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Ion rates in the ISS during the December 2006 SPE

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Abstract

Solar Particle Events (SPEs) are a major concern during prolonged space missions. During such events, a large amount of light ions, mostly protons and helium nuclei, are accelerated with enough energy to traverse the spacecraft hull and therefore represent a high hazard for the crew health.

The ALTEA particle telescope was collecting continuous data inside the USLab module of the International Space Station (ISS) during most of the December 2006 SPEs.

The telescope is able to measure protons and helium respectively in the 42-45 MeV and 42-250 MeV/nucleon energy ranges, heavier ions up to relativistic molybdenum, and to discriminate nuclei for $Z \geq 5$.

First measurements of the charged radiation environment inside the USLab during a SPE are presented. The data averaged over the entire SPE week show an increase of the light ion rate (about a factor 1.5 in the energy range of the detector) when compared to quiet Sun conditions. The increase becomes much higher during the SPE climax (December 13th) reaching a factor 10 (when averaged over three ISS orbits showing the highest activity). The extension of these results beyond the detector range is discussed. Conversely, the rates of ions with $Z \geq 5$ are shown not to change significantly during the SPE week.

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1. Introduction

Radiation hazards are of highest concern when planning long human presence in space for the future exploration, on the Moon, Mars and beyond, but also during prolonged presence in the International Space Station (ISS) [1].

Space radiation is composed of high-energy ions, with a dominant component in quiet Sun condition consisting of 99% H and He ions and 1% heavier nuclei, along with particles accelerated during explosive solar events such as Solar Particle Event (SPE). A SPE can be caused by a coronal mass ejection or by a solar flare. The former is an eruption of plasma of the enclosed magnetic field from the solar corona into the interplanetary space and is potentially more dangerous than a solar flare. The latter is a violent explosion in the Sun's atmosphere with an energy emission up to 10^{25} J that seems to happen when energy stored in twisted magnetic fields, usually above sunspots, is suddenly released. Solar flare events take place in the solar corona and chromospheres and are probably primarily due to magnetic reconnection mechanisms. They heat plasma to tens of millions degrees and accelerate the resulting electrons, protons and heavier ions to near the speed of light.

The rate and nature of radiation play an important role in the quantification of the health risks related to the exposure of humans to the space radiation environment [2]. A SPE may produce a sufficient amount of radiation to increase the risk well above acceptable thresholds during space voyages outside the protective shielding provided by the Earth's geomagnetic field [3, 4]. The dominant contribution are primarily protons and we expect to observe inside the ISS an increase of light ion components, while the heavy ion radiation environment is not expected to change significantly.

The ALTEA facility has been placed in the USLab since July 2006, and it has been operative almost continuously from August 2006 to July 2007 and from June 2009 to present. The device, which is the development of our previous detectors [5, 6], was designed in the framework of the ALTEA program [7] which aims at monitoring the radiation environment inside the ISS and investigating its effects on the brain function of the astronauts. We present here a characterization of the radiation environment inside the ISS (USLab) during the SPE events occurred between December 5th and December 14th 2006. A comparison with analogous measurements during quiet Sun conditions is also shown.

2. Methods

The ALTEA-Space particle detector is composed by six identical telescopes (Silicon Detector Units, SDUs), arranged on a helmet shaped holder[1]. Every SDU consists of three couples of parallel detector planes; each plane consists of two (striped square) silicon chips with a size of 8cm x 8cm and a thickness of 380 μm. Every silicon plane is divided in 32 strips with 2.5 mm pitch and alternatively oriented along the X and Y directions (see figure 1). The energy resolution of the detector ranges from a threshold of 3 keV/μm to 800 keV/μm (LET in Si).

