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Development of the space radiation dosimetry system 'PADLES'

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1. INTRODUCTION

Radiation dosimetry on board the International Space Station (ISS) is very important for investigating biological effects in a space radiation environment. Personal radiation dosimetry for astronauts is also a necessary manned space technology.

We have developed a Passive Dosimeter for Life Science Experiments in Space (PADLES). The PADLES package consists of two types of passive and integrating dosimeters, a CR-39 Plastic

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Nuclear Track Detector (PNTD) and a ThermoLuminescence Dosimeter (TLD). PADLES is to be utilized for monitoring radiation doses in the Japanese Experiment Module 'Kibo' of the ISS and the personal dosimetry of Japanese astronauts. Because the PADLES package is light, compact and battery-less, it is convenient to use in space from the following aspects: less crew time required, maintenance free, installation extremely close to biological samples, and easy to attach to astronaut's clothing and ExtraVehicular Activity (EVA) suits.

Thus far, some Japanese research groups have frequently used a combination of the CR-39 and TLD for space radiation dosimetry in a Low Earth Orbit (LEO) where the ISS and Space Shuttles fly(1-7). In 1998, some of the authors measured radiation doses using the combination of CR-39 and TLDs for space radiation effect research of human culture cells on the STS-95 shuttle mission(8). Through these past space radiation measurements using the CR-39, there was seriously recognition that manual measurements of a large number of etch pits of the CR-39 were inefficient, laborious, tedious, and needed too much time to get results. Japanese researchers related to space radiation dosimetry, therefore, recognized a strong need for making a well-calibrated 'standard' dosimeter package, establishing a higher-speed automatic analyzing system of the CR-39 and securing technical experts in charge of the actual operations of radiation dosimetry for supporting Japanese space programs that extend over a long period of time. In 2000, we therefore started to develop the PADLES system for a future routine dosimetry service on the ISS in the space environment utilization center of the Japan Aerospace Exploration Agency (JAXA). Since 2001, we have carried out ground-based experiments with gamma rays from ^{137}Cs and ^{60}Co, and heavy ion beams from a HIMAC accelerator of NIRS, Japan, to obtain the TLD and CR-39 response data over a wide linear energy transfer (LET) range from an ionization minimum of 0.2 keV/μm up to several hundreds of keV/μm(9). PADLES has also been examined on board the ISS, parallel with the development of the PADLES system.

In this paper, we first describe the characteristics of space radiation to be measured with PADLES. We then describe the present status of PADLES; including the package configuration, the methodology, the procedure for space radiation dosimetry, and the analysis system. The performance of an automatic analysis of the CR-39 etch pits is also discussed.

2. Characteristics of space radiation in LEO

There are three primary radiation sources (galactic cosmic rays, solar particle events, and protons trapped in Earth's radiation belts) in free space outside spacecraft in LEO with an altitude of 300 to 500 km. The radiation environment inside spacecraft, however, becomes more complicated. When passing through the walls and facilities of the spacecrafts, these primary space radiations produce many secondary particles due to their interactions with electrons and nuclei that constitute the spacecraft's mass. These secondary particles such as energetic charged particles and neutrons, contribute to increase doses for astronauts and the bio specimens used for space experiments. The space radiation environment in LEO is characterized as follows: 1) remarkably high contribution of high LET radiation having a high quality factor (QF) influential to living entities; 2) absorbed dose rates in space have a value of a few hundred times as much as those on the ground; 3) radiation damage under microgravity.

3. PADLES

CR-39s have been utilized by Japanese researchers in space radiation dosimetry and for tracking High-Z and high-Energy (HZE) particles in space biological experiments along with bio-specimens, for example, silkworm and human cell culture. One year's effort was needed to obtain the results from the CR-39, because of the manual measurements for a number of etch pits with an optical microscope. The bio-specimens involved changed generations within a few months. In future biological experiments on board the ISS, therefore, it is desired that CR-39s be analyzed as soon as possible so that biologists can reasonably make an experiment program for the recovered bio-specimens based on the dosimetric results given by the CR-39.

PADLES has been developed as an exclusive system for space radiation dosimetry in JAXA. Using this system, we can promptly obtain radiation doses for a loading period with high statistical accuracy, and without encountering errors in the manual measurements of a CR-39.

