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Nordström, Birgitta; Andersen, Johannes; Hansen, Terese

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Origin and distribution of the lightest and heaviest elements in the primitive halo

B. Nordström[1], J. Andersen[1,2], and T. Hansen[1,3]

[1] The Niels Bohr Institute, Copenhagen University, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark, e-mail: `birgitta@nbi.ku.dk`
[2] Nordic Optical Telescope Scientific Association, Apartado 474, ES-38700 Santa Cruz de La Palma, Spain
[3] Landessternwarte, Heidelberg University, Königstuhl 12, D-69117 Heidelberg, Germany

Abstract. The detailed abundance patterns of extremely metal-poor (EMP) stars are our best guide to the earliest stages of the synthesis of the heavier chemical elements. For carbon and the heaviest neutron-capture elements, this is best studied in stars in which these elements are strongly enhanced relative to the pattern in the general EMP population. It is then crucial to know if these excesses were inherent in the material from which these stars were formed, or whether they are just a surface pollution deposited by a local source, i.e. a binary companion that evolved through the AGB or even supernova stage. We report on a programme to test the fundamental paradigm underlying the latter scenario.

Key words. Galaxy: abundances – Stars: Population II – Galaxy: halo

1. Introduction

The cosmic abundance pattern of nearly all the chemical elements is imprinted in exquisite detail in samples of meteorites from the early Solar system. Increasingly refined spectroscopic analyses over the last several decades have shown that this pattern is shared by the vast majority of stars in the Milky Way galaxy. In parallel, progress in nuclear physics has largely clarified the processes by which nuclear fusion and neutron-capture processes gradually synthesised the elements from the (almost) pure mix of hydrogen (H) and helium (He) left by the Big Bang and galactic evolution models have been developed to describe how the freshly produced elements were added and recycled through successive generations of stars. With comparatively minor refinements, this picture has been textbook material for the last half century.

More recently, attention has focused on how it all began in the Milky Way and its retinue of dwarf galaxies, at metallicities (i.e. iron abundances) below – hence presumably at times earlier than – the formation of the most metal-poor globular clusters ([Fe/H] ≤ -2.5). 8-10m-class telescopes and efficient high-resolution spectrograph and detectors have been used to show that the very same abundance pattern is found to apply precisely in stars of much lower metallicity (Cayrel et al. 2004; François et al. 2007), both in giant stars and the harder-to-observe dwarfs (Bonifacio et al. 2009).

But elements at the lightest and heaviest ends of the periodic system have presented difficulties, because the CNO abundances in some stars have been modified by CNO cycling in the stars themselves, followed by extensive mixing in their envelopes (Spite et al. 2005, 2006), and the heaviest neutron-capture elements are too rare to be visible in "normal" stars of very low [Fe/H].

However, a small fraction of extremely metal-poor (EMP) stars ([Fe/H] $\leq\sim -3$) may come to the rescue of observers, since they show enhancements of carbon, in particular, or neutron-capture elements by 1-2 dex or even more. The much-reduced background of spectral lines of the iron-group elements then makes precise abundance determinations easier. This, however, raises the fundamental question whether the observed excess of these elements was inherent in the material from which they formed, or was added to the star – perhaps later – from a local source, i.e. a binary companion that evolved to the AGB or SN stage and transferred enriched material to the surface of the star we now see (Masseron et al. 2010; Qian & Wasserburg 2001).

In the latter case, *all* such "peculiar" stars should be members of binary systems, as found long ago for the Ba and CH stars (McClure & Woodsworth 1990). If not, the excess elements in these stars must have been imprinted on their natal clouds by an external source at great distance, implying incomplete mixing and an inhomogeneous early ISM.

This paper is a progress report on an observational project designed to examine the empirical evidence for the paradigm underlying the binary mass transfer hypothesis and to explore the consequences.

2. Observations and first results

In order to assess the frequency and orbital characteristics of any binaries among the highly C- and *r*-process-element enriched EMP stars, we have monitored the radial velocities of a sample of such stars since 2007, using the échelle spectrograph FIES at the Nordic Optical Telescope, NOT, at La Palma, Spain, at a resolution of $R \sim 45,000$. Analysing low-S/N spectra by cross-correlation has allowed us to reach a precision of $\sim$ 100 ms^{-1}per observation and securely detect any long-period, low-amplitude binaries in the sample.

Our preliminary results for 17 of the rarer *r*-element enriched stars (Hansen et al. 2011) showed that most stars are in fact single, with a limit for any orbital motion well below $\sim$ 500 ms^{-1}over several years. Moreover, the three binaries discovered (a standard binary frequency of ~20% for giant stars) have completely normal orbital properties (periods, eccentricities) when compared to a sample of giant binaries in Galactic clusters (Mermilliod et al. 2007).

So binaries as such played no role in the preferential enrichment of these stars with *r*-process elements. A full analysis of our complete material is in preparation.

