PROCEEDINGS OF SCIENCE

Science Objectives and Goals of the TIGERISS mission

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TIGERISS, the Trans-Iron Galactic Element Recorder for the International Space Station, is an Ultra-Heavy Galactic Cosmic Ray (UHGCR) detector that is planned to be launched to the ISS in 2026. TIGERISS is a continuation of the TIGER and SuperTIGER mission heritage that will be able to measure the elemental abundances from $_5$B to $_{82}$Pb that exceed an energy threshold of 350 MeV/nucleon for an acrylic Cherenkov detector used on the instrument.. With a minimum geometry factor of 1.3 m^2 sr, TIGERISS, in less than one year of operation, will match the statistics seen by the 55 day SuperTIGER-1 balloon flight without the need for atmospheric corrections. By using SiPMs instead of PMTs, TIGERISS will improve upon SuperTIGER's charge resolution providing single-element peak resolution over its full dynamic range. All of these factors will allow us to provide the first single-element measurements through the lanthanides and up to lead within the interstellar medium, allowing us to test a wide range of source and propagation models for cosmic-ray origins and acceleration. With TIGERISS being able to cover the entirety of the s-process, r-process, and rp-processes of nucleosynthesis, we will add to the wider multi-messenger effort to determine the relative contributions of supernovae (SN) and Neutron Star Merger (NSM) events.

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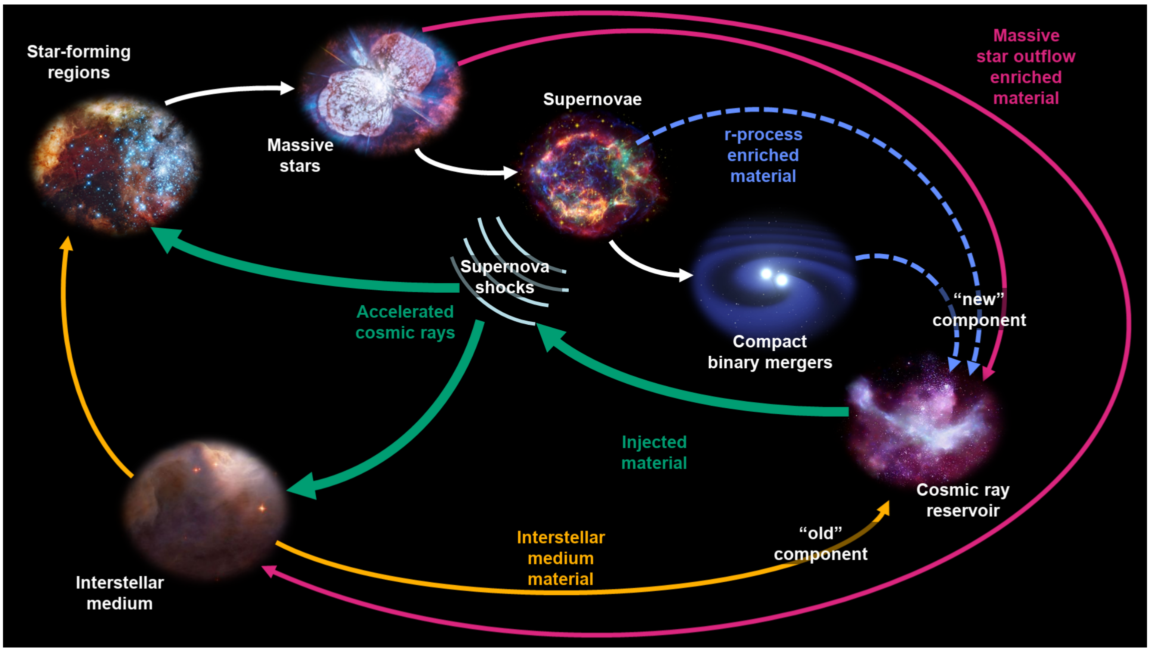

Figure 1: The cycle of matter in the Galaxy. Star forming regions create massive stars that inject matter into the interstellar medium via stellar wind and supernova shocks. The heaviest nuclei are produced in the most energetic processes: supernovae and NSMs.