3.1. Methodology

PADLES measures an absorbed dose, a Linear Energy Transfer (LET) distribution of heavy-charged particles for ≥ 10 keV/μm-water and a dose equivalent based on a QF-LET relation recommended by ICRP60 (ICRP, 1991) [10]. The original dosimetric concept was described in detail in previous papers [1] [10] [11]. In the present PADLES method, the total doses are expressed in terms of the sum of the dose for < 10 keV/μm and that for ≥ 10 keV/μm.

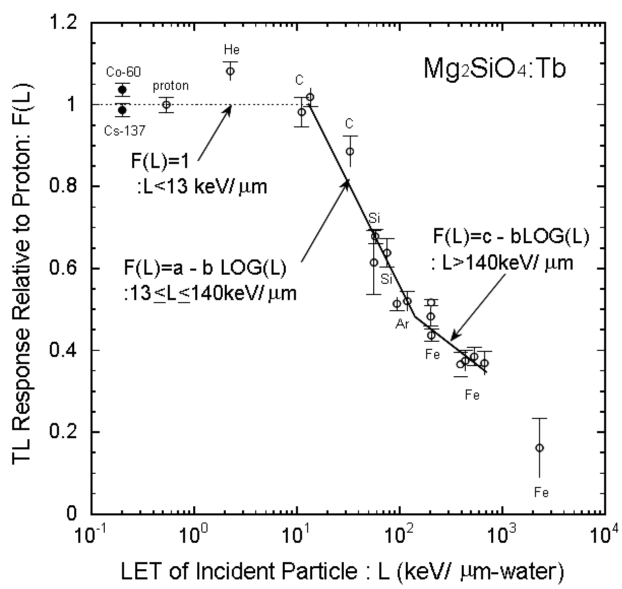

Fig. 1 TL response as a function of LET used in the PADLES system.

The LET distribution from 10 to 50 keV/μm is measured with a CR-39 plate etched for 13.5 h. This somewhat long etching time is required for detecting Long Range Particles (LRPs). Because LRPs often have lower LET values in space radiation fields, a longer etching time is needed for developing a sufficient etch-pit size to observe under an optical microscope. The LET distribution for ≥ ~ 50 keV/μm is measured with a CR-39 plate etched for 5.5 h. This shorter etching time is required for detecting Short Range Particles (SRPs) with high LET values such as target fragments induced by primary space radiation. The absorbed dose and dose equivalent for ≧ 10 keV/μm can be calculated from the LET distribution.

TLD readouts are calibrated with 160 MeV protons and corrected for fading effects at their loading temperatures[11][12]. The absorbed dose for < 10 keV/μm is obtained by subtracting the part of the TLD readout due to space radiation exceeding 10 keV/μm, $D_{tld\geq10}$, from the total TLD readout. We experimentally obtained the LET response function of TLD (Mg_2SiO_4:Tb) as illustrated in Fig.1. $D_{tld\geq10}$ is estimated by using the LET distribution for $\geq$ 10 keV/μm measured by the CR-39 and the LET response functions of TLD for $\geq$ 10 keV/μm in Fig.1.

3.2. Analysis procedure

Figure 2 gives a schematic diagram of the standard PADLES analysis procedure. Two programs, "TLDPADLES" and "AutoPADLES" were developed for a prompt and routine analysis. This system drastically reduces the maximum analysis time of the PADLES package, typically down to about two weeks.

3.2.1. Preparation of packages

A standard PADLES package consists of four CR-39 plastic plates (HARZLAS TD-1: Fukivi Chemical Industry) and seven TLD elements (TLD-MSO: Kasei Optonics, LTD.) as depicted in Fig.3. A TLD is Mg_2SiO_4 powder sealed in a glass tube with Ar gas. The dosimeter package is wrapped in Al foil and permacel tape to shield the TLD elements from light. One of the CR-39 plates is a sample previously exposed to heavy ions (448 MeV/n ^{28}Si, 410 MeV/n ^{56}Fe) with the HIMAC heavy ion accelerator. This plate is used as a reference to check sensitivity stability of the CR-39 during a space flight experiment. The external size of the package is typically 2.5 cm x 2.5 cm x 0.6 cm. Ground-control packages are prepared along with the flight packages for each space experiment. To measure the positions and the LETs of HZE particles incident to biological samples, we use a stack of CR-39 plates and the biological samples are used for tracking particle trajectories.

