Silicon Charge Detector (SCD) for Cosmic Ray Measurements

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On behalf of the SCD team of ISS-CREAM
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• High Energy Cosmic Rays
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• Plan and Prospects
High Energy Cosmic Rays
Accelerators that reach above $10^{20}$ eV
ZeVatrons ($10^{21}$ eV)
but...
What are they?
Where are they?
1912 discovered by Victor Hess (after Wilson & others)

a compilation of direct and indirect cosmic ray observations integrated into a single spectrum

12 orders of magnitude

1938 Pierre Auger discovered Extensive Air Showers (EAS) > 10^{15} \text{ eV}

Energy range:
~ 10^9 \text{ eV} to > 10^{20} \text{ eV}

Grand-Unified Cosmic Ray Spectrum

Cosmic origin

Fluxes of Cosmic Rays

(1 particle per m^2-second)

Knee (1 particle per m^2-year)

Anide (1 particle per km^2-year)

Taken from Simon Swordy
http://hep.uchicago.edu/~swordy/crspec.html
Direct Measurements of Cosmic Rays

Fluxes of Cosmic Rays

Direct Measurements

Indirect Measurements

32 orders of magnitude

Energy (eV)

$E^{-2.7}$

$10^{15}$ eV

$E^{-3.1}$

Proton Satellite Mission

(1 particle per m²-second)

Knee

(1 particle per m²-year)

Ankle

(1 particle per km²-year)
Mystery of High Energy Cosmic Ray

1. How are cosmic rays accelerated to such very high energies?
2. Where do they come from?
3. What is the composition?

- No one knows

Now to be a Century Old Puzzle!
at all energies... (since 1912, discovery of cosmic ray by Hess)

Energy range:
~ $10^9$ eV to $>10^{20}$ eV

Fluxes of Cosmic Rays

10$^{15}$ eV

Supernova: Source up to the Knee energy?

Taken from Simon Swordy
http://hep.uchicago.edu/~swordy/crspec.html

a compilation of direct and indirect cosmic ray observations integrated into a single spectrum
Supernova Remnant Shock Wave

Origin: Supernovae believed to be a source

- Enrico Fermi first (1949) explained how cosmic rays are accelerated
  - Stochastic collision with moving magnetic clouds produced from SNR

- Acceleration limit
  - $2 \times 10^{14} x Z \text{ (eV)}$
  - Change in element composition
ISS-CREAM: The payload on ISS in 2014
ISS-CREAM proposed for ROSES 2010

Increase the exposure by an order of magnitude

- The ISS is nearly ideal for our quest to investigate the low fluxes of high-energy cosmic rays.
Science Questions & Goals
- Do supernovae really supply the bulk of cosmic rays?
- What is the history of cosmic rays in the galaxy?
- What is the origin of the ‘knee’ around $3 \times 10^{15}$ eV in the cosmic ray energy spectrum?
- Can the energy spectra of cosmic rays result from a single mechanism?

Mission Goal
- Extend the energy reach of direct measurements of cosmic rays to the highest energy possible to probe their origin, acceleration and propagation.

Measurement Objectives
- Measure the energy spectra from $10^{12}$ to $>10^{15}$ eV over the elemental range from protons to iron, and study the composition change
  ✓ Determine how the observed spectral differences of protons and heavier nuclei evolve at higher energies approaching the “knee”
  ✓ Measure potential changes in the spectra of secondary nuclei resulting from the interactions of primary cosmic rays with the interstellar medium
  ✓ Search for spectral features, such as a bend in the proton spectrum
Proposal selected by NASA
## Instrument Requirements and Capabilities