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[1] This structure has been chosen to perform also measurements of the radiation impinging on the astronauts' head; in this case the astronaut would position his/her head inside the helmet shaped detector [7]

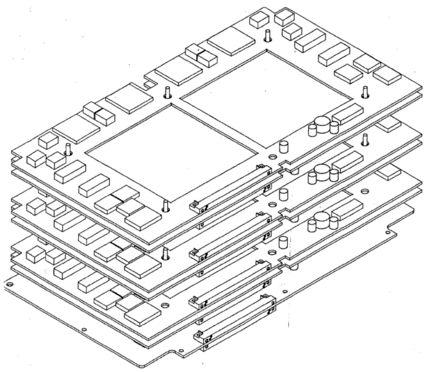

Figure 1: Schematic view of the inside of one SDU. Three pairs of detector planes are visible and, at the bottom, the electronic board. On the superior plane the two square silicon chips are visible. The two chips are striped, alternatively in each detector plane, either in the X or in the Y directions.

Each SDU can discriminate particle trajectory and the corresponding energy deposition with a threshold selectable from 0.9 to 3 keV/µm (in silicon) [8, 9]. During the presented measurements the threshold was set at 3 keV/µm. The particle rate is obtained considering the events that traverse at least five of the six planes. The distribution of the energy deposited on each detector plane by each ion is measured taking into account pedestals subtraction and normalization to the vertical direction (for details see [10]). Here we present particle rate and the energy deposition spectrum from SDU1, which is the telescope that was operative over the entire time frame considered. This telescope was oriented along the transversal axis of the USLab module, thus facing a direction with the lowest amount of shielding, measured to be equivalent to 5 cm Al [11, 12]. The analysis was performed only on "fast particles" events, i.e. events whose energy loss difference between the first and the last couple of silicon planes was less than 10%. This filter is needed to use the ion recognition algorithm described below, and, taking also into account the 3 keV/µm threshold, corresponds to select protons with energy of approximately 42-45MeV and heavier ions up to Fe with energy greater than 187 Mev/nucleon[2] [10]. The contribution of each ion type, with Z≥5, has been calculated from energy spectrum with a multiple Landau fit [10], using a software developed within the Minuit framework of the *(CERN)* ROOT software package [13]. This package provides three output parameters for each peak, namely amplitude, most probable energy value and width (standard deviation). We fitted the measured spectrum with the sum of several Landau curves, each fitting single nuclear specie. The Landau fit is therefore given by:

$$f(\lambda) = p_0 \int_0^{\infty} u^{-u}\ e^{-u(\lambda - p_1)p_2}\ \sin(\pi u)\ du$$

where λ is a dimensionless variable, p_0 is proportional to the height of the single nuclear peak, p_1 is proportional to the most probable energy value of each peak in the spectrum and p_2 is related to the standard deviation of the peak. This fitting method features a quite good agreement with the ALTEA data [10]. We also tested the method with a Monte Carlo simulation demonstrating a good agreement between simulated and experimental data.

The ALTEA SPE rates of the nuclear species from B up to Si and Fe have been obtained dividing each ion abundance by the effective operation time (the dead time of the instrument has been also considered). In order to assess the SPE contribution over the galactic radiation environment, we compared

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[2] This correspondence does not take into account straggling. We expect to select with this filter a smaller subset of these ions, as in many cases the straggling effect would make the ions not meeting the selection criteria

the rates measured during the SPE with those measured during a reference week (November 2nd – 8th 2006), characterized by quiet Sun conditions. To assess the influence of light ions ($Z<5$) on the energy spectrum, the SPE rates for heavy ions ($Z\geq5$) have been obtained by fixing the most probable energy value and the standard deviation of B ($Z=5$) and C ($Z=6$) peaks to the values obtained from the analysis of the reference week and leaving as free parameter only the peak amplitude.

The climax of the SPE (maximum recorded particle rate) was reached during three ISS orbits on December 13th. Because of the short time of observation when focusing on these 3 orbits, the statistics of heavier ions (i.e. C, N, O and Fe) was too low to allow the analysis of the spectrum with the Landau fit method. In this case the rate estimates have been obtained using a different data analysis technique [14], based on the comparison of the energy loss spectrum with a reference spectrum (the one relative to the time interval August 2006 - July 2007) on which was possible to apply the standard multiple-Landau fit analysis. The number of particles of a given Z in an energy bin is proportional to the ratio for that Z and that energy bin between the Landau curve and the total fitting function calculated on the reference spectrum. This method has been validated on simulated data and proved ion recognition accuracy better than 1 sigma.

