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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 ground based indirect measurements to answer questions on cosmic-ray origin, acceleration and propagation. The balloon-borne CREAM was flown successfully for about 161 days in six flights over Antarctica to measure elemental spectra of $Z = 1$–26 nuclei 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: Cosmic rays; Elemental spectra; CREAM; Direct measurements

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1. Introduction

The balloon-borne Cosmic Ray Energetics And Mass (CREAM) experiment was flown six times over Antarctica between 2004 and 2010, thereby accumulating ~161 days of flight time, the longest exposure to date for a single balloon project. The instrument was designed and initially constructed to measure cosmic-ray elemental spectra to the highest energy possible with a series of Ultra Long Duration Balloon (ULDB) flights (Ahn et al., 2007). 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 from the ground. The ULDB vehicle is still not proven, but six flights were successfully carried using conventional zero pressure balloons for Long Duration Balloon (LDB) flights (Seo, 2012). The balloons were launched from McMurdo, Antarctica, and each flight subsequently circumnavigated the South Pole one to three times. The launch and termination dates and the duration for each flight are summarized in Table 1. A photo of the CREAM instrument is shown in Fig. 1. The float altitude was kept stable between ~38 and ~40 km with a corresponding average atmospheric overburden of ~3.9 g/cm^2 for all 6 flights. 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 International Space Station (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.

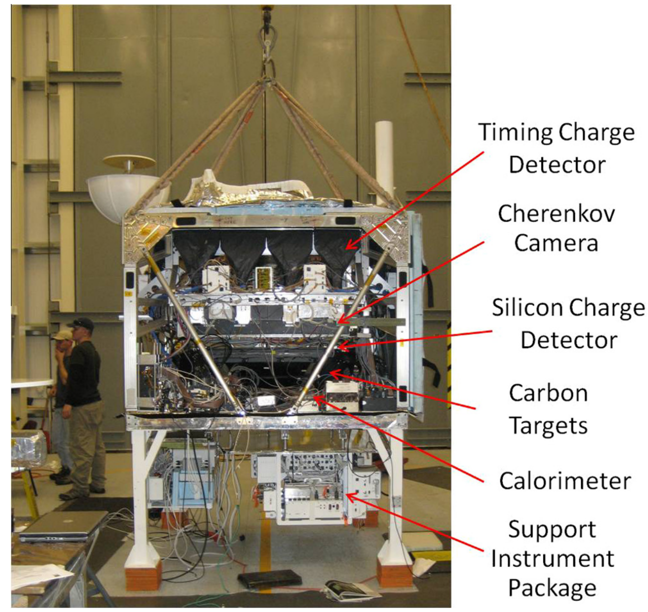

Fig. 1. Photo of the CREAM instrument during CREAM-V integration at Williams Field near McMurdo, Antarctica. The same instrument configuration was flown on CREAM-III and CREAM-IV. A Transition Radiation Detector was flown on CREAM-I instead of Cherenkov Camera.

2. Instrument

The ISS-CREAM instrument is configured with the CREAM calorimeter (Lee et al., 2009) including carbon targets for energy measurements and four layers of a finely segmented Silicon Charge Detector (Park et al., 2007) 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 (Ahn et al., 2010). 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 consist of a plastic scintillator and 400 photodiodes. As shown in Fig. 2, the TCD is located between the instrument's carbon target and the calorimeter, and the BCD is located below the calorimeter. These detectors provide 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

Table 1
Summary of the six CREAM balloon flights in Antarctica.

	Launch	Termination	Duration
CREAM-I	2004.12.16	2005.1.27	42 days
CREAM-II	2005.12.15	2006.1.13	28 days
CREAM-III	2007.12.19	2008.1.17	29 days
CREAM-IV	2008.12.18	2009.1.7	19 days
CREAM-V	2009.12.1	2010.1.8	37 days
CREAM-VI	2010.12.21	2010.12.26	6 days

