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The chemical evolution of the Milky Way and dwarf spheroidals of the Local Group

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Abstract. We present a scenario for the chemical evolution of the Milky Way. In particular, we suggest that the Galaxy formed out of two major gas accretion episodes: during the first episode the halo, the bulge and the thick disk formed relatively quickly, whereas during the second episode the thin disk formed on much longer timescales increasing with galactocentric distance (inside-out scenario). By means of these assumptions and by means of a detailed chemical evolution code, we are able to reproduce the main observations relative to the Galactic chemical evolution, such as the [X/Fe] vs [Fe/H] relations, the abundance gradients along the thin disk and the stellar metallicity distribution of the G-dwarfs in the solar vicinity. The chemical evolution code takes into account detailed nucleosynthesis from SNe of all types (II, Ia, Ib/c). The same nucleosynthesis is then applied to models for the evolution of dwarf spheroidals of the Local Group. The different [α/Fe] vs. [Fe/H] patterns observed in these galaxies relative to the Milky Way are interpreted in terms of less efficient star formation than in the Galaxy and of strong galactic outflows in these systems.

Key words. Galaxy: abundances – Galaxy: evolution

1. Introduction

The Milky Way galaxy has four main stellar populations: 1) the halo stars with low metallicities (the most common metallicity indicator in stars is [Fe/H]=$\log(Fe/H)_* - \log(Fe/H)_\odot$ and eccentric orbits, 2) the bulge population with a large range of metallicities and dominated by random motions, 3) the thin disk stars with an average metallicity <[Fe/H]>$= -0.5$ dex and circular orbits, and finally 4) the thick disk stars which possess chemical and kinematical properties intermediate between those of the halo and the thin disk. The halo stars have average metallicities of <[Fe/H]>$= -1.5$ dex and a maximum metallicity of ~ -1.0 dex, although stars with [Fe/H] as high as -0.6 dex and halo kinematics are observed. The average metallicity of thin disk stars is ~ -0.6 dex, whereas the one of bulge stars is ~ -0.2 dex.

The kinematical and chemical properties of the different Galactic stellar populations can be interpreted in terms of the Galaxy formation mechanism. Eggen, Lynden-Bell, & Sandage (1962), in a cornerstone paper, suggested a rapid monolithic collapse for the formation of the Galaxy lasting $\sim 2 \cdot 10^8$ years.

Later on, Searle & Zinn (1978) measured Fe abundances and horizontal branch morphologies of 50 globular clusters and studied

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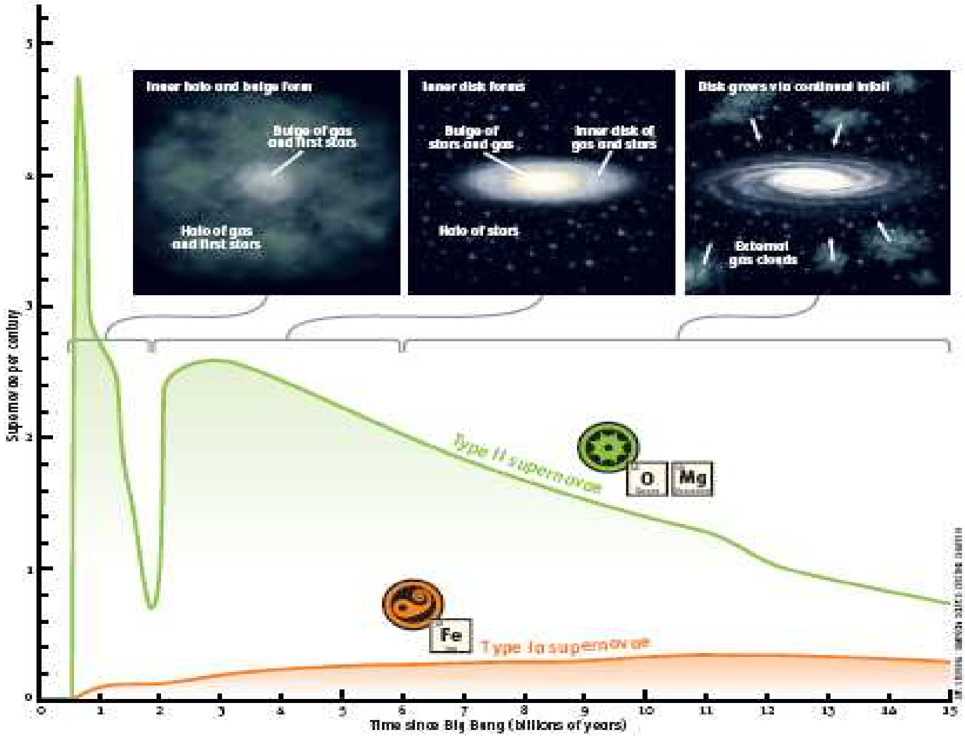