<table>
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<tr>
<th>Measurements</th>
<th>Instrument Requirements</th>
<th>Instrument Capabilities</th>
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</thead>
<tbody>
<tr>
<td>Charge Range</td>
<td></td>
<td>SCD: 1(H) ≤ Z ≤ 28 (Ni)</td>
</tr>
<tr>
<td>Charge Resolution</td>
<td></td>
<td>SCD: δZ ~ 0.2 e</td>
</tr>
<tr>
<td>Energy Range</td>
<td></td>
<td>CAL: from 1 to &gt; 1000 TeV/nucleus</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td></td>
<td>CAL: δE/E ~ 40 %</td>
</tr>
<tr>
<td>Energy Calibration</td>
<td></td>
<td>CAL: Better than 10%</td>
</tr>
<tr>
<td>Collection Power</td>
<td></td>
<td>3 year mission gives 1 m²-sr-year</td>
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</table>

**SCD:** Silicon Charge Detector  
**CAL:** Calorimeter
Concept of ISSCREAM Payload at ISS

Two major instruments: SCD for composition & Calorimeter for energy measurement

SCD (four layers of silicon)
Carbon target
Calorimeter (W-Fiber sandwitch)

Dimensions: 100x185x95cm³
Excellent Charge Distribution from SCD

Cosmic ray data measured with CREAM SCD

Z=1 (H) to Z=28 (Ni)!
Charge resolution ~0.2e

H.S. Ahn et al. (ApJL. 714, L89-L93, 2010)
Experimental Heritage: Balloon borne experiment CREAM
6 Flights with 161 days cumulative exposure

CREAM-I
12/16/04 – 1/27/05
42 days

CREAM-II
12/16/05-1/13/06
28 days

CREAM-III
12/19/07-1/17/08
29 days

CREAM-IV
12/19/08 - 1/7/09
19 days 13 hrs

CREAM-V
12/1/09 – 1/8/10
37 days 10 hrs

CREAM-VI
12/21/10 – 12/26/10
5 days 16 hrs

“NASA Group Achievement Award” in 2006
 ✓ Elemental composition near the knee
 ✓ Direct measurement of Energy & Charge of primary cosmic rays
 ✓ Optimized arrangement of several components

TCD: Timing based Charged Detector
identify incoming particle ID
TRD: Transition Radiation Detector
measure velocity for Z≥3
SCD: Silicon Charge Detector
identify particle ID for Z<28
CAL: Tungsten-SCN Calorimeter
measure energy for Z≥1
S1-3: Hodocope
trigger & charge measurement
Experiment Cycle

Landing

Launch

Move to Antarctica

SCD-1 built in Korea

Integration at NASA

Space Qualified at UMD

Park I.H., KARI–NASA meeting at KARI on Apr. 21, 2009
Elemental Spectra over 4 decades in energy

Excellent charge resolution from SCD
CREAM results contradict the traditional view that a simple power law can represent cosmic rays without deviations below the “knee” around 3 x10^{15} eV.

- It provides important constraints on cosmic ray acceleration and propagation models, and it must be accounted for in explanations of the electron anomaly and mysterious cosmic ray “knee.”
Silicon Heritage
Principle of Charge Measurement in Silicon

- Energy loss of a charged particle in the matter by Bethe-Bloch formula

\[ -\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z^2}{A} \beta^2 \left[ \ln \left( \frac{2m_e \gamma^2 v^2 W_{\text{max}}}{I^2} \right) - 2\beta^2 - \delta - 2 \frac{C}{Z} \right] \]

with

\[ 2\pi N_a r_e^2 m_e c^2 = 0.1535 \text{ MeVcm}^2/\text{g} \]

\[ r_e: \text{classical electron radius} = 2.817 \times 10^{-13} \text{ cm} \]
\[ m_e: \text{electron mass} \]
\[ N_a: \text{Avogadro's number} = 6.022 \times 10^{23} \text{ mol}^{-1} \]
\[ \delta: \text{density correction} \]
\[ \rho: \text{density of absorbing material} \]
\[ z: \text{charge of incident particle in units of } e \]
\[ \beta = \frac{v}{c} \text{ of the incident particle} \]
\[ \gamma = \frac{1}{\sqrt{1 - \beta^2}} \]
\[ I: \text{mean excitation potential} \]
\[ Z: \text{atomic number of absorbing material} \]
\[ A: \text{atomic weight of absorbing material} \]
\[ W_{\text{max}}: \text{maximum energy transfer in a single collision.} \]

