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Stellar abundances and the chemical evolution of stellar systems: the Italian contribution

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Abstract. The chemical composition of stellar systems is crucial in understanding evolution of galaxies. In the last few years, exciting results have been obtained, thanks to availability of large telescopes and efficient spectrographs. Italians are at forefront in this field. We review some of the most important results in this area.

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

1. Introduction

The chemical composition of stellar systems is crucial in understanding evolution of galaxies. In the last few years, exciting results have been obtained, thanks to availability of large telescopes and efficient spectrographs (like FEROS UVES, FLAMES and CRIRES at ESO, and SARG at TNG). Italians are at forefront in this field, with several important contributions. In this short review, we will comment about some of the exciting results obtained by Italian groups in this area. We apologize for incompleteness that certainly plagues this presentation.

2. (Old) Open clusters

An area where Italians have been very active in the last few years concerns the composition of stars in clusters, both Open and Globular. Open clusters (OCs) are important to establish the run of the galactic gradient with time, because ages and distances can be accurately determined, and their actual locations are close to the original ones. Up to now, abundances from high resolution spectra have been obtained for stars in about forty OCs; about half of these clusters (the majority of the most interesting and difficult ones) have been observed by Italians in the last few years (see Table 1). These results have provided a much more detailed view of the Galactic abundance gradient that was possible insofar (see Figure 1): there appears to be a quite steep gradient in the inner regions of the Galaxy, with a much flatter trend in the outer part of the disk. The scatter around this relation seems remarkably small, in particular when compared to older similar plots: this shows the gain in more accurate abundance analysis, although for the inner region of the disk only very few clusters have been observed insofar.

When compared to determinations obtained using other methods, e.g. Cepheids (see e.g. Andrievsky et al. 2004), the galactocentric metallicity gradient derived from OCs seems steeper (see Figure 1). This is in agreement with indications that this gradient becomes

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Table 1. Metal abundances in OCs using high resolution spectroscopy by Italian groups

Cluster	Age (Gyr)	Rgc (kpc)	[Fe/H] (dex)	Source
NGC6791	9	6.1	+0.39 ± 0.05	Carraro et al. 2006
			+0.47 ± 0.04	Gratton et al. 2006a
NGC6253	3	6.6	+0.36 ± 0.20	Carretta et al. 2000
			+0.46 ± 0.08	Carretta et al. 2007b
			+0.36 ± 0.07	Sestito et al. 2007
Cr 261	6	6.96	−0.03 ± 0.03	Carretta et al. 2005
NGC 6134	0.9	7.2	+0.15 ± 0.07	Carretta et al. 2004
IC 4651	1.1	7.2	+0.11 ± 0.01	Carretta et al. 2004
NGC6819	2	7.71	+0.09 ± 0.03	Bragaglia et al. 2001
NGC3960	0.9-1.4	7.80	+0.02 ± 0.04	Sestito et al. 2006
M67	4.5	8.2	+0.03 ± 0.01	Randich et al. 2006
NGC2660	1	8.68	+0.04 ± 0.04	Sestito et al. 2006
Mel 66	2.8	8.8	−0.25	Gratton & Contarini 1994
Saurer 2	7.1	9.7	−0.38	Carraro et al. 2004
NGC 2243	1.1	10.2	−0.35	Gratton & Contarini 1994
NGC2506	1.7	10.38	−0.20 ± 0.02	Carretta et al. 2004
Be 32	6-7	11.3	−0.29 ± 0.04	Sestito et al. 2006
NGC1883	0.65	12.3	−0.20 ± 0.22	Villanova et al. 2007b
Be 66	5.0	12.4	−0.48	Villanova et al. 2005
Be 22	1.1	15.4	−0.32	Villanova et al. 2005
Be 29	1.1	22.5	−0.44	Carraro et al. 2004

flatter with time, as derived e.g. from the analysis of Planetary Nebulae (see discussion in Maciel et 2006), and with the trend shown by the same OCs, although the sample of observed clusters is still quite limited for an adequate division in age subsets. The observation that the galactic abundance gradient becomes shallower with time agrees with some models of the evolution of the galactic disk (e.g. Hou et al. 2000), but not with others (e.g. Chiappini et al. 2001). This difference depends on details of the models (rate of infall, etc.: see Chiappini et al. 2001 and the recent discussion by Cescutti et al. 2007). Accumulation of further data on OCs will allow to strongly constrain models of disk formation and evolution.

