# The Early Local Universe – Inside and Outside the Stars

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## Context:

Extremely metal-poor (EMP) halo stars with [Fe/H] below ~ -3 are considered to be fossil records of conditions in the early halo. In the naïve picture in which iron is a proxy for overall metallicity and indirectly for time, EMP stars formed well before the Galactic globular clusters. Their detailed abundance pattern is very uniform and essentially scaled Solar, except for the α-enhancement typical of halo stars. A minority are, however, dramatically enhanced in carbon (C) and/or *r*-process elements, with or without a concomitant excess of *s*-process elements (CEMP-n and CEMP-*s* stars). How were these elements produced – as a surface contamination deposited locally by a binary companion or far away in the early Galaxy? Are these stars mostly binaries; if so, does it matter? If not, how were the excess elements implanted in the natal clouds of the stars we see today?

## The Origin of Carbon in the Early Galaxy: Local or External

The dramatic excess of C in many EMP stars may arise in either of two fundamentally different ways: *(i)* by local contamination of the stellar surface with processed material transferred by Roche lobe overflow and/or a stellar wind from an evolved (AGB) binary companion, or *(ii)* by preferential C enrichment of the natal cloud of a star in the early ISM from an external source at typical interstellar distances.

In the former case, at least the CEMP-*s* stars may be written off as local anomalies, like the well-known Ba or CH stars, which are enriched in *s*-process elements and are all members of long-period binary systems. But the jury is still out regarding the status of the CEMP-no stars, which show no signatures of AGB nucleosynthesis. If they, like the *r*-process enhanced EMP stars (Hansen et al. 2011), are generally *not* binaries, these stars indicate the existence of enrichment mechanisms that are not included in current models of chemical evolution of the ISM in early halo. ⇨

## Binary Properties of the Samples

As documented in detail by Hansen et al. (2015abc), the binary frequency of the EMP-*r* and CEMP-no stars is just 17±5%, identical to the 16±4% found by Carney et al. (2003) for halo giants or the 22±3% for the Mermilliod et al. (2007) Pop I cluster giants. *Thus, the presence of a binary companion is not related to the unusual composition of these stars, which must reflect that of the material from which they were formed.*

In contrast, ~80% of the CEMP-*s* stars are binaries with orbital periods up to ~10,000 days (30 years!) and low velocity amplitudes, while the remaining 20% have very constant velocities and are apparently single. So the 'local mass-transfer' scenario may apply to *most* CEMP-*s* stars, but ***some** acquired their excess C from a source more distant than a binary companion.*

Our ability to distinguish between binary and single stars – even with long and/or akward periods – is illustrated by the three EMP-r binaries at right: The lower one – HE1523-0901, in which even U has been measured – has an amplitude of only 250 m $s^{-1}$. ⇩

