, how the energy gets transformed into a light signal to the brain. Is there any light involved, or is it perhaps direct stimulation of rods and cones by the penetrating particle? Other questions also remain, and particularly it is desirable to have measurements as independent as possible of subjective effects. Therefore a continuation of the SilEye studies, under the name ALTEA, is planned for the International Space Station (Narici, L. et al., 2000). Among other features, ALTEA foresees to include EEG measurements simultaneous with LF observations and particle tracking detector data.

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References

Pinsky L.S. et al., Science **183**, 957 (1974);
Fremlin J.H., New Scientist **47**, 42 (1970).
Charman W.H. et al, Nature **230**, 522 (1971).
Tobias C.A. et al, Nature **230**, 596 (1971).
Budinger T.F. et al, Science **172**, 868 (1971).
Charman W.N. and Rowlands, C.M., Nature **232**, 574 (1971).
D'Arcy F.J. and Porter, N.A., Nature **196**, 1013 (1962).
McNulty J., Nature **234**, 110 (1971).
Akatov Yu. et al., Proc. 6th European Symp. On Life Sciences Research in Space (Trondheim, Norway, 1996), 153.
Pinsky L.S. et al, Science **188**, 928 (1975);
Budinger T.F. et al., Apollo-Soyuz Test Project Summary Science Report, NASA SP-412, 193 (1977).
Furano G. et al., Proc. 26th ICRC (Salt Lake City, 1999), vol. 5, 128 (1999). OG 4.2.13;
Bidoli, V. et al., Nucl. Instr. Meth. A399, 477 (1997)
Avdeev, S. et al, " submitted to Acta Atronautica (2001).
Bidoli, V. et al., Adv. Space Res. **25**, 2075 (2000).
Narici, L. et al., presented at the "Life Sciences in Space" Conf., May 2000, in Santorini, Italy.