33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

ICRC 2013

Constraints on Galactic Cosmic-Ray Origins from Elemental and Isotopic Composition Measurements

W. R. BINNS[1], E. R. CHRISTIAN[2], A. C. CUMMINGS[3], G. A. DE NOLFO[2], M. H. ISRAEL[1], R. A. LESKE[3], R. A. MEWALDT[3], E. C. STONE[3], T. T. VON ROSENVINGE[2], M. E. WIEDENBECK[4]

[1] *Washington University, St. Louis, MO 63130, USA*
[2] *NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[3] *California Institute of Technology, Pasadena, CA 91125, USA*
[4] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA*

wrb@wustl.edu

Abstract: The most recent measurements by the Cosmic Ray Isotope Spectrometer (CRIS) aboard the *Advanced Composition Explorer* (*ACE*) satellite of ultra-heavy cosmic ray isotopic and elemental abundances will be presented. A range of isotope and element ratios, most importantly ^{22}Ne/^{20}Ne and $_{31}$Ga/$_{32}$Ge show that the composition is consistent with source material that is a mix of $\sim$80% interstellar medium material (with Solar System abundances) and 20% outflow/ejecta from massive stars. In addition, our data show that the ordering of refractory and volatile elements with atomic mass is greatly improved when compared to an $\sim$80%–20% mix rather than pure interstellar medium material. We conclude that these data are consistent with an OB association origin of galactic cosmic rays.

Keywords: cosmic ray, cosmic ray origins, OB associations

1 Introduction

The study of the origin of galactic cosmic rays (GCRs) has always been understood to consist of two aspects: the mechanism and location of acceleration, and the source material that is accelerated. Cosmic-ray and gamma-ray measurements are providing important and complementary information relevant to understanding the origin of GCRs [1]. Recently gamma-ray emission has been detected coming from the supernova remnants (SNR) W44 and IC443 [2] that is consistent with π^0 decay and is therefore indicative of hadronic acceleration. These SNRs are both remnants of core-collapse supernovae. Distributed emission, also consistent with hadronic acceleration, has been observed from a "cocoon" corresponding to the Cygnus superbubble extending from Cygnus OB2 to NGC 6910 [3]. Other gamma-ray sources consistent with hadronic acceleration, all but one of which are the remnants of core collapse supernovae (SNe), are discussed in [4]. Thus, gamma-ray observations appear to have identified specific acceleration sites, which are primarily the remnants of core-collapse SNe. Since cosmic rays are charged particles, they do not point back to the source as gamma rays do, but the elemental and isotopic abundance patterns can be used to identify the pool of material that is being accelerated and thus "point" to the classes of objects that provide this source material.

The *ACE*-CRIS experiment was originally designed to measure the elemental and isotopic abundances of cosmic ray nuclei with charge $4 \leq Z \leq 30$ [5]. Owing to the long duration of the *ACE* mission and the large geometrical factor of the CRIS instrument, we have been able to collect a sufficiently large number of events so that measurements of elemental and isotopic abundances beyond the original design limits of the instrument are possible. We have obtained measurements of the isotopic abundances of nuclei through $_{32}$Ge and elemental abundances, for the most abundant elements, through $_{38}$Sr. In this paper we present these results and show that they are consistent with a cosmic ray origin in which the source material consists of a mixture of $\sim$80% ISM (with Solar System abundances [6]) and 20% outflow/ejecta from massive stars. This is consistent with GCRs originating in associations of massive stars (OB associations) and the superbubbles that they form.