OCs are also crucial to study stellar evolution. A very interesting study concerns the element abundances of unevolved stars in the OC M67 (Randich et al. 2006). Pasquini et al. (1997) had previously shown that there is a large spread in Li abundance among main sequence stars in this old OC, a striking result when compared to the rather small spread obtained for much younger clusters like the Hyades, or even old ones like NGC 188 (Randich et al. 2003). The reason for this large scatter is not yet understood. Possible explanations includes pollution of the sample by stars not members of the cluster (not plausible, because the stars considered by Pasquini et al. should belong to M67 based on both proper motions and radial velocities), a different penetration of the convective region due to differences in chemical composition (> 0.05 dex in Fe or CNO), or a spread in the initial rotational velocity: in this last case Be should be correlated with Li. Two following studies by Randich et al. (2002, 2006) seem to dismiss both these alternative explanations: in fact the first paper showed that there is no variation in Be correlated with Li variations, while the second demonstrated that M67 is very homogeneous in chemical composition. Hence the reason for the large spread in Li abundances is still unknown.

OCs formation mechanisms are not well understood yet. To have a better insight into this issue, Palla et al. (2005) have considered the star formation history of a very Young OCs: the Orion Nebula. Star formation histories in various nearby star-forming regions might extend over a period of time ($\sim 10^7$ yr) longer than the free-fall time ($\sim 10^6$ yr). Studies of several OCs and associations show that stars begin to form at modest levels roughly 10 Myr ago, and then at an accelerating rate with typical e-folding time of 1-3 Myr. In the case of the Orion Nebula star formation recently ended with the dispersal of the remnant molecular gas from the winds and UV radiation of the massive Trapezium stars. However, the empirical

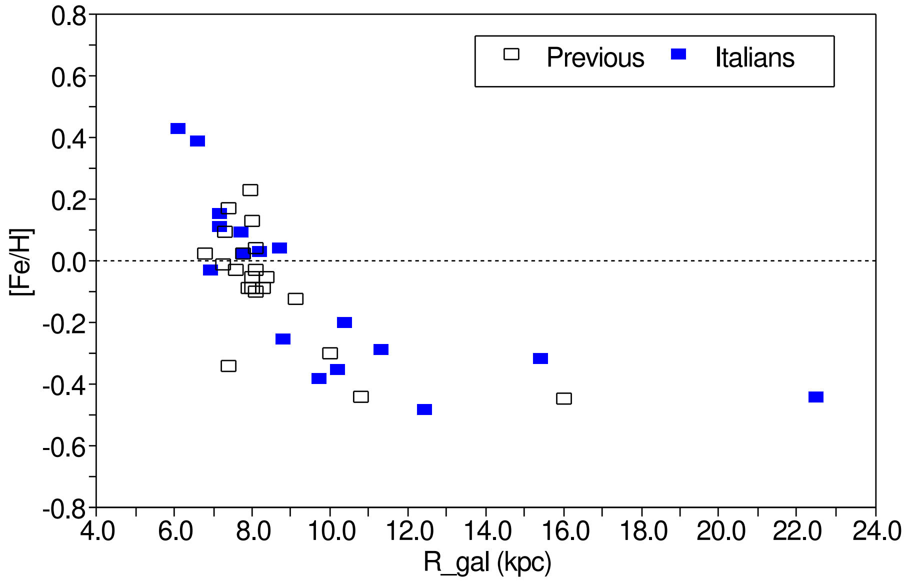

Fig. 1. Run of the metallicity [Fe/H] with galactocentric distance for OC. Only determinations from high dispersion spectra are plotted. Closed symbols are results obtained by Italian groups; open symbols are results from other groups. The solid line represents the run of the average abundances for Cepheids (from Andrievsky et al. 2004)