About two thousand TLD elements were prepared for PADLES. Every element was exposed to gamma rays from ^{137}Cs and ^{60}Co to check the individual TL response. TLD PADLES manages a database of all TLD elements, including serial number, history of use, present status, individual calibration constants for protons and ^{60}Co gamma rays, and TL readouts in past exposure experiments. By using TLDPADLES, a set of TLD elements is selected for each flight experiment so that the response deviation is less than 5%. The TLD elements are annealed at 500^{o}C for 20 min before packaging.

After the flight experiments, the PADLES packages are disassembled in a JAXA laboratory, and the TLD and CR-39 are analyzed following the procedure outlined in Fig.2.

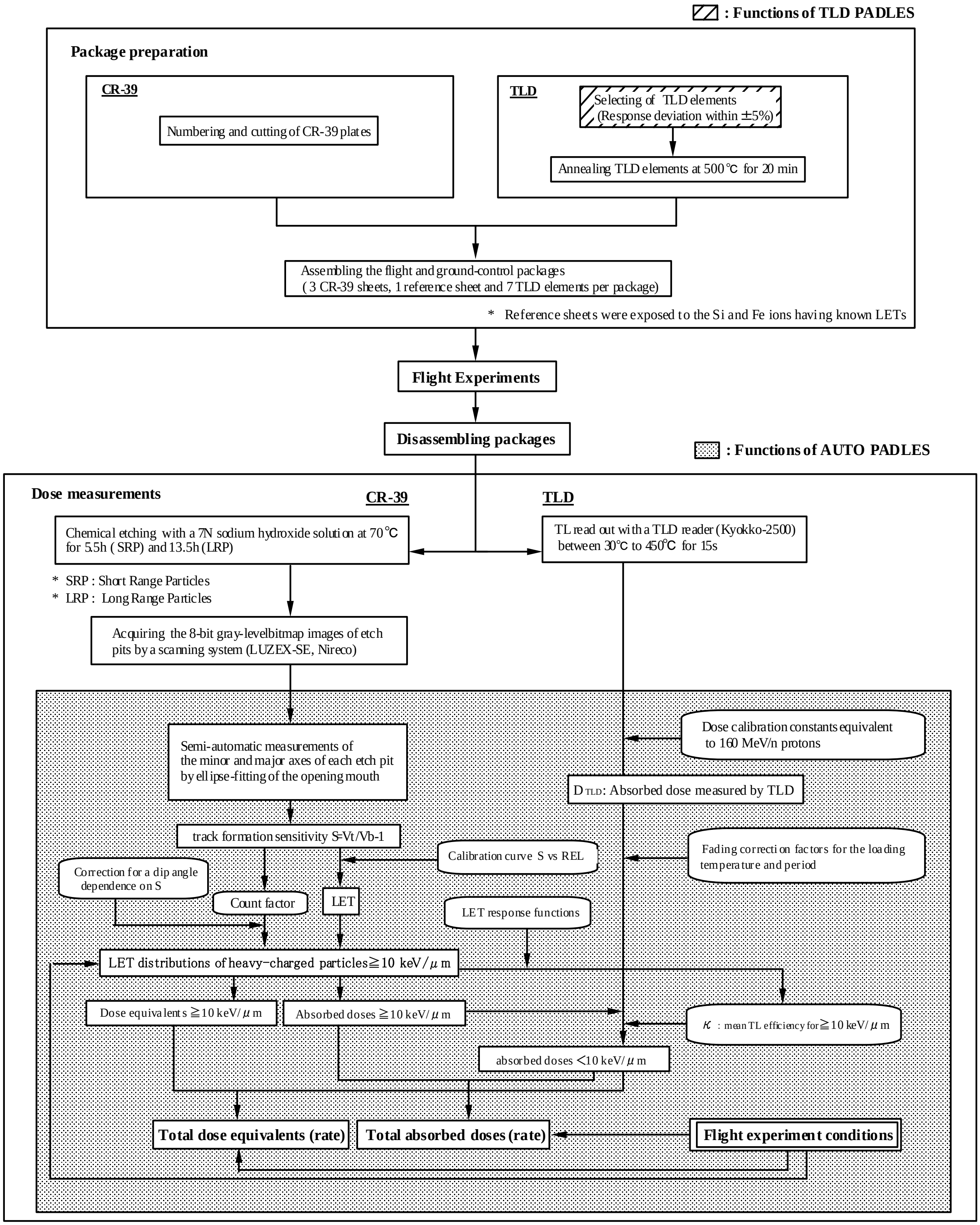

Fig. 2 Standard procedure of space radiation dosimetry by PADLES.

