Ultra-Heavy GCR measurements beyond SuperTIGER: The Heavy Nuclei eXplorer

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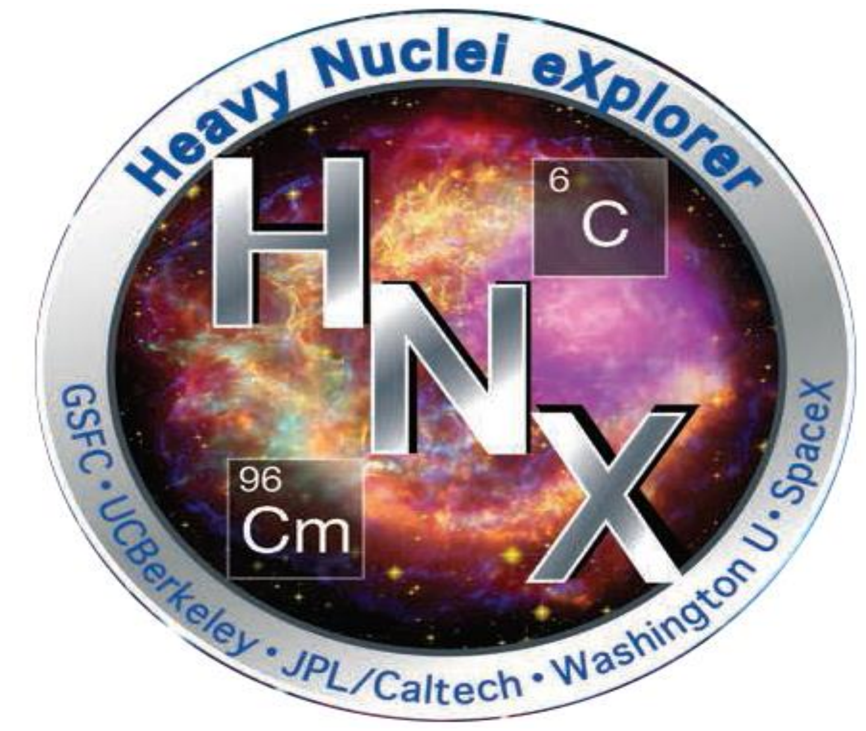
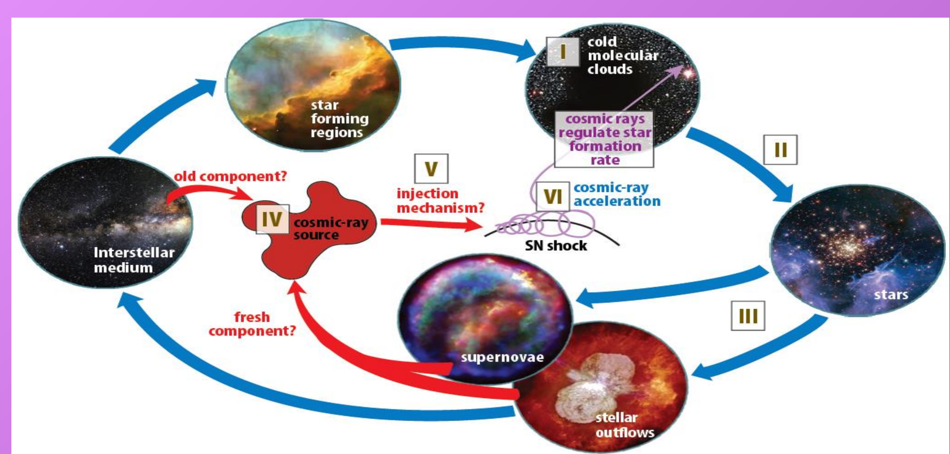


