White Paper on Ultra-Heavy Cosmic-Ray Astrophysics

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1. New opportunities and compelling themes arising from recent accomplishments

Galactic cosmic rays play an important role in the dynamics of matter and magnetic fields in the interstellar medium, and probably also play an important role in star formation. In spite of their importance, and despite much recent progress, significant questions about the origin of cosmic rays remain. There is an opportunity during the coming decade to give definitive answers to these questions by making measurements of the relative abundances of every individual element, including the rarest elements of the highest atomic numbers.

Recent progress in measurements of the isotopic composition of cosmic-ray nuclei with atomic number $Z \leq 28$ (Binns et al. 2005, 2008) and the elemental abundance of the relatively rare elements with atomic number in the interval $28 < Z \leq 34$ (Rauch et al. 2009) have given strong evidence that cosmic rays originate from the interstellar material in OB associations, where there is a mix of old material with an elemental and isotopic composition similar to that of our Solar System and newer material from the outflow of massive stars – both stars in their Wolf-Rayet phase and supernovae.

A large-area detector system placed in low-Earth orbit for a period of about three years will enable, for the first time, extension of high precision measurements of the abundance of individual elements to the rarest, heaviest elements – the actinides ($_{90}$Th, $_{92}$U, $_{93}$Np, $_{94}$Pu, $_{96}$Cm, and perhaps beyond). There are well-established instrumental techniques that can be used to realize such a detector system.

The important questions that will be addressed by such a comprehensive high-precision measurement of cosmic-ray elemental abundances are:

- **Do the cosmic rays include a component of recently synthesized heavy elements? If so, what is the age of that component?**
- **Are OB associations in fact the source of the material and the location of the acceleration of most Galactic cosmic-ray nuclei?**
- **How does the process of diffusive shock acceleration of cosmic rays operate differently on interstellar grains and gas?**

Answers to these questions can be expected to lead to identification of the source of Galactic cosmic rays (GCR). Further, once the nature of the GCR source has been elucidated, these measurements will provide invaluable information about the local Galactic abundances of the elements, which in turn will improve our understanding of the chemical evolution of our Galaxy.

2. Three central questions ripe for answering

A) Do the cosmic rays include a component of recently synthesized heavy elements? If so, what is the age of that component?

The presence of any Pu and Cm in the GCR would be a clear and unambiguous signature of the presence at the GCR source of freshly synthesized material. The abundance of (Pu + Cm) relative to (Th + U) would be a measure of the fraction of the GCR that do indeed come from such freshly synthesized material.

The individual actinide elements serve as radioactive clocks to measure GCR ages, and because their half-lives neatly span the timescales for galactic chemical evolution, their relative abundances strongly depend on the mean age of the GCR source material. A measurement of these elements will enable differentiation among current models of GCR origin. Recent r-process calculations predict substantial Cm and Pu yields, with Cm/Th and Pu/Th ~1. The half-lives of the longest lived isotope of each element and expected yields from the r-process (Pfeiffer, et al. 1997; Lingenfelter, et al. 2003) are:

Isotope	Half-life (yr)	r-process yield (Th=1)
${}_{90}^{232}Th$	1.4×10^{10}	=1.00
${}_{92}^{238}U$	$4.5 \text{ X } 10^{9}$	2.0
${}_{93}^{237}Np$	2.1×10^{6}	0.7
${}_{94}^{244}Pu$	8.0×10^{7}	0.7
${}_{96}^{247}Cm$	1.6×10^{7}	1.05

If the r-process operates in a region continuously over a period of time the relative abundances of the various actinide elements will depend on the length of time over which the r-process has operated. Figure 1 shows the dependence on the duration of the r-process of abundances of U, Pu, and Cm relative to Th (Lingenfelter et al. 2003). At the formation of the Solar System the relative abundances of U and Th were about as shown in this figure for an r-process that had been going on for a period of about 5 Gyr. If the GCRs include a component representative of the material produced in supernovae over the lifetime of an OB association ~50 Myr, then that component would have an actinide composition as indicated by the vertical line near the middle of this figure.