datum for a prolonged star formation may be spurious if ages for a few stars are overestimated because, due to disk occultation, true luminosities might have been underestimated. Ages for very young stars can be derived by comparing their magnitudes and colours with those predicted by isochrones, and using Li abundances, since Li is expected to be progressively depleted during the pre-main sequence phase of low mass, fully convective stars. Since ages from Li abundances are not affected by errors due to the presence of disks, they can be used to check ages derived from c-m arguments. Palla et al. used this method to show that there is a fairly good agreement between ages from isochrones and Li depletion, supporting the significant age spread previously found for stars in the Orion Nebula.

3. Globular Clusters

An area where the Italian contribution is traditionally very important is that of globular clusters (GCs), and in particular abundance determination for individual stars from high resolution spectra. Abundances of stars in GCs are important for a variety of reasons: they may be used to constrain stellar evolution, trace galactic evolution, or the same chemical evolution of the GCs themselves, a field which is becoming more and more exciting in the last years.

Many GCs show signs of an internal chemical evolution. The most famous and clear case is the giant globular cluster ω Cen. Exciting discoveries were made by Italian groups in the last few years. Bedin et al. (2004) have shown that the main sequence (MS) of this cluster is bimodal, and later Piotto et al. (2005) have found that the bluer MS is more metal-rich than the reddest one, forcing it to have a (much) higher He-content (as much as Y = 0.4!). Villanova et al. (2007a) and Sollima et al. (2005) have studied the metallicity of the different sequences of stars discernible in the Subgiant Branch (SGB) region of ω Centauri, complementingprevious studies made on the upper Red Giant Branch (RGB: Pancino et al. 2003). The results of these studies allowed to define chemical composition and ages of these different sequences. The resulting scenario is extremely complex, with old metal-rich and young metal-poor SGBs. This requires a chemical evolution history where both infall of (diluting) metal-poor material and outflows of metal-rich ones have played important rôles. Run of different element abundance ratio against [Fe/H], have been determined, including C, N, Ca, Ti, Ba; this may be combined with the He abundances from the MS to provide constraints on the type of stars that contributed to the metal enrichment of ω Cen. The scenario is far from being well understood. Exciting news are expected in the next few years.

Beside ω Cen, most of the remaining GCs show evidences for different generation of stars and some chemical evolution (see Gratton et al. 2004). The most widespread effect concerns the elements involved in H-burning at high temperature. This effect is well known since several years; its most known manifestation is the anticorrelation between abundances of O and Na among stars in GCs (see Kraft 1994). A very significant progress has been obtained by the ESO Large Program on Abundances in MS stars in GCs (Gratton et al. 2001; Carretta et al. 2005). Using these data, Gratton and coworkers clearly demonstrated that the O-Na anticorrelation, is at least in part due to a chemical evolution process of GCs, since it is observed also among MS stars, whose centers are too cool for hot H-burning. A further important step forward has been the recognition by D'Antona & Caloi (2004) and D'Antona et al. (2005) that the He production that should result from this H-burning might be responsible for part of the second parameter effect - the anomalous blue horizontal branches (HBs) found in many clusters. In fact, since He is produced in CNO burning, N-rich, O-poor stars have higher He, their tun off mass is smaller. This can be seen from the location on the HB, if the mass loss is similar to that of N-poor, O-rich stars. A clear example of this effect in action is NGC2808 with its bimodal HB: Piotto et al. (2007) and D'Antona et al. (2005) showed that this cluster also has a multiple MS, that can be interpreted as due to stars with different He abundances.