1. Introduction

The overall TIGERISS mission goal is to increase our understanding of how the Galaxy produces and distributes the elements [1]. As noted by the NASA decadal survey there are open questions on neutron star mergers being the main site of r-process nucleosynthesis, or whether there are supernovae and other core collapse events that contribute significantly to the r-process budget of the universe [2]. This has been a timely topic since the joint detection of GW170817 in gravitational waves, GRB 170817A in gamma rays, and the subsequent kilonova observed at optical wavelengths, which re-energized debate about where and how heavy nuclei are created across the Galaxy. Galactic cosmic rays (GCRs) provide clues on this issue, as GCRs are one of our few direct samples of matter from outside the Solar System. Their relative rarity at the highest charges, however, means that most absolute UHGCR individual elemental abundances are difficult to obtain. In fact, single-element abundances above nuclear charge Z = 56 remain unknown. TIGERISS will employ silicon detector technology from a vantage point on the ISS to obtain novel data on these rare UHGCRs to illuminate the grand cycle of matter in the Galaxy shown in Figure 1. TIGERISS will have the unprecedented ability to measure GCR abundances of elements spanning the periodic table from boron to lead (Z = 5 to Z = 82).

Additionally, the decadal survey asks how the "injection of energy, momentum, and metals from stars" circulates matter. We believe OB associations in giant molecular clouds are a key environment for exploring this question. UHGCR abundance measurements indicate that massive star material (MSM) produced and ejected by supernovae and Wolf-Rayet stars contributes to injection of energy, momentum and metals into the Galaxy. TIGERISS will directly measure material accelerated from OB associations, constraining models of nucleosynthesis and cosmic-ray acceleration. These observations will allow us to play a part in that, by interpreting broadband electromagnetic observations, as those require detailed simulations that account for, among other effects, the realistic production, acceleration, and transport of cosmic rays.

2. Ultra-Heavy Element Origins

2.1 Sources of Nucleosynthesis

To get the observed flux of GCRs arriving at Earth we find that cosmic-ray particles need highly energetic sources. In this new era of multi-messenger astronomy we find that there is a combination of options available that would be able to provide the necessary abundances and acceleration mechanisms.

2.1.1 Supernovae

The first option is Supernova (SN) explosions. These are one of the most energetic processes in the Galaxy, with each SN releasing $\sim 10^{51}$ ergs [3] and occurring with relative frequency, on the order of 2.8 ± 0.6 per century [4]. There are two main types of SN: core-collapse (SNII and Ib/c), where an isolated star or one in an accreting binary system reaches the point where the star collapses in on itself to form a neutron star or black hole and ejects a significant portion of its mass in the process. The extreme case of this, a hypernova or collapsar, ejects particles with an order of magnitude more in kinetic energy. The other type SN Ia, is a thermonuclear explosion of older smaller white dwarf stars in an accreting binary system. Stars with greater than 8 solar masses reach a point where the fusion burning inside the core cannot support the energy and radiative pressure to overcome internal gravitation. The bulk of supernovae in the Galaxy are core-collapse, occurring at roughly a 4 to 1 ratio with SN Ia.

In both cases, the SN occurs when the pressure and gravitational equilibrium goes out of balance from neutrino flavor conversion and the exterior layers fall into the core accelerating to supersonic speeds before reaching a critical density in the core. That causes an immediate bounce that creates an explosive shock wave travelling radially away from the dense nuclear core, creating a proto-neutron star (PNS) [5]. As the shockwave travels it initially loses energy to the surrounding stellar material, accelerating it to relativistic speeds, and gets reinvigorated by the neutrino pulse emitted from the newly created neutron star.

With this in mind, one theory is that the majority of GCRs can originate from OB associations, loose clusters of young, massive, short-lived O and B type stars, leading to a high rate of SNe that can occur in close proximity to one another [6]. These O and B stars can create strong stellar winds leading to the formation of large, rarefied gas cavities (aka superbubbles) around the OB associations. The material left within these superbubbles is enriched by SNe and stellar winds creating the heavy GCRs.

2.1.2 Binary Neutron star Mergers

Another reasonable secondary source for GCRs is mergers of binary neutron stars. LIGO's observation of GW170817 and the co-incident γ-ray burst and then the post-merger follow-up in optical and radio observations confirmed that binary neutron star mergers (BNSMs) do occur and can produce r-process nuclei. These post-merger observations all saw distinct signals of emission lines corresponding to heavy r-process elements. Recent work suggests the spectral observations support an enhancement of the heaviest nuclei relative to the ISM and MSM. Some UHGCR isotopes are made exclusively by either the s-process or the r-process, but others are made by both processes.