Ultra-Heavy Galactic Cosmic Rays

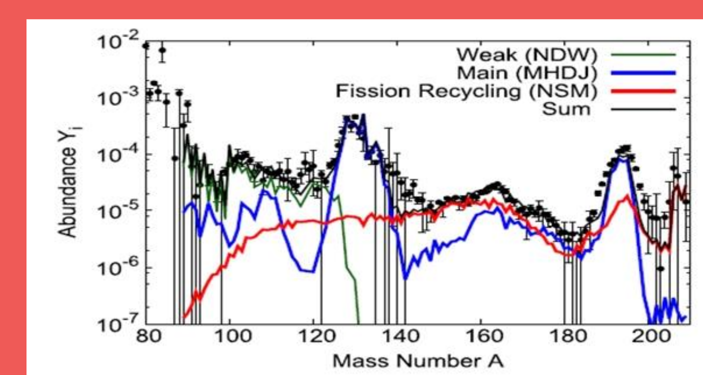


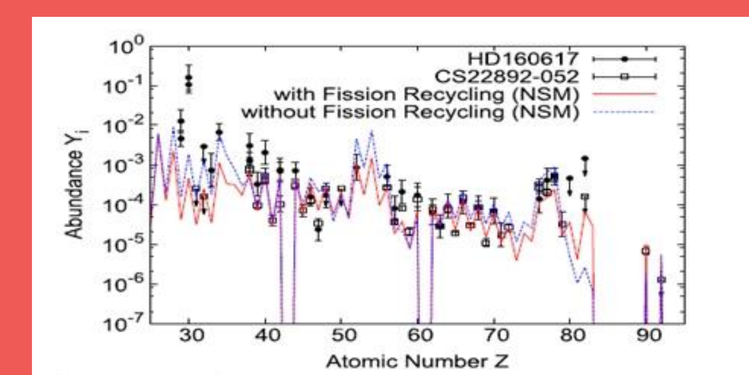
- **How are UH Elements Synthesized**
  - –Ratios of heavy nuclei probe age of accelerated material
  - –Mix of nucleosynthesis processes (r and s process)
  - –Actinide (Uranium group) "radioactive clocks" measure UHGCR age - relative abundances probe mixture of old and new material
  - –Site of Synthesis: OB associations, binary neutron star mergers and possibly others.
- **Where/how are UHGCR accelerated and what is their history**
  - –Element abundances carry the signature of the site of injection into the accelerator and the mechanism of selection for acceleration
    - •Acceleration from dust (refractory) or cold ISM gas (volatile)
  - –Secondary to primary ratios measure the integrated material pathlength of UHGCRs from acceleration to measurement

Ultra-Heavy Particle Production in Binary Neutron Star Mergers

- Scientists have suspected for decades that the production of UH cosmic rays, particularly those with Z > 50 may be produced in binary neutron star and neutron star black hole mergers (Freiburghaus, 1999)
- The August 17 binary neutron star merger (NSM) observed by LIGO, VIRGO, FERMI and other experiments provided spectroscopic evidence ultra-heavy elements are produced in binary neutron star mergers.
- Unlike photos, it is impossible to directly measure the flux of particles from a NSM so indirect measurements are needed.
- Ultra-heavy cosmic-ray measurements by HNX would provide critical insights into the nucleosynthesis of ultra-heavy elements by binary neutron NSMs s by providing a direct sampling of galactic material and measurement of ultra-heavy elements abundances

Artists illustration of two merging neutron stars. (National Science Foundation/LIGO/Sonoma State/A Simonnet)



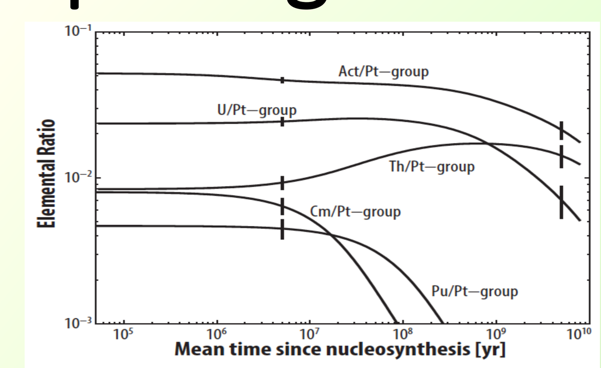


Model of material produced in a SNE and NSM. (Shibagaki et al. ApJ 816:79 (2016).

