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# Insights into the *s*-process and *r*-process as revealed by globular clusters

**D. Yong,[1] A. I. Karakas,[1] D. L. Lambert,[2] A. Chieffi,[3] and M. Limongi[4]**

[1]Australian National University, Mount Stromlo Observatory, Australia
[2]W. J. McDonald Observatory, University of Texas, Austin, TX, USA
[3] Istituto Nazionale di Astrofisica, Istituto di Astrofisica Spaziale e Fisica Cosmica, Rome, Italy
[4]Istituto Nazionale di Astrofisica-Osservatorio Astronomico di Roma, Rome, Italy

**Abstract.** We present abundance measurements for a large number of neutron-capture elements in giant stars of the globular clusters M4, M5, and M13. The relative abundance ratios differ between all three clusters. For all clusters, we find that the mean abundances for the elements from Ba to Hf can be well explained by scaled versions of the solar *s*- and *r*-process abundances, albeit with different mixtures of *s*- and *r*-process material for each clusters.

**Keywords.** Galaxy: abundances, globular clusters: individual (M4, M5, M13), stars: abundances

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Globular clusters continue to provide ideal laboratories for testing the predictions of stellar evolution (e.g., Gratton *et al.* 2004). With the exception of $\omega$ Centauri and M15 (e.g., Norris & Da Costa 1995, Sneden *et al.* 2000), in general only a handful of neutron-capture elements have been measured in globular clusters. For example, the *s*-process is usually represented by measurements of Y, Zr, Ba and/or La whereas Eu measurements are often the sole indicator of the *r*-process. Possible explanations for the lack of abundance measurements for additional neutron-capture elements include limited wavelength coverage and signal-to-noise ratios.

M4 and M5 are particularly well suited for refining our understanding of stellar nucleosynthesis of the *s*-process elements. This pair of clusters was extensively studied by Ivans *et al.* (1999, 2001) who showed that they have essentially identical metallicities, [Fe/H] = $-1.2$, and very similar abundance ratios [X/Fe] for many $\alpha$- and Fe-peak elements. However, the *s*-process elements Ba and La are overabundant in M4 relative to M5. We have obtained very high quality spectra (R = 55,000 and S/N = 800 per resolution element at 8000Å) using the MIKE spectrograph (Bernstein *et al.* 2003) on the Magellan Telescope of 12 bright giants in M4 and 2 bright giants in M5 to further probe the relative abundances of neutron-capture elements in these two clusters.

Using standard analysis techniques, we measured the relative abundances of some 16 neutron-capture elements from Rb to Th in both clusters. This comprehensive analysis is only possible due to the large wavelength coverage, high spectral resolution, and high S/N ratios. We confirm that all *s*-process elements are overabundant in M4 relative to M5 and find that the *r*-process elements may be slightly overabundant in M5 relative to M4 (Yong *et al.* 2008a, 2008b).

Since there is no detectable star-to-star abundance dispersion for any neutron-capture element, we suppose that the abundance differences between these two clusters were present between the clusters' natal clouds. Relative to M5, the M4 stars formed from gas enriched in *s*-process products but deficient in *r*-process material. This conjecture may

