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

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The Cosmic Ray Energetics And Mass for the International Space Station (ISS-CREAM) instrument is designed and built to measure elemental spectra of cosmic-ray nuclei ($1 \leq Z \leq 26$) and electrons. It will measure energy of incident cosmic rays from 10^{11} to 10^{15} eV with a tungsten/scintillator sampling calorimeter and densified carbon target with an interaction length of ~ 1 λ_L. A finely segmented, four-layer silicon charge detector will identify the elemental composition with a resolution of ~ 0.15e. The instrument is triggered by selectable, independent, and combined algorithms from the calorimeter and a scintillator-based counting detector on the top and bottom of the calorimeter. The counting detectors also provide separation of protons and electrons using differences in the shower shapes. A boronated scintillator detector provides additional e/p separation by looking at late scintillation light produced by a particle interacting in the calorimeter system. ISS-CREAM underwent vibrational, electromagnetic, thermal/vacuum, and telemetry systems tests at various NASA facilities to qualify for rocket transportation and space operations. All testing and integration were completed and ISS-CREAM was delivered to NASA. It is now flight ready and waiting for launch on SpaceX-12 in 2017. ISS-CREAM integration, environmental qualification, and instrument performance will be presented.

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1. Introduction

The ISS-CREAM instrument is a next-generation space-based payload for the direct measurement of charged Galactic cosmic rays up to 10^{15} eV, complemented by a coterie of other recently launched instruments: NUCLEON ([1], satellite launched 12/26/2014), CALET ([2], ISS deployed 8/16/2015) and DAMPE ([3], satellite launched 12/17/2015). The science objectives of ISS-CREAM are to address long-standing astrophysical questions: (1) What is the origin of the "knee" in the all-particle cosmic-ray spectrum? (2) Is a single mechanism responsible for the cosmic-ray energy spectrum? (3) Are supernovae the primary source of cosmic rays? (4) What is the propagation history of cosmic rays in the interstellar medium? ISS-CREAM will be the first space mission capable of measuring low particle fluxes with the required precision at cosmic-ray energies approaching the knee at a few times 10^{15} eV. To achieve these primary astrophysical objectives, ISS-CREAM will: (1) determine how the observed spectral differences between protons and heavier nuclei evolve at energies approaching the knee; (2) measure detailed spectra of secondary nuclei that result from primary nuclei interacting with the interstellar medium; (3) conduct a high-statistics search for spectral features such as a softening of the proton spectrum; (4) accurately measure electrons to determine the possibility of nearby cosmic-ray sources. Further details on how ISS-CREAM measurements will address these scientific objectives is presented elsewhere [4]. ISS-CREAM will improve on the direct measurements of cosmic rays by an order of magnitude increase in exposure compared to that of balloon flights. Figure 1 depicts the expected spectra of helium and heavy nuclei after a three-year exposure of ISS-CREAM on the ISS, compared to the current data. The expected spectra for He and heavy nuclei is calculated by extending the duration of data taking to 3 years using the trigger rates and spectra indices from previous CREAM results [5]. ISS-CREAM is an external payload to be installed on the JAXA Experimental Module Exposed Facility (JEM-EF). The anticipated three-year (minimum) exposure will allow an increase in the energy reach and reduction of uncertainties by at least an order of magnitude compared to balloon flights [4].

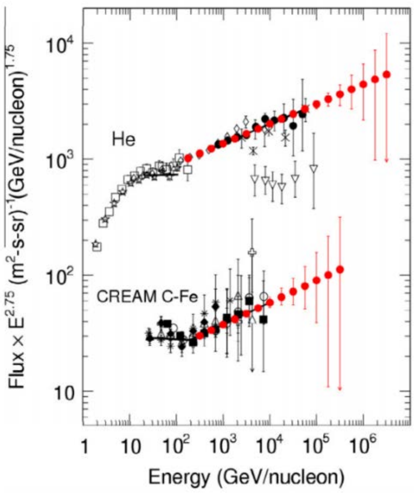

Figure 1. Expected high-energy spectra for a three-year ISS-CREAM mission (red circles, E.S. Seo, et al 2014) compared with selected existing data (black symbols). Existing data include BESS (open square, Sanuki 2000), ATIC-2 (open diamond, Panov 2009), JACEE (X, Asakimori 1998), and RUNJOB (open inverted triangle, Derbina 2005). CREAM heavy nuclei data (Ahn 2010) include carbon (open circles), oxygen (filled squares), neon (open crosses), magnesium (open triangles), silicon (filled diamonds), and iron (asterisks).

