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First Results from the RadMap Telescope

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The RadMap Telescope is a compact instrument designed to characterize the primary spectrum of cosmic-ray nuclei and the secondary radiation field created by their interaction with the shielding of spacecraft. Its main purpose is to precisely monitor the radiation exposure of astronauts, and it is the first instrument with a compact form factor that can measure both the charge and energy of individual nuclei with energies up to several GeV per nucleon. This capability is enabled by a tracking calorimeter made from scintillating-plastic fibers, which can record the energy-loss profile of particles in three dimensions and with nearly omnidirectional sensitivity. We present first results from the RadMap Telescope's first orbital deployment on the International Space Station between April 2023 and January 2024.

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1. Introduction

Protecting spacecraft and their crew from the exposure to cosmic and solar radiation is one of the major challenges of missions to the Moon, Mars, and other deep-space destinations [1, 2]. At present, uncertainties in predicting the medical consequences of exposure to the space radiation environment greatly limit the maximum permissible duration of crewed deep-space missions [3]. This uncertainty to a large degree stems from our incomplete understanding of the biological effects of highly ionizing radiation [4, 5] but is also due to a lack of detailed data on the radiation environment beyond (low) Earth orbit. Though some spacecraft have carried radiation-monitoring instruments into deep space, these missions provided, with few exceptions [6], only short-term measurements.

For the Moon in particular, some recent missions carried experiments that provided new data on the lunar radiation environment with limited scope, like the Lunar Lander Neutron and Dosimetry (LND) experiment on the Chang'E 4 lander [7] and the Matroshka AstroRad Radiation Experiment (MARE) on Artemis I [8]. Despite these and other valuable measurements, additional long-term observations with instruments capable of accurately resolving the various components of the deep-space radiation environment are urgently required to help reduce the uncertainties of radiation-related risk predictions [9].

In this contribution, we present first results from the RadMap Telescope, a compact yet powerful radiation monitor that not only demonstrates new sensor technologies but also aims to combine the capabilities of several current-generation devices in a bid to reduce the number of instruments required aboard future spacecraft.

2. The Space Radiation Environment – Relevant Components

The space radiation environment is a complex field of particles and nuclei that stem from multiple time-varying sources. It is dominated by galactic cosmic rays (GCR)—consisting of mostly electrons, protons, and fully ionized nuclei—with energies spanning many orders of magnitude. The most abundant GCR are protons and helium nuclei; heavier nuclei (i.e., those with higher nuclear charge) make up only about 1% of cosmic rays [10] but play an important role in radiation protection because they inflict severe damage in biological systems [11]. The flux of GCR is highest at energies of several hundred MeV to several GeV per nucleon.

Another source of (mostly) protons and helium nuclei is the Sun, which emits them in high-intensity bursts at irregular intervals. These so-called solar energetic particles (SEP) have energies of tens to hundreds of MeV per nucleon [12]. Despite their lower energies, SEP bursts can nonetheless be a critical threat to astronauts because of their high intensity, especially if the crew is in a lightly shielded environment at the time of a burst [13]. A third source are protons and electrons trapped in radiation belts around planets with magnetic fields, for example Earth [14].

To predict the medical risks resulting from exposure to this environment, next-generation radiation monitors must be able to measure its time-varying composition, i.e., the charge and energy of individual particles. This knowledge allows determining the biological effectiveness of the radiation field more accurately than possible with the data of the simple dosimeters that are (mostly) used today [15, 16]. Another advantage is that it reduces our reliance on post-processing of measurements based on models and simulations that are fraught with uncertainty [17–19].

3. The RadMap Telescope

With the development of the RadMap Telescope, our objective was to develop a detector technology that can provide comprehensive measurements of the charged-particle radiation environment inside crewed spacecraft. To that end, our research is aimed at providing biologically meaningful dose and dose-rate measurements in real time, record particle-dependent energy spectra for protons and nuclei, and determine the directionality of incident radiation. The instrument is designed to be most sensitive to the part of the radiation spectrum most relevant to radiation protection, i.e., to nuclei with energies of tens of MeV to a few GeV per nucleon.