Note that the ultra-heavy cosmic rays observed near Earth are a quite contemporary sample of the material in the region where the GCR are accelerated. Because of the short interaction mean-free-path of these nuclei in the interstellar medium, the actinides and the more abundant elements that have been detected with atomic numbers in the interval ~75 to 83 cannot have been accelerated more than a few million years prior to their being observed. This duration of the cosmic-ray transport in the Galaxy is at least an order of magnitude shorter than the lifetime of a typical OB association, so the relative abundances among the actinide elements observed in the GCR will not be substantially different from those in the region where the GCR are accelerated.

Given today's capabilities, described briefly in section 5 below, it is possible to build an instrument with sufficient collecting power so that if just 20% of the GCR source consists of outflows of massive (and thus relatively short-lived) stars, Pu and Cm will be detected with high confidence. Over a period of three years in orbit such an instrument would detect ~100 actinides even if the cosmic-ray source had nothing but old material with composition similar to the Solar System. If the OB-association model is correct the number of actinide nuclei detected would be greater. Figure 2 shows the result of a Monte-Carlo calculation for three possible outcomes from such an instrument – (a) a completely recent source, in which all the cosmic rays come from material synthesized over a 13 Myr period (vertical red dashed line added to Figure 1), the average age of the three components of the nearest OB association, Sco OB2 (Preibisch & Mamajek, 2008); (c) a completely old source, in which the composition is similar to that of the Solar System when it formed; and (b) the mixture of 80% Solar-System-like material and 20% recent massive star outflow as suggested by the isotopic and elemental abundances that have been measured at much lower atomic number. It is clear from this picture that these three possible origins of GCR can be reliably distinguished with such a measurement.

For reference, Figure 2 also shows (d) the result of the only measurement to date of individual actinide element abundances in the GCR, which was obtained by the Trek instrument (Westphal, et al., 1998). That instrument detected six nuclei that could be certainly identified as actinides, four of which could be assigned a precise charge. Clearly the measurement advocated in the present White Paper would give an enormous improvement in our understanding of GCR origin.

The r-process yields used above, from Lingenfelter et al. (2003), are probably appropriate; however there are model dependent variations of the r-process yields (Goriely & Arnould, 2001); and it is possible that the cosmic-ray observations will ultimately help constrain those nucleosynthesis models.

B) Are OB associations in fact the source of the material and the location of the acceleration of most Galactic cosmic-ray nuclei?

The most unambiguous evidence for the OB-association model would be that the actinide abundances of the GCR do indeed fit the 80%/20% mix modeled in Figure 2. The abundances of Pu and Cm would establish the contribution of recently synthesized material, and then the U/Th ratio would be a measure of the mean age of the bulk of older material.

Further evidence for the location of the GCR source would come from the precise measurement of the elemental abundances of all the other elements with $Z > 30$. Measurements of elements with $Z \leq 34$ (Rauch et al, 2009) have already given strong evidence for a GCR source composition composed of old material of similar composition to the Solar System with ~20% admixture of recent outflow from massive stars, as would be expected in the region of an OB association. Individual abundances of all the elements in the interval $30 \leq Z \leq 83$ would give a further definitive test of this model. Just as the observation of Pu and Cm would indicate a contribution of recently synthesized r-process material, one would expect other signatures of enhanced r-process contribution, such as in the abundances of $_{52}$Te and $_{54}$Xe (which are primarily made in the r-process) relative to $_{50}$Sn and $_{56}$Ba (which are primarily made in the s-process).

C) How does the process of diffusive shock acceleration of cosmic rays operate differently on interstellar grains and gas?

