Mem. S.A.It. Vol. 88, 692

Memorie della

The most metal poor stars

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Abstract. About a dozen stars are presently known with [Fe/H] < − 4.5. Their mere existence shows that stars with sub-solar masses formed out of almost primordial gas, though the cooling and the physical processes are still to be clearly understood. They all but one are CEMP-no stars but their C abundance is unrelated to stellar metallicity. They differ from the CEMP-s at higher metallicities where C is about solar and thought, together with s-elements, to result from a mass exchange with an AGB companion and form a group which can be directly linked to the first stars . C comes likely from faint SNae but the small dispersion of heavy elements (> Al) and the presence of n-capture elements suggest a more complex scenario possibly involving an additional contribution from CCSN. The six unevolved stars of this sample show a Li abundance much below the Spite plateau magnifying the melt down already noted at [Fe/H] <-3.0. A possible explanation could be found within the model which foresee significant destruction and accretion of Li along the pre-main sequence phase. These stars are barely seen in the local group galaxies but quite surprisingly are not found in the Galactic Bulge or in the Damped Lyman-α galaxies at high redshift. Thus, while they offer a unique window into a totally unexplored evolutionary phase, at the same time they show several unexpected properties which challenge current views.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: abundances – Cosmology: observations

1. Introduction

My friendship with Francesco dates back to the late 80's when I got his support as researcher representative in the CRA and will last forever. Recently we interacted closely for several initiatives regarding Galileo, some of which have now been suddenly interrupted. Francesco's approach was rigorous but very relaxing and I always enjoyed doing things with him. He reminds me of the lightness of Calvino's American Lessons. Here I will talk on a topic that I had the pleasure to discuss with him while working within the ISIS project EUROPA on first stars lead by Carla Coppola, so that while writing these notes I will think about him and his ever-present smile.

That stars have different compositions was first realized by Chamberlain & Aller (1951) in their study of the famous HD 140283. They apparently were disappointed by their finding since in their conclusions they wrote that the abnormally small amounts of Ca and Fe was an *undesirable factor*. This result was then incorporated in the concept of stellar populations and of chemical evolution in the landmark paper of B^{2}FH paper of 1957 (Burbidge et al. 1957). Afterwords the search for metal poor stars has been pursed by looking at stars with high radial velocities with sometimes serendipitous discoveries (Bessell & Norris 1984). In the 80's the H&K survey of Beers et al. (1985) set the scene for a more extensive search of metal poor candidates. The high resolution follow up produced several very metal poor stars with [Fe/H] $\approx$ -4 stars (Molaro & Castelli 1990; Molaro & Bonifacio 1990) revealing an anomalous spread in the neutron capture elements (Norris et al. 1993; Primas et al. 1994) as well as the finding that a large fraction of stars are enriched in carbon, the CEMP stars. In the late 90's a puzzling star was found by Norris et al. (1997) and Bonifacio et al. (1998) independently one another (the two papers were submitted 3 weeks apart) showing a carbon enhancement without any detectable presence of the neutron capture elements. I remember we struggled to find an explanation and then we published it just noting the *surprisingly* (not undesirable) low neutron abundance. It is good to see that after two decades this is now the prototype of a class apparently connected to the earliest phases of the chemical evolution.

2. The Hateful Eight

Now we know over three hundred stars with [Fe/H]< -3.0 but only very few with [Fe/H]< -4.5. At the time of the review by Frebel & Norris (2015) there were only eight such stars and for a curious coincidence in the same year came out the movie *The hateful eight* by Tarantino, with the subtitle : *no one comes up here without a damn good reason* which is even more appropriate. A few more have been added later the SD 1313-0019 (Allende Prieto et al. 2015; Frebel & Norris 2015), SDSS J0929+0238 (Caffau et al. 2016) and another star announced in a conference by Aguado et al. (2017) of which we do not know much about. All these stars with their fundamental properties are reported in Tab 1.

The mere existence of these stars is remarkable and shows that indeed small mass stars with masses of the order of the sun or smaller do form at the lowest metallicities. Most of these stars show a large abundance of C which provides a possibility to cool the gas by means of CII (and OI) radiation. However, the Caffau et al. (2012)'s star, often referred to as the star that should not exist, has less C than required and calls for a more complex mechanism such as dust cooling (Schneider et al. 2012) or turbulent fragmentation (Greif et al. 2012) .