3.2.2. CR-39 analysis

The CR-39 plates are etched in a 7N NaOH solution at 70 °C for 5.5h and 13.5h immediately after the return. The bulk etch rate of TD-1 is approximately 1.7 μm/h. Etched plates are rinsed in running water and are desiccated in a desiccator with silica gel at room temperature for two days. Etched surfaces are scanned by a digital image acquisition system with an optical microscope (LUZEX-SE; Nireco) to acquire 8-bit gray-level bitmap images. The minor and major axes of the opening mouths of etch pits are semi-automatically measured by the AutoPADLES program with an ellipse-fitting algorithm(13). Even if the opening mouths are overlapped, the ellipse-fitting algorithm can effectively separate and analyze them. As a result, we can drastically reduce the CR-39 analysis time compared to former fully-manual measurements, although some part of the etch pits still require to manual re-analyzation.

The track formation sensitivity of an etch pit is calculated from the major and minor axes of the etch pit, and a bulk etch amount. The track formation sensitivity is converted to the LET value of a incident particle using a calibration curve (Fig. 4). The detection efficiency of the particles having the LET value is also calculated from a critical angle of the track formation sensitivity on the assumption that the space radiation field is isotropic. The detection efficiency in the present PADLES method is corrected for a dip angle dependence(14).

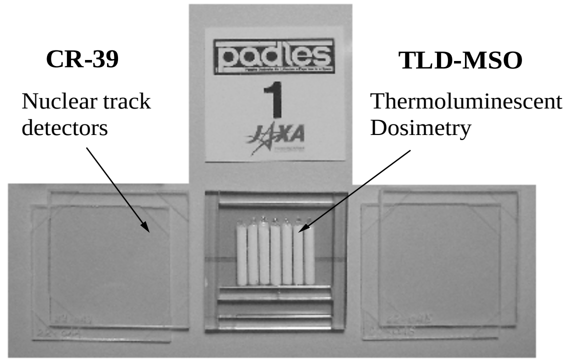

Fig. 3 Standard PADLES package.

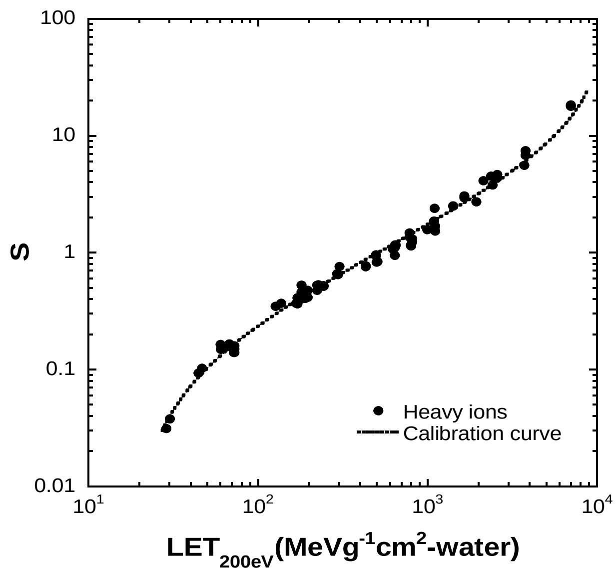

Fig. 4 Calibration curve for high-energy heavy ions of TD-1. The curve can be applied to both the 5.5 h and 13.5 h etched samples.

3.2.3. TLD analysis

TLD elements are measured by a KYOKKO TLD reader 2500 (Kasei Optonics, LTD). The TL signals are integrated from 30 °C to 400 °C for ~15 sec. These readouts are converted to absorbed doses using the calibration factors determined by exposure to 160 MeV protons because