Relative abundances of elements with atomic number $Z \leq 38$ (Rauch et al, 2009) confirm earlier indications from Meyer et al (1997) and Ellison et al (1997) that elements found in interstellar grains are preferentially accelerated compared with those elements that are more volatile and thus more likely to be found in the interstellar gas. As shown in Figure 3, there is generally good agreement with a model of the cosmic-ray source that includes three features – (1) a mixture of sources 80% Solar-System-like and 20% fresh massive-star outflow, (2) preferential acceleration of refractory elements, and (3) atomic-mass dependence of acceleration efficiency of both the refractory and the volatile components. These three features would be tested if several of the elements in this figure (eg. $_{31}$Ga, $_{32}$Ge, $_{34}$Se, and $_{38}$Sr) could be measured with much greater statistical accuracy, and if the figure could be extended to include elements of higher mass. It would be particularly interesting to confirm the apparent mass dependence of acceleration of the refractory elements, since Ellison et al (1997) have a cosmic-ray acceleration model that gives a mass dependence of the volatile elements similar to that shown in this Figure 3, but in their model there is no mass dependence of the refractory elements.

<u>3. An area with additional discovery potential</u>

As “bonus science”, the large instrument capable of measuring the actinide abundances would also conduct the most sensitive search to date for possible long-lived super-heavy elements, which are expected to lie in the island of stability near $^{288}110$ and $^{290}110$ (Notation is ^{A}Z) (Möller, 1994). These isotopes lie on the neutron-rich side of the island of stability, and are difficult or perhaps impossible to synthesize by fusion in laboratory collisions of accelerated heavy nuclei. But if super-heavy elements are synthesized in the r-process, neutron-rich isotopes are inevitably produced; some might have sufficiently long half-lives to survive to be detected. Indeed, it is most appropriate to conduct a search for such isotopes among the GCRs, the youngest sample of matter to which there is direct access.

4. Scientific context – Connections to other topics in astrophysics and nuclear physics

The GCRs are a direct sample of the local Galaxy. The isotopic composition of oxygen in the Solar System is peculiar with respect to that of the local galaxy; it is unlikely that this difference is due to galactic chemical evolution (Young, et al., 2008). Comparison of the elemental composition of GCRs over the full range of elements with that of the Solar System may help to elucidate the origin of the apparent anomalous composition of the Solar System.

The arguments given by Pfeiffer et al. (1997) and Lingenfelter et al. (2003) for the r-process yields that are used in section 3 above are compelling. However, there is a range of other models (Goriely & Arnould, 2001) that give different yields. The direct GCR observation of material recently synthesized in r-process events can be expected to constrain those nucleosynthesis models.

The measurements described here would motivate work in theory across astronomy and physics. They would provide critical inputs to understanding diffusive shock acceleration of cosmic rays, defining stellar models of nucleosynthesis, and improving models of GCR transport in the Galaxy.

5. Key advances in observation and theory needed to realize opportunity

To realize the opportunity that the confluence of these scientific goals and existing techniques for measurement provide, it will be necessary to develop an instrument to be flown in space with very large effective collection power, ~35 m^2 sr. Such an instrument utilizing silicon detectors, Cherenkov detectors, and a scintillating fiber hodoscope is capable of making precision measurements of charge from neon through the actinides and beyond for energies above 0.3 GeV/nucleon. This instrument concept has gone through a NASA Phase-A study (HNX), and is currently one of two instruments being studied under NASA funding in an "Astrophysics Strategic Mission Concept Study" as part of the "Orbiting Astrophysical Spectrometer in Space (OASIS)". The detectors and measurement techniques used in this instrument are well understood and have extensive balloon-flight and space heritage. A space flight of an instrument with these characteristics for three years will provide the required collecting power to answer the above "central questions".

The technology for accomplishing this mission is well in hand. There are no technological advances required. All that is needed is a commitment to build and launch the instrument.