Leaving the Caffau's star aside, all the other stars with [Fe/H] < -4.5 are CEMP (Carbon Enhanced Metal Poor) stars. Spite et al. (2013) noted that the [C/H] was increasing with the decreasing of [Fe/H], which means that the Carbon abundance remains constant at the lowest metallicity end. By using stars selected to avoid internal mixing they suggested the existence of two groups: one with C approximately solar and a second one with C lower by $\approx$ -1.5 dex. The two groups are more clearly seen at lower metallicities but merge at higher metallicities due to the increase of C. The presence of neutron capture elements is an additional feature that characterizes the two bands. The High-C band shows enhancements in their neutron abundances and [Ba/Fe]> 1 while for the ones in the Low-C band for which there are sensitive observations we observe always [Ba/Fe] <1. Spite et al. (2013) proposed a different origin for the C in the two bands. In the High-C band carbon is coming from an AGB companion along with a conspicuous abundance of n-capture elements, while the origin of carbon in the Low-C band is more directly related to the first SNae. This hypothesis has been tested with radial velocity studies to detect the binary fractions and found that in the High-C band the stars are almost all binaries while in the Low-C band they are almost all single Hansen et al. (2016) Hansen et al. (2015). The few exceptions found could be easily explained if few systems are seen pole-one or if there are binaries which contain stars which does not evolve into an AGB phase. Bonifacio et al. (2015) confirmed the presence of these two groups with additional two stars with [Fe/H]< -4.5 and also the last arrivals match pretty well this division. Although with a limited statistics, all the stars with [Fe/H] <-4.5 belong to the low-C and low n-capture elements showing that this is the preferred root of formation of the first low mass stars. It remains to be explained why similar objects among the High-C band group are not seen (but see

Table 1. Stars with [Fe/] < -4.5 in chronological order of discovery.

Star #	[Fe/H]	T_{eff}	log g	[C/Fe]	[Ba/Fe]	[Sr/Fe]	A(Li)	Main Ref
HE 0107-5240	−5.3	5100	2.2	+3.70	<-0.9	<-0.2	-	(1)
HE 1327-2326	−5.4	6180	3.7	+4.26	<1.4	1.3	<0.6	(2)
HE 0557-4840	−4.8	4900	2.2	+1.65	<0.0	<-1.0	< 0.7	(3)
J1029+1729	−4.99	5811	4.0	< 0.93		<-0.2	<1.0	(4)
SM 0313-678	<-7.5	5125	2.3	> 4.90	<1.2	< 0.6	0.7	(5)
HE 0233-0343	−4.7	6100	3.4	3.48	<0.8	+0.3	1.77	(6)
HE 1035+0641	<-5.2	6262	4.0	>3.52			1.90	(7)
J1742+2531	−4.8	6345	4.0	3.6			< 1.77	(8)
SD 1313-0019	−5.0	5200	2.6	2.96	<0.22	<-0.28	<0.80	(9)
J0929+0238	−4.97	6000	3.7	3.91	<1.46	<0.7	<1.2	(10)
-	−5.8	−	d	+5.0			-	(11)

References. (1) Christlieb et al. (2002); (2) Frebel et al. (2005); (3) Norris et al. (2007); (4) Caffau et al. (2012); (5) Keller et al. (2014); (6) Hansen et al. (2014); (7) Bonifacio et al. (2018, 2015); (8) Bonifacio et al. (2015); (9) Allende Prieto et al. (2015); (10) Caffau et al. (2016); (11) Aguado et al. (2017).

Bonifacio et al. 2018). It looks like binary systems with stellar masses in the range to evolve into an AGB did not form initially, for which there is no obvious explanation.

3. Progenitors of the 2nd generation

The extremely low abundance of these stars suggests that only few and hopefully one progenitor polluted the gas out of which these stars formed. The C anomaly has been explained by faint SNae with energy of 10^{51} erg together with fallback and mixing (Umeda & Nomoto 2003). However, the models are not unique. For instance, several different progenitors have been proposed for the Keller's star with masses in the range from 12 to 60 $M_{\odot}$ (Ishigaki et al. 2014; Nordlander et al. 2017).

It is interesting to note that within fallback models a large dispersion up to two orders of magnitude is foreseen in [Fe/Ca] (Ishigaki et al. 2014) which is not observed. In fact Bonifacio et al. (2015) pointed out that the light elements with atomic number lower than Al when measured with reference to Ca show a dispersion of almost 2 dex while the heavier ones show relatively little dispersion < 0.5 dex. Bonifacio et al. (2015) proposed a double source between the elements with the lighter ones synthesized by faint SNae and the heavier by more conventional CCSN.

CEMP-no does not imply complete absence of neutron capture elements but only that they are not enhanced. For most of them there are only available upper limits to their abundances at the solar value or slightly below. However, in the CEMP-no stars of Hansen et al. (2014) and Frebel et al. (2005) Sr has been measured and is relatively abundant (cfr Table 1). Thus neutron capture elements need to be synthesized already at the very beginning in large quantities and at comparable levels of iron. In my view this favours the scenario which foresees the contribution from CCSN in addition to faint SNae, though the latter may provide the seed nuclei.