- For relativistic particle, energy deposit, \( \frac{dE}{dx} \), doesn't depend strongly on energy

\[ -\frac{dE}{dx} \propto z^2 \]

\[ \text{current} \]

\[ \text{P+ 0.6um} \rightarrow (1,1,1) 5 \text{ k}\Omega \rightarrow N\text{-type} \rightarrow \text{N+1.0um} \]

\[ \text{High Energy Particle} \]

\[ \text{current} \]

\[ \text{P+ 0.6um} \rightarrow (1,1,1) 5 \text{ k}\Omega \rightarrow N\text{-type} \rightarrow \text{N+1.0um} \]

\[ \text{High Energy Particle} \]
Z dependence of Energy Loss

- $dE/dx \propto Z^2$
- Linearity in detector gain confirmed over the wide range of $Q$

2005 CERN Beam Test of SCD
Fabrication of Silicon Sensors

- PIN diode, DC type
- Wafer: (1,1,1) type, 380 or 525 um, 6”, single polished, high resistivity ( >5 kOhm.cm)
- P+ implantation process, while N+ diffusion process, three guard rings
- The silicon sensor is designed to have low leakage current with optimized size of pixel. The overall size of the silicon sensor is 6.5cm x 5.8cm, and the sensors have pixels of about 1.5cm x 1.3cm in size arranged in an active area.
Characteristics of Typical Silicon Sensor

Fabricated sensors shows very low leakage current ~ a few nA/pixel
Process of Sensor Packaging

1. Sensor Fabrication
   Fabricate sensor
   Wafer size: 6 inch, 525 μm
   Pixel size: 15.5 × 13.7 mm²
   Array: 4 × 4 matrix

2. Dicing & Attachment of FPCB

3. Wire bonding
   Double or triple wire bonding is applied with Al wire of 1.25mil(~31μm) in diameter.

4. Glob top

5. Making Modules

6. Assemblage of Module (named ladder)
   One ladder is composed with 7 sensor module.

Full assembled SCD including thermal strips to eliminate heats from the detector

*PROPRIETARY DATA* - The information in these document(s) can only be shared among the ISS-CREAM project team and their designated review authorities on a need-to-know basis.
Overall Production Yield ~ 70%
Overview of Electronics: Readout, Control, Power

Same for SCD-1, 2, 3, L

- Analog Board
- ACP Board
- High Voltage Power Supply
- ADC
- Control
- Sensor
- Sparsification Board
- Command Board
- Calibration Board
- Slow Control Board
- PC
Analog Frontend Electronics with CR1.4 chip

- Developed for the Pamela Experiment
- 16 channels of charge inputs (integrating the charge pulses -> DC levels)
- Gain: 1mV/fC
- Dynamic Range: 4000
  - up to 150 pF capacitance with leakage currents as high as 100 nA. It measures charge from 2.2 fC to 9 pC.
- Noise ~ 5000 e
- Power: 0.3 mW/ch
- The outputs of the T/H circuits are multiplexed to a common output buffer that is capable of driving a load of 1k and 100 pF.
- The output of chip swings from -3V to 4V
Digital Electronics

In charge of ADC, Control, Power distribution
2008 CERN Beam Test of 525 micron thickness silicon

100GeV electron beam
- Bias: ±75V (150V)
- Beam I_leakage: ~1um
- Scintillator trigger
- Signal to noise ratio : 17
  = (150-20.4)/7.5

150GeV proton beam

Noise RMS: 4.26
S/N: 11.73
SCD-1 for CREAM-1 (flown in 2004/2005)

- Total size = 818.39 x 818.39 x 7 (mm)
- Total Height = 21.5 mm (including shielding box)
  - Total sensor area = 779 x 797 (mm)
  - Active area = 777 x 795 (mm)
- Total 2912 channels, 128 sensors
- No dead area between sensors
- 26 analog boards, 4 digital boards
- Total ~ 13 kg, total height ~ 25 mm

All developed and made by Korea
Dual Layer SCD-2 for CREAM-2,3,4,5,6 (2006~2011)

