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The Galactic halo: stellar populations and their chemical properties

John E. Norris

Research School of Astronomy and Astrophysics, The Australian National University, Weston, ACT 2611, Australia
email: jen@mso.anu.edu.au

Abstract. Below [Fe/H] = –3.0, there is an enormous range in [C/Fe]. We discuss the properties of C-rich ([C/Fe] > +0.7) and C-normal ([C/Fe] $\leqslant$ +0.7) stars in this regime, and suggest that there existed two different gas cooling channels in the very early Universe.

Keywords. stars: abundances, Galaxy: abundances, Galaxy: halo, cosmology: early Universe

1. Introduction

The stellar populations of the Galactic halo provide insight into the manner in which the Milky Way formed, while its most metal-poor stars have the potential to constrain the nature of the first stars, believed to have formed some 100 Myr after the Big Bang. We refer the reader to Frebel & Norris (2011) and Carollo (this volume), and references therein, for the rich background to these topics. Here we shall concentrate on the origins of C-rich and C-normal stars having [Fe/H] $\lesssim$ –3.0.

2. The C-rich and C-normal populations below [Fe/H] $\sim$ –3.0

2.1. *Chemical abundances for stars with [Fe/H] < –3.1*

Many researchers have contributed to the search for the most metal-poor stars. Here we utilize the recent work of Yong *et al.* (2012), to whom we refer the reader for the chemical abundances (and related references)of some 85 stars with [Fe/H] < –3.1. Suffice it to say that Yong *et al.* report new abundances for some 16 elements in $\sim$ 20 stars in this abundance range, together with abundances re-determined for a further $\sim$ 65 objects from the literature. Of this sample, some 18 are C-rich, with [C/Fe] > +0.7. Of the remainder, 35 have [C/Fe] $\leqslant$ +0.7, which we shall refer as C-normal stars.

Norris *et al.* (2012) have used these data to investigate the abundance trends and other relationships between the two groups. We refer the reader to that work for details. Their main results include:

• All of the C-rich stars belong to, or appear related to, the CEMP-no subclass of Carbon-Enhanced Metal-Poor stars (Beers & Christlieb 2005). None are CEMP-s, -r, or r/s.

• The C-rich stars are oxygen rich; the light elements Na, Mg, and Al are enhanced relative to Fe in half the sample; and for Z > 20 (Ca) there is little evidence for enhancements relative to solar values.

• While more radial-velocity data are required, there is no support for the hypothesis that the C-rich stars are all members of binary systems. That is to say, the binary statistics for CEMP-no stars are decidedly different from those of CEMP-s stars.

2.2. *Possible explanations for the abundance patterns*

Here are suggestions that may be relevant for an explanation of the observations:

- Fine-structure line transitions of C II and O I as a major cooling agent in the early Universe (Bromm & Loeb 2003)
- Supermassive ($M > 100\ M_\odot$), rotating stars (Fryer *et al.* 2001)
- "Mixing and fallback" Type II SNe ($M \sim 10-40\ M_\odot$) (Umeda & Nomoto 2003)
- Rotating, massive ($\sim 60\ M_\odot$) stars (Meynet *et al.* 2006)

In particular, the chemical abundances of the C-rich stars are best explained in terms of the admixing and processing of material from H-burning and He-burning regions as achieved by nucleosynthesis in zero-heavy-element models of "mixing and fallback" supernovae (SNe), and of rotating massive stars. The existence of a large fraction of C-rich and O-rich stars at lowest Fe abundances is suggestive of a strong role by carbon and oxygen in the formation of stars at the earliest times.

2.3. *A scenario for the earliest times*

We suggest that the C-rich and C-normal populations result from two different gas cooling channels in the very early Universe, of material that formed the progenitors of the two populations. The first was cooling by fine-structure line transitions of C II and O I (to form the C-rich population); the second, while not well-defined (dust-induced cooling? e.g., Schneider *et al.* 2006), led to the C-normal group. Here is a possible sequence:

- The first stars form in "mini dark halos" from material comprising only H and He; the cooling is provided by molecular hydrogen; and the mass function of these objects is top-heavy ($M \gtrsim 20-300\ M_\odot$). None of these objects survives until the present time.
- Some fraction of the first population synthesizes large amounts of C and O, as described by the above stellar evolutionary models (the rotating $60-300\ M_\odot$ stars of Meynet *et al.* 2006 and Fryer *et al.* 2001) and/or the 'mixing-and-fallback" models (Umeda & Nomoto 2003). During subsequent star formation, material with large enhancements of C and O cools via the fine structure lines of C II and O I, and fragments to form low-mass, long-lived stars still observed today. This is the C-rich population.
- The remainder of the first generation stars does not produce large amounts of carbon, but rather more solar-like abundance patterns. This material has more difficulty in cooling and fragmenting, but several possibilities exist (e.g. dust-induced star formation). A second channel forms carbon normal low-mass, long-lived stars, on a longer timescale. This is the C-normal population.

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