In 1996, Wasserburg et al. [7] proposed that there are two distinct r-process sources, and that mass (with a tipping point around 140 amu (atomic mass units), or Z = 58) predicts which process creates a given r-process nucleus. This was based on the inferred abundance of $^{182}_{72}$Hf in the early solar nebula being comparable to what is produced by uniform long-term r-process nucleosynthesis in SN that can produce actinides. But in comparison, Wasserburg et al. saw that $^{129}_{53}$I and $^{107}_{46}$Pd were present at far lower abundances than what they should have been if they came from the same sources. In fact, the ratio of the isotopes $^{129}_{53}$I/$^{127}_{53}$I compared to $^{182}_{72}$Hf/$^{180}_{72}$Hf precludes the r-process from being the same in different SN. Depending on variations of mass and concentration, BNSMs and neutron star-black hole merger simulations show that though the BNSM fraction of r-process production in the 140-amu-region can vary considerably between models [8, 10], BNSM-produced nuclei can account for SS abundances as low as A = 90 or Z = 40. It is noteworthy to point out that this is where GCR abundances from the OB association GCR source model deviate for SuperTIGER [11].

Many recent papers suggest that BNSMs contribute much of the Galaxy's r-process material with mass ≥ 130 amu (Z ≥ 54), with models that predict BNSMs could eject as much as 0.005 - 0.05 solar masses of highly neutron-rich material. However, the frequency of BNSMs in the Galaxy is poorly constrained [12], but best estimates do indicate they may eject enough material to produce most, or perhaps all, r-process material for Z ≥ 54 [13].

2.2 Observation-based models

The general understanding of how these two processes influence the overall GCR abundances is derived from spectral observations of metal rich stars, supernovae, and BNSM merger events. The kilonova spectral component of GW170817 provided a wealth of knowledge into the r-process production, allowing for models to be developed around the kilonova event [9] and the BNSM itself [10]. The two figures shown in Fig. 2a and 2b are examples of some of the many models for spectral observation and nucleosynthesis and should be nominally consistent with actual observations of GCRs.

2.3 Direct GCR Observations

TIGERISS will be the first detector to do single-element charge-resolution measurements extending from $_5$B to $_{82}$Pb yielding abundances of the heaviest UHGCR nuclei, allowing for direct comparisons to the more abundant lighter nuclei. This is not to say that TIGERISS is the only instrument capable of measuring these UHGCR elements, that would be a disservice to the many predecessor instruments (Table 1 and Figure 4), but rather we will be the first to do it with one single instrument.

For example, SuperTIGER results must be combined with measurements from missions such as HEAO-HNE and ACE-CRIS to clearly show continuing separation of refractory and volatile

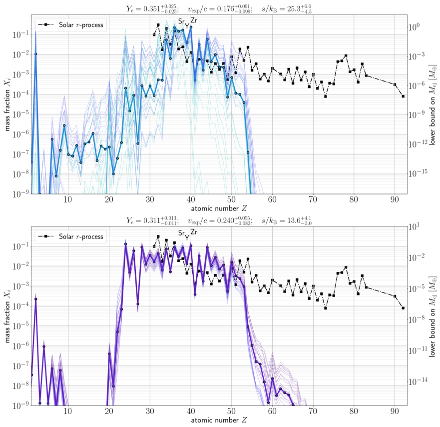

Figure 2(a): (Figure taken from Nicholas Vieira et al. 2023 ApJ 944 123 DOI:10.3847/1538-4357/acae72; licensed under a Creative Commons Attribution (CC BY) license.") Image shows two models of r-process production from the kilonova in GW170817. The solid lines indicate the best fit, while the semi-translucent lines reflect how uncertainties in electron fraction, entropy, and expansion velocity of the ejecta create uncertainties in the abundances.

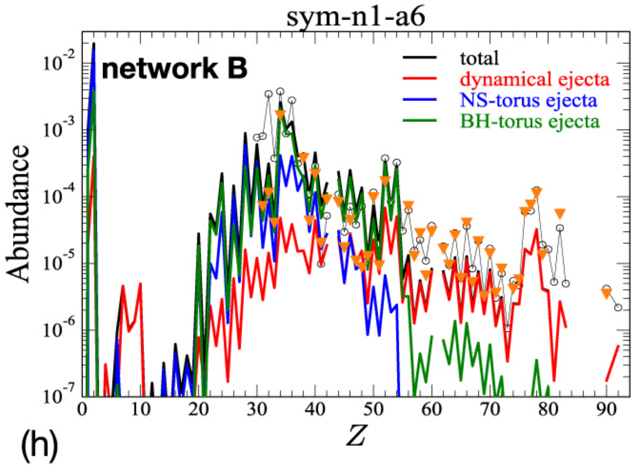

Figure 2(b): (Figure taken from O. Just et al. 2023 ApJL 951 L12 DOI:10.3847/2041-8213/acdad2) This shows a combination of ejecta models for material from multiple BNSM merger models, with comparisons to solar abundances and abundances observed for the metal-poor star HD 222925.