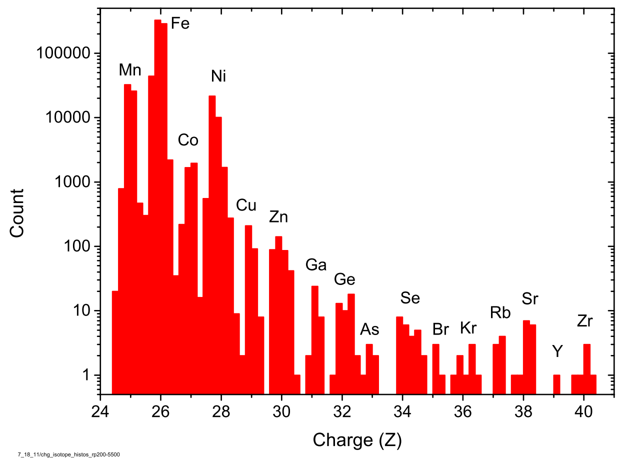

Figure 1: Histogram of elements.

2 Measurements of Ultra-heavy Elements

Figure 1 is a histogram of elements from $_{25}$Mn through $_{40}$Zr. These data were collected from 4544 days between 4 December 1997 and 2 April 2011. The energy ranges vary with charge, but is approximately 180-510 MeV/nucleon for ultra-heavy (UH) nuclei with $30 \leq Z \leq 40$). We have obtained excellent resolution in charge over the full range

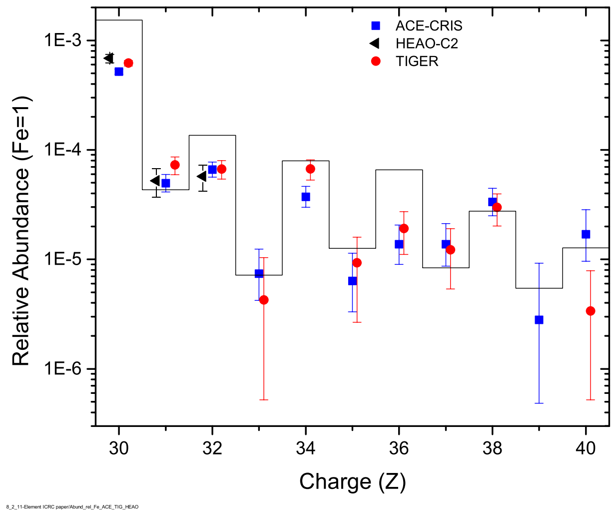

Figure 2: Elemental abundances relative to iron compared to solar system abundances [9].

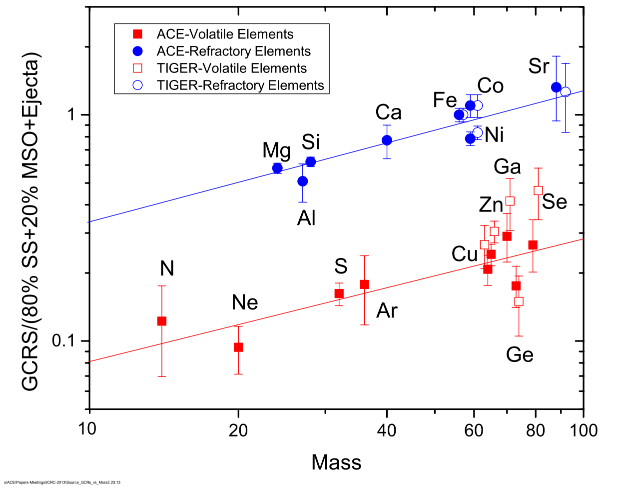

Figure 4: Plot of galactic cosmic ray source abundances relative to the 80(solid symbols) and TIGER data (open symbols). Note the clear separation between refractory and volatile elements.