At the heart of the RadMap Telescope is an active-target detector made from 1024 scintillating-plastic fibers arranged in layers with alternating orientation in a roughly cubic volume. The segmentation of this Active Detection Unit (ADU) given by the fibers allows us to record the energy-loss profile, and hence the change of the linear energy transfer (LET), along a particle's track through the detector. From this information, we can not only determine a particle's energy and the direction it came from but also establish its identity using a method called Bragg curve spectroscopy [20]. The particle identification is most precise for protons and light ions with energies that translate to a penetration depth that is shorter than or comparable to the size of the detector's active volume; it becomes increasingly imprecise for heavier nuclei and at higher energies. Besides the ADU, RadMap is equipped with a customized version of the M-42 dosimeter designed at the German Aerospace Center (DLR) [21], which provides accurate measurements of the radiation field's energy deposition in a silicon diode. We refer to previous presentations at this conference for a more detailed description of the instrument [22].

The ADU's omnidirectional sensitivity results in a geometrical acceptance of $1013\,\mathrm{cm^2sr}$ if only a single fiber must be hit; to allow reconstruction of particle tracks, at least four fibers must produce a signal, resulting in a slightly lower acceptance of $925\,\mathrm{cm^2sr}$ [20]. Our track reconstruction achieves an angular resolution of about 2° and we can determine the energy of protons with energies up to 1 GeV with a resolution of better than 10%. The energy resolution decreases for higher particle energies and, because of ionization quenching [23], for heavier nuclei. Above a certain (as yet undetermined) threshold, we can only record a particle's (constant) LET and the energy it deposited in the detector.

4. Operations on the International Space Station

We operated the RadMap Telescope on the International Space Station (ISS) between April 2023 and January 2024. During that time, the instrument rotated through three modules of the station: the Node 3 module (also known as *Tranquility*), the Japanese Experiment Module (JEM), and the U.S. Laboratory. We requested this rotation schedule to assess the differences in the radiation field in different parts of the station.

We operated the ADU with a minimum-bias trigger, i.e., we recorded every event for which at least one fiber in the detector produced a signal. This allowed us to compare the particle flux it measured to that in the M-42 dosimeter by simply scaling the measured count rates with the geometric factors of the respective sensors. The upper panel of Fig. 1 shows the result at the example of an eight-hour period of data recorded in the JEM on 10 August 2023. Since the ADU has a