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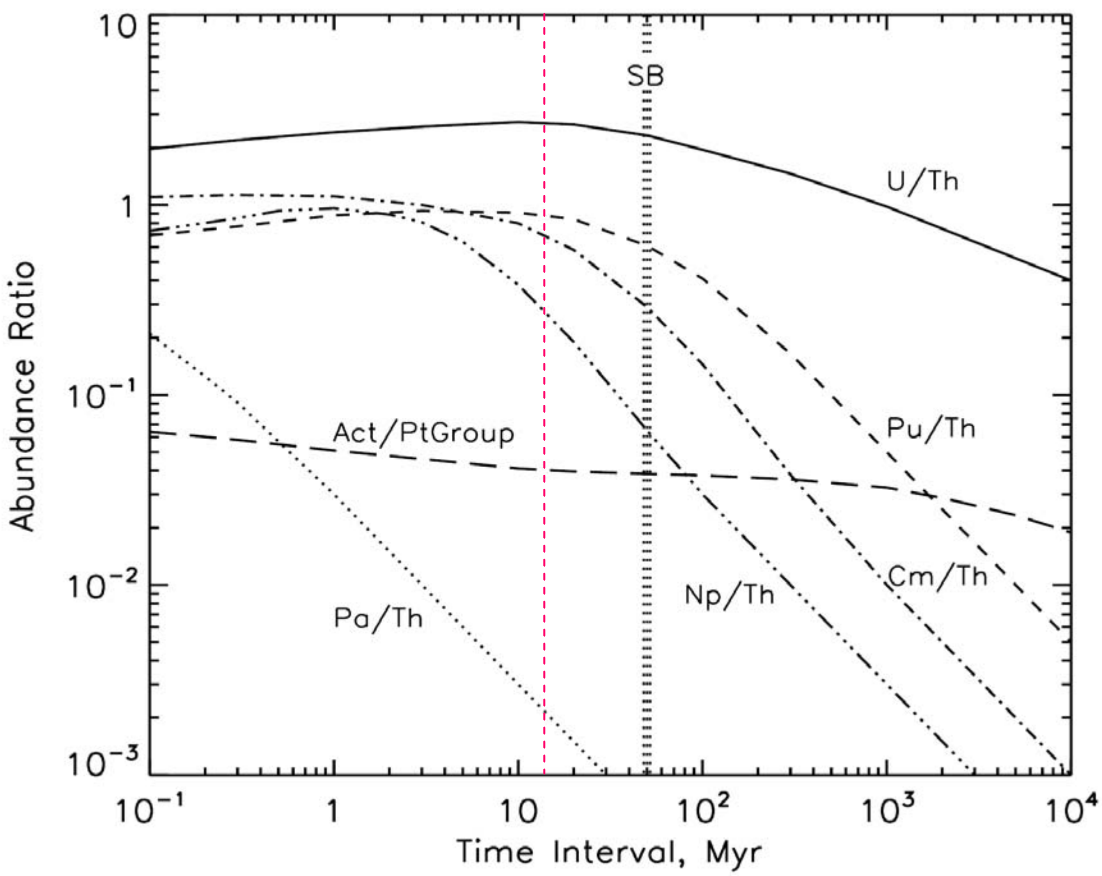

FIG. 1.—Mean actinide abundance ratios from *r*-process yields of core-collapse supernovae in their accumulating ejecta averaged over various time intervals, assuming a constant supernova rate during those intervals. The typical cosmic-ray acceleration time span in the supernova-active cores of superbubbles of roughly 50 Myr is indicated by the dashed line (SB).

Figure 1 (from Lingenfelter, et al. 2003 with red dashed line at 13 Myr added)