Fig. 1. Artistic view of the two-infall model by Chiappini, Matteucci, & Gratton (1997). The predicted SN II and Ia rates per century are also sketched, together with the fact that Type II SNe produce mostly α-elements (e.g. O, Mg), whereas Type Ia SNe produce mostly Fe. (Illustration credit: Chiappini 2004).

their properties as a function of the galactocentric distance. As a result of this, they proposed a central collapse like the one envisaged by Eggen et al., but also that the outer halo formed by merging of large fragments taking place over a considerable timescale > 1 Gyr. The Searle & Zinn scenario is close to what is predicted by modern cosmological theories of galaxy formation. In particular, in the framework of the hierarchical galaxy formation scenario, galaxies form by accretion of smaller building blocks (e.g. White & Rees 1978; Navarro, Frenk, & White 1997). Obvious candidates for these building blocks are either dwarf spheroidal (dSph) or dwarf irregular (dIrr) galaxies. However, as we will see later, the chemical composition and in particular the chemical abundance patterns in dSphs are not compatible with the same abundance patterns in the Milky Way (see Geisler et al. 2007), thus arguing against the identification of the building blocks with these galaxies. On the other hand, very recently, Carollo et al. (2007) have obtained medium resolution spectroscopy of 20,336 stars from the Sloan Digital Sky Survey (SDSS). They showed that the Galactic halo is divisible into two broadly overlapping structural components. In particular, they found that the inner halo is dominated by stars with very eccentric orbits, exhibits a peak at [Fe/H]=−1.6 dex and has a flattened density distribution with a modest net prograde rotation. The outer halo includes stars with a wide range of eccentricities, exhibits a peak at [Fe/H]=−2.2 dex and a spherical density distribution with highly statistically significant net retrograde rotation. They conclude that most of

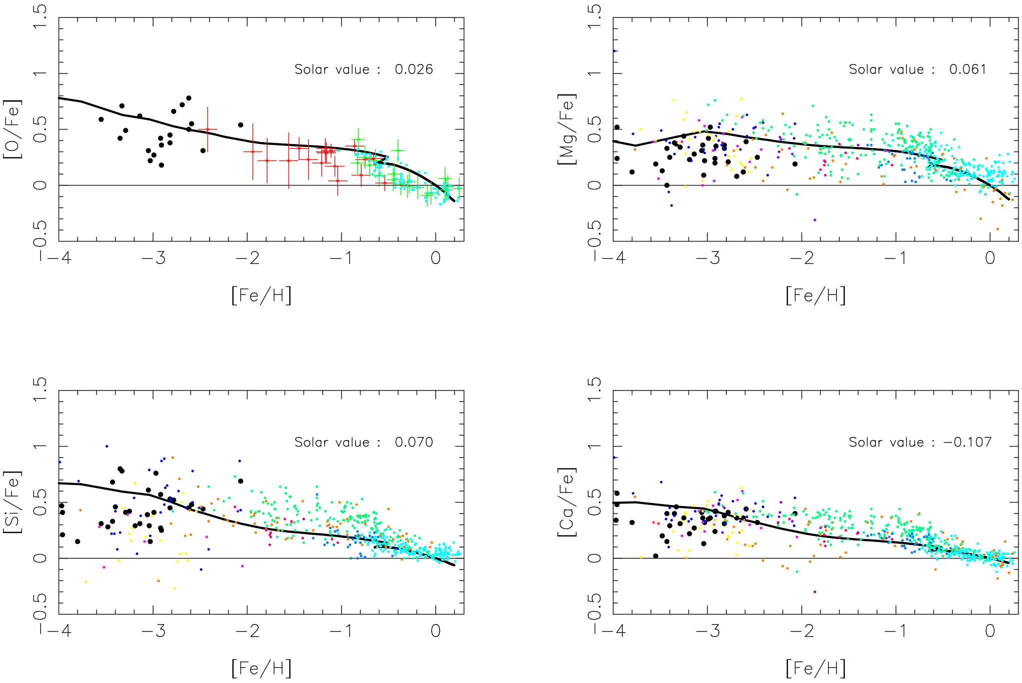

Fig. 2. Predicted and observed [α/Fe] vs. [Fe/H] in the solar neighborhood. The models and the data are from François et al. (2004). The models are normalized to the predicted solar abundances. The predicted abundance ratios at the time of the Sun formation (Solar value) are shown in each panel and indicate a good fit (all the values are close to zero).

the Galactic halo should have formed by accretion of multiple distinct sub-systems.