3. The CEMP enigma

The origin of the first C is complex, and several factors act to confuse the picture. In Population I and the inner-halo (moderately metal-poor) Population II, the primary C producers are believed to be thermally pulsating AGB stars, generally with a concurrent production of *s*-process elements. The classical Ba, CH and S stars display the chemical signature of AGB star material, which was believed to originate in a former AGB companion that transferred processed material onto the surface of the observed stars through a strong stellar wind. And these stars have indeed been proved to all be long-period binaries with (near-)circular orbits and a (generally now invisible) WD companion (McClure & Woodsworth 1990; Jorissen et al. 1998; McClure 2000).

The situation for the carbon-enhanced EMP (CEMP) stars is less clear-cut. Preston & Sneden (2001) found that half of their small sample of CEMP stars appeared single despite their strong observed *s*-process signatures (CEMP-s stars). In contrast, Lucatello et al. (2005) observed a limited sample of CEMP-s stars and concluded that all were likely to be binaries; the details have, however, never been published in full.

Meanwhile, the existence of a two-component halo has been proposed (Carollo et al. 2012) and debated, in which the less metal-poor and more flattened inner halo contained

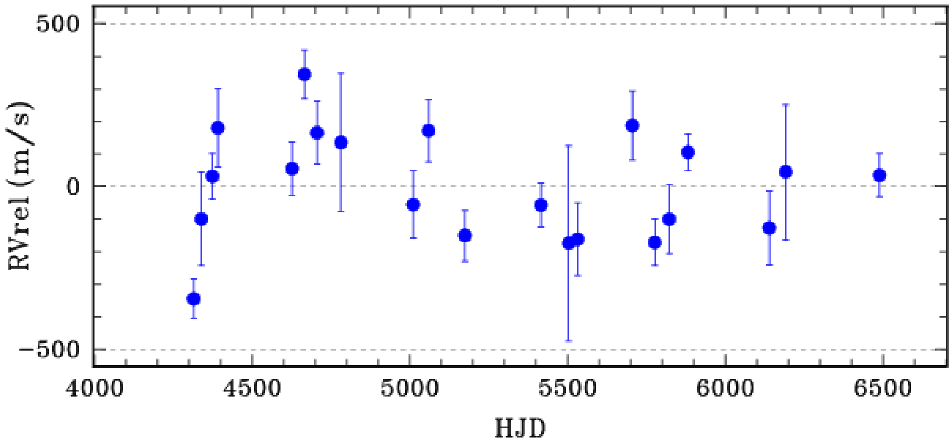

Fig. 1. FIES/NOT radial velocities vs. time for the single, prototypical, highly *r*-process enriched CEMP-no star CS 22892-052.

up to ∼ 20% predominantly CEMP-s stars at the lowest metallicities ([Fe/H] ∼ − 2.5), while the non-rotating or retrograde and even more metal-poor outer halo had a CEMP star fraction up to 40% at [Fe/H] ∼ − 3.5 and below, mostly consisting of 'CEMP-no' stars without *s*-process signatures (see Norris et al. 2013 and references therein).

Many studies have dealt with the detailed modelling of CEMP (and implicitly CEMP-s) stars in terms of AGB star nucleosynthesis and dilution in the assumed mass transfer by a stellar wind (Masseron et al. 2010; Lee et al. 2013), taken the interacting binary model for granted. From the point of view of galactic chemical evolution, the key distinction is really between local (i.e. binary) or non-local enrichment, while subtleties of the AGB nucleosynthesis and binary mass transfer model are of relatively minor importance: if the C enrichment is not a purely local process, the production site must be sought further afar, in a scientific as well as a geographic sense.

Alternative production sites are fast-spinning, massive zero-metallicity stars or 'faint' supernovae (see discussion in Norris et al. 2013), which are not expected to produce *s*-process signatures. In this regard it is noteworthy that C enrichment of the ISM by AGB stars would likely be in the form of C dust grains, while the alternatives would feed C-enriched *gas* into the ISM. The latter is what one would expect to be the origin of the metal-poor, C-enriched DLA systems observed by Cooke et al. (2011, 2012). The characteristics of the CEMP-no stars then assume a place of central importance in this context, and we have recently re-focused our observing programme to include more stars of this type.

4. Results and conclusions

The results so far have been ambiguous, both because the data are still somewhat sparse and because the available data on the *s*-process abundances of our targets are limited in accuracy and/or completeness.

Fig. 1 shows the current status of our observations of the famous C-enhanced and 'prototype' r-II star CS 22892-052 (no *s*-process signatures), for which Preston & Sneden (2001) suggested a possible variation with $K \sim 1$ kms^{-1}and $P \sim 128$d. Our upper limit for this and several CEMP-no stars is an order of magnitude below this, demonstrating that not *all* CEMP-no or *r*-process enhanced stars are binaries.

We conclude that the binary mass transfer scenario is not *the* universal explanation for the observed strong abundance anomalies: they existed in the material from which the stars formed. Alternative sources external to the natal clouds are required, and their input of newly formed gas and/or dust to the early ISM needs to be explored in more detail.

Our observations will continue through 2014, and the full data set will then be presented and discussed in detail.

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