Other important outputs of the ESO Large program include the analysis of the abundances of Li (Bonifacio et al. 2002, 2007; Pasquini et al. 2005) and of neutron capture elements (James et al. 2004a, 2004b). A cosmological abundance of Li was found in NGC6397; however, in stars of NGC6752 and 47 Tuc, clusters that show a more extended O-Na anticorrelation, Li is observed to be anticorrelated with Na. The fact that some Li is observed also in the most O-poor, Na-rich stars, is evidence that the products of high temperature H-burning are mixed with some material having the original composition. For what concern the n-capture elements, no evidence was found for any star-to-star variation in the clusters considered: this rule out contribution by the lower mass of the intermediate mass range to the chemical evolution in these GCs, at variance with the case of ω Cen, where the most metal-rich stars are very rich in elements produced by the s-process (see e.g. Smith et al 2000).

An extensive statistical study of Na-O anticorrelation and its relation to the HB is in progress, headed by Eugenio Carretta (NaaaH collaboration: Carretta et al., 2006, 2007a, 2007b, 2007c; Gratton et al., 2006b, 2007). The aim of the project is to understand if GCs can be really considered as true example of Simple Stellar Population, and if they were able to sustain self-enrichment of metals. The NaaaH group intends to probe the first billion years in the life of GCs, to test: (a) if a second generation of stars born from the ejecta of intermediate mass stars does exist in GCs and (b) if any correlation exists between the cluster properties (in particular the extension of the HB) and the distribution of stars along the Na-O anticorrelation. Hence, Carretta and coworkers started a program with FLAMES to observe Na and O abundances in about 100 RGB stars in each of ~20 GCs with different HB morphologies and overall properties. Preliminary results show that, as expected, there is a correlation between the extensions of the HB and O-Na anticorrelations, and that most massive clusters tend to show a more extended O-Na anticorrelation.

A further area of research considered is the abundance of Be and its use as a cosmochronometer. Be is produced by the interaction of Cosmic Rays with the interstellar medium, through spallation of heavy element nuclei. Due to the fact that cosmic rays are generated and transported globally on a Galactic scale, Be is expected to be characterized by a smaller dispersion than the products of core collapse supernovae, whose abundances in the early Galaxy are affected by the dispersed character of star formation and inefficient mixing of gas. To test this hypothesis Pasquini et al. (2004) carried out the first measurements of Be abundances in a GC (NGC 6397), for which an independent age estimate from isochrone fitting was available (Gratton et al. 2003). Be was detected at a level consistent with that of stars in the field with the same [Fe/H] abundance. By comparing their Be values with models of galactic evolution of Be as a function of time, they concluded that the cluster formed about 0.2-0.3 Gyr after the onset of star formaton in the halo, in very good agreement with the age derived from MS fitting.

This approach can be extended to test if samples of halo and thick disk stars are coeval. Such a test was conducted by Pasquini et al. (2005b) on two groups of stars identified to belong to these two populations by Gratton et al. (2003b), who considered a kinematical class composed of stars with significant galactic rotation velocity (broadly corresponding to the classical Eggen et al., 1962, dissipative collapse population), and a class composed by non rotating or counter rotating stars (roughly corresponding to the accreted population first proposed by Searle & Zinn, 1978). These two components differ not only in their kinematical properties, but also in their chemical composition: the dissipational component has a very well defined trend of [α/Fe] ratios with metallicity and kinematics (galactic rotation velocity), with very small scatter around the mean relation. The accretion component has on average a smaller excess of $\alpha-$elements, and a much larger scatter around the average value (see Gratton et al. 2003b). Pasquini et al. (2005b) showed that the dissipative component also has a very well defined correlation between [α/Fe] and Be abundances, with a very small scatter: this agrees with the consideration that both of them describe time. At a given Be abundance (i.e. time) the accretion population has a larger scatter in [α/Fe], and seems to follow a distinct relation, consistent with a lower star formation rate. However, interpretation of Be abundances in GCs may be more complex, because Be can be destroyed at the temperatures characteristics of hot H-burning. Pasquini et al. (2007) examined the Be abundance in two turn-off stars in NGC6752, a cluster which exhibits an extended O-Na anticorrelation. The stars were selected having different compositions: one representative of the O-rich, Li-rich component, and the other of the Li-poor, O-poor one. Be abundance measurements are intrinsically difficult, so, as expected, Be lines were indeed detected on the spectrum of the O-rich, L-rich star and only an upper limit could be obtained for the O-poor, Li-poor one. This upper limit is enough to conclude that this second star has not more Be than the other (and hence cannot be much younger), but it is not enough to severely constrain the type of polluters that were active in this star.