From the theoretical point of view, one of the most popular models for the chemical evolution of the Milky Way is the two-infall model of Chiappini, Matteucci, & Gratton (1997), which predicts two main episodes of gas accretion: during the first one, the halo the bulge and thick disk formed, while the second gave rise to the thin disk. In Fig. 1 we show an artistic representation of the formation of the Milky Way in the two-infall scenario. In the upper panel we see the formation of the inner stellar halo, following a monolithic-like collapse of gas (first infall episode) but with a longer timescale than originally suggested by Eggen et al.: here the time scale is 1-2 Gyr. During the halo formation also the bulge is formed on a very short timescale in the range 0.1-0.5 Gyr. During this phase also the thick disk assembles or at least part of it, since part of the thick disk, like the outer halo, could have been accreted. The second panel from left to right shows the beginning of the disk formation, namely the assembly of the innermost disk regions just around the bulge. This is due to the second infall episode which gives rise to the thin disk. The thin-disk assembles inside-out, in the sense that the outermost regions take a much longer time to form. This is shown in the third panel. In Fig. 1 each panel is connected to temporal phases where the Type II and then the Type Ia SN rates are present. So, it is clear that the early phases of the halo and bulge formation are dominated by Type II SNe (and also by Type Ib/c SNe) producing mostly α-elements such as O and Mg on short timescales (from few Myr to few tenths of Myr). On the other hand, Type Ia SNe start to be non negligible only after 1 Gyr and they pollute the gas during the thick and thin disk phases over a large range of timescales. The minimum shown in

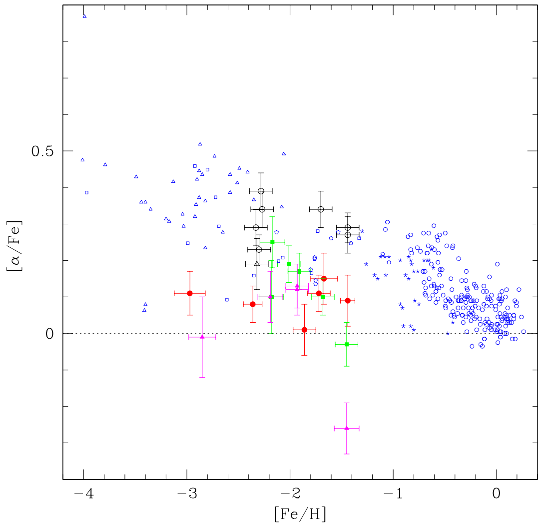

Fig. 3. Observed [α/Fe] vs. [Fe/H] in the Milky Way (small points) and in dSphs (points with error bars). Figure from Shetrone, Coté, & Sargent (2001).

the Type II SN rate is due to a gap in the star formation rate occurring as a consequence of the adoption of a threshold density in the star formation process.

2. Milky Way results

We present here some results for the solar vicinity, namely the local ring at 8 Kpc from the galactic center. In particular, we compute the evolution of the abundances of several chemical species (H, D, He, Li, C, N, O, α-elements, Fe, Fe-peak elements, s-and r- process elements). We take into account detailed nucleosynthesis (see François et al. 2004) from low and intermediate mass stars, Type Ia SNe (originating from white dwarfs in binary systems) and Ib/c and II SNe (originating from core-collapse of massive stars).

2.0.1. The time-delay model

What we call time-delay model is the interpretation of abundance ratios such [α/Fe] (where α-elements are O, Mg, Ne, Si, S, Ca and Ti) versus [Fe/H], a typical way of plotting the abundances measured in the stars. The time-delay refers to the delay with which Fe is ejected into the interstellar medium (ISM) by SNe Ia relative to the fast production of α-elements by core-collapse SNe. Tinsley (1979) first suggested that this time delay would have produced a typical signature in the [α/Fe] vs. [Fe/H] diagram. In the following years, Greggio & Renzini (1983), by means of simple models (star formation burst or constant star formation) studied the effects of the delayed Fe production by Type Ia SNe on the [O/Fe] vs. [Fe/H] diagram. Matteucci & Greggio (1986) included for the first time the Type Ia SN rate formulated by Greggio & Renzini in a detailed model for the chemical evolution of the Milky Way. The effect of the delayed Fe production is to create an overabundance of O relative to Fe ([O/Fe]$>$ 0) at low [Fe/H] values, and a continuous decline of the [O/Fe] ratio until the solar value ($[\mathrm{O/Fe}]_{\odot} = 0.0$) is reached for [Fe/H]$> -1.0$ dex. This is what is observed and indicates that during the halo phase the [O/Fe] ratio is due only to the production of O and Fe by SNe II. Then, since the bulk of Fe is produced by Type Ia SNe, when these latter start to be important the [O/Fe] ratio begins to decline. This

