Cosmic Ray Energetics And Mass for the International Space Station (ISS-CREAM)

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Abstract: The Cosmic Ray Energetics And Mass (CREAM) instrument is configured with a suite of particle detectors to measure TeV cosmic ray elemental spectra from protons to iron nuclei over a wide energy range. The goal is to extend direct measurements of cosmic ray composition to the highest energies practical, and thereby have enough overlap with the ground-based indirect measurements to answer questions on cosmic ray origin, acceleration and propagation. The balloon-borne CREAM was flown successfully six times over Antarctica to accumulate a duration of about 161 days. The elemental spectra for Z = 1–26 nuclei have been measured over the energy range 10^{10} to $> 10^{14}$ eV. Transforming the balloon instrument into ISS-CREAM involves identification and replacement of components that would be at risk in the International Space Station (ISS) environment, in addition to assessing safety and mission assurance concerns. The transformation process includes rigorous testing of components to reduce risks and increase survivability on the launch vehicle and operations on the ISS without negatively impacting the heritage of the successful CREAM design. The project status, including results from the ongoing analysis of existing data, and particularly plans to increase the exposure factor by another order of magnitude utilizing the International Space Station are presented.

Keywords: CREAM, elemental spectra, balloon, space based experiment, direct measurements.

1 Introduction

The balloon-borne Cosmic Ray Energetics And Mass (CREAM) experiment was flown six times over Antarctica between 2004 and 2010, and it accumulated ~161 days of flight time, the longest exposure to date for a single balloon project. The instrument was initially designed and constructed to measure cosmic-ray elemental spectra to the highest energy possible with a series of Ultra Long Duration Balloon (ULDB) flights [1]. The goal was to understand the origin, acceleration and galactic propagation of the bulk of cosmic rays by extending direct measurements of cosmic-ray composition to energies capable of generating gigantic air showers that have mainly been observed on the ground. The ULDB vehicle is still not proven, but six flights were successfully carried on conventional zero pressure balloons for Long Duration Balloon (LDB) flights [2]. The exceptional performance of both the science instrument and flight support systems can be attributed to the fact that they were developed with a rigorous process for 100-day ULDB missions. Building on the success of the balloon flights, the payload is being transformed for accommodation on the ISS. While another 5 LDB flights would increase our exposure by a factor of two, an order of magnitude increase is possible by utilizing the ISS to reach the highest energies practical with direct measurements.

2 Instrument

The ISS-CREAM instrument is configured with the CREAM calorimeter [3] including carbon targets for energy measurements and four layers of a finely segmented Silicon Charge Detector [4] for charge measurements. These detectors have already demonstrated their capabilities to determine the charge and energy of high-energy cosmic rays from 10^{10} to $>10^{14}$ eV for the proton to iron elemental range with excellent resolution [5]. In addition, two new compact detectors are being developed: Top/Bottom Counting Detectors (TCD/BCD) and Boronated Scintillator Detector (BSD). The TCD and BCD each consists of a plastic scintillator and 400 photodiodes. As shown in Fig. 1, the TCD is located between the instrument's carbon target and the calorimeter, and the BCD is located below

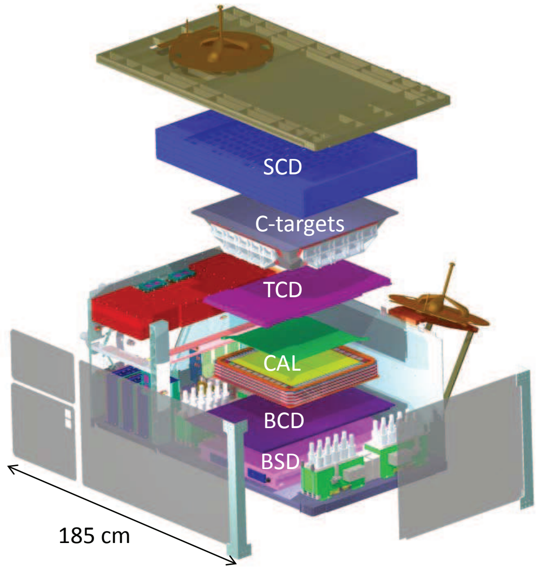

Fig. 1: Exploded view of the ISS-CREAM Instrument.

the calorimeter. These detectors provide the capability for electron separation from protons, a redundant energy trigger for the calorimeter, and a cosmic ray trigger for test and calibration on the ground. Details of the TCD/BCD design and measured performances are presented elsewhere [6, 7]. The hadron rejection power derived from the e/p shower shape difference can be significantly enhanced by making use of the thermal neutron activity at late (>400 ns) times relative to the start of the shower. Hadron-induced showers tend to be accompanied by significantly more neutron activity than electromagnetic showers. The ISS-CREAM BSD measures this late thermal neutron shower activity by detecting the boron capture of these thermal neutrons in a boron-loaded plastic scintillator (5% boron concentration by weight and the natural ^{10}B abundance of 20%) located below the BCD under the calorimeter. Results from a 2012 beam test and the expected performance are discussed in another paper [8].