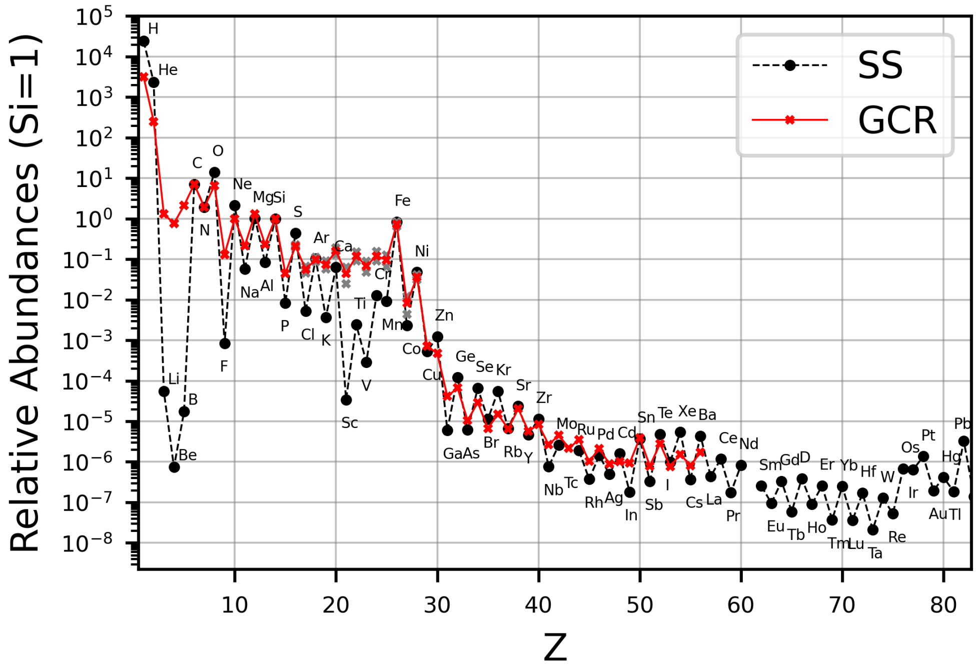

Figure 3: Solar System (SS) [14] and Galactic cosmic-ray (GCR) relative abundances at 2 GeV/nuc. The red line depicts average GCR data, sourced for $1 \leq Z \leq 2$ from [15], $Z = 3$ from [16], $4 \leq Z \leq 28$ from [17], and $16 \leq Z \leq 56$ from [18] normalized to $_{14}$Si. Grey dots depict overlapping measurements from [17] and [18].

	$14 \leq Z \leq 30$	$31 \leq Z \leq 56$	$Z \geq 57$
Single Element Resolution	ACE-CRIS AMS-02 CREAM DAMPE HEAO-3-C2 TRACER Ulysses-COSPIN Voyager	ACE-CRIS ($Z \leq 38$) CALET ($Z \leq 44$) SuperTIGER TIGER	Trek ($70 \leq Z \leq 92$)
Multi-Element Resolution		Ariel-6 HEAO-3-C3	

Table 1: The current state of GCR experiments broken down into detection region. This not a complete list, but serves to show how there is a dearth of measurements beyond $_{26}$Fe and even less at higher Z.

elements outside its range. These instruments all measure different energy ranges, with HEAO-3-C2/C3, Ariel-6, and CALET all measuring energy $\geq\sim$ 0.3 GeV/nuc, with most nuclei between 0.8 and 10 GeV/nuc, while ACE-CRIS samples lower energies (0.16 – 0.6 GeV/nuc) in the $Z < 40$ charge range. These instruments have all operated at different times with varying solar intensities. This makes cross-comparisons between instruments complicate and can cause discrepancies between measurements. To get to Figure 3 requires publications that break down results by energy and when dealing with low statistic high-Z events this is a broad energy range that can be hard to define.

For the highest Zs, some of these measurements run into issues with low statistics and/or low resolution. HEAO-3-C3, could only resolve odd-even element charge pairs for $33 \leq Z \leq 60$ and by element groups for $Z \geq 60$. HEAO-3-C3 recorded just 36 events with $74 \leq Z \leq 80$. Ariel-6 results were similar, with odd-even element charge pairs for $33 \leq Z \leq 48$ and binning Z by decade for $Z \geq$