The uncertainties on the rates have been evaluated taking into account the statistical errors from the fit parameters and the corrections related to the ALTEA apparatus (instrumental efficiency and packet loss).

3. Results

The December 2006 SPE events occurred between the 6th and the 14th originated from the active region NOAA 10930. December the 6th event originated at the East limb, resulting in a gradual proton event reaching the Earth on December the 7th and lasting until the events of December the 13th and the 14th. On December the 13th at 0238 UT, an X3.4/4B solar flare occurred in the same active region NOAA 10930 (S06W23). The intensities of the events were unusual for a solar minimum condition, because of the poor magnetic connection of the interplanetary field lines.

Figure 2 shows the plot of fast particle rate from SDU1, recorded for the period 2006, December the 7th to the 14th (ALTEA was turned off before December the 7th and after 12pm of December the 14th). The comparison with the (>50 MeV) proton flux measured by GOES-11 satellite [*15*] shows the good time coincidence of the events recorded with the two instruments.

The ALTEA particle rate as a function of time depends on the modulation due to the geomagnetic field on the particle trajectories. The faster oscillation, with a period of about 45 minutes is due to the latitude effect (reflecting the highest geomagnetic cut off value in the equatorial region, allowing only the high energy ions to penetrate). The larger period oscillation, with a period of almost 24 hours, depends on the longitude of crossing the cutoff regions, and is due to the inclination of the geomagnetic dipole axis with respect to the Earth's rotation axis. The highest isolated peaks in the particle rate of figure 2 represent the passages of the ISS over the South Atlantic Anomaly (SAA), the region out of the Brazil coast characterized by trapped proton rate inside the Van Allen Belt. The SPE effects can be finally identified in the unusually high rate peaks of figure 2, happening for example on December 7th and 13th.