- Total 4992 channels, 312 sensors
- Sensitive area 77.9*79.5 cm². No dead area between sensors
- 48 analog boards, 28 digital boards, Consume power of 136W
- Total 56kg, total height 97.5mm
**Dual Layer SCD-3 for CREAM-7,8,9,10,11 (2012-)**

**Replica of SCD-II**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>818.4x818.3x100 mm³</td>
</tr>
<tr>
<td>Layer</td>
<td>2 layers</td>
</tr>
<tr>
<td>Channel (sensor)</td>
<td>5824 ch. (364 sensors)</td>
</tr>
<tr>
<td>Detection area</td>
<td>77.9x79.5 cm²</td>
</tr>
<tr>
<td></td>
<td>100% (No dead area)</td>
</tr>
<tr>
<td>Analog board</td>
<td>48 analog boards</td>
</tr>
<tr>
<td>Digital board</td>
<td>28 digital boards</td>
</tr>
<tr>
<td>Power</td>
<td>136W</td>
</tr>
<tr>
<td>Mass</td>
<td>56kg</td>
</tr>
</tbody>
</table>
Large SCD (SCD-L) for Balloon Flights from 2012

- Area = 2.3 times of the existing SCD
- No material in front
- 3 layer tracking capable combined with SCD
- Improved charge resolution
Large Area SCD-L for CREAM-7,8,9,10,11 (2012-)

One block assembly

Frame
ACP & Sub
Connector Panel
Ladder

Three block assembly

Top Honeycomb plate
Assembly completed

Bottom Honeycomb Plate

1200 x 1200 x 100 mm³
Single layer
6720 ch (420 sensors)
100% (No dead area)
60 analog boards
30 digital boards
136W, 80kg

All developed and made by Korea
Silicon Charge Detector (SCD) of ISS-CREAM
SCD Requirements and Specification

- 4 layer Silicon Charge Detector to measure the charge of cosmic rays with the best ever resolution
- Silicon PIN diode sensor equipped with analog ASIC chips and digital electronics
- 182 sensors/layer, total 910 sensors
- 130 Analog ladders, 65 Digital boards
- Volume 1200x 900 x 200(h) mm³
- Active area per layer: 818x 818 mm²
- Dynamic range: $1 \leq Z \leq 28$
- Expected charge resolution $< 0.2$ e
- Mass: ~130 kg
- Power consumption: ~250 W
Best “EVER” Charge Measurement
(MC simulation)

2d cut with 2 layer

With 2 layer

3d cut with 3 layer

With 3 layer
Sensor module

Sensor (4x4 pixel)

Sensor glued to PC by 3M-DP100

Analog board to PC

Ladder

Attachment holes for ladder

Sensor module

Analog board

1 layer

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Structure of A Layer
Overall View of ISS-CREAM SCD

4 layer dimension with cover: 1225.4 x 878 x 163.5 mm$^3$

Active area ~ 818 x 818 mm$^2$
(No dead region)
ISS-CREAM Payload at ISS (Launch in 2014)

SCD (Silicon Charge Detector) by SKKU

Electronic Boxes

Grapple (FRGF)

Target

Calorimeter

TCD by Kyungpook Nat’l U.

Calorimeter by U. Of Maryland

JEMRMS Transfers Payload to Berthing Location on EF

ISS-CREAM (EFU #2)

ISS Direction of Travel

EF Customers
Plan and Prospects

• Sensors, ladders, electronics are available
• Fabrication of single layer structure and overall support structure is under way
• Various analysis and adaption/modification for space qualification such as thermal/vacuum, stress/strain, and shock/vibration, is in progress
• Modification of electronics for radiation hardness is non-trivial and under study
• Delivery of the entire SCD for ISS-CREAM is foreseen in the middle of 2013
• Launch of ISS-CREAM is planned in 2014 for at least three years operation at ISS
• 1000 days of total exposure would be enough to achieve the science goals (to unveil the origin, acceleration, and propagation of cosmic rays)
ISS-CREAM Collaboration

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