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The Heavy Nuclei eXplorer (HNX) Mission

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Abstract. The primary scientific objectives of HNX, which was recently selected by NASA for a Small Explorer (SMEX) Mission Concept Study, are to measure the age of the galactic cosmic rays (GCR) since nucleosynthesis, determine the injection mechanism for the GCR accelerator (Volatility or FIP), and study the mix of nucleosynthetic processes that contribute to the source of GCRs. The experimental goal of HNX is to measure the elemental abundances of all individual stable nuclei from neon through the actinides and possibly beyond. HNX is composed of two instruments: ECCO, which measures elemental abundances of nuclei with Z≥72, and ENTICE, which measures elemental abundances of nuclei with 10≤Z≤82. We describe the mission and the science that can be addressed by HNX.

1. Introduction

The Heavy Nuclei eXplorer (HNX) mission that is currently being studied as a possible Small Explorer Mission (SMEX) has the primary objective of determining the origin of the galactic cosmic rays. The abundance patterns of the elements and isotopes in the GCRs provide the key because they are the fingerprints of GCR origin. HNX will, for the first time, measure with high precision the abundance of every individual element in the periodic table from neon through the actinides (thorium, uranium, plutonium, curium, and perhaps beyond). The HNX spacecraft will carry two high-precision instruments, the Extremely-heavy Cosmic-ray Composition Observer (ECCO) and the ENergetic Trans-Iron Composition Experiment (ENTICE), which cover overlapping ranges of the periodic table (Figure 1). ECCO is a large array of glass track-etch detectors, which will measure individual elemental abundances for elements with Z>70, with sufficient collecting power to collect >100 actinides. ENTICE is an electronic instrument with large dynamic range that will measure individual elemental abundances from Ne (Z=10) through Bi (Z=83) plus a handful of actinides. The two instruments will be configured such that a substantial number of Pt-Pb nuclei, as well as a few actinides, will traverse both instruments, thus inter-calibrating the two instruments. ECCO is designed to measure charges of ions with E>0.9 GeV/nucleon. ENTICE will measure charges of nuclei with E>0.5 GeV/nucleon and will measure energy spectra up to about 7 GeV/nucleon. These measurements, when combined with knowledge from previous experiments for Z<30, will definitively distinguish between current models of the origin of GCRs.

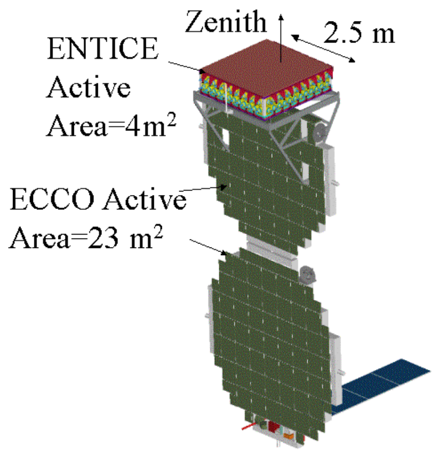

Figure 1—HNX is shown in its deployed configuration.

Since ECCO must be recovered for data analysis, HNX will be launched and recovered by the Space

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Shuttle. HNX will be placed in a 51.6° inclination orbit to maximize the particle flux and facilitate deployment and recovery.

2. Scientific Goals and Objectives

The abundances of the elements with Z≤30 have been measured with good precision by several instruments (e.g., C-2 on HEAO-3, COSPIN on Ulysses, CRIS on ACE). Since the early 1980's the best data on the UH composition over the entire charge interval Z>30 has been the combination of the results from the C-3 experiment on HEAO-3 and from Ariel-6 (Binns, et al., 1989; Fowler, et al., 1987). Those two experiments had charge resolution adequate to determine abundances of even-Z elements for Z≤60, but not the less abundant adjacent odd-Z elements. For Z>60 the combination of inadequate resolution and small statistics of these earlier experiments limited results to abundances of groups of several elements. Recent results from the Trek experiment have sufficient statistics and charge resolution to resolve individual even-Z elements in the Pt-Pb region**.**

The elemental abundances in the cosmic-ray source(s) (CRS), inferred from direct observations by correcting for the secondary component that originates in interstellar fragmentation of heavier nuclei, are very similar to the abundances of elements in the solar system (SS). In addition, the ACE measurements show that the GCR isotopic abundances for Z≤30 are also similar. However, there appears to be a preferential acceleration governed by atomic properties of the elements, which causes systematic deviations of CRS from SS abundances.

One reasonably successful way of ordering the variations of the ratio CRS/SS is by the first ionization potential (FIP) of the elements. Elements with FIP>10.5eV have CRS/SS approximately one-eighth to one-fifth that of elements with FIP<8.5eV. Elements with intermediate FIP have intermediate CRS/SS. Since the accelerator is likely to work only on ionized atoms, and easily ionized elements appear to be preferentially accelerated, this correlation suggests that the CRS consists of a partially ionized medium, with a characteristic temperature of ~10^4K. Meyer suggested that this partially ionized medium consists of the chromospheres of sun-like stars, from which ions are picked up and accelerated to modest energies by stellar flares (Meyer, 1985). This suprathermal population is then accelerated to high energy by SN shocks. The observation of just such a FIP-biased preferential acceleration in solar energetic particles and in the solar wind lent credence to this model, although some crucial details are controversial.