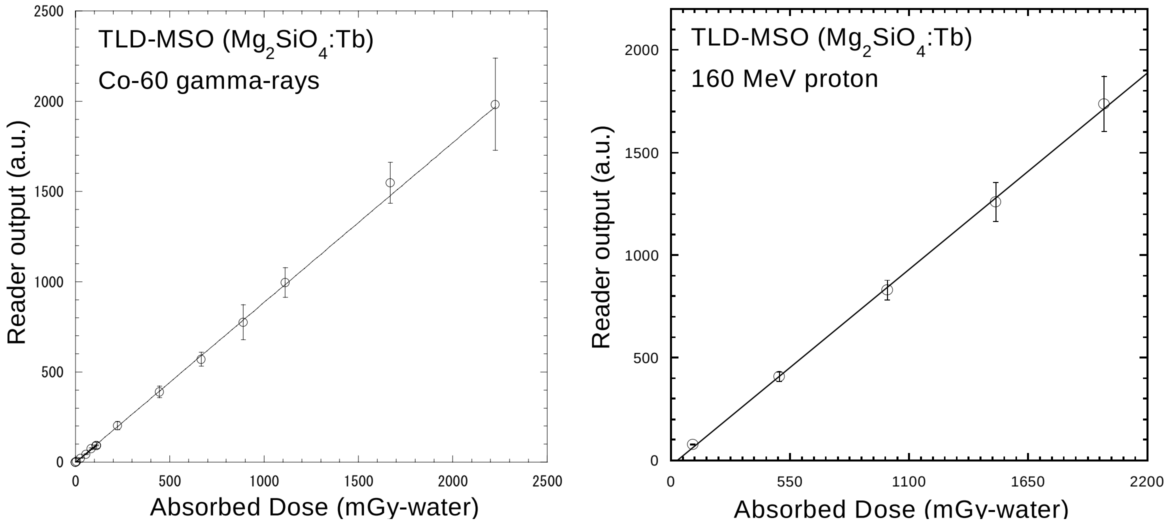

Fig. 5 Relative thermoluminescence yields of Mg_2SiO_4:Tb for gamma rays and 0.54 keV/μm protons as a function of an absorbed dose up to 2 Gy.

the absorbed dose in LEO is dominated by protons having several hundreds of MeV.

The PADLES packages will be regularly recovered from JEM every 6 months. The absorbed dose for 6 months on the ISS is expected to be about 35 to 55 mGy from results of past space experiments, depending upon solar activity. We confirmed the linearity in the TL response of TLD-MSO up to 2 Gy-water with 160 MeV protons and ^{60}Co gamma rays as illustrated in Fig.5. We also confirmed that the linearity for heavy ions (274 MeV/n ^{12}C, 448 MeV/n ^{28}Si, 443 MeV/n ^{40}Ar, 410 MeV/n ^{56}Fe) is good up to 100 mGy(12).

The PADLES packages will always be kept adjacent to the biological samples. The TLD elements therefore undergo different storage temperatures of -80 °C to 37 °C for up to 6 months. We investigated the fading characteristics of TLD for high-energy heavy ions (160 MeV/n H, 150 MeV/n ^{2}He, 500 MeV/n ^{56}Fe) at different temperatures of -80 °C to 60 °C for up to 6 months as shown in Fig.6. The fading rates in TL response, as functions of temperature and time during space radiation exposure, were incorporated into AutoPADLES to correct absorbed doses measured by the TLD.

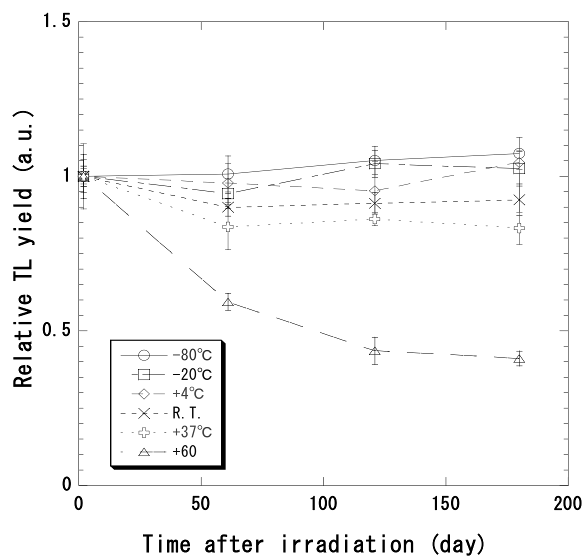

Fig. 6 Fading effect of Mg_2SiO_4 :Tb irradiated by 10 mGy protons up to 6 months.

