Measurements of ULTRA-Heavy Galactic Cosmic-Ray (UHGCR) Nuclei Beyond SuperTIGER: TIGERISS on The ISS and The Heavy Nuclei eXplorer (HNX)

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HNX Science Objectives

• Determine whether ultra-heavy galactic cosmic rays (UHGCRs) are accelerated from newly synthesized or old material, and find their age since nucleosynthesis
  – Ratios of heavy nuclei probe age of accelerated material
  – Actinide (Uranium group) “radioactive clocks” measure UHGCR age - relative abundances probe mixture of old and new material
• Determine where/how UHGCR are accelerated and their subsequent history
  – Element abundances carry the signature of the site of injection into the accelerator and the mechanism of selection for acceleration
    • OB associations?
    • Binary neutron star mergers?
    • Acceleration from dust (refractory) or cold ISM gas (volatile)?
• Determine the mix of nucleosynthesis processes (r and s process) for UHGCRs
• Search for superheavy nuclei and strange quark matter
  – Superheavy elements may live long enough to be accelerated
  – Search for predicted strange quark matter “nuggets” with mass as much as 5 orders of magnitude heavier than Uranium.
TIGER in Space

• SuperTIGER (ST) has been very successful. However, has basic limitations:
  • Exposure time: ST has limited statistics above about Z=50
  • Charge resolution: ST has reduced element resolution above Z=50
    • Result of saturation of scintillator light production.
  • Solution is multiple layers of thin solid-state detectors that have signal directly proportional to ionization energy deposit.

• Two mission concepts have been developed using same technology for electronic instrument
  • TIGERISS—International Space Station—JEM-EF attachment point
  • Heavy Nuclei Experiment (HNX)—Space-X Dragon Lab
TIGERISS

Major Astrophysics Missions on the International Space Station

- NICER (2017)
- AMS-02
- ISS CREAM (2017)
- CALET
- MAXI
- JEM-EUSO (TBD)
The HNX Experiment on Space-X Dragon Lab

HNX uses two complementary instruments to span $6 \leq Z \leq 96$ ($Z > 96$ if flux exists) with the needed high exposure factor and charge resolution.

ECCO (Extremely-heavy Cosmic-ray Composition Observer)
- Uses $\sim 21$ m$^2$ of Barium Phosphate (BP-1) glass tiles covering the walls and part of the top of the DragonLab Capsule to measure $Z \geq 70$ (Yb) nuclei
- Recovery is required for post-flight processing of glass

CosmicTIGER (Cosmic-ray Trans-Iron Galactic Element Recorder)
- 2 m$^2$ electronic instrument using – silicon strip detectors and Cherenkov detectors with acrylic and silica-aerogel radiators in the pressurized DragonLab Capsule

DragonLab Capsule Accommodation
- Pressurization of capsule reduces complexity of CosmicTIGER – no high-voltage potting, convective/forced air cooling and Temperature Stability for ECCO
- Mission duration baseline is 2 years, can be extended since there are no consumables
• 2 Layers of SSD (10 cm x 10 cm x 500 μm); 3.12 mm strip pitch (50 μm gap) at top and bottom.
• Orthogonal strips give X and Y coordinates.
• Cherenkov detectors (acrylic and aerogel) use light integration boxes lined with Gore DRP reflector.
• 40 Hamamatsu R6233-100 PMTs each with 7 cm photocathodes and 30% QE
• Dimensions of TIGERISS on JEM-EF are \(~1.55 \text{ m} \times 0.7 \text{ m}\); \(A\Omega \approx 2.3 \text{ m}^2\text{sr}\)
• Mass \(~300\text{kg}\); Power \(~200 \text{ W}\)
• TIGERISS uses engineering developed at Wallops Flight Facility (WFF) for the ISS-CREAM pallet.

CALET (Calorimetric Electron Telescope) on Kibo since August 2015
Results from 2015 CERN Lead test beam run: HNX planar silicon detectors with discrete CSA electronics

**Beam Test Setup**

- **Fixed Table**
- **Moving Table**
- **Fixed Table**

**Charge Resolution**

**HNX Si Planar prototypes:**

\[ \delta Z \leq 0.15 \text{ cu} \]

**Current HNX Detector Development**

- We have ordered 5 HNX prototype silicon strip detectors for 2016 CERN Pb test run:
  - 10 cm \( \times \) 10 cm \( \times \) 500 um
  - single-sided, DC coupled
  - 32 channels
  - 3 mm strip pitch
- Caltech PHASIC readout of strips (16 channels) Ohmic side read out with space-proven preamp/shaper.
- Will assess the performance of the HNX strip detectors with the PHASIC in the laboratory at GSFC and at a CERN Lead test beam run scheduled for late 2016.
ECCO Charge Identification

- coring
- calibration
- wafering
- Grind and polish
- etch

Automated scanning with robotic handling

• Accurate Z measurement – results from Au beam shown
• $\sigma_z \leq 0.35e$ for $Z \geq 70$
• $\sigma_z \leq 0.25e$ for $Z \geq 70$ with reduced statistics

April 17, 2016

2016 APS April Meeting
• These instruments will measure the composition of the ultra-heavy cosmic rays with single element resolution from $\text{^{6}C}$ to $\text{^{96}Cm}$, or through $\text{^{82}Pb}$, depending upon the version flown.

• Builds on heritage from Trek (Mir), HEAO, TIGER, SuperTIGER, and Solar Probe Plus as well as the HNX-Shuttle Phase A study.

• All components and systems have very high technology readiness levels.