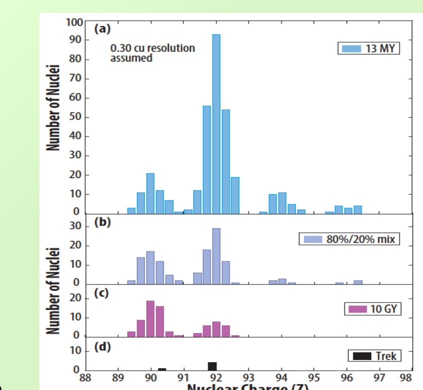
Left: Average final abundances from the "weak r-process" (neutrino driven wind of core-collapse SNe), "main-r-process" (MHD driven jets in core-collapse SNe) and "fission-recycling r-process" (in NSN). This is compared with observed r-process abundances in the solar system (Goriely, A&A,342 1999).

Right: Elemental abundance distribution calculated with and without NSM material compared to the observed r-process abundances of two well studied metal-poor r-process enriched stars. Comparing these measurements to those of the UH GCR elemental abundances would provide great insight to the validity of models and perhaps hint at additional sources for nucleosynthesis.

Exploring Cosmic Ray Origins

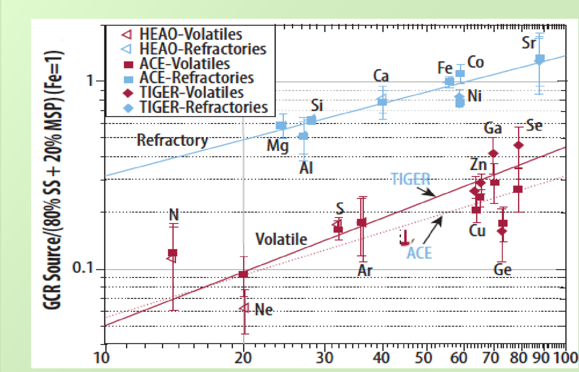


- Measuring the abundance of platinum and lead has been a "Holy Grail" of nucleosynthesis research for over 40 years
- Half-lives span the timescales for galactic chemical evolution
- Relative abundances strongly depend on the age of the GCR source material
- Ratios of daughter/parent nuclei important: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

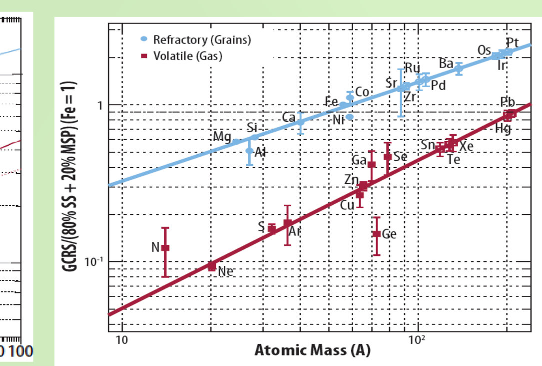


HNX Pt/Pb measurements would provide a clear signature of nucleosynthesis.

- ACE isotopes and TIGER, ACE, and HEAO element abundances are best represented by a source that is ~20% massive star production (wind + SN ejecta) and 80% normal ISM
- Refractory elements are significantly more abundant than volatile elements
- Refractories depend on mass as ~$A^{2/3}$ (not expected since they are initially accelerated as grains). Volatiles depend on mass as ~$A^{2/3}$ to A^{1}.
- **HNX will measure >1800 nuclei 38 ≤ Z ≤ 83 to probe UHGCR processes**

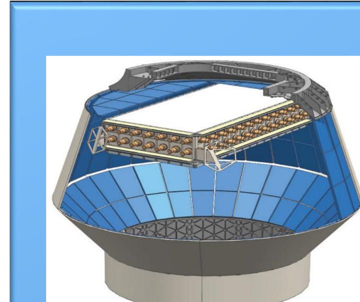


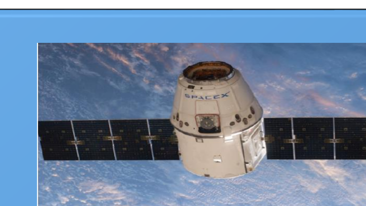
Combined TIGER, ACE, and HEAO element abundances Rauch et al., ApJ 697:2083 (2009).