Finally, abundance analysis can be used to gain insight on mechanisms of formation of peculiar stars in GCs. Blue stragglers (BSS) may be formed by different channels (merging or mass transfer in primordial binaries, collisions of stars in the dense core of some GC). Ferraro et al. (2006) used high-resolution spectra obtained with VLT to measure surface abundance patterns of 43 BSSs in 47 Tuc. They discovered that a subpopulation of BSSs shows a significant depletion of C and O with respect to the dominant population, suggesting the presence of CNO burning products on the BSS surface coming from a deeply peeled parent star, as expected in the case of a mass transfer process. This is the first detection of a chemical signature clearly pointing to a specific BSS formation process in a GC.

On the other hand, Ferraro et al. (2003) measured radial velocities of the companion to the eclipsing millisecond pulsar PSR J1740-5340 in NGC 6397. The radial velocity curve confirms that the observed star is orbiting the pulsar, and this enables them to derive the most accurate mass ratio for any non-relativistic binary system containing a neutron star. Assuming a pulsar mass in the range 1.3-1.9 $M_{\odot}$, the mass of the companion spans the interval 0.22-0.32 Msolar. Sabbi et al. (2003a) presented a detailed study of the Hα and He I spectral lines whose morphology precludes the existence of any residual disk around the millisecond pulsar. It suggests the presence of a stream of material from the companion to the neutron star whose surface is however never reached, as the material is driven back by the pulsar radiation far beyond the companion. Finally, Sabbi et al. (2003b) analyzed the chemical composition of the companion finding that abundances are fully compatible with those of normal unperturbed stars in NGC 6397, with the exception of a few elements (Li, Ca, and C). The lack of C suggests that the star has been peeled down to regions where incomplete CNO burning occurs, favoring a scenario where the companion is a turn-off star which has lost most of its mass. The large Li abundance, suggests that fresh Li has been produced on the stellar surface.

4. Dwarf Spheroidals

Italian researchers are also active in the field of chemical composition of dwarf satellites of the Milky Way. The Ital-FLAMES collaboration surveyed the Sagittarius dwarf spheroidal (Sgr DSph) galaxy, determining the chemical abundances of bright RGB stars (Monaco et al. 2005), the abundances in Terzan 7, a Sgr dSph GC (Sbordone et al. 2005), and finally studying in detail the element-to-element abundance ratios in a representive sample of stars in this galaxy (Sbordone et al. 2007). These studies showed that stars in Sgr DSph have an exotic chemical composition, with a very distinctive abundance pattern for what concerns a large variety of elements, including the α-elements, Na, Al, Sc, V, Co, Ni, Cu, Zn, Y, Ba, La, and Nd. In general all these data are compatible with a slow metal enrichment, as well as with the presence of outflows related to the explosion of supernovae (SNe). Studies are in progress, trying to relate this pattern with a best determined history of mass loss from this galaxy.

5. Extremely metal poor stars

In the first three minutes of the big bang, before the cosmic expansion cooled the Universe too much, primordial nucleosinthesys took place, leading to the formation of ^{2}H, ^{3}He, ^{4}He and Li. Later on (~13 Gyr ago), after H recombination, which essentially made the Universe transparent, the first stars are formed. The importance of these stars is twofold: they were a source of UV radiation capable of ionizing H (contribution to re-ionization of the Universe) and they were the first source of heavy nuclei (atomic number Z>3).