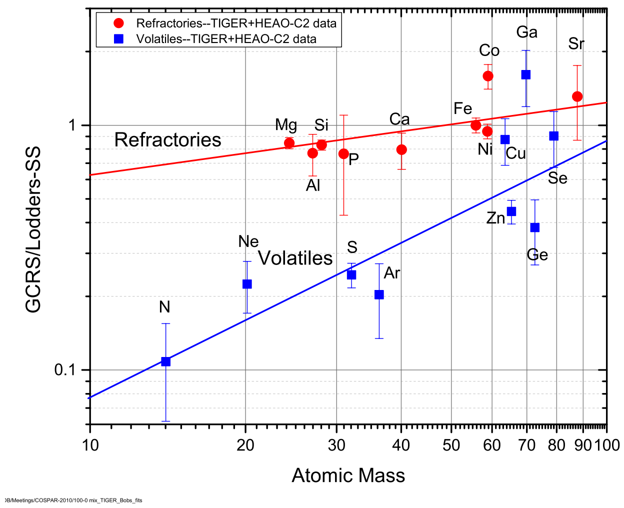

Figure 3: Plot of galactic cosmic ray source abundances relative to solar system for TIGER data ($Z \geq 26$) [7] and HEAO-C2 data ($Z < 26$) [11] vs. atomic mass of nuclei. Note that for iron and lighter elements, there is a clear separation. However, for heavier elements the data points for refractory and volatile elements are co-mingled.

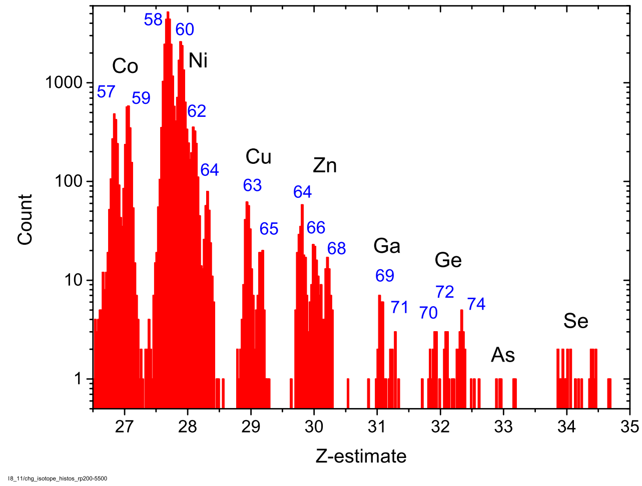

Figure 5: Histogram of isotopes showing clearly resolved isotope peaks up through $_{32}$Ge.

plotted, as can be seen from the figure, with limited statistics at the highest charges. The numbers of events obtained are comparable to those obtained by the balloon-borne Trans-Iron Galactic Element Recorder (TIGER) instrument [7].

Figure 2 shows our measured elemental abundances relative to iron compared to TIGER [7]and HEAO-C2 [8] abundances. We see that there is generally good agreement between the measured abundances. The solid line is a plot of solar system abundances [9] relative to iron. Perhaps the most striking observation from this plot is that the abundances of $_{31}$Ga and $_{32}$Ge are very similar, while in the solar system $_{32}$Ge is $\sim$3x more abundant than $_{31}$Ga. Both of these elements are considered to be volatile elements (i.e. elements that reside primarily in the gas phase in the ISM), so it is expected that they should both be under-abundant compared to solar system abundances, but they should not be approximately equal. However, Woosley and Heger [10] show that for combined outflow and ejecta of massive stars, $_{31}$Ga has the largest "overproduction factor" relative to solar system abundances of any element. Thus, in the "elevated" $_{31}$Ga abundance, we may very well be seeing a nucleosynthetic signature of massive star origin in the cosmic rays.

Ellison et al. [8] noted that in the cosmic rays, the abundances of elements that exist primarily as grains in interstellar space (refractory elements) are over abundant compared to elements existing primarily as gas, when taken relative to solar system abundances. Furthermore, the volatile abundances showed a mass dependence while the refractories appeared to be nearly mass independent. In Figure 3 we show an updated version of this figure using the TIGER [7] and HEAO-2 [8] data. We see, in agreement with Ellison et al., that the volatile ratio shows a mass dependence