2. The ISS-CREAM Instrument

In order to achieve the science and measurement goals several detectors with specific capabilities are required. The calorimeter (CAL) is used to measure the incident energy of cosmic rays from 1 to 1000 TeV/nucleon with an energy resolution of 50% and a calibration within 10%. The silicon charge detector (SCD) measures charge to identify the elemental nuclei from $1 \leq Z \leq 26$ at a resolution of 0.2*e*. The top and bottom counting detectors (T/BCD) provide an independent trigger and provide electron/hadron separation. The boronated scintillator detector (BSD) detects the tail-end of the particle shower leaving the CAL and is sensitive to thermal neutrons generated within the CAL showers to provide additional separation between electrons and hadrons. Details of the CAL, SCD, T/BCD, and BSD can be found elsewhere [4][6][7][8] and are shown in Figure 2.

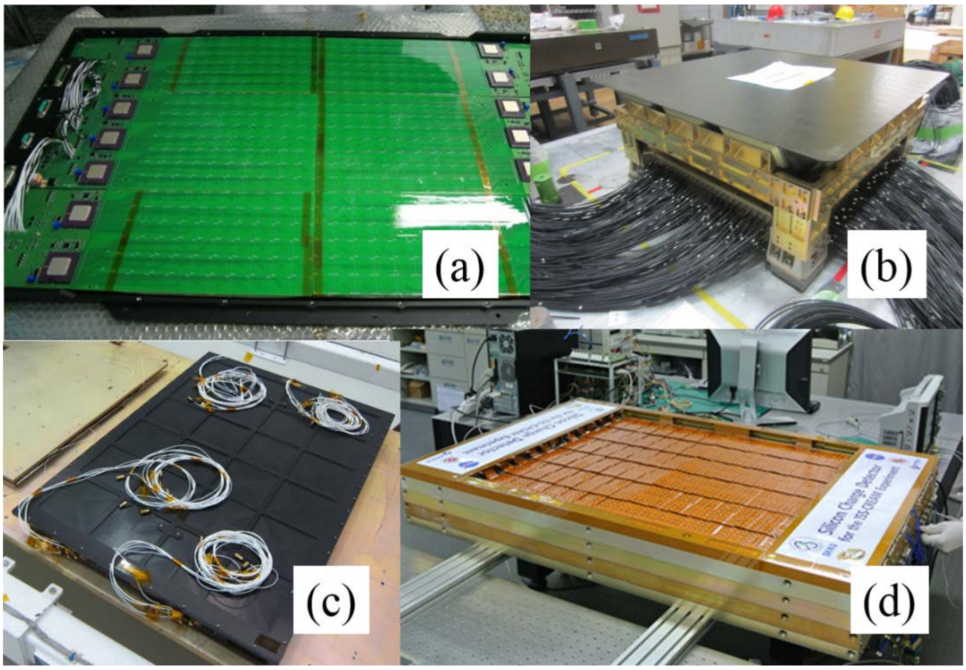

Figure 2. Photos of the (a) T/BCD, (b) CAL, (c) BSD, and (d) SCD

2.1 Detector Modifications for Launch and ISS Environment

For the ISS implementation of CREAM, the CAL was modified to accommodate the increased mechanical forces due to transportation on the Space-X Falcon rocket as compared to balloon deployment. Some structural changes from the basic design of the calorimeter result from gluing together the tungsten layers and scintillating fiber ribbons, encasing the graphite target in a fiberglass shell, and redesigning the calorimeter and target mechanical support structure. The components for each CAL layer comprise a tungsten plate, a fiberglass sheet with epoxy, scintillating fiber ribbons, another fiberglass sheet with epoxy, with a similar structure repeating for 20 layers total. The fiberglass sheets provide structural support for the epoxy to hold it within the area of the tungsten plates. Above and below the CAL layers are aluminum sheets that are glued to the tungsten-layer structure.

In a repeat of the balloon CREAM instrument design [9], the same carbon target ($\rho = 1.92$ g/cm^3) is implemented in ISS-CREAM as part of the calorimeter system to generate particle showers from the incident cosmic rays. Some modification from the balloon design was needed to accommodate the ISS-CREAM mechanical structure and maintain the integrity of the carbon. The two pieces of the target are encased in a carbon-fiber shell and bonded together to maintain the structural integrity of the graphite. On each side of the target are five rectangular pads bonded to the carbon-fiber that mount to the targets' mechanical structure. Figure 2 (a) is a photo of the target and CAL showing the top and mechanical structure of the target and the sides of the CAL with the black-jacketed cables.

The balloon-borne SCD with dual layers had demonstrated its excellent capability for cosmic-ray identification with a charge resolution of 0.2*e* during six flights over Antarctica [10][11]. The SCD for the ISS-CREAM experiment adopted this proven detector technology, with some modifications in the electronics. These include the replacement of non-radiation-hard electronics components from the balloon-borne detector with radiation-hard components, and the implementation of protection measures against single event latch-ups for the ADC components. The supporting mechanical structure is designed in such a fashion as to minimize the material in front of silicon sensors and to guarantee effective heat conduction between major heat-dissipating electronics components and mechanical structure.