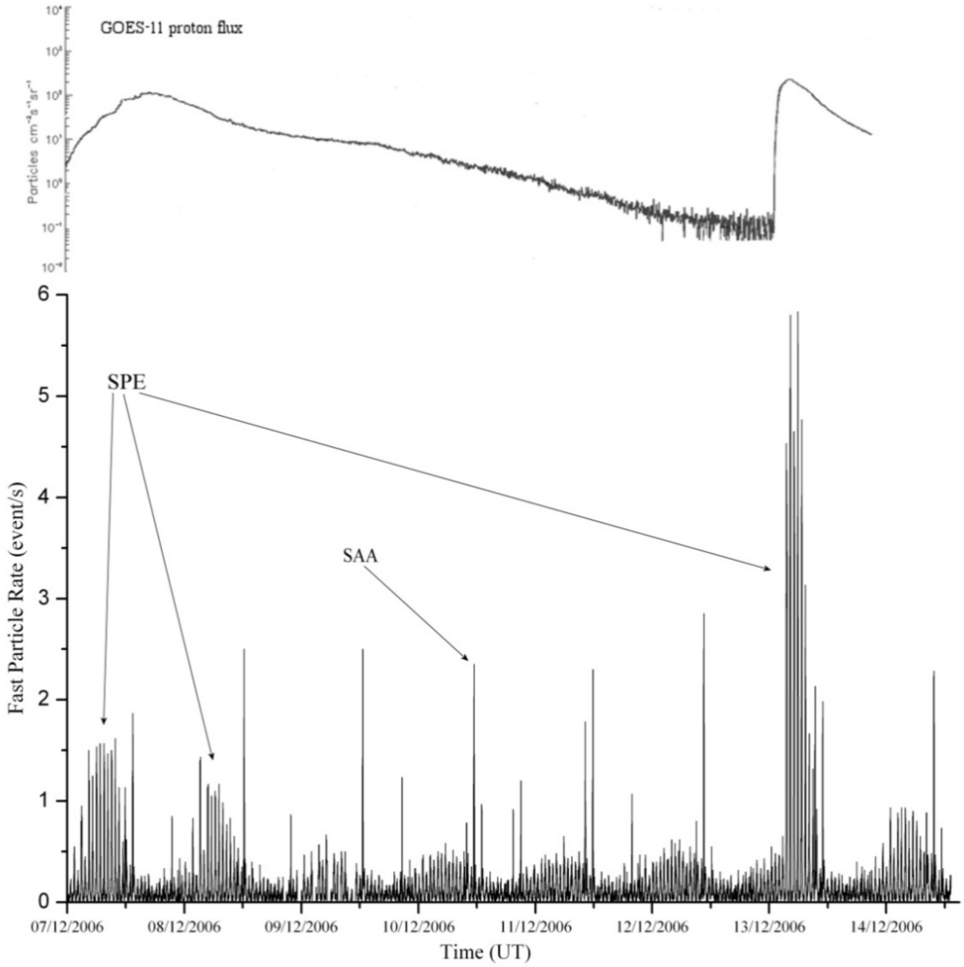

Figure 2: SDU1 rate for fast particles during the SPE week in comparison with the GOES-11 (> 50 MeV) proton flux during the same period of time. Each day starts from 00:00am UT. In the figure the longitude effect, the passages of the ISS over the SAA and the SPE effects are well visible. It is worth noting that the lack of a portion of the rate peak during December 7th (until the beginning of the 8th) is related to the geomagnetic cutoff.

Figure 3 shows the energy loss distribution of the particles triggering the detector during the whole SPEs (same period of figure 2). Distinguishable peaks are those up to Si. Also the Fe peak is clearly visible, while the others are just slightly pronounced. In the inbox the zoomed spectrum fitted with a sum of Landau curves up to the silicon peak is shown.

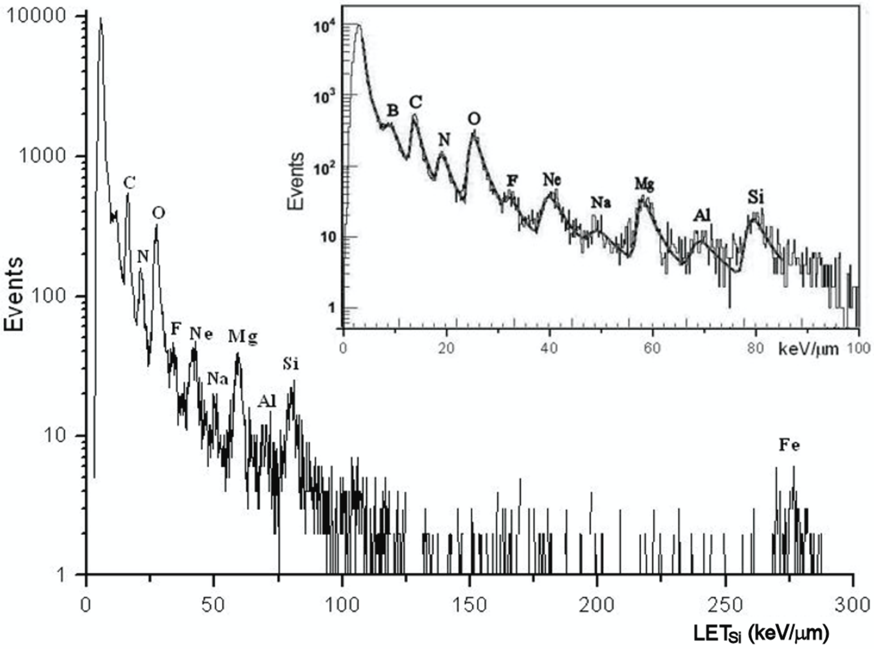

Figure 3: Energy loss distribution up to Fe, during the whole SPE week. In the inbox, Landau fit of the energy loss spectrum up to Si, by SDU1, as a function of the Linear Energy Transfer (LET) in Si.

The leftmost peak in figure 3 is due to protons and helium (more than 99%), as well as about 1% of lithium and beryllium nuclei that ALTEA is not able to resolve. The tail of this peak distribution gives a contribution to elements up to Z=18. The influence of this tail on the boron peak is most evident in figure 4, where a comparison between the deposited energy spectra during the SPE and the reference quiescent week is displayed up to oxygen.