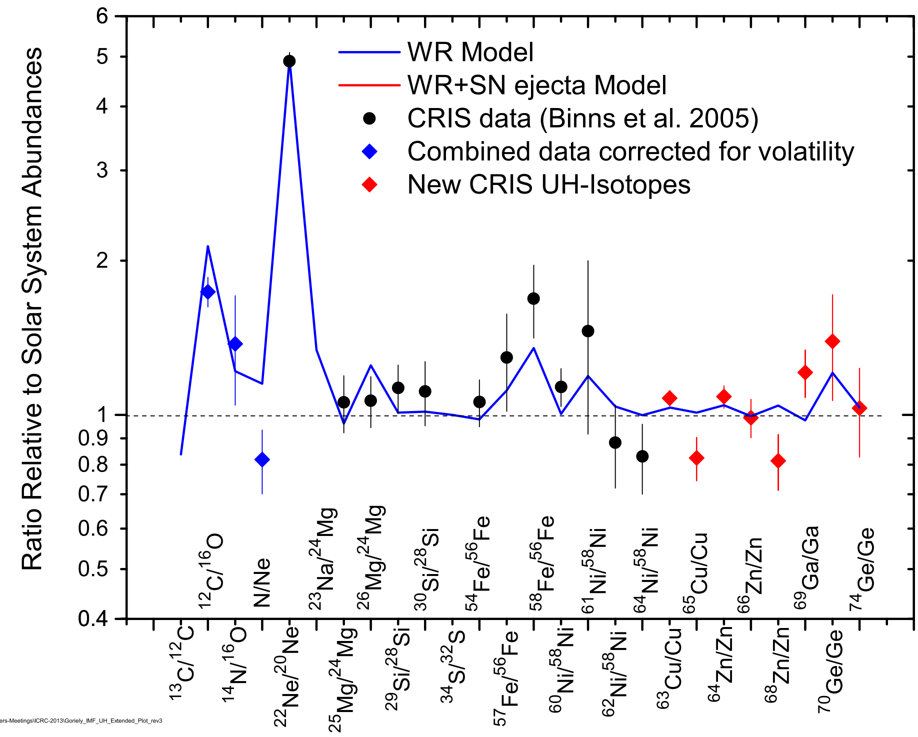

Figure 6: Plot of isotope and element ratios relative to solar system abundances [6]. The solid line was obtained by mixing massive star outflow material [15] with normal ISM until it matched our measured ^{22}Ne/^{20}Ne ratio.

while the refractories show only a slight mass dependence. However, for nuclei heavier than Nickel the volatiles and refractories are confused.

In Figure 4 we plot the cosmic ray source abundances derived from our ACE-CRIS measurements (closed symbols) relative to a mix of ∼80% normal ISM (assumed to have solar-like abundances) and ∼20% massive star outflow plus supernova ejecta [10] versus atomic mass, instead of relative to solar system abundances. We see that the volatile and refractory elements are clearly separated, with refractory elements having an abundance enhancement ∼4x greater than volatile elements. In addition, their slopes are very similar. The ordering of refractories and volatiles is greatly improved over that observed in the plot of Figure 3. We take this very significant improvement in ordering to indicate that the pool of material from which cosmic rays originate is a mixture of ∼80% normal ISM material with ∼20% massive star outflow and ejecta.

The elemental abundances measured by *ACE*-CRIS are in generally good agreement with the TIGER results (open symbols in Figure 4) [7]. We note that, except for $_{32}$Ge, the abundances of $_{29}$Cu–$_{36}$Kr measured by CRIS are systematically slightly lower than in the TIGER data, even after allowing for a known effect of exceeding the dynamic range for high-Z particles with large incidence angles, for which we have made corrections. To this point we have not been able to identify any mechanism that would result in such a bias. Work is on-going to study the possibility of a systematic measurement bias for these elements.

3 Measurements of Ultra-heavy Isotopes

Figure 5 is a histogram of isotopes extending from $_{27}$Co through $_{34}$Se. We see well resolved isotope peaks from $_{27}$Co through $_{32}$Ge with sufficient statistics for a meaningful measurement. The charge calculated from CRIS *dE/dx* vs. total energy measurements (Z-estimate in Figure 5) also has a dependence on mass [5] such that each charge peak actually consists of a set of closely spaced peaks corresponding to the isotopes of the element.