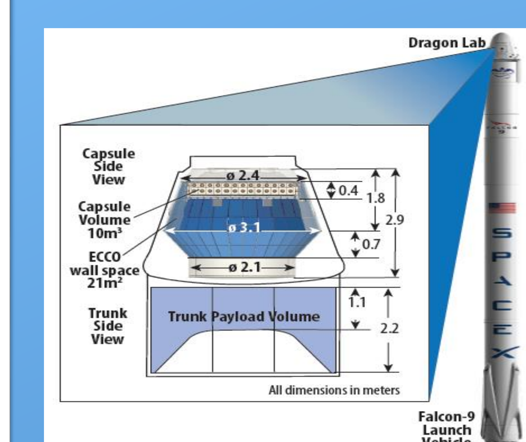


HNX will greatly improve old/new value and accurately determine mass dependence

HNX Mission Concept



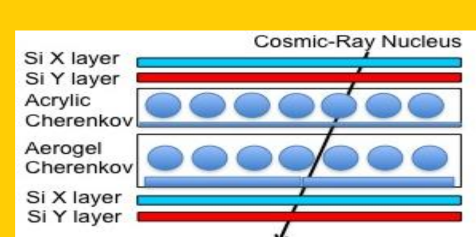


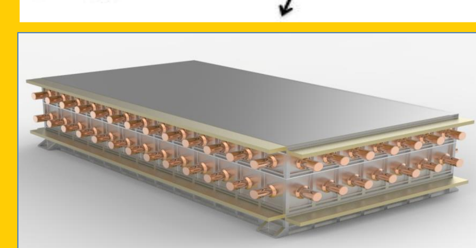


- HNX uses two complimentary instruments ECCO and CosmicTIGER to span a huge range in atomic number (6 ≤ Z ≤ 96). The detectors are sensitive to particles with Z > 96 but the flux of these particles is unknown.
- HNX uses the SpaceX DragonLab launched on a SpaceX Falcon 9 Launch vehicle
  - DragonLab is a free-flying "laboratory" based on the Dragon ISS supply and DragonRider commercial crew spacecraft
  - DragonLab consists of a pressurized and temperature controlled capsule and unpressurized trunk.
    - HNX would fly inside the capsule and a second instrument could be accommodated in the trunk. This rideshare arrangement helps reduce cost.
    - HNX is extremely compatible with a wide variety of co-manifested instruments. Most instruments wish to fly in the trunk to have an unobstructed view of space.
    - Capsule is recoverable, trunk is not. This is important as ECCO requires recovery for post-exposure processing.
    - DragonLab supplies all services including power, telemetry and thermal control.
- DragonLab will be certified for 2 year flights with safe recovery (this may be increased to 3-4 years with further maturation)