However, observations made by HEAO (Binns et al, 1989), Ariel (Fowler et al., 1987), and most recently Trek (Westphal et al., 1998) of the heaviest elements in the periodic table showed an abundance pattern that is not consistent with this scenario. The Trek data confirm, with much better charge resolution, what the HEAO-3 and Ariel data had indicated: a Pt/Pb ratio at the cosmic-ray source that is substantially larger than in the solar system. While the HEAO experimenters had interpreted that result as indicative of an r-process enrichment of the heaviest cosmic rays, the Trek experimenters have also made a strong case for interpreting the result as an indication that Pb, which has a FIP similar to Pt, is underabundant because of atomic fractionation effects other than the FIP effect. Another deviation from FIP ordering of cosmic-ray abundances had been noted by the HEAO experimenters, who pointed out a Ge/Fe ratio in the cosmic rays that is a factor of two below that in the solar system, in spite of Ge and Fe having the same FIP (Israel et al., 1983).

Meyer, Drury, & Ellison (1998) argue that the apparent correlation with FIP is coincidental and that the data are better understood by considering the volatility of the elements. In this model, interstellar dust grains near a pre-supernova star are charged by photo-ionization; SN shocks efficiently accelerate these charged dust grains because of their large magnetic rigidity. Ions sputtered from these dust grains are then efficiently accelerated to cosmic-ray energies. As a result refractory elements, which tend to be found in grains, would be overabundant in the GCRs. We note that if the GCRs were accelerated from the ambient interstellar gas or dust, then we would expect the GCRs to have an average age since nucleosynthesis of several Gy.

On the other hand, Higdon et al. (1998) infer, from the constancy of Be/Fe in stars over a wide range of metallicity, that GCR acceleration is not solely from the general interstellar medium, but must include freshly synthesized nuclear matter. The observation by Binns et al. (1989) that the heaviest GCRs appear to be enhanced in r-process elements lends credence to this suggestion. Recent observations of the Fe, Co, and Ni isotopes in the GCRs by the ACE-CRIS experiment (Wiedenbeck et al., 1999) show that ^{59}Ni (an electron-capture primary isotope with lifetime 7.6 x 10^4y) has completely decayed to ^{59}Co. This leads to the conclusion that there has been at least a 10^5-year time interval between nucleosynthesis and GCR acceleration, which implies that most of the GCRs are not accelerated directly out of freshly synthesized material. Higdon et al. argue that superbubbles, which form from large OB associations in giant molecular clouds provide a mechanism by which newly synthesized material from supernovae can be injected into the low-density medium in superbubbles without significant mixing with the general ISM, and then accelerated to GCR energies by subsequent supernovae in the superbubble. Since the frequency with which supernovae occur within OB associations is ~10^5 y, if much of the refractory material is ejected as fast grains, the ^{59}Ni could decay, thus being consistent with the ACE-CRIS ^{59}Ni results. This suggests for this model, that interstellar grains from the general ISM are not significant sources of cosmic rays. It also suggests that the typical age of GCR nuclei is comparable to the typical lifetime of OB associations, 10^7 y.

Thus the fundamental question is: What is the source of material for the cosmic rays, and what is the injector for this accelerator?

3. Measurements Required to Test the Models

Cosmic Ray Age:The individual actinides serve as radioactive clocks to measure the age of the GCR nuclei, 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. A measurement of these relative abundances will enable us to distinguish among current models of GCR origin. Their half-lives and expected yields from the r-process are given in Pfeiffer et al, 1997. An elemental abundance measurement cannot distinguish among the three long-lived isotopes of uranium. Nevertheless, the abundance of uranium as a function of mean age is straightforward to calculate, and is presented in a companion paper on ECCO presented at this conference by Westphal, et al.

If the GCRs are accelerated from the ISM, the average age will be several Gy. If, however, GCRs are enhanced in r-process material by a factor of ~2, approximately one-half of these nuclei will be very young, since substantial mixing with ambient galactic material is unavoidable on long timescales. Similarly, the superbubble model of Higdon et al. predicts a dramatic enhancement in freshly synthesized material, with an age characteristic of the age of an OB association, $\sim 10^7$y.

The presence of Cm in the GCRs would be a clear and unambiguous signature of the presence at the GCR source of freshly synthesized material. To the extent that the GCR actinides come from a single type of source, the abundances of Th, U, and Pu would be nearly identical to their primary nucleosynthetic yields. A measurement of these yields would naturally improve our understanding of r-process nucleosynthesis, which is of fundamental interest to astrophysicists studying the physics of extreme environments. But there is also a cosmological connection: these yields are crucial, but unmeasured parameters, in models of cosmochemical evolution in the galaxy. These models are used to measure the age of our galaxy and to understand global histories of nucleosynthesis. Results from HNX could substantially improve the uncertainty in the measurement of the age of the Galaxy, currently estimated at ~2Gy, using these models.