The T/BCD were designed with the explicit goal of permitting electron and γ-ray identification beyond the core ISS-CREAM mission of making definitive measurements of nuclei. The T/BCD also have the capability of providing a redundant ISS-CREAM instrument trigger and a low-energy electron trigger [12]. The T/BCD detectors consist of an EJ-200 plastic scintillator (Eljen Technology) coupled to a 20×20 array of silicon photodiodes (PDs).

The BSD is designed to sample signals in its scintillator block occurring approximately 1-6 μs after a shower due to a cosmic-ray parent particle interacting in the graphite target blocks and developing in the CAL. Detection of this late light can be used to distinguish between nuclear and electron primaries when used in conjunction with energy data from the calorimeter. This measurement will complement electron-hadron separation via shower shape and interaction depth by the T/BCD and CAL.

3. Science Flight Computer

Central to the data-acquisition system is the SFC. It consists of a redundant pair of flight computers (SFC-A and SFC-B), where one is powered and the other is a cold spare. Each flight computer consists of a commercial off-the-shelf (COTS) single-board computer and USB host-controller board (USB-HCB). The USB-HCB contains the USB host controller, one EIDE boot-source flash drive (boot-0), and three USB boot-source flash drives (boot-1, -2, -3). Only one boot source is powered at a time with the other three as cold spares. The USB-HCB is the main USB interface of the SFC and connects directly to the SFC-interconnect (SFC-IC) and instrument-interface unit (IIU). Also on each SFC-IC card are four USB flash drives, independent of the boot-source flash drives, for on-board data storage.

New to ISS-CREAM implementation is the use of the instrument-interface unit to control SFC power switching, boot-source selection, and rebooting. The purpose of the IIU is to autonomously monitor the proper functionality of the SFC and take corrective actions if necessary. Management of these functions is performed by logic programmed onto the IIU FPGA through the use of two watchdog timer (WDT) conditions called local-USB WDT and ground WDT. The local-USB WDT is a ten-minute timer that receives a periodic response initiated by the ISS-

CREAM data-acquisition system running on the SFC (CDAQ server). The ground WDT is a three-hour timer that receives a periodic response by ground-based data-acquisition systems (CDAQ client) via command. Each WDT is reset independently by its respective source. ISS systems are also able to send CDAQ commands to ISS-CREAM through a timed commandable sequence called a time-liner.

4. Integration

All detectors, electronics boxes, temperature sensors, wire harnessing, and JEM-EF interfaces were integrated into the payload and mechanical structure at NASA Wallops Flight Facility (WFF). Integration started in December 2014 and ended April 2015. This was the first time for integration of ISS-CREAM components and sub-systems. Electronics systems were tested and optimized for noise reduction, the thermal coolant loop was tested for leaks and optimal thermal coolant, and the detectors were tested using external muon detectors. A photo of the completely integrated ISS-CREAM payload is shown in Figure 3.

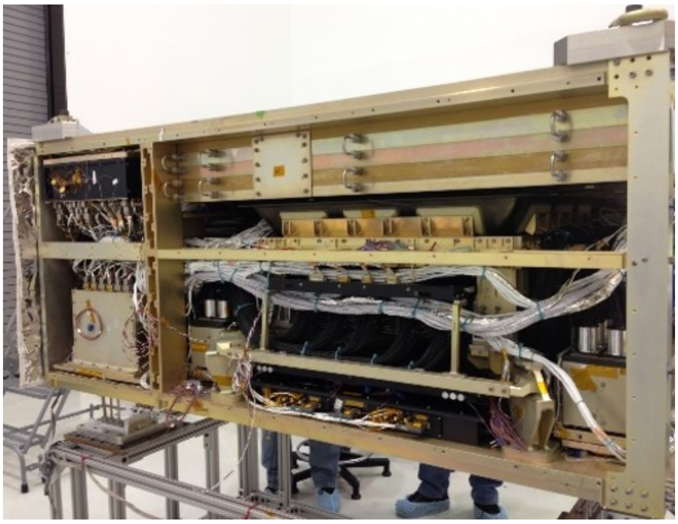

Figure 3. Photo of the ISS-CREAM payload after integration is complete and all systems tested and functionality verified.