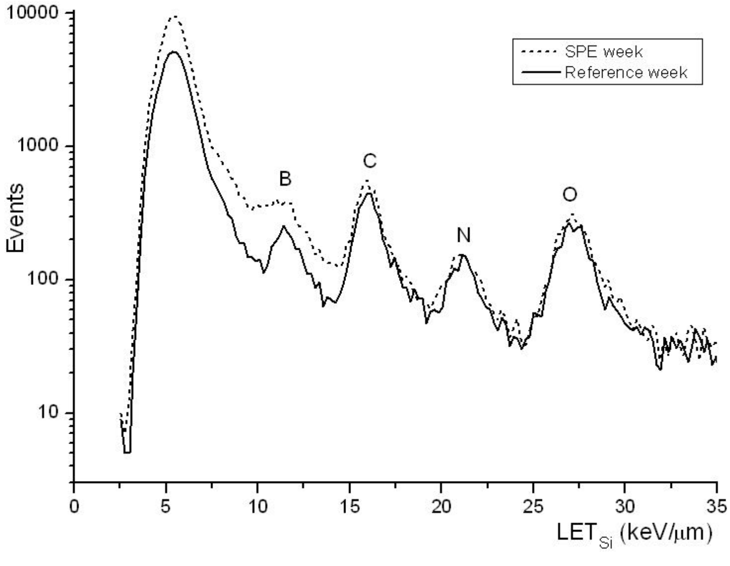

Figure 4: Comparison of the spectra up to oxygen acquired with SDU1 during the SPE week and the quiescent Sun (reference) week. The highest peak on the leftmost part of the figure encloses the contribution of the light ions (Z<5).

The SPE rates averaged over the whole week of the nuclear species up to silicon, plus iron, are in figure 5 compared with the particle rates relative to the quiet Sun reference week.

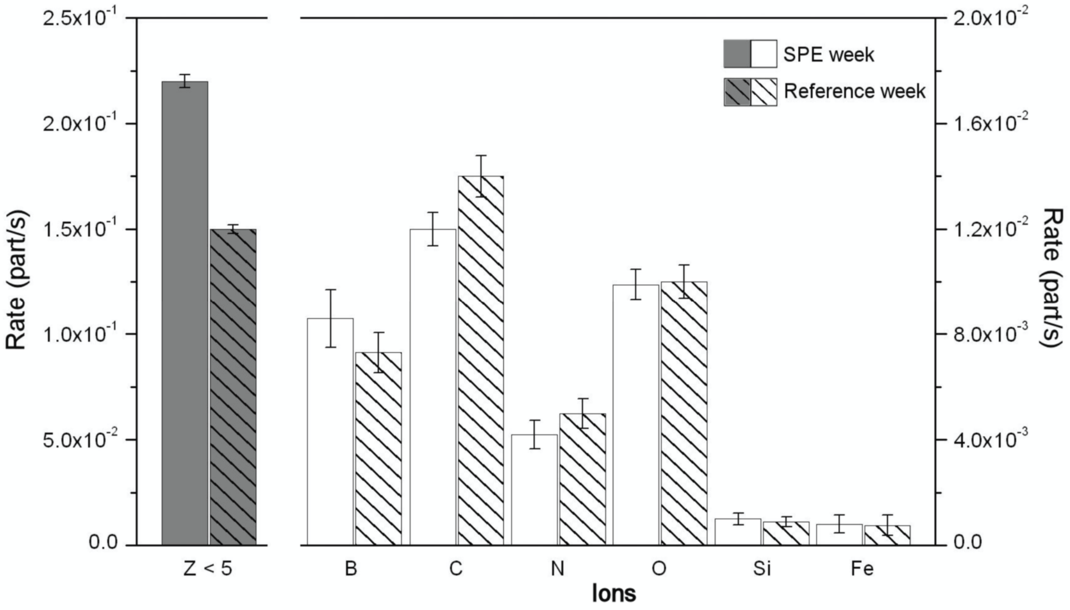

Figure 5: Particle rates during the SPE and during the reference week (quiet solar conditions). The left scale refers to the Z<5 values, the right scale to all the other species.