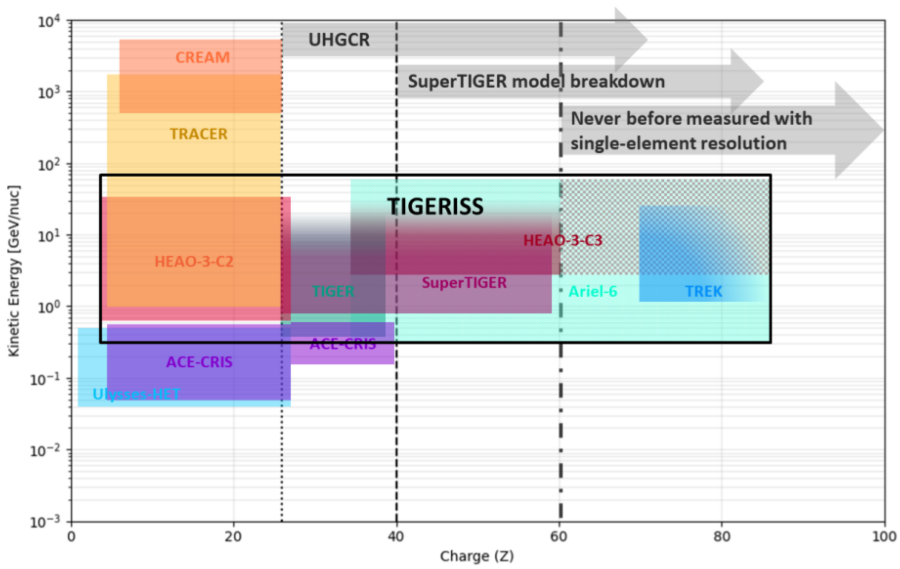

Figure 4: Visualization of the overlap of charge and energy range for some of the experiments in Table 1.

50 and seeing only 172 events for all Z ≥ 60.

Measurements with the passive Trek detector on MIR, the only existing results with single-element resolution at the highest charges, are nearly impossible to normalize, given the lack of other comparable measurements and Trek's sensitivity to Z ≥~70 at kinetic energies 0.9 GeV/nucleon. The charge resolution is also poor, barely adequate to resolve individual elements with $\sigma_Z \sim 0.45$e, compared to TIGERISS's $\sigma_Z \leq 0.25$. Trek additionally has low statistics across its measurements, 192 events in total, and no particles measured in the actinide gap (83 ≤ Z ≤ 89).

3. TIGERISS Projections

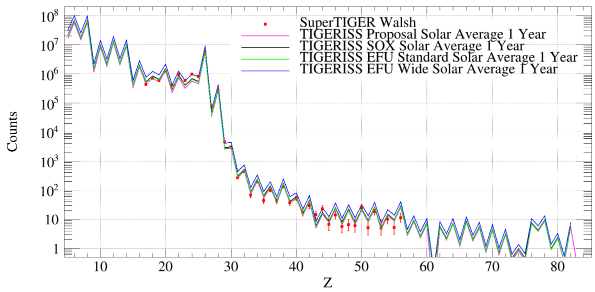

Figure 5: Predicted abundances measured by TIGERISS for 1 year operation on the three potential ISS configurations. We can see that 1 year of operation would generate statistics that are comparable to SuperTIGER's 55 day long-duration-balloon flight. See [19] for further details.

In ~1 year with our proposed instrument acceptance we expect to measure ~50 - 60% of the Z > 56 statistics observed by HEAO3-HNE and statistics equivalent to SuperTIGER. [19] TIGERISS will have the ability to reliably determine charge in the Z > 60 region where the limited Poisson statistics preclude much peak formation.

While it is true that longer collection times would allow TIGERISS to draw more significant scientific conclusions from Z > 60 observations, just the limited 1-year TIGERISS data set, with its good charge resolution and assignment fidelity, will provide new insight into how the charge groups measured by HEAO3-HNE are partitioned. By comparing the results of TIGERISS to various nucleosynthesis production models for SN and BNSM events we can rule out models with various levels of confidence.

Our 1-year observations from the ISS, with a superior instrument, will allow us to also address known systematic issues with the SuperTIGER measurements through Z = 56, including atmospheric energy losses and nuclear spallation, scintillator saturation effects, and the discontinuity between high- and low-gain channels around Z = 48 that corrupted measurements of at least 47 ≤ Z ≤ 49, further expanding the confidence in measurements in the charge-region.

4. Conclusions

When TIGERISS launches to the ISS in Fall 2026, it will begin to make measurements of elements up to $_{82}$Pb. Within a year we should have the first single-element resolution of individual peaks and with a mission extension to the end of the ISS, we would be able to deliver spectra complementary to other long running experiments. By looking at differences in expected nuclei modeled from the kilonova spectra and the resultant TIGERISS GCR measurements we can also gain understanding of the propagation of elements.

5. Acknowledgements

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