4. Fully-automatic analysis of CR-39 using AutoPADLES

So far, PADLES has been utilized twice for radiation effect research in space. One was for biological effect research in the STS-95 mission of the Space Shuttle Discovery (8.9 days from 29 October to 7 November 1998). This mission had a unique orbit of a high altitude (574 km) and a low inclination (28.45°) (NASDA and Eril Research 2003)(15). The other was for radiation damage research with Charge-Coupled Devices (CCDs) of a High-Definition Television camera (HDTV). This was a long-term experiment on the ISS Russian segment for 446 days from 21 August 2001 to 10 November 2002, and three PADLES packages were loaded for radiation monitoring and tracking of HZE particles incident to CCDs. The orbit of the ISS Russian segment was 389 km in average altitude and 51.6° in inclination, which was a normal ISS orbit. The three PADLES packages were exposed for 71, 256, and 446 days respectively.

Using CR-39 plates loaded in the STS-95 mission and the ISS Russian segment, we examined the performance of automatic etch-pit analysis by AutoPADLES in space radiation dosimetry. First, we automatically obtained LET distributions by AutoPADLES without any manual correction. For verification of AutoPADLES, an operator checked every ellipse analyzed by AutoPADLES for a manual correction; removing etch-pit-like objects due to dust and artificial scratches, and reanalyzing objects on which AutoPADLES failed in ellipse fitting. Figure 7 depicts LET distributions in the ISS Russian segment for 71 days. The LET distribution from Auto PADLES was higher than that with the manual correction for LET values exceeding 10 keV/μm, but the difference was small as shown in Fig. 7(a). We also calculated LET distributions from LRP samples (13.5 h etching) and SRP samples (5.5 h etching). Figure 7 (b) shows that the LET distribution from the SRP sample was in agreement with that from the LRP sample in a lower LET region. This result

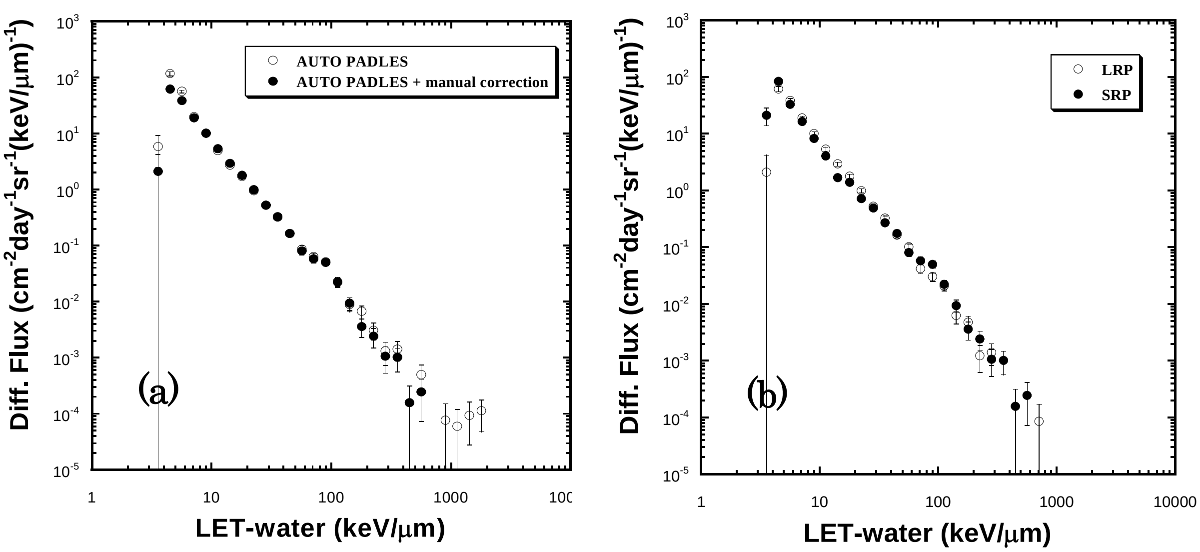

Fig. 7 LET distributions in the ISS Russian segment for 71 days. (a) Comparison of LET distributions measured by AutoPADLES without a manual correction for ellipse fitting of etch pits and that with the manual correction. (b) Comparison of LET distributions measured from a SRP sample and that from a LRP sample.

indicated that the present PADLES system has the ability to estimate LET distributions for 10 keV/μm using only 5.5 h etched samples for radiation dosimetry in LEO.