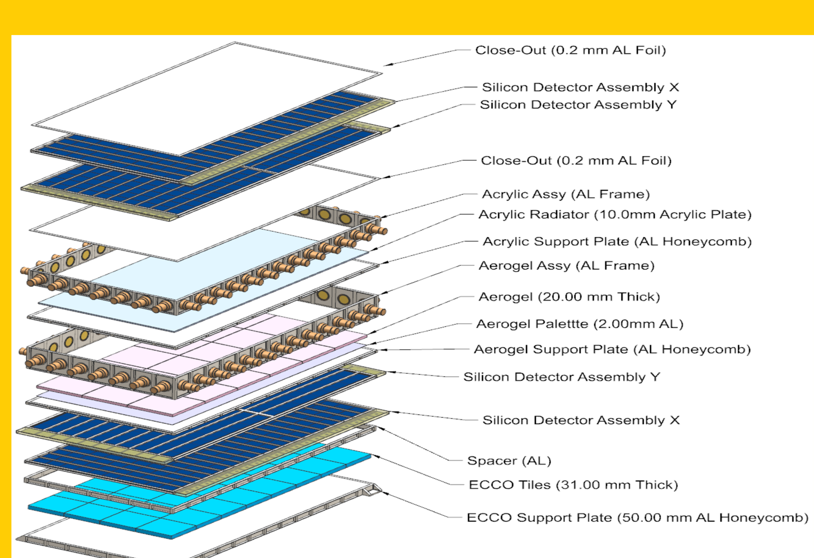
HNX: CosmicTIGER

- Large (2 m² active area, AΩ = 4.2 m²sr.) electronic particle detector system with single element charge resolution from Z ≥ 6 to the end of the periodic table (adds to ECCO area for Z ≥ 70).
- Proven performance and hardware from accelerator tests, TIGER, SuperTIGER, HEAO, STEREO and Parker Solar Probe.
- Detector system consists of three detector subsystems which measure charge and energy using dE/dx vs Cherenkov and Cherenkov vs Cherenkov Technique.
  - Silicon strip detector (SSD) arrays at top and bottom measure ionization energy deposit (dE/dx) and trajectory
  - Cherenkov detector with acrylic radiator (optical index of refraction n=1.5) measures charge and velocity E_K ≥ 325 MeV/nucleon (β ≥ 0.67)
  - Cherenkov detector with silica aerogel radiator (n=1.04) measures velocity E_K ≥ 2.25 GeV/nucleon (β ≥ 0.96)

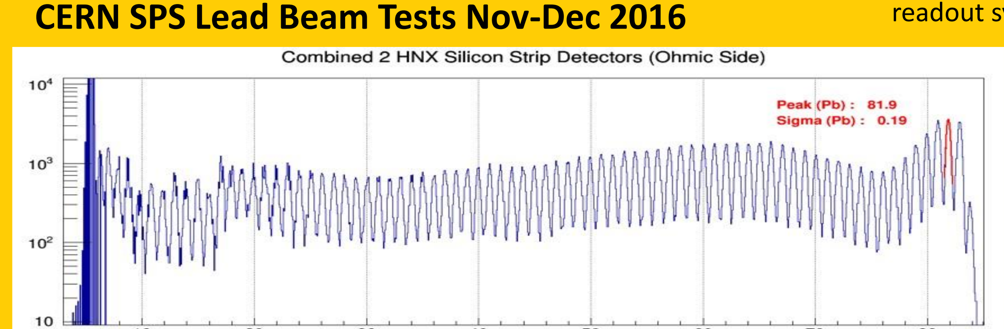




- SSD Detector
  - 2 Layers of orthogonal SSD strip detectors (3.12mm strip pitch) measure charge and energy of particle in addition to providing trajectory measurement of incident particles. Performance of strip detectors tested at CERN in 2016 (see plot below)
  - Readout by PHASIC ASIC chip.
- Cherenkov Detectors
  - Cherenkov detectors (acrylic and aerogel) use light integration boxes lined with Gore DRP reflector.
  - PMT or SIPMs used to measure light in boxes and read out with SuperTIGER based readout system.

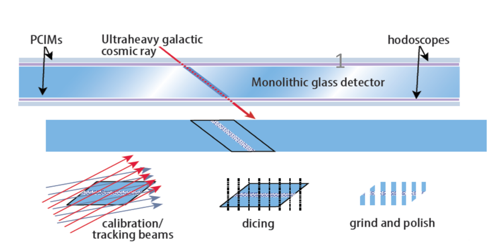


CERN SPS Lead Beam Tests Nov-Dec 2016

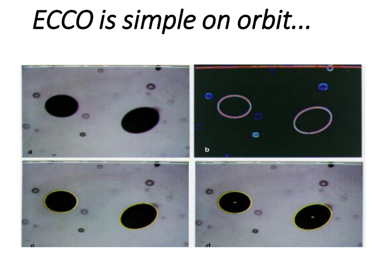


HNX Silicon Strip Detectors (6 <= Z <= 84)