The principal goal of ECCO is to measure the abundances of the individual actinides with respect to each other and with respect to the platinum group. The size of ECCO is driven by the extreme rarity of the actinides in the GCRs, and in particular the rarity of ^{247}Cm, which would be the smoking gun pointing to a freshly synthesized GCR source. ECCO has sufficient collecting power that if the GCR source is young, Cm will be detected with high confidence even if the r-process yield of Cm is extremely and unexpectedly small. Most recent r-process calculations predict much larger Cm yields, with Cm/Th ~1 (Pfeiffer, 1999). With this active area, ECCO will collect a minimum of 110 actinides, the expected statistics if the GCRs originate purely in the ancient ISM, and ~285 actinides if GCRs originate purely in freshly synthesized material. The actual GCR source may be a mixture of old and young material. Based only on the U/Th ratio, ECCO will be sensitive to an admixture of fresh r-process material with local galactic material at the 6% level, which will test the hypothesis of OB association origin of GCRs (Higdon, et al. 1998). On the other extreme, for a source that is principally fresh, with abundances as predicted by Pfeifer, et al. (1997), ECCO is sensitive at the 1σ level to an admixture of ~13% of local galactic material.

Test of Preferential Acceleration: Most of the elements with low FIP are refractory, so it is difficult to distinguish between the FIP and volatility models. Meyer, Drury, & Ellison point out that there are a few elements that break the degeneracy between low-FIP and refractory elements. Elements that are volatile or semi-volatile, but have low FIP, and for which it should be possible to infer source abundances, are $_{32}$Ge, $_{37}$Rb, $_{50}$Sn, $_{55}$Cs, $_{82}$Pb, and $_{83}$Bi. Among these elements source abundances have been established only for Ge, Sn, and Pb. HNX will measure the abundance of every element from Ne through the actinides, including the odd-Z elements that were previously not resolved.

*Nucleosynthetic Mix:*The HEAO-3 data indicated a mix very similar to the solar system for Z<60 but an enhancement of the r-process nuclei in the cosmic rays relative to the solar system for Z>60. That enhancement was seen as an excess in the interval $62 \leq Z \leq 80$; however, with the limited charge resolution and low numbers of events in that interval of HEAO data, it was not possible to cleanly separate secondaries from primaries nor to verify that individual elements had the relative abundances expected of an r-process source. In order to account for such a composition, at least two distinct types of r-processes are required, at least one of which preferentially yields elements with Z > 60 compared to the r-process abundances observed in the solar system. Recently Wasserburg, et al. (1996) proposed just such a two-component r-process, based on the extinct fossil radioactivities in ancient meteorites ^{129}I and ^{182}Hf. If the r-process enhancement for Z>60 is confirmed by HNX, this would have important implications for both GCR astrophysics and our understanding of the r-process, which is responsible for for roughly half of the nuclei in the universe with Z>30.

The question of whether the heaviest GCRs originate in r- and s-process material that is similar to the solar system or are enriched in r-process elements will be addressed by a measurement of the abundances of individual elements in the interval 62≤Z≤83. Normalizing the nuclei in the Pt-Pb region to the full range of the charge spectrum down to Fe will be important in making this determination.

Nearby Sources: The amount of interstellar material traversed by GCRs between acceleration and observation is indicated by the abundance of cosmic-ray secondaries, elements that are generally rare relative to heavier elements.

HNX will probe the short-pathlength end of the distribution of material traversed, giving information about pathlengths of a fraction of a g/cm^2. Under plausible assumptions about the diffusion mean-free-path of cosmic rays in the galaxy (Ptuskin & Soutoul, 1998), 0.5g/cm^2 corresponds to a distance diffused of roughly 150 parsecs, and a transport time for a relativistic particle of about a half million years.

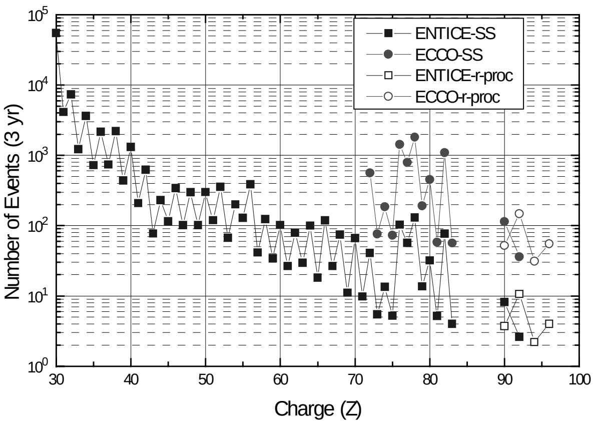

Figure 2: Expected statistics versus element for ENTICE (squares) and ECCO (circles). Both local galactic (closed symbols) and fresh r-process yields (open symbols) are shown for the actinides.

4. Instrument Performance:

Figure 2 shows an estimate of the numbers of nuclei whose charge would be measured independently by ENTICE and ECCO. Particles that undergo nuclear fragmentation in the ENTICE detector have been excluded. For Z≤83, HEAO-3 abundances have been used for nuclei with measured abundances. For unmeasured odd-Z charges, we have assumed abundances that are 33% of the even-Z neighbors.

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