5. Environmental Qualification

Any payload that will operate on the ISS must pass a variety of tests that qualify it for travel on a rocket and operation in low-earth orbit. Environmental tests consist of vibration, electromagnetic, and thermal/vacuum qualifications that ISS-CREAM must meet. These tests were performed at NASA's Goddard Space Flight Center (GSFC) facilities for several sub-components in April – November 2014, and the payload as a whole in April – August, 2015. To qualify the mechanical structure, ISS-CREAM was subjected to low-frequency (0-20Hz) vibrations on a specialized table and to high-frequency (20 – 1600Hz) vibrations in an acoustic chamber. All tests were performed to qualification levels of 1.25 times expected flight levels. Table vibration tests the payload for strength (sine-burst) and over a range of frequencies (sine-sweep) in each coordinate orientation x, y, and z. The acoustic chamber tests were performed for random frequencies in the aforementioned range in of launch levels +3dB (116 – 132dB) for 60s. ISS-CREAM passed both vibration and acoustic tests. ISS-CREAM is also required to meet certain electromagnetic (EM) characteristics in order to safely operate on the ISS near other science payloads and ISS equipment. Specifically ISS-CREAM EM emissions must not interfere with other ISS equipment and payloads (emissions), must operate within range of outside EM emissions (susceptibility), and maintain power quality sufficient for ISS-CREAM and the JEM-EF power supply. Together these tests are known as electromagnetic induction and electromagnetic compatibility (EMI/EMC). The purpose of testing in a thermal/vacuum chamber (TVAC) is to check for damaging corona effects, and to produce temperature levels and gradients that replicate the thermal environment of the ISS space environment. The payload and subsystems are subjected to survival and operational temperature levels. Survival levels are the maximum limits that are possible for materials and electronics or limits experienced in flight in an unpowered state. Operational levels are maximum limits for electronics in a powered state. Several sub-components of ISS-CREAM were individually tested in TVAC tests as well as the payload as a whole. For the payload, TVAC temperature cycles included one cycle at hot and cold survival limits and two cycles at operational limits. All tests concluded satisfactorily and the ISS-CREAM instrument satisfactorily passed all flight readiness review and was deemed ready to launch by August 2015. The payload has been delivered to NASA’s Kennedy Space Center where it is maintained in a nitrogen-controlled storage chamber in anticipation of a 2017 launch and deployment to the ISS.

6.Flight Operations and Data Handling

Flight operations will be managed at the Science Operations Center (SOC) at UMD by ISS-CREAM collaboration members, in coordination with the Payload Operations Integration Center at Marshall Space Flight Center. Operators will staff the SOC 24/7 to command the instrument, receive and monitor data and instrument performance, as well as back-up and archive data on additional UMD servers and distribute data to collaboration sites. The facilities and processes at UMD are the same that have been used for the Antarctic balloon flights. Data will be produced as downlinked through the TDRSS satellite system at an average rate of ~ 500 kbps with an expected 5.4 GB per day. There is 32 GB of on-board storage system with four-fold redundancy (128 GB total) to store data on a single drive for up to 24 days in case of prolonged loss of signal. ISS-CREAM will have a continuous downlink of housekeeping and science data in near real-time. Commanding to adjust operational parameters will be done periodically as needed. Once ISS-CREAM is installed on the JEM-EF, the instrument parameters will be optimized within the first two weeks and nominal data collection and operations will continuously run for a minimum of three years or end of station life. All parts of operation and data handling have been tested with the SOC and POIC systems.

Calibration and science data will be processed into the ROOT format and divided into levels called L0, L1, and L2. L0 is the first level used to analyze detector performance and determine in-flight calibration parameters. It consists of raw instrument signals with pedestals subtracted. Calibrations and channel mappings are then applied to the L0 data in order to generate L1 data that consists of signals in physics units such as energy and charge. The final level of processing for data analysis is the reconstruction of incident particle energy, charge, and trajectory into the L2 dataset. Each level of the processing and data is shared between collaboration institutes. This method of data processing, reconstruction, and distribution has been used by the CREAM collaboration for the Antarctic balloon flights.

7. Conclusion

The Cosmic Ray Energetics And Mass Instrument on the International Space Station (ISS-CREAM) was designed and built to extend the direct measurements high-energy (10^{12} – 10^{15} eV) cosmic rays by an order of magnitude from previous balloon-borne investigations. In order to achieve this goal ISS-CREAM will measure the energy and identify the elemental composition of incident cosmic-ray nuclei ranging from electrons and protons to heavier nuclei up to iron ($1 \leq Z \leq 26$). With an anticipated three-year exposure to cosmic rays on the ISS, we will address long-standing astrophysical questions: (1) What is the origin of the "knee" in the all-particle cosmic-ray spectrum? (2) Is a single mechanism responsible for the cosmic-ray energy spectrum? (3) Are supernovae the primary source of cosmic rays? and (4) What is the propagation history of cosmic rays in the interstellar medium? ISS-CREAM will be the first space mission capable of measuring low particle fluxes with the required precision at cosmic-ray energies approaching the astrophysical knee. Detector elements, their readout systems, and the data acquisition scheme used to accomplish these astrophysics goals are robust and have a rich balloon heritage.

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