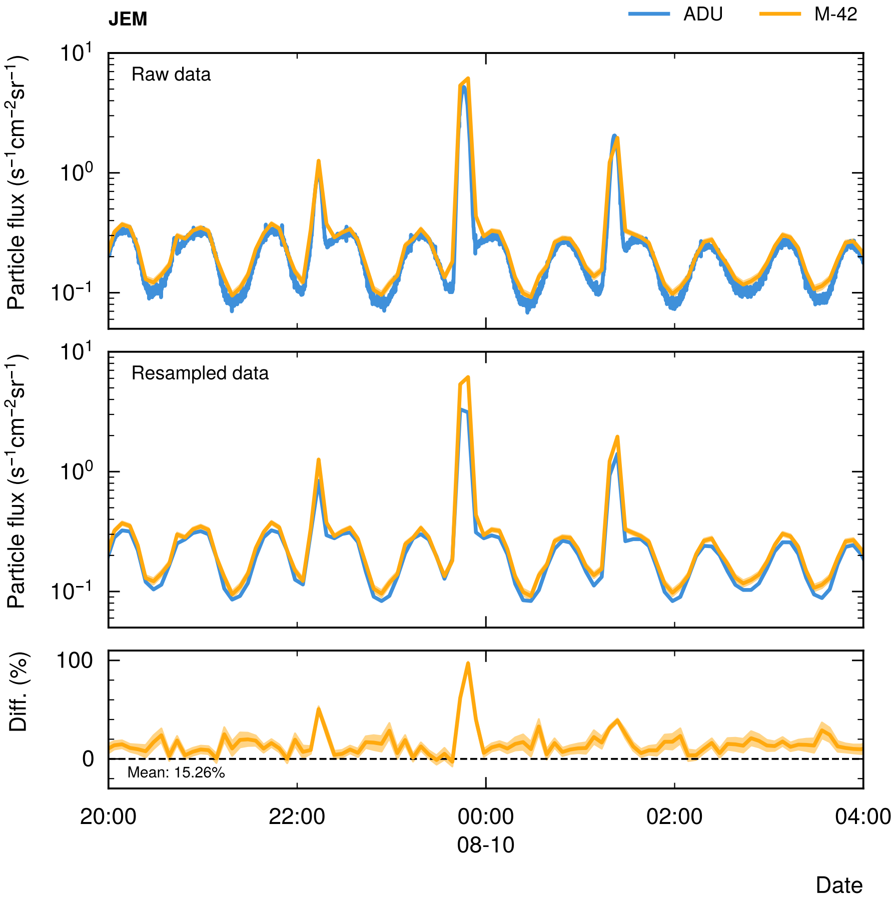

Figure 1: Comparison of the particle fluxes measured by the ADU and the M-42 dosimeter in the JEM for an eight-hour period on 10 August 2023. The upper panel shows the raw data, i.e., the fluxes calculated from the unprocessed count rates. The middle panel shows the ADU data resampled to the integration windows of the M-42. The lower panel shows the difference between the two, normalized to the ADU data. The uncertainty band on the M-42 data is the square root of the count rate. Analysis of the ADU data is not yet advanced enough to determine errors on the count rate.

significantly higher time resolution, we resampled its count rates to the integration window of the M-42 to allow a better comparison (see middle panel).

Both graphs show the expected latitude-dependent variation of the radiation field, and the much higher particle fluxes recorded during passes of the South Atlantic Anomaly (SAA). They also show that the measurements of the two sensors are in good agreement. The lower panel of Fig. 1 further highlights this by displaying the difference of the two, normalized to the values of the ADU. On average, the flux measured by the M-42 is about 15% larger than that of the ADU over the eight-hour period shown, with larger deviations during passes of the SAA. Further investigation is required to conclusively determine the origin of the differences. It does, however, appear likely that they are caused by the M-42's higher sensitivity to low-energy electrons and to photons (X-rays and gamma rays) that are created in interactions of GCR and SEP with the station's shielding.

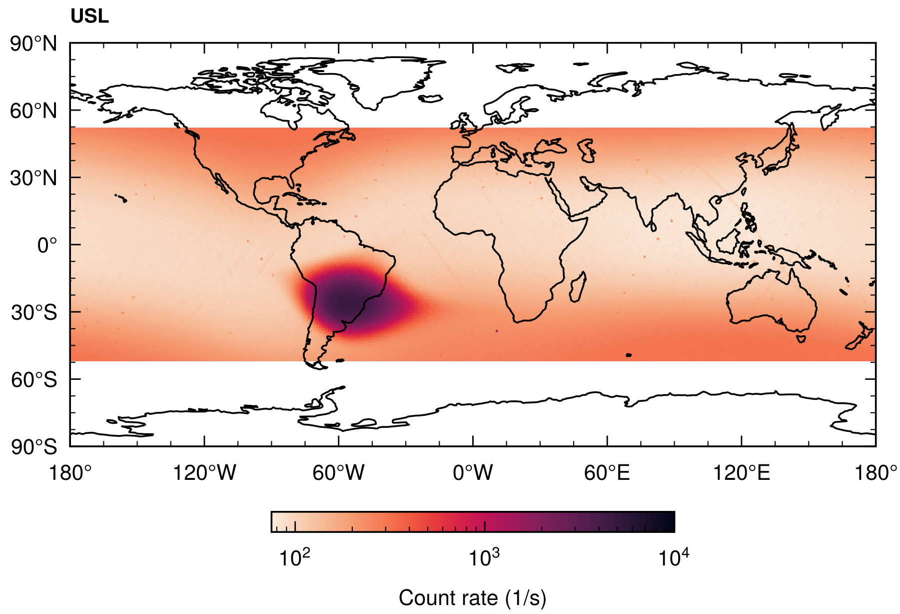

Figure 2: Correlation of the ADU's count rate in the U.S. Laboratory with the orbit position of the ISS. The graph shows the average count rate in bins with a size of 1° in latitude and 1° in longitude.

Fig. 2 shows how the ADU's count rate correlates with the orbit position of the ISS, using data accumulated over about a month. Such a map is largely qualitative in nature but allows to perform an excellent consistency check. It exhibits the expected latitude and longitude dependence (e.g., see [24, 25]) and the SAA is prominently visible over South America. It also demonstrates how the detector's large geometric acceptance, and hence high count rates, enables the mapping of the radiation environment with high spatial resolution.