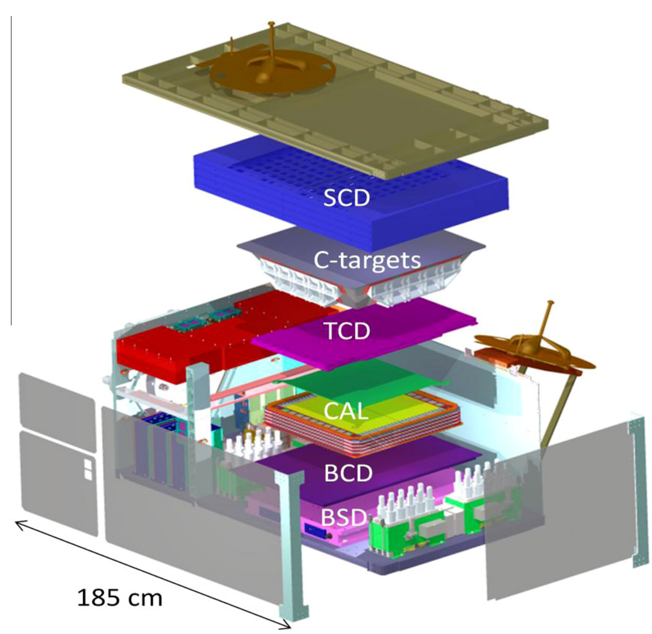

Fig. 2. Exploded view of the ISS-CREAM Instrument.

and measured performances are presented elsewhere (Park et al., 2013; Hyun et al., 2013). 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 20% natural ^{10}B abundance) located below the BCD under the calorimeter. Results from a 2012 beam test and the expected performance are discussed in another paper (Anderson et al., 2013).

3. Current results and expected performance

The ongoing analysis of CREAM data shows that TeV energy spectra, where the calorimeter trigger is fully efficient and its energy dependence is negligible, are harder (have weaker energy dependence) than lower energy data from previous experiments (Ahn et al., 2010). 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 ± 0.02 and -2.58 ± 0.02, respectively, for protons and helium. Both spectra are harder than lower energy data from previous experiments, e.g., the Alpha Magnet Spectrometer (AMS) spectral indices of -2.78 ± 0.009 for protons and -2.74 ± 0.01 for helium (Aguilar et al., 2002). While the helium spectrum is harder than the proton spectrum, the individual energy spectra of heavy nuclei, C, O, Ne, Mg, Si, and Fe, have spectral shapes (Ahn et al., 2009) similar to each other and to helium.

The heavy nuclei spectra can be represented by a single power law fit with an index of -2.66 ± 0.04. Note that this power law fit extends to lower energy per nucleon for nuclei heavier than helium. 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 $\gamma_1 = -2.77 \pm 0.03$ and $\gamma_2 = -2.56 \pm 0.04$. As shown in Fig. 3, the spectral index γ_1 is consistent with the low energy helium measurements, e.g., the AMS index of -2.74 ± 0.01, whereas γ_2 agrees remarkably well with the CREAM helium index of -2.58 ± 0.02 at higher energies.

A hardening of proton and helium spectra around 240 GV, similar to the spectral hardening first reported by CREAM (Ahn et al., 2010), has also been reported by PAMELA (Adriani et al., 2011) 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 sharp structure at 240 GV reported by PAMELA was not confirmed by recent AMS-02 data (Choutko et al., 2013; Haino et al., 2013). AMS-02 data up to its maximum detectable rigidity (~2 TV) confirmed that the helium spectrum is harder than the proton spectrum.