HNX: ECCO

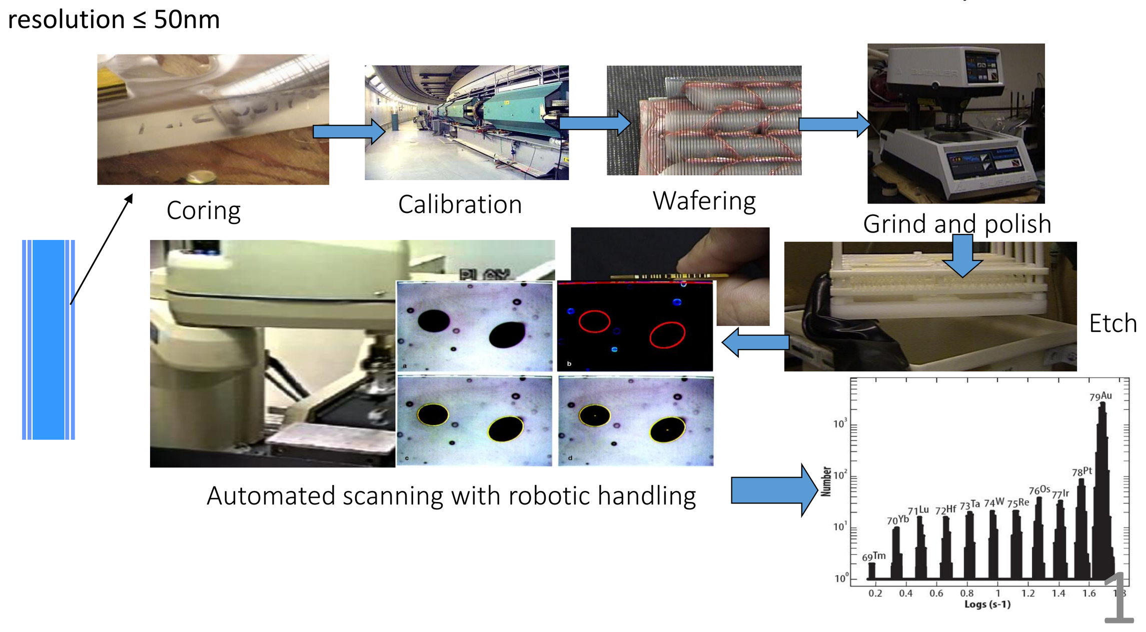


ECCO is simple on orbit…

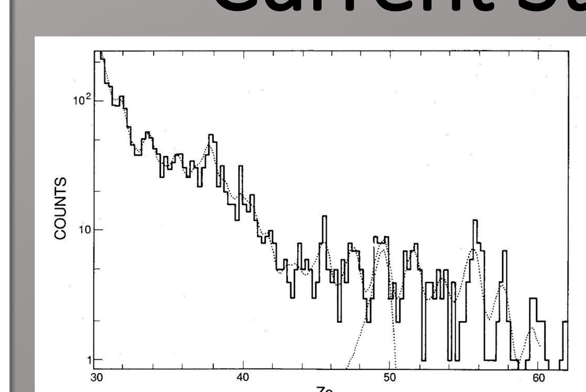


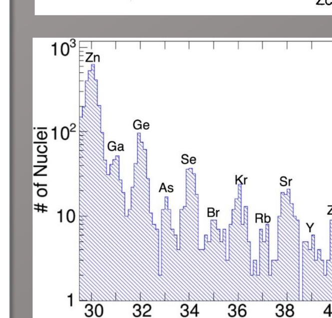
… all the sophistication is in the laboratory

- ECCO is based on TREK experiment on MIR
- ECCO BP-1 detector modules cover capsule walls, part of top, and beneath CosmicTIGER
- Active area 21 m², AΩ = 48 m²sr
- 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 must recovered to analyze in laboratory.
  - Glass is etched to "develop" nuclear tracks
  - Tracks are measured using fully automated microscope system with resolution ≤ 50nm