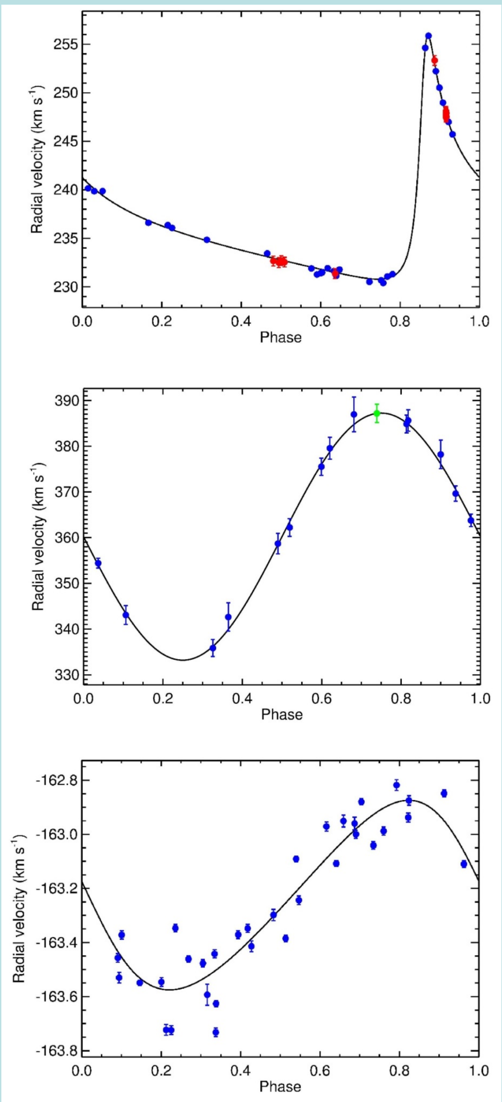
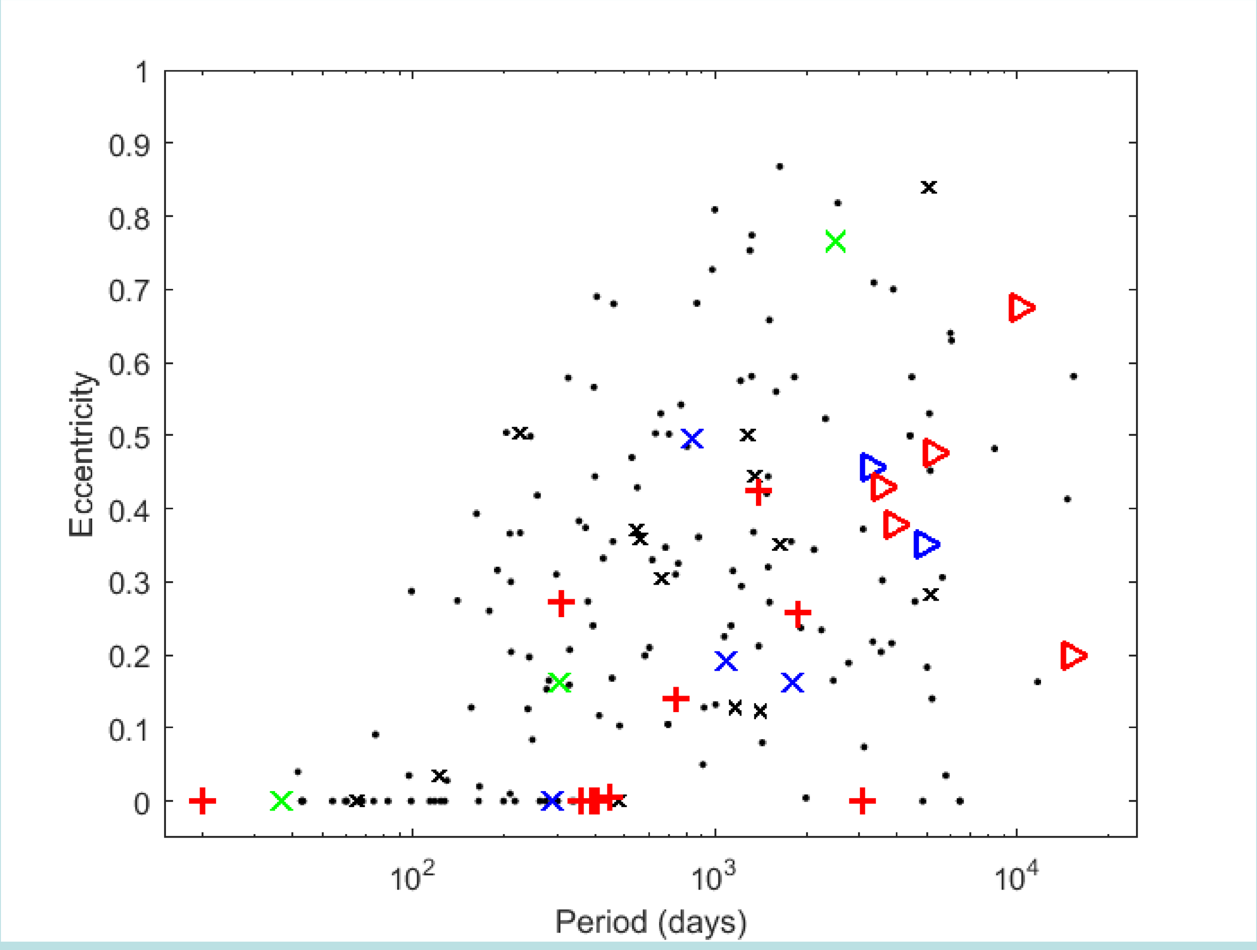



**Fig. 2.** Orbital solutions for the three binary systems found in our programme. Top: HE 0442−1234 (blue this work, red P. Bonifacio private comm.), middle: HE 1044−2509 (blue this work, green Barklem et al. (2005)) and bottom: HE 1523−0901.

## Tidal Interaction in Binary Systems

As seen in the plot below, the orbital eccentricities of our EMP-*r* and CEMP-no binaries are distributed just like other Pop I and II systems with giant primaries. The larger cutoff period for circular orbits among CEMP-s binaries (5-600 d) may reflect the larger radii of their presumed former AGB (and initially more massive) secondaries. ⇗




Period-eccentricity plot for giant binaries with well-determined orbits.

**Black dots and crosses:** Population I and II giants (Mermilliod et al. 2007; Carney et al, 2006); **green** crosses: our three EMP-*r* binaries; **blue** and **red** crosses: binary orbits for our **CEMP-no** and **CEMP-*s*** stars. Right-pointing triangles: incomplete long-period orbits.