3 Current Results and Expected Performance

One of the key results from the ongoing analysis of CREAM data is an observed spectral hardening for each element above ~200 GeV/nucleon, indicating a departure from a single power law [5]. Proton and helium spectra in the energy range from 2.5 to 250 TeV are represented by power-law fits with spectral indices of -2.66 $\pm$ 0.02 and -2.58 $\pm$ 0.02 for protons and helium, respectively. Both spectra are harder than lower energy data from previous experiments, e.g., the Alpha Magnet Spectrometer (AMS) spectral indices of -2.78 $\pm$ 0.009 for protons and -2.74 $\pm$ 0.01 for helium [9]. A broken power law fit for C, O, Ne, Mg, Si, and Fe with spectral indices γ_1 and γ_2, respectively, below and above 200 GeV/nucleon, resulted in γ_1 = -2.77 $\pm$ 0.03 and γ_2 = -2.56 $\pm$ 0.04. As shown in Fig. 2, the spectral index γ_1 is consistent with the low energy helium measurements, e.g., the AMS index of -2.74 $\pm$ 0.01, whereas γ_2 agrees remarkably well with the CREAM helium index of -2.58 $\pm$ 0.02 at higher energies. A hardening of proton and Helium spectra around 240 GV, similar to the spectral hardening first reported by CREAM, has also been reported by PAMELA [10] using a permanent magnet spectrometer with a variety of detectors. The experimental uncertainties are too large to debate the exact starting point of the hardening, whether it is 240 GV or 200 GeV/nucleon.

The exact cause of the spectral hardening is still under investigation, although a number of possible explanations of these results have been proposed [11, and references therein]. The hardening may result from modification of gas flow in the shock precursor by the cosmic ray pressure, which shapes the concave energy spectrum of cosmic rays. Alternatively, the observed hardening could be due to nearby sources, as suggested for the recent observations of an enhanced high-energy electron spectrum [12, 13]. A multi-source model by Zatsepin and Sokolskaya [14] considered novae stars and explosions in super-bubbles as additional cosmic ray sources. Whether it results from a nearby isolated SNR [15] or the effect of distributed acceleration by multiple remnants embedded in a turbulent stellar association [16] is another question.

Whatever the explanation, the CREAM results contradict the traditional view that a simple power law can represent cosmic rays without deviations below the “knee” around 3 $\times 10^{15}$ eV. The pervasive discrepant hardening in all of the observed elemental spectra provides important constraints on cosmic ray acceleration and propagation models, and it must be accounted for in explanations of the electron anomaly and cosmic ray “knee”. Donato & Serpico [17] reported that the spectral hardening reported by CREAM would lead to appreciable modifications for the secondary yields, such as antiprotons and diffuse gamma rays, in the sub-TeV range. They concluded that using a simple power law to model the astrophysical background for indirect dark matter searches, as often done in the literature, might lead to wrong conclusions about the evidence of a signal. Or, if a signal should be detected, use of a power law could lead to bias in the inferred values of the parameters describing the new phenomena. Yuan and Bi [18] have demonstrated how tension between the AMS positron fraction [19] and the total electron (including positron) spectra detected by Fermi and HESS can be removed by taking a harder primary electron spectrum at high energies, similar to the nuclei spectral hardening, for either pulsar or dark matter annihilation/decay scenario as the primary positron sources.

CREAM has pushed direct spectral measurements of nuclei, including the important secondary elements (e.g., boron), to ever-higher energies with Antarctic LDB experiments. For primary element spectra, the energy region around 10^{15} eV is challenging to explore, because direct measurements run out of statistics at such high energies. Indirect ground-based measurements cannot resolve individual elements, and they encounter systematic problems caused by uncertainties in modeling hadronic interactions in the atmosphere. ISS-CREAM can take the next major step to 10^{15} eV, and beyond. A 3-year exposure on the ISS would greatly reduce the statistical uncertainties and extend CREAM measurements to energies beyond any reach possible with balloon flights, as illustrated in Fig. 2. Being above the atmosphere, ISS-CREAM would be far superior to multiple balloon flights.