4. Lithium

In the restrict sample of stars with [Fe/H]< -4.5 there are six unevolved stars with effective temperatures between 5800 and 6345 K which all show Li abundances or stringent upper limits below the Spite and Spite plateau (cfr Tab 1). A meltdown of the Spites plateau at metallicities below [Fe/H] =-3 was already noted by Sbordone et al. (2010). The stars with metallicities <-4.5 are consistent and magnify this trend. The new Aguado's star is a dwarf and it would be interesting to see the Li abundance eventually measured. Fu et al. (2015) suggested a stellar fix to the cosmological Li problem by invoking a substantial pre main sequence depletion followed by accretion of gas with primordial Li composition at the level of A(Li)=2.7 as inferred from the CMB power spectrum or the D/H extragalactic measurements. Fu et al noted that the presence of overshooting, which is required by helioseismology, leads to a substantial Li burning in the pre main sequence evolution which needs to be compensated somewhat by a later accretion. Assuming an accretion rate of 10^{-8} $M_{\odot}$ yr^{-1} at the birth-line which then decays exponentially till is halted by the photo-evaporation provides a sort of self-regulating mechanism able to reproduce the Spite plateau for a limited range of masses. A possible break of this self regulating mechanism could explain at least qualitatively the observed deficiency of Li in the EMP. These stars are in fact smaller and hotter and the tenuous accretion disk could be dissipated before the restoring of the initial Li is completed.

5. Universality

It is of great interest to establish the universality of the pattern observed in the Milky Way. CEMP stars are observed in the local group galaxies but their incidence seems lower than what observed in the Galaxy. Considering the absolute C abundances of stars in the local group galaxies from the compilation of Salvadori et al. (2015) there are four CEMP-no stars which are close to the Low-C band. Three are in Bootes with A(C) = 7.6, 7.5, 7.13, and [Fe/H] = -3.5; -3.0, -2.7, respectively, and one in Seg1 with A(C)= 7.4, and [Fe/H]= -3.5. One CEMP-s star in Seg1 shows A(C)= 8.6 and [Fe/H] = -1.2 and thus falls in the High-C band. Other few objects lay on or very close to the line of [C/Fe]=1.0 which divides the carbon enhanced from the normal stars. Though there is an intrinsic deficit of CEMP stars the few observed suggests that the duality observed in the Milky Way extends to the local dwarfs (Salvadori et al. 2018).

The Galactic Bulge has been explored by Howes et al. (2015) who found 9 stars with metallicities between $-4.0 < [Fe/H] < -3.0$. Among these no CEMP stars were found at odds with the galaxy where at the same metallicities the fraction of CEMP stars is almost 50% , which suggests that the difference could be real and perhaps due to the different time scale of the chemical enrichment between the Bulge and the Milky Way Halo.

At high redshift the C abundance can be measured in the metal poor Damped Lyman-α systems (DLA) where the CII lines are not saturated (Cooke et al. 2017). There are about 16 measurements with [C/H] in the range -3.4 < [C/H] < -2 but none shows evidence of C enhancements of the kind observed in the Milky Way. A claim of a DLA with C enriched turned out normal at a second inspection (Cooke et al. 2012; Dutta et al. 2014). The most metal poor DLA found at redshift 3.076 towards the QSO J0903+2628 measured [C/H]=-3.4 which is at the lowest levels observed in the Caffau's star and lower then all stars with [Fe/H] <-4.5. For this DLA Cooke et al. (2017) derived [O/H]=-3.0, which implies [Fe/H] ≈ -3.4, and therefore [C/Fe] ≈ 0. It is difficult to understand wether in DLAs we have not reached enough low metallicities or the DLAs and the Galaxy followed different chemical evolution paths.

6. Conclusions

Metal poor stars with [Fe/H] ≈ -5 are an unique window onto a totally unexplored phase of chemical enrichment but show several properties which challenge current views.

1. Why only one star like the Caffau's star was found and what cause the relative proportions of CEMP and normal stars at the very low metallicity end?
2. Why CEMP-s are not observed in the High-C band at [Fe/H] ≈ -5? (see Bonifacio et al. 2018)
3. Why CEMP-no stars are so rare in the Local Dwarf Galaxies and why the Bulge and the DLAs do not show the same pattern?
4. Where are synthesized the observed n-capture elements at [Fe/H]≈ -5?

5. Why Li is depleted in almost all the relatively hot (Teff ≈ 6000 K) dwarfs with [Fe/H]≈ -5?

Acknowledgements. I am grateful to Stefania Salvadori, Piercarlo Bonifacio and Elisabetta Caffau for several discussions.

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