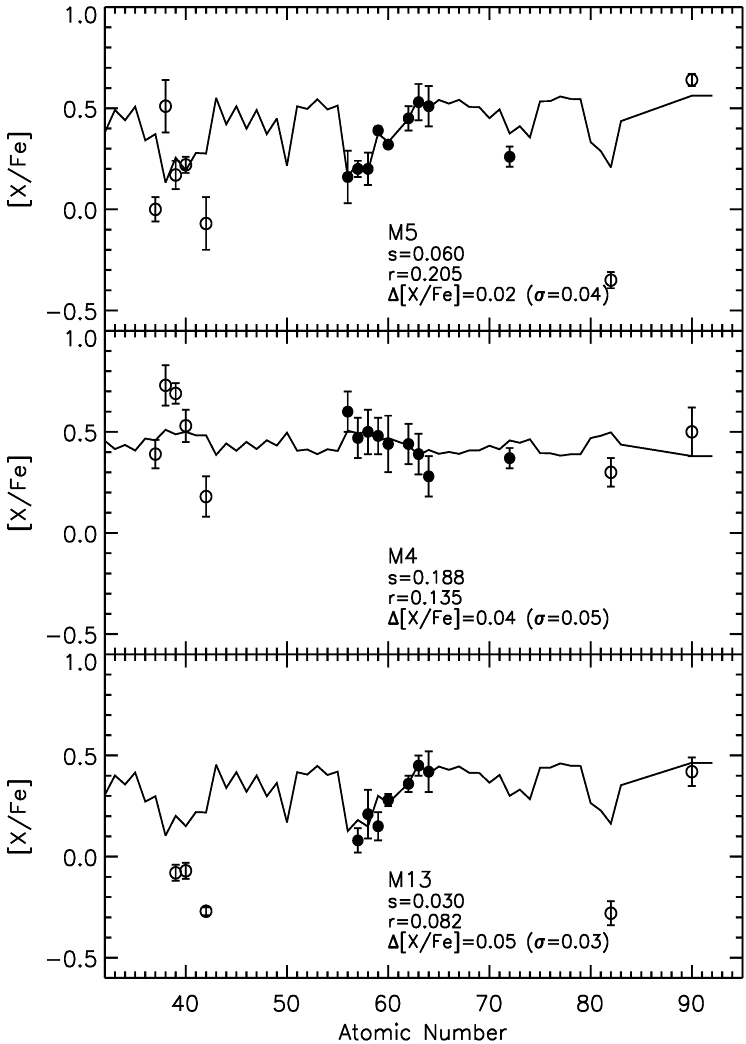


**Figure 1.** Abundance ratios [X/Fe] for the elements from Rb to Th in M5 (upper), M4 (middle), and M13 (lower). We show the best-fit predictions to the elements from Ba to Hf (filled circles) using scaling factors **"s"** and **"r"** which were multiplied by the solar *s*-process and *r*-process abundances, respectively.

be subject to quantitative analysis if we assume that the *s*- and *r*-process contributions to each cluster are scaled versions of the solar *s*- and *r*-process abundances respectively. Taking linear combinations of the Simmerer *et al.* (2004) solar *s*- and *r*-process abundances, we determined the optimal scaling factors for the *s*- and *r*-process. That is, our optimal scaling factors are the relative fractions of solar *s*- and *r*-process material that best produce the measured abundances. In Figure 1 we plot the measured abundances along with the best fit predictions using the scaling factors **"s"** and **"r"** which were multiplied by the solar *s*-process and *r*-process abundances, respectively. For both clusters, the predicted and measured abundances are in excellent agreement. Therefore, although M4 and M5 have very different abundance distributions of the neutron-capture elements, both clusters can be well explained by simply taking linear combinations of scaled versions of the solar *s*- and *r*-process material.

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For M13, existing measurements (Yong *et al.* 2006a, 2006b) were supplemented with additional neutron-capture elements. Based on these preliminary measurements (made with the assistance of two summer research scholars, Benjamin Sparkes and Andrew Cameron), we again find that we are able to fit the measurements using scaled versions of the solar *s*- and *r*-process abundances. However, for all three clusters, the lighter elements (Rb-Mo) are not well matched by the predictions.

We have additional observations that will allow us to perform a similar dissection of the neutron-capture abundances for other clusters and field stars. To complement these new measurements, it is important to extend the stellar yields (e.g., Chieffi & Limongi 2003, Karakas & Lattanzio 2007) and chemical evolution models (e.g., Travaglio *et al.* 2004, Karakas *et al.* 2006, Marcolini *et al.* 2009) to include a larger suite of neutron-capture elements if possible.

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