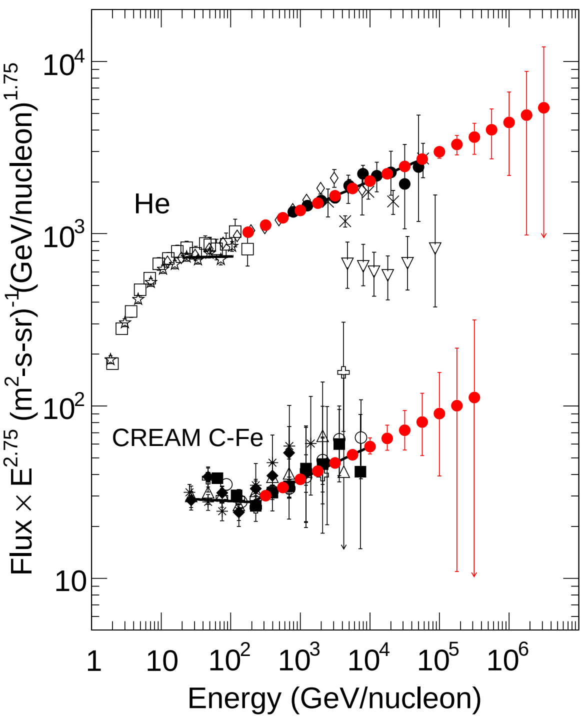

Fig. 2: Comparison of the high-energy spectra from a nominal ISS-CREAM mission (red circles) with existing data (black symbols) [5]. Data from previous experiments include BESS (open squares), ATIC-2 (open diamonds), JACEE (X), and RUNJOB (open inverted triangles). Some of the overlapping BESS and AMS data points are not shown to achieve better clarity. The lines for helium represent a power-law fit to AMS (open stars) and CREAM (filled circles), respectively. The lines for C-Fe data represent a broken power-law fit to the CREAM heavy nuclei data: Carbon (open circles), Oxygen (filled squares), Neon (open crosses), Magnesium (open triangles), Silicon (filled diamonds), and Iron (asterisks).

4 Status and Plan

The CREAM instrument is being reconfigured for accommodation on NASA's share of the Japanese Experiment Module Exposed Facility (JEM-EF) for at least an order of magnitude increase in the exposure factor. The scope of work required for the ISS investigation includes modification of instrument components for the ISS environment, in addition to assessing safety and mission assurance concerns. The instrument must be functionally tested and qualified to meet the launch vehicle and on-station requirements for operations on the ISS. The instrument needs to be repackaged within a structure that meets the JEM-EF interface requirements.

The basic design of the instrument is mature, and it has heritage operating over many years in the near-space environment. The radiation effects on electronic circuits need to be adequately addressed for ISS-CREAM. Components are selected and utilized in a manner to prevent the possibility of failures as a result of Single Event Latch-up (SEL), and to assure that Single Event Upset (SEU) and Single Event Transient (SET) effects will have minimal impact on data collection. The issue of SEU could result in occasional corrupted data, and relatively infrequent reboots of the computer. The power supplies were designed with overcurrent trip circuits in the power distribution sections to rapidly remove power from any subsystem that exhibits a high current condition, which might be caused by a SEL. Our parts and components were evaluated for any destructive SEL failures by the Radiation Effects and Analysis Group at Goddard Space Flight Center (GSFC). Replacement parts used to mitigate effects of space (e.g., radiation) were taken from NASA-approved parts lists and/or are undergoing rigorous environmental tests [20]. Where the design includes Field-Programmable Gate Arrays (FPGAs), the control logics are being modified to use triple mode redundancy (TMR) to mitigate errors caused by SEUs. Related software updates are being made, and development testing was conducted at the NASA Marshall Space Flight Center (MSFC) in Spring 2013. The actual Command and Data Handling (C&DH) setup on the ISS was simulated by connecting the ISS-CREAM Science Flight Computer to the Payload Rack Checkout Unit. During the testing, reliable flow of commands and telemetry between MSFC and Science Operation Center at the University of Maryland was established [21].

The launch vehicle and ISS accommodations will be accomplished using the stringent interface requirements provided by NASA Johnson Space Center (JSC) and their relationship with JAXA and Space-X for design, safety and operational challenges. The transformation process includes rigorous testing of components to reduce risks and increase survivability on the launch vehicle and operations on the ISS without negatively impacting the heritage of the successful CREAM design. Following the Systems Requirement Review, the instrument Preliminary Review was completed in 2012, followed by the Phase 0/1 Safety Review. The ISS Program Office at NASA JSC completed an ISS and launch vehicle accommodation study for ISS-CREAM. The ISS-CREAM payload is about the size of a refrigerator (see Fig. 1) with ~1,300 kg mass, including government furnished equipment such as grapple fixtures and a Payload Interface Unit (PIU). The estimated ~600 W power and nominal data rate of 350 kbps are all within the available JEM-EF resources. ISS-CREAM utilizes an Active Thermal Control System, a Fluorinert fluid loop, provided by the JEM-EF through the standard PIU. Detailed thermal analyses of the ISS-CREAM payload are being performed. ISS-CREAM is in its implementation phase to complete the detailed design, component fabrication, integration and testing of the fully integrated CREAM payload. As done for the ULDB system, NASA GSFC Wallops Flight Facility (WFF) is providing project management and engineering support for ISS-CREAM. Following environmental testing, the payload will be delivered to Kennedy Space Center for launch by Space-X in 2014.

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