In Figure 6 we have plotted our measured isotope source abundances relative to solar system over a broad range of charges. The black data points (circles) for ratios from $_{10}$Ne to $_{28}$Ni were reported previously [12] and led to the conclusion, in agreement with Higdon and Lingenfelter [13], that the likely source of a substantial fraction of GCRs is clusters of massive stars called OB associations and their associated superbubbles [12, 13, 14]. The error bars for these data points include estimates of systematic uncertainty. The red data points show our recent preliminary measurements of the isotopes of $_{29}$Cu through $_{32}$Ge. The error bars for these data points are statistical only, and do not include any systematic uncertainties. The solid line in the figure was obtained using a two-component model in which outflow from stars with sufficient mass to evolve into Wolf-Rayet stars ($\gtrsim$30M$_\odot$) [15] was mixed with normal ISM material (with solar system abundances [6]) such that the modeled ^{22}Ne/^{20}Ne ratio would reproduce our measured ratio [12, 14]. The mix required for this normalization was 80% normal ISM material plus ∼20% massive star outflow. For that mix, the model then predicts the values that we should observe for other ratios (solid line). We see that our abundance ratios for the isotopes of $_{29}$Cu through $_{32}$Ge are close to those expected for the mixture, but also to solar system abundances; i.e. they do not discriminate between the source material being pure ISM or the 80%–20% mix. Thus, these improved ($_{29}$Cu and $_{30}$Zn) and new ($_{31}$Ga and $_{32}$Ge) measurements are not inconsistent with a GCR origin in OB associations and their associated superbubbles.

It also appears that we have resolved isotopes for elements up through $_{34}$Se, although additional statistics are needed to obtain clearly resolved peaks. For $_{34}$Se the tentative mass numbers assigned to the "clumps" of particles have about the expected spread (based on solar-like isotopic composition), but clear peaks, which require more particles, would help to confirm the mass identification. Furthermore, $_{33}$As, which has only one stable isotope, provides a useful check on the mass assignments. Additional data and careful analysis of events that have been rejected in our current data set, with the possibility of reclaiming some of them, might result in clear peaks and mass assignments. This would provide another isotope group that could be used to test models of cosmic ray origin.

4 Conclusions

We conclude that the elemental and isotopic abundances of galactic cosmic rays provide important constraints upon the cosmic-ray source. The substantial improvement in ordering of the refractory and volatile elements when compared to the 80%–20% ISM/massive star mixture, instead of normal ISM alone, points to cosmic ray origin in OB associations. Furthermore, the agreement of the isotopic abundances with a similar mixture gives a completely independent indication that OB associations are the likely source of a large fraction of galactic cosmic rays.

Acknowledgements

This research was supported by NASA at Caltech, Washington University, JPL, and GSFC under grants NNX08AI11G and NNX10AE45G.

References

[1] W. R. Binns, Science 334 (2011) 1071.
[2] M. Ackermann, et al., Science 339 (2013) 807.
[3] M. Ackermann, et al., Science 334 (2011) 1103.
[4] C. D. Dermer & G. Powale, A&A 553 (2013) A34.
[5] E. C. Stone, et al., Space Sci. Rev. 86 (1998) 285.
[6] K. Lodders, ApJ 591 (2003) 1220.
[7] B. F. Rauch, et al., ApJ 697 (2009) 2083.
[8] D. C. Ellison, et al., ApJ 487 (1997) 197.
[9] K. Lodders, et al., In Landolt-Bornstein, New Series, Vol VI/4B, Chap. 4.4, J. E. Trumper (ed), Springer Verlag (2009) 560.
[10] S. E. Woosley & A. Heger, Phys. Rpts. 442 (2007) 269.
[11] J. J. Engelmann, et al., A&A 233 (1990) 96.
[12] W. R. Binns, et al., ApJ 634 (2005) 351.
[13] J. C. Higdon & R. E. Lingenfelter, ApJ 590 (2003) 822.
[14] W. R. Binns, et al., New Astron. Revs. 52 (2008) 427.
[15] G. Meynet & A. Maeder, A&A 404 (2003) 975.