• All we need is money!
Backups
Signature of a Young Sample

Actinides (Th, U, Pu, Cm) are clocks that measure absolute age of the UHGCR

- Holy Grail” of nucleosynthesis research for over 40 years
- Half-lives span the timescales for galactic chemical evolution
- Relative abundances strongly depend on the age of the GCR source material
- Ratios of daughter/parent nuclei important: Th/U, (Th,U, Pu)/ Cm
- HNX will measure ~50 actinides to probe the UHGCR age

Possible actinide abundances from 2 years of HNX data compared to Trek (Mir) measurements. LDEF UHCR experiment has high statistics but limited resolution.
HNX Science Design

- HNX explores to the end of the periodic table
- Elements in the upper 2/3rds are extremely rare

- Requires a very large instrument with a long exposure in space!
- HNX uses complementary active (CosmicTIGER) and passive (ECCO) detectors to give the required ~ 50 m²sr geometric factor
- ECCO uses BP-1 (barium phosphate) glass detectors
  - Trek experiment on Mir used BP-1 to record the only cosmic-ray actinides (4 nuclei) reported
  - Requires return to Earth for processing ➔ SpaceX DragonLab
- CosmicTIGER electronic instrument is based on TIGER and SuperTIGER balloon instruments as well as HEAO and Solar Probe Plus space instruments
Kibo-EF attachment sites

- **FOV obstruction**
  - 2
  - 6 kW; Ethernet, 1553, Video

- **3 kW; Ethernet, 1553, Video**
  - 4

- **3 kW; Ethernet, 1553, Video**
  - 6

- **3 kW; Ethernet, 1553, Video**
  - 8

- **Slight obstruction from camera mount; obstructed during EP berthing**

- **Pressurized Module**

- **JEM-EF**
  - **Good zenith viewing**
    - 11
    - 3 kW; Ethernet
  - **Currently unoccupied; reserved for ICS back-up**
  - **Dedicated to ICS**
  - **Temporarily Parking**
    - 12
    - 3 kW; Ethernet

- **EPMP Berthing location**
  - 10

- **Only location with Port view**
  - 9
  - *Capability for 2.5 MT payload*

- **ISSP OZ 3/Chang**
ECCO Overview

- ECCO based on TREK experiment on MIR
- ECCO BP-1 detector modules cover capsule walls, part of top, and beneath CosmicTIGER
- Active area 21 m², \( A\Omega = 48 \text{ m}^2\text{sr} \)
- Five layer module made of barium-phosphate BP-1 glass
  - Preliminary Charge Identification Modules (PCIMs – 1 mm): identify charge group
  - Hodoscopes (1.5 mm): initial identification and trajectory determination
  - Monolithic central detector (25 mm): make accurate charge measurements and slow nuclei to measure energy
- Glass is etched to “develop” nuclear tracks
- Tracks are measured using fully automated microscope system with resolution ≤ 50nm

ECCO is simple on orbit...

... all the sophistication is in the laboratory
Japanese Experiment Facility (Kibo-EF)
**Organization**
- PI: John W. Mitchell/NASA Goddard Space Flight Center
- DPI: Andrew J. Westphal/ U. C. Berkeley
- Co-I: W. Robert Binns/Wash. U. St. Louis
- Co-I: Mark E. Wiedenbeck/JPL-Caltech
- Spacecraft/Launch: SpaceX

**Science Goals**
- Investigate the origin and age of ultra-heavy galactic cosmic-ray (UHGCR) elements.
- Determine the injection mechanism for galactic cosmic-ray acceleration.
- Probe coronal acceleration to high-energy spectral “knee”

**Instruments**
- CosmicTIGER – Electronic detector system measuring \( {^{10}\text{Ne}} \) to \( {^{83}\text{Bi}} \).
- ECCO – Barium Phosphate Glass track-etch detector system measuring \( {^{70}\text{Yb}} \) to the actinides.

**Mission Overview**
- HNX Plus flies in pressurized SpaceX DragonLab capsule for entire mission
- LEO (ISS inclination or higher) for 2 years
- SpaceX (DragonLab + Launch) $74 million
- ECCO Tiles must be returned to Earth for analysis

**HNX SMEX Schedule – HNX Plus Shift Later 2 Years**
Primary HNX Science Goals

• Record a direct sample of matter from the birthplace of heavy nuclei – to the end of the periodic table
  – Supernova (SN) shocks accelerate material from recent SN and stellar winds. (ACE, TIGER, SuperTIGER)
  – HNX is a “sample return” mission of nuclei that will almost certainly contain recently synthesized material
  – Young sample (<20 Myr since acceleration) probes nucleosynthesis through the ratios of heavy nuclei
  – **Actinide (Uranium group) elements act as radioactive clocks** to measure galactic cosmic ray (GCR) ages - relative abundances indicate mixture of old and new material

• **Determine how cosmic accelerators work**
  – Verification of fresh material in the heaviest cosmic rays would strongly support supernova hadron acceleration observations by Fermi Large Area Telescope
  – Relative element abundances carry the signature of the site of injection into the accelerator and the mechanism of selection for acceleration
    • OB associations?
    • Relative importance of dust (refractory material) or gas (volitale) from cold Interstellar Medium

• **Determine how and where heavy elements are synthesized**
  – Rapid neutron capture (r-process) elements are produced in supernova explosions
  – Slow neutron capture (s-process) elements are produced in massive stars
Investigate the two least understood, but critically important, aspects of the grand cycle of matter in the galaxy: the nature of the astrophysical reservoirs of nuclei at the cosmic-ray sources and the mechanisms by which nuclei are removed from the reservoirs, injected into the cosmic accelerators, and then accelerated.