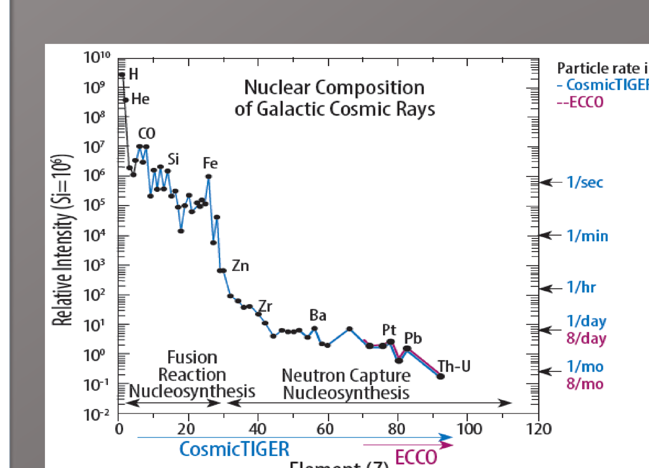
Current State of UHGCR Measurements

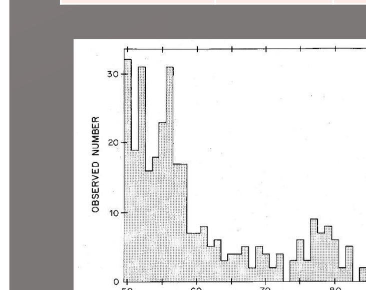




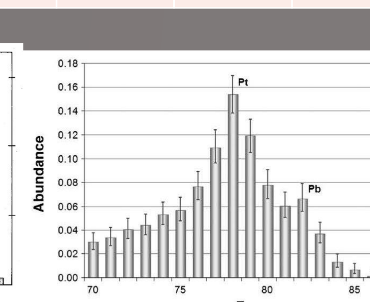
Top: Results from HEAO 3 Heavy Nuclei Experiment (Binns et. al. Astrophysical Journal , **346**, 1989)
Left: Results from SuperTIGER (Murphy et al. Astrophysical Journal, **831**, 2016)
Below: GCR Elemental Flux

UHCR Experiment	Ball/Sat	Date	Duration	Area	Ref.	Detectors used
First detection of Z>30 nuclei was in meteorite crystals; Fleischer, Price, Walker, and Maurette (1967) JGR 72, 331						
Texas Flights VHCRN	Balloon Texas	1966	0.6 days	4.5 m²	Fowler et al. 1967	Four layers of nuclear emulsions with absorber interleaved
Barndoor I,II, & III	Balloon Texas	1967-1970	2.8 days	15 m²	Wefel 1971	Plastic track detectors and nuclear emulsions
Heavy Nuclei Experiment	HEAO-3 Satellite	1979	1.7 years	~2 m²	Binns et al. 1989	Ionization chambers, Cherenkov counters, wire ionization hodo.
HCRE	Areal-6 Satellite	1979	1 year equiv.	0.5 m²	Fowler et al. 1987	Spherical gas scintillator and acrylic Cherenkov detector
UHCRE	LDEF Satellite	1984	5.75 years	20 m²	Donnelly et al.2012	Plastic track detectors (Lexan)
Trek	Mir Satellite	1991	1/3rd 2.5 y 2/3rd 4.2 y	1.2 m²	Westphal et al.1998	Glass track detectors-Barium Phosphate Glass (BP-1)
CRIS	ACE Satellite	1997	17 years	0.03 m²	Stone et al. 1998	Silicon detector stack & scintillating optical fiber hodo.
TIGER	Balloon-Antarctica	2001, 2003	50 days	1.3 m²	Rauch et al. 2009	Plastic scint, acrylic & aerogel Cherenkov, scint fiber hodo.
SuperTIGER	Balloon-Antarctica	2012	44 days equiv.	5.6 m²	Binns et al. 2014	Plastic scint, acrylic & aerogel Cherenkov, scint fiber hodo.

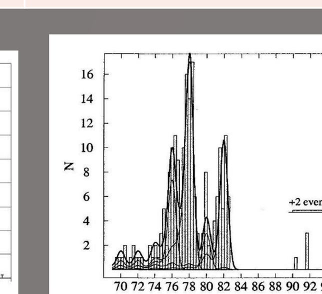




HEAO-3 C3



UHCRE



TREK

From left to right, Z > 70 results from HEAO-3 C3 (Binns et al., ApJ, 1985), UHCRE (Donnelly et al., ApJ, 2012), and TREK (Westphal et al., Nature 1998)