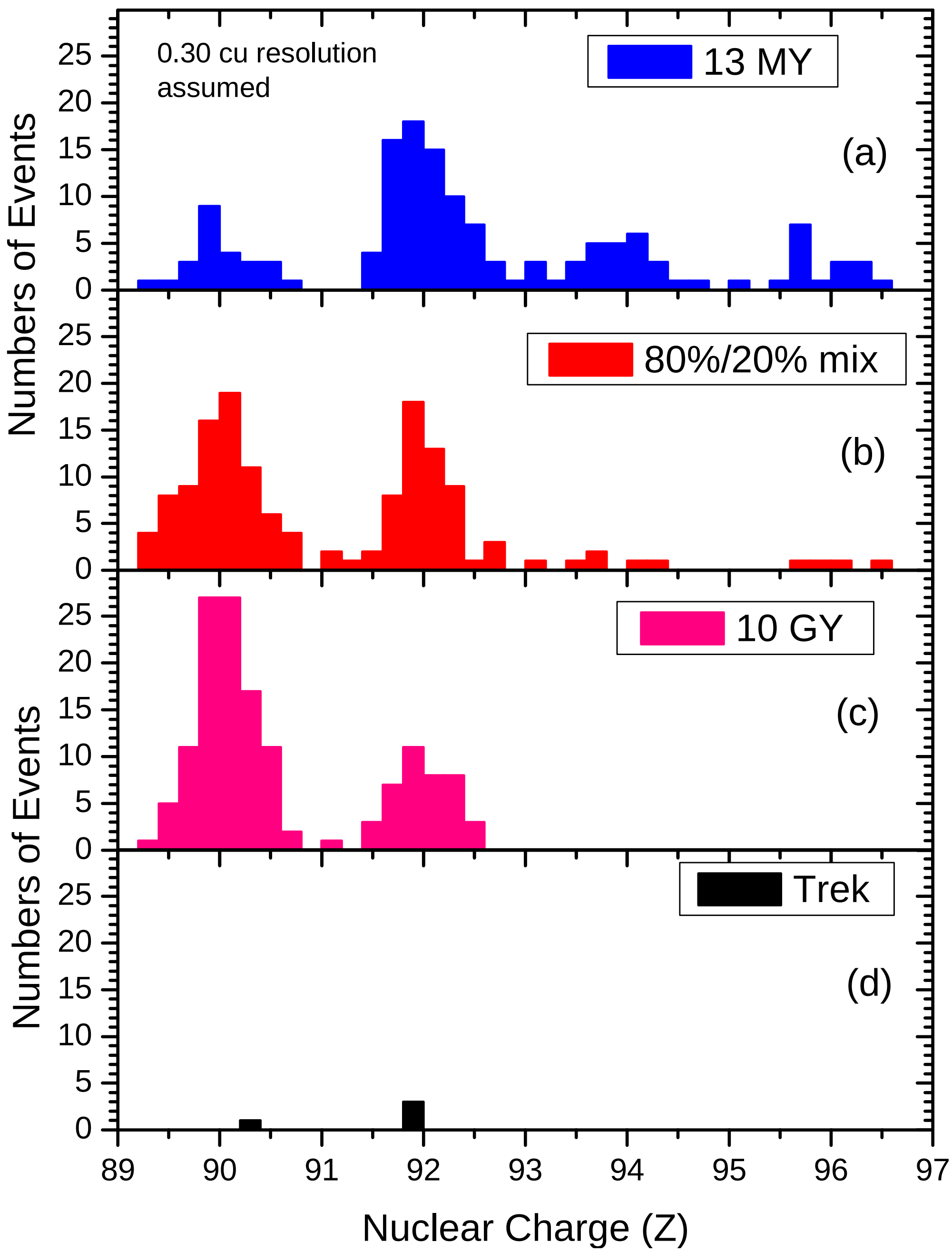

Figure 2 The top three panels show the result of a Monte Carlo calculation of expected observation from 100 m^2 sr yr in orbit for three different cosmic-ray sources (as described in text). Panel (d) shows the results of the only GCR observation to date in which there is clear individual-element resolution of the actinides (Westphal et al. 1998). (While the Trek results suggest disagreement with the 10 GY model, the low statistical weight of this observation does not permit it to rule out the 10 GY model with any substantial confidence.)