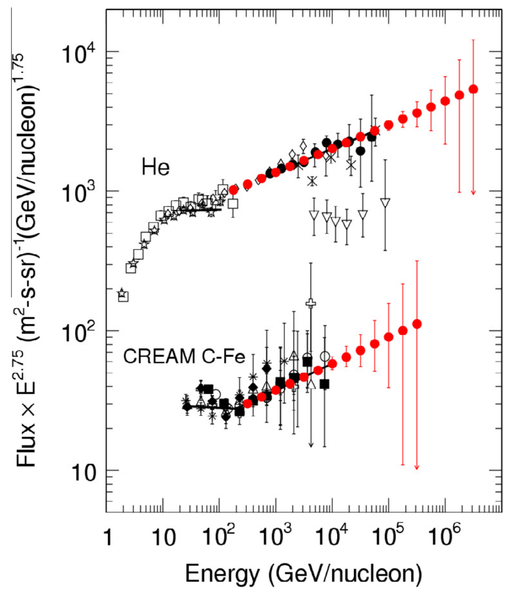

Fig. 3. Comparison of high-energy spectra from a nominal ISS-CREAM mission (red circles) with existing data (black symbols). Data from previous experiments include BESS (open squares), ATIC-2 (open diamonds), JACEE (X), and RUNJOB (open inverted triangles). The CREAM heavy nuclei data: Carbon (open circles), Oxygen (filled squares), Neon (open crosses), Magnesium (open triangles), Silicon (filled diamonds), and Iron (asterisks). See Ahn et al. (2010) and references therein for complete legend. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The exact cause of spectral hardening is still under investigation, although a number of possible explanations have been proposed (Ptuskin et al., 2013, 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 (Chang et al., 2008; Abdo et al., 2009). A multi-source model by Zatsepin and Sokolskaya (2006) considered nova stars and explosions in super-bubbles as additional cosmic-ray sources. Whether spectral hardening results from a nearby isolated supernova remnant (Ptuskin et al., 2010) or the effect of distributed acceleration by multiple remnants embedded in a turbulent stellar association (Medina-Tanco and Opher, 1993) 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 3×10^{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 e^-e^+ anomaly and the cosmic-ray "knee." Donato and Serpico (2011) 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. Examples of secondary origin of a rising positron fraction that does not require additional primary sources, such as pulsars or dark matter, can be found in Biermann et al. (2009) and Blum et al. (2013).

Yuan and Bi (2013) have shown how properties of the extra source derived from the e^-e^+ data depend on the forms of the cosmic-ray background spectra. They pointed out a tension between the AMS positron fraction (Aguilar et al., 2013 and references therein) and the total electron (including positron) spectrum detected by Fermi and HESS. They demonstrated how this tension 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 scenarios as the primary positron sources. It should be noted that there is no compelling evidence that primary electrons and nuclei are produced by the same mechanism. Gaisser et al. (2013) demonstrated how the recent data from ground-based indirect measurements, including IceCube/IceTop, can be explained with an extrapolation of rather hard elemental spectra from CREAM to higher energies and simple rigidity-dependent acceleration limits for three different types of accelerators.

CREAM has pushed direct spectral measurements of nuclei, including the important secondary elements (e.g., boron), to ever-higher energies with Antarctic LDB experiments. The energy region around 10^{15} eV is challenging to explore for primary element spectra 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. Exposing a CREAM payload on the ISS (dubbed ISS-CREAM) will take the next major step to 10^{15} eV, and beyond. A 3-year exposure on the ISS will greatly reduce the statistical uncertainties and extend CREAM measurements to energies beyond any reach possible with balloon flights, as illustrated in Fig. 3. Being above the atmosphere, ISS-CREAM would be far superior to multiple balloon flights.

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 also 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 over-current trip circuits in the power distribution sections to rapidly remove power from any subsystem that exhibits a high current condition due to any anomalous behavior. Active components that were not demonstrated to be latch-up free during SEE testing have over-current trip circuits that will rapidly remove power from the circuit in the event of a latch-up condition caused by SEL. Our parts and components were evaluated for any destructive SEL failures by the Radiation Effects and Analysis Group at the 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 they are undergoing rigorous environmental tests (Amare et al., 2013). 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 ISS-CREAM Science Flight Computer was connected to the Payload Rack Checkout Unit to simulate the actual Command and Data Handling (C&DH) setup on the ISS. During the testing, reliable flow of commands and telemetry between MSFC and the Science Operation Center at the University of Maryland was established (Angelaszek et al., 2013).

The launch vehicle and ISS accommodations will be accomplished using the stringent interface requirements provided by the NASA Johnson Space Center (JSC) and their relationship with Japan Aerospace Exploration Agency (JAXA) and Space Exploration Technologies Corp. (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 Design 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

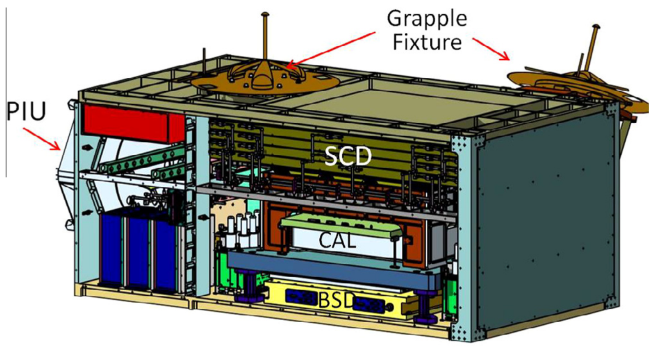

Fig. 4. The ISS-CREAM payload configuration. The Payload Interface Unit (PIU) is the attachment point of the payload to the ISS JEM-EF. Grapple fixtures are used by the ISS remote manipulator system (RMS) and JEM RMS to transfer the payload from the launch vehicle to the ISS. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 4) with ∼1300 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 payload are being performed. ISS-CREAM is in its implementation phase to complete the detailed design and component fabrication, as well as the integration and testing of the fully integrated 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 late 2014.

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