The 20-day CEMP-s star might result from common-envelope evolution.

NOT at Observatorio del Roque de los Muchachos..

The FIES vault is seen at far right.

(Photo: P.A. Wilson)

## The Smoking Gun

An observational test is straightforward: In the "local pollution" scenario, these stars should all be members of binary systems and exhibit orbital motion like the Ba and CH stars. Taking the latter as a model, orbital periods are expected to be long (~decades) and radial velocity (RV) amplitudes low; therefore, long-term, homogeneous series of precise RV observations, prompt follow-up, and persistence(!) are required.

In this project, we observed a sample of 17 EMP-*r*, 24 CEMP-no, and 22 CEMP-s stars with the 2.5m Nordic Optical Telescope on La Palma and its high-resolution, fiber-fed, bench mounted échelle spectrograph FIES, stably installed in a thermally controlled underground vault. Low S/N spectra were obtained in service mode over 8 years at monthly typical intervals, and RVs were derived by cross-correlation. ⇙

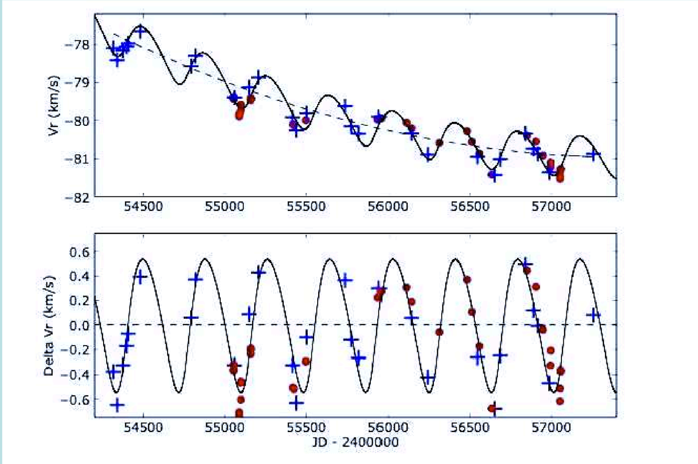



**Fig. 2.** The radial-velocity curve of HE 0017+0055 showing the short- and long-term orbital fits combined (top) as well as the short-term orbit alone (red dots: HERMES velocities; blue plusses: NOT velocities).

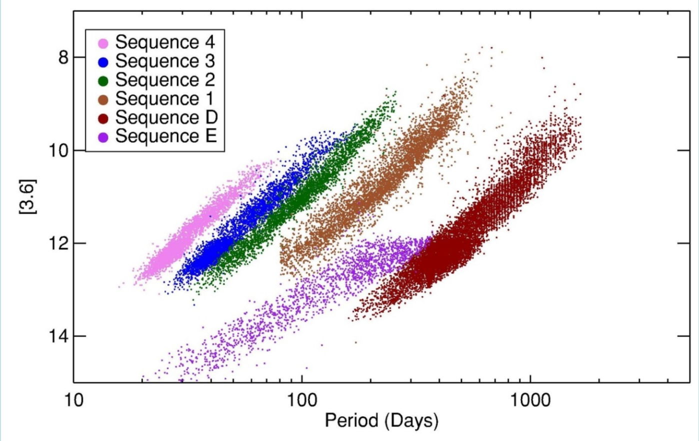



**Figure 1.** Period–luminosity sequences for evolved stars in the LMC. Sequence 1 consists of stars pulsating in the fundamental mode, while sequences 2–4 are higher order pulsational modes. Sequence E consists of ellipsoidal binary systems, and the mechanism responsible for the variation on sequence D is not known. The naming convention follows that of Fraser et al. (2008).

## Binary Motion vs. Pulsations:

Our precise velocity data enabled us to detect very small periodic motions (left) – too small, in fact, to ascribe to any rare face-on binary orbits. One binary CEMP-s star (left) thus shows velocity variations due to regular pulsations of the type seen in cool C-rich LMC giants and AGB stars (right). This may enhance their stellar wind, but also impede the separation of long-period binary motion from other non-obvious effects.

## Conclusions

Our eight-year NOT project has led to several unexpected conclusions:

- The spectra of the EMP-r and CEMP-no stars reflect their initial composition.
- The binary frequency of the CEMP-*s* stars is high, but ***not*** 100%.
- The C in single CEMP stars was produced at interstellar distances – maybe by 'faint' SNe II; the enrichment mechanisms were non-local and inhomogeneous.
- High-*z* C-rich DLA systems (Cooke et al. 2012) may be due to such a process.
- Future models of the early chemical evolution of galaxy halos must include this.

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