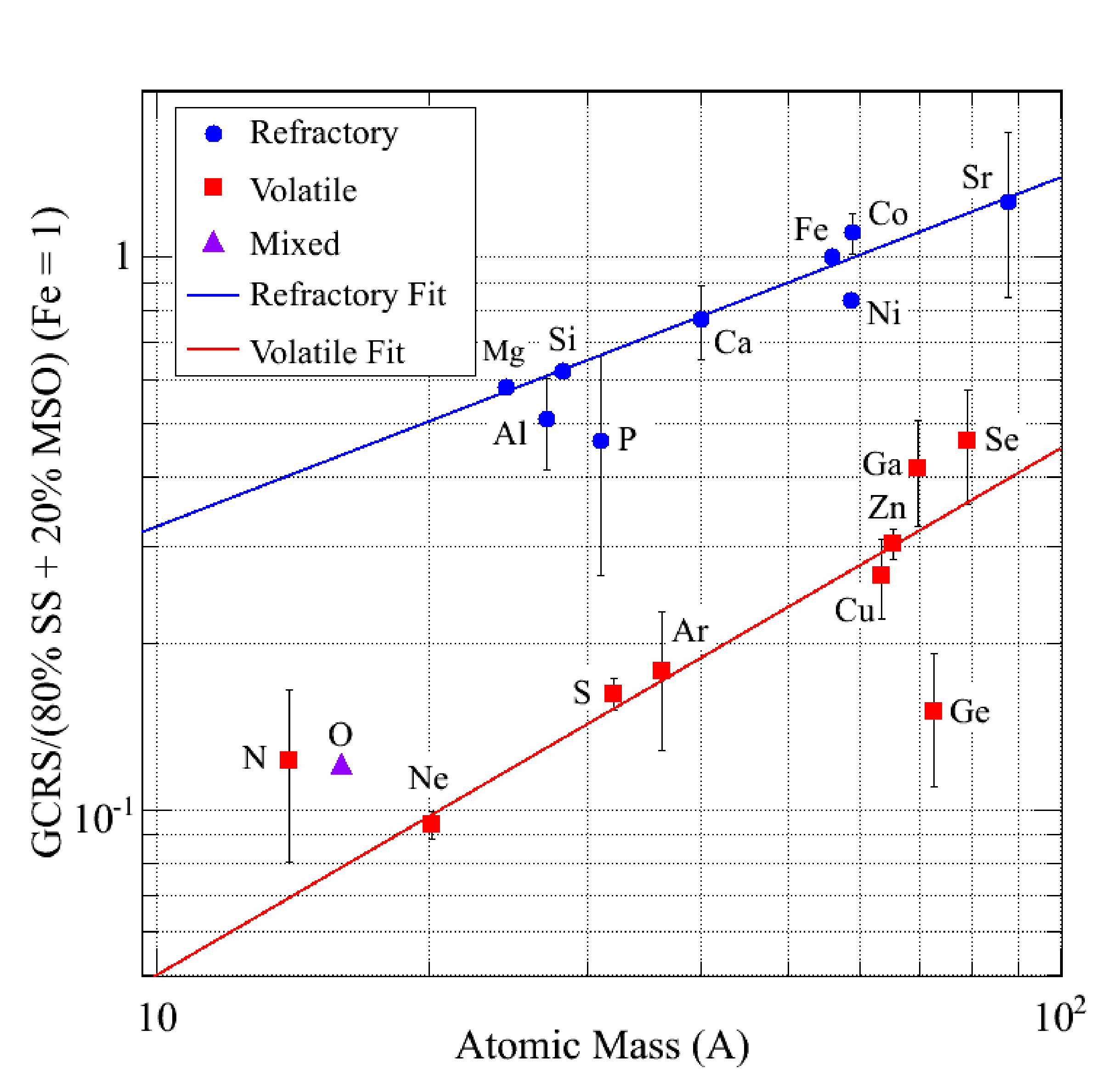

Figure 3 GCR source abundances relative to 20% massive-star outflow plus 80% of solar system composition material. This plot demonstrates preferential acceleration of refractory elements found in interstellar dust grains, and demonstrates an atomic-mass dependence of acceleration efficiency.