The largest event occurred on December the 13th (figure 2). To detail the radiation monitoring during this more intense activity, we followed the particle rate over each single orbit, in order to average the effect of the geomagnetic cut off in a consistent way. Figure 6 represents the rate for light ions (Z<5), as function of the December 13th ISS orbits. Each orbit corresponds to a revolution period of about 91 minutes. The SPE strongest effect was detected in the time interval ranging from the 3rd to the 5th orbit (i.e. from 03:03:16amUT to 07:38:09amUT, the start time being December 13th at 00:00am UT).

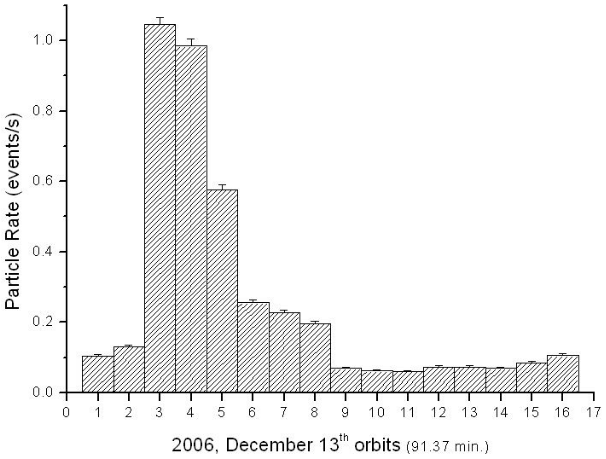

Figure 6: Light particles (Z<5) rate distribution during December the 13th. The particle rate is calculated summing up the events recorded along each orbital revolution of the ISS. The climax of the solar event corresponds to the 3rd-5th orbit-time frame, i.e. from 03:03:16amUT to 07:38:09amUT.

To investigate whether the SPE had a significant effect on the radiation field, the ratio between the rate during the SPE climax (three orbits with the maximum activity on December 13th) and the rate during the quiescent Sun week has been estimated for several ion types. The results are reported in figure 7, for light ions (Z<5), for the complex C – N – O and for Fe. If averaged only during passages of the ISS over the polar regions, the relative flux for Z<5 is >>10.

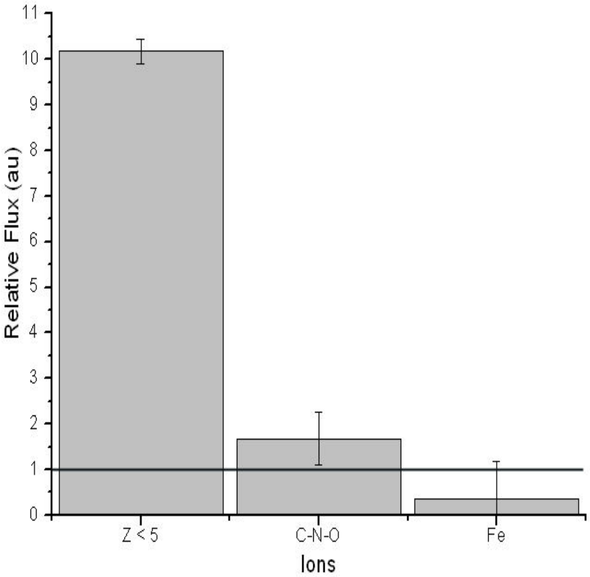

Figure 7: Rate of light ions (Z<5), C-N-O group and Fe during the 3 (ISS) orbits (December 13th) of the SPE maximum activity, normalized to the values of the reference week.

4. Discussion

In this work we have presented the first measurements of the charged radiation environment inside the ISS-USLab during a SPE, discriminating the nuclear species from B to Fe.

The data show remarkable variations of the particle rate during the main phases of the solar event (mostly on December 7th, 8th, 13th and 14th) compared to the normal geomagnetic modulation due to the passages over the Poles and the Equator and to the longitude effect.