The study of First Stars is fundamental for the understanding of Galaxy formation and evolution and chemical enrichment processes. In the last 15 years, an impressive observational effort has been (and it is still being) made to find the first stars. Dedicated surveys (e.g. HK, Beers et al 1992; HES, Christlieb et al. 1999) have now targeted a few ten thousands halo stars aiming at finding primordial composition objects. Follow-up high resolution spectroscopy has been performed for a grand total of over 300 candidate extremely metal poor stars (EMP i.e. stars with an iron content [Fe/H]< −2.5) using UVES at VLT, HDS at Subaru, HIRES at Keck. So far, no metal free star has been found (the most iron poor star known, HE 1327-2326, has [Fe/H]=−5.45). Such efforts have yielded surprising results, showing very unexpected features of the low end of the galactic metallicity distribution.

In fact, there seems to be a gap in the metallicity distribution (no stars between −4.2 and −5.2 see e.g. Frebel et al. 2006). The results of the largest so far spectroscopic high resolution project targeting EMP stars, the ESO *First stars* large program (PI Cayrel, Bonifacio and Molaro Co-I's) showed that the observed scatter for several abundance ratios (e.g. Ca, Ti, Sc, Cr indexed to Fe) is accountable in terms of observational errors and thus the expectation of finding the signature of individual SN events has not been met. On the other hand, at least 1 out of 5 EMP stars shows considerable enhancements in C and N (so called C-rich, extremely metal poor stars, CEMP hereafter), accompanied with a varying degree of neutron capture (r and/or s) elements enrichment. The Li abundance in dwarf EMP stars is $\log \epsilon$ (Li)=2.1, lower than what predicted by Big Bang Nucleosynthesis (Bonifacio et al. 2007)

These results seem to indicate that the gas from which the stars formed in the Early Galaxy was remarkably well mixed, and the current zero (or low) metallicity SNe models cannot reproduce the observed abundance ratios (Cayrel et al. 2004). On the other hand, given that most of the C and N rich EMP stars arise from AGB mass transfer (analogously to classical CH stars), the high incidence of CEMP hints to the high incidence of AGB stars, hence to an IMF shifted toward higher masses with respect to the present time one (Lucatello et al 2005).

The statistics of EMP stars to date is still very limited, and not sufficient to constraint the range of phenomena emerging at low metallicity. Italian astronomers are part of several surveys looking for more EMP stars as well as follow up observational programs aimed at improving our understanding of the physical phenomena related to stellar evolution and nucleosynthesis in the Early Galaxy. The SEGUE survey, part of SDSSII, is currently ongoing. At its completion it is expected to yield several thousand EMP candidates (S. Lucatello external collaborator member).

RAVE (RAdial Velocity Experiment) is also an ongoing survey which will observe tens of thousands of halo stars, providing radial velocities and metallicities (U. Munari team member). The HERES (Hamburg/ESO r-enriched star search) survey has collected high resolution spectra for a sample of about 100 CEMP stars (the largest so far). Analysis is currently underway (Lucatello et al 2006, Lucatello et al 2007 in preparation) and will provide a wide set of statistically sound constraints for low metallicity AGB models.

Abundance analyses information need to be complemented. The study of the kinematics and the dynamics of these objects is crucial to understand the formation of the halo as well as the star formation processes. The SEGUE, RAVE collaborations will provide radial velocity for large samples of EMP stars allowing to obtain statistically significant information on the relationship between kinematics and metallicity distribution in the halo.

On the other hand, the Lick EMP Multiplicity Study has started over 2 years ago and is aimed at obtaining long term radial velocity monitoring for a sample of about 60 EMP stars. The long term aim is to determine the multiplicity of stars as a function of metallicity among EMP, to ultimately shed light on star formation processes at low Z (S. Lucatello Co-I).

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