Table.1 compares absorbed doses and dose equivalents among four different CR-39 analysis methods. The absorbed doses were in good agreement within errors among the four methods. Because 90 % of absorbed doses in LEO is attributable to the lower LET radiation of <10 keV/μm, the difference in the etch-pit measurements contributes less to total absorbed doses. The total dose equivalents obtained by "fully-automatic AutoPADLES" were about 9 % higher than those obtained by "semi-automatic AutoPADLES" in both space flights of LEO. Results by the automatic ellipse-fitting in AutoPADLES included dust. The major and minor axes of inclined tracks were frequently overestimated because a binarization process before the ellipse fitting in AutoPADLES extracts an excessively dark tail along with etch-pit mouths. Such overestimations in the etch pit analysis of AutoPADLES is currently under investigation. The dose equivalents measured by "SRP+LRP" were in good agreement within errors with those by "SRP" as depicted in Table 1. If LET distributions are able to be estimated by using only SRP samples, we can further save the labor in the CR-39 analysis.

The result of PADLES on STS-95 and the Russian service segment were very consistent with past flight results on ISS.

Table 1 Comparison of results with different CR-39 analysis methods in LEO radiation dosimetry by PADLES. "Fully-automatic AutoPADLES" implies a fully-automatic ellipse fitting of etch-pits. "Semi-automatic AutoPADLES" implies that ellipses fitted in AutoPADLES were manually corrected by an operator. "SRP+LRP" implies that the LET distribution for $\geq$ 50 keV/μm was measured with a SRP sample and the LET distribution from 10 to 50 keV/μm with a LRP sample. "SRP" implies that the LET distribution over the whole region for $\geq$ 10 keV/μm was measured with only a SRP sample. Errors are statistical ones (one standard deviation).

	Fully-automatic AutoPADLES		Semi-automatic AutoPADLES	
	SRP+LRP	SRP	SRP+LRP	SRP
ISS Russian service segment (71 days)				
Absorbed Dose Rate [mGy/day]	0.28 ± 0.01	0.28 ± 0.01	0.28 ± 0.01	0.28 ± 0.01
Dose Equivalent Rate [mSv/day]	0.58 ± 0.02	0.58 ± 0.02	0.53 ± 0.02	0.53 ± 0.02
Mean QF (ICRP60)	2.08 ± 0.13	2.07 ± 0.13	1.93 ± 0.12	1.89 ± 0.12
STS-95 mission (8.9 days)				
Absorbed Dose Rate [mGy/day]	1.53 ± 0.18	1.53 ± 0.18	1.52 ± 0.18	1.52 ± 0.18
Dose Equivalent Rate [mSv/day]	3.02 ± 0.19	2.97 ± 0.19	2.80 ± 0.19	2.73 ± 0.19
Mean QF (ICRP60)	1.98 ± 0.26	1.95 ± 0.26	1.84 ± 0.25	1.80 ± 0.25

5. Future works

At present, PADLES packages are being applied to the MATROSHKA and ALTCRISS projects on board the ISS. MATROSHKA is an international project conducted by the German Aerospace Center in Cologne (DLR: Deutsches Zentrum fuer Luft und Raumfahrt) for estimating an astronaut's exposed dose during EVA with various types of passive and active dosimeters. A human phantom was set up with the dosimeters in a pressurized container, the thickness of which simulates the shielding effect of a space suit. The container was installed on an outside wall of the Russian segment for 538 days in the first flight from 19 January 2004 to 11 October 2005. The ALTCRISS project was conducted by the National Institute of Nuclear Physics (INFN), and one of the objectives is to study the ISS radiation environment at various positions in the ISS under different shielding configurations. In 2007, after JEM is attached to the International Space Station (ISS), the PADLES system will be widely applied for monitoring radiation environments inside JEM, a personal dosimetry for Japanese astronauts, and international experiments such as MATROSHKA and the ISS biological research experiment proposed in the international announcement of opportunity in order to investigate biological effects produced by a space radiation environment. Data will be offered to astronauts and researchers from 2008 and will be regularly recovered from the ISS every 6 months.

6. Summary and conclusions

We developed the PADLES system in order to support Japanese space programs that extend over a long period of time. This system includes a 'standard' dosimeter package consisting of CR-39 PNTDs and TLD-MSOs, a high-speed scanning system for the CR-39 PNTDs, the TLDPADLES program managing TLD elements and the AutoPADLES program for automatic analysis of CR-39 etch pits. AutoPADLES also has the function of automatic calculation of space radiation doses from readouts of the CR-39 PNTDs and TLDs based on detailed response data of the dosimeters for high-energy heavy ions. The PADLES system allows us to provide dosimetric results for biological researchers within 2 weeks after the return of their PADLES packages to JAXA.

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