The highest rates (December 7th and 13th) are synchronous with the (>50MeV) proton rate increases as measured by GOES-11 satellite - the missing part of the peak rate between December 7th and 8th is related to the geomagnetic cutoff. The days from December the 9th to December the 12th do not show instead any deviation from solar quiet condition. All spectra show, as expected, even Z nuclei more abundant than odd ones [10].

The influence of the H – Be peak on the adjacent B peak is most noticeable in figure 4 where the two spectra can be almost superimposed from carbon to oxygen while they differ for the lighter ions. This effect is the reason for fixing the width and most probable value of the B and C peak parameters to those measured in the quiet Sun period (only the amplitude of the peaks are left free, see Methods). In this way the contamination of the light ions peak in the analysis of heavier ions is minimized.

Although the ALTEA detector has a narrow acceptance window for protons (from 42 to 45 MeV), we have proved that the SPE produces, as expected, a strong increase in the rate of the light ions (Z<5, but essentially protons and helium nuclei) with respect to the values recorded during the quiescent period. This trend is evident in the rate averaged over the whole SPE week (see figure 5), where an increase of about 50% is observed and becomes much more relevant during the 3 orbits with the strongest solar activity (figure 7) when, averaging over each orbit, it increases of about a factor 10. This ratio represents a lower limit of the SPE contribution to the proton rate due to the limited acceptance window for this particle species. It should also be remarked that the ratio refers to a value averaged over full orbits, including the equatorial regions where, due to the high geomagnetic cutoff, the low Z low energy SPE radiation cannot penetrate. During the passages over the polar regions, characterized by a much lower geomagnetic cutoff, our measured ratio is >> 10.

By contrast, and as expected, there is no significant increasing of the heavy ions component, as selected by our “fast particle” filter (see Methods section), neither in the averaged rate (figure 5) nor during the hours with the strongest solar activity (figure 7). The slight increase of CNO with respect to the reference week is most likely due to the contribution of lower Z ions, which is minimized but not cancelled by the procedure described in Methods. It should also be noted that the Fe rate might not be accurate due to low statistics: the relative rate is based only on 2 ions detected during the three orbits of maximum activity, against an average of 1.5±1.1 ion/orbit detected during the reference week in November 2006.

As mentioned, the results show the first nuclear discriminated measurements of the charged radiation inside a space vessel during a solar flare. These are of interest in the frame of radiation risk assessment. As far as heavy ions are concerned ($Z \geq 5$), the measurements are compatible with an unchanged radiation environment with respect to quiescent Sun conditions (see Introduction).

For the light ions ($Z<5$, but mostly protons and, in a lesser extent, helium) we are suffering the narrow energy acceptance window for protons. To fully exploit the radiation protection value of these results, the proton spectral components that cannot be measured by ALTEA should be reconstructed. This problem can be approached using an algorithm based on independent proton measurements, such as the ones obtained with the Pamela spectrometer [16, 17], during SPE and quiescent solar periods, in LEO at a comparable geomagnetic cutoff. This reconstruction algorithm should also rely on a suitable code for the transport in the ISS, so to match our measurement inside, within our energy window. This work just started and will be the object of a future paper.

Nevertheless these results indicate that a SPE affects significantly the Linear Energy Transfer (LET) in the ISS producing a substantial increase of low LET radiation rate which reaches the highest values in quite short periods, confirming the need to consider SPE in those biological processes for which radiation rate plays an important role.

5. Conclusions

In this work we have shown the charged radiation rates obtained with the ALTEA detector on board of the ISS during the solar particle events of December 2006 and compared them with analogous measurements during quiet Sun conditions. These results provide first information for charged radiation risk assessment in space habitats during a SPE. The SPE produces, as expected, an increase of the light ions ($Z<5$) rate with respect to the values recorded during the quiescent times. In our limited acceptance window for proton, the mean measured rate over the whole SPE week is 1.5 times greater than the rate of the quiescent condition, but the ratio rises to about 10 (lower limit) when averaged over the solar most active period (three ISS orbits). By contrast, the abundance of heavier nuclei results unchanged within the errors with respect to quiet Sun conditions.

6. Acknowledgements

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