Finally, Fig. 3 exemplarily shows the energy-deposition spectra of GCR and radiation-belt particles in the U.S. Laboratory recorded on 23 November 2023. In the absence of a full calibration of the detector (which is still in work), the energy deposition is calculated as the sum of the ADC codes of all 1024 channels. The GCR spectrum peaks at lower energy depositions due to the prevalence of high-energy, almost-minimum-ionizing protons that deposit only little of their energy in the detector. The relative suppression at higher energy deposition is caused by the shielding of the low-energy part of the GCR spectrum due to the magnetosphere. Conversely, the radiation-belt spectrum peaks at higher energy deposition because Earth's magnetic field can only trap particles with lower energies and higher stopping power (and hence larger energy deposition in the detector). The events with very large energy deposition in the right-hand tail of the GCR spectrum are likely due to fragmenting nuclei that produce a shower of lighter particles with high stopping power. A more detailed interpretation will be possible once we can identify individual particles and perform a particle type-dependent analysis.

5. Summary

Even though the analysis of ADU data that we show here is largely qualitative and only covers first steps, it shows that the instrument is performing as expected. The consistency of its measurements

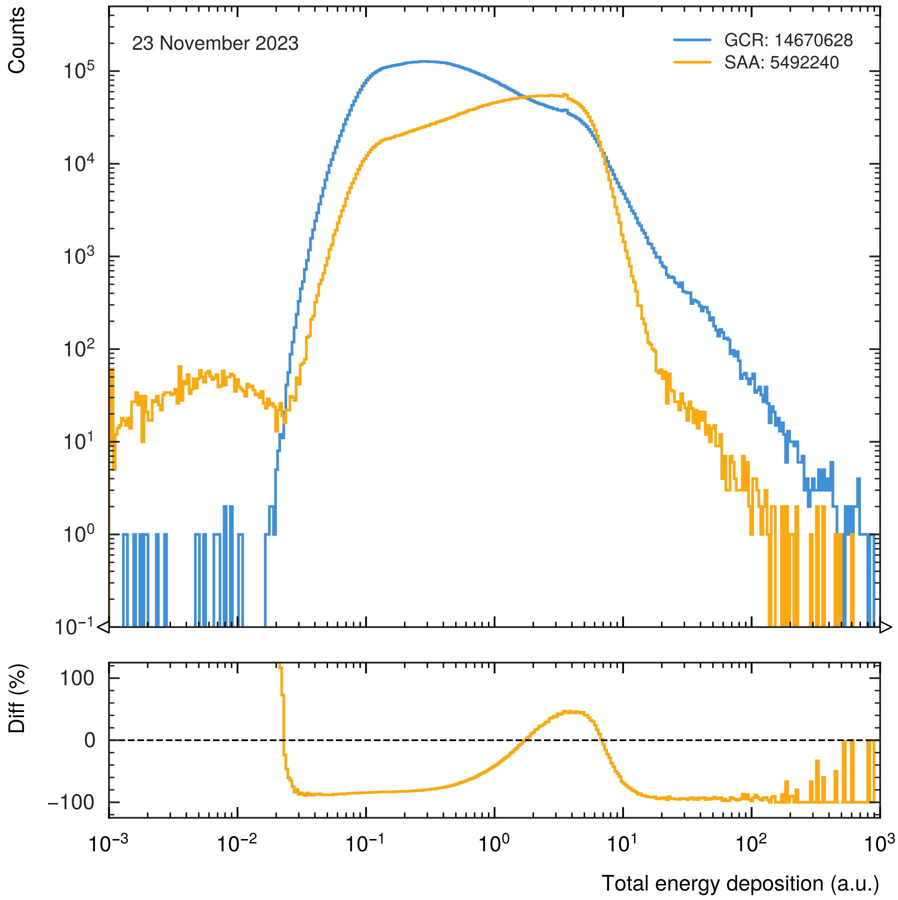

Figure 3: Uncalibrated energy-deposition spectra of GCR and radiation-belt particles (the latter labeled SAA) recorded in the U.S. Laboratory module of the ISS on 23 November 2023. The lower panel shows the difference of the spectra, highlighting the excess of high-LET particles in the SAA.

with those of the M-42 dosimeter is promising, as is the fact that we performed no pre-selection of events except for dropping a few corrupted ones.

We are currently still working on finalizing the track reconstruction, which is required for a more detailed analysis, including particle identification and energy measurement. Yet, despite the work still ahead of us, the qualitative analysis already shows that the instrument promises to evolve into a useful tool for the detailed characterization of the radiation environment inside spacecraft like the ISS. If nothing else, the sensor's high count rate and the clean total-energy deposition spectra, though uncalibrated so far, will open new pathways for detailed statistical investigations not possible based on the much sparser data of other instruments.

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