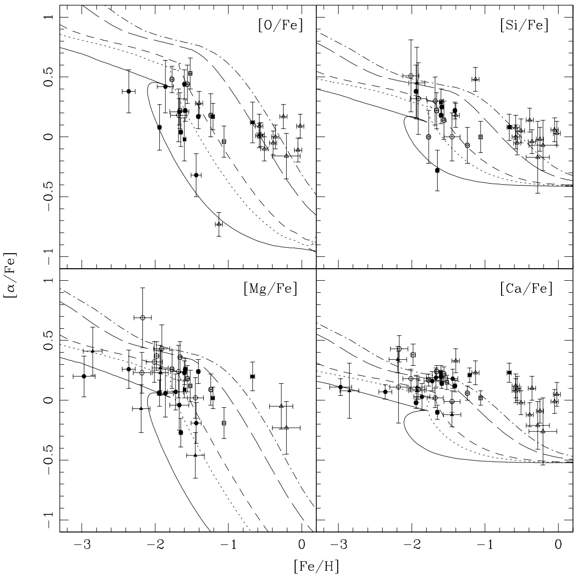

Fig. 4. Observed and predicted [α/Fe] versus [Fe/H] for dSphs of the Local Group. The different lines refer to the “standard model” with different star formation efficiencies, going from 1 (dashed-dotted lines) to 0.01 Gyr^{-1} (continuous lines). The points represent stars in different dSphs: Sagittarius (open triangles), Draco (filled hexagons), Carina (filled circles), Ursa Minor (open hexagons), Sculptor (open circles), Sextans (filled triangles), Leo I (open squares) and Fornax (filled squares). Figure and references from Lanfranchi & Matteucci (2003).

effect was predicted by Matteucci & Greggio (1986) to occur also for other α-elements (e.g. Mg, Si). At the present time, a great amount of stellar abundances is available and the trend of the α-elements has been confirmed.

As an illustration of the time-delay model we show in Fig. 2 the [X/Fe] vs. [Fe/H] relations both observed and predicted for stars in the solar vicinity belonging to halo, thick- and thin-disk. The adopted yields for massive stars are those suggested by François et al. (2004) in order to best fit these relations and the solar abundances (namely the abundances in the ISM 4.5 Gyr ago). These yields are obtained by applying some corrections to the yields of Woosley & Weaver (1995) for massive stars ($M > 10 M_\odot$).

3. Results for dwarf spheroidals

Cold dark matter (CDM) models for galaxy formation predict that the dSphs, systems with luminous masses of the order of $10^7 M_\odot$, are the first objects to form stars and that all stars in these systems should form on a timescale < 1 Gyr, since the heating and gas loss, due to reionization, must have halted the star formation soon. However, observationally all dSph satellites of the Milky Way contain old stars indistinguishable from those of Galactic globular clusters and they seem to have experienced star formation for long periods (>2 Gyr, Grebel & Gallagher 2004). The histories of SF for these galaxies are generally derived from the color-magnitude diagram (e.g. Mateo 1998).

A different pattern for the [α/Fe] vs. [Fe/H] relation compared to the solar vicinity is observed in dSphs of the Local Group, as shown in Fig. 3, and this can be easily interpreted in the framework of the time-delay model coupled with different star formation histories. In fact, if the star formation rate is less efficient than in the solar vicinity, then the bulk of Fe from Type Ia SNe occurs when the ISM is still quite metal poor ([Fe/H]< -1.0 dex), thus producing a smaller plateau for the [α/Fe] ratio at low metallicities and a steeper decline of this ratio for larger metallicities (see Matteucci 2001). A slow star formation rate is at variance with a fast episode of star formation truncated by heating due to photoionization.

Lanfranchi & Matteucci (2003, 2004) developed models for dSphs of the Local Group. First they tested a "standard model" devised for describing an average dSph galaxy. This model was based on the following assumptions:

- one long star formation episode of duration ~ 8 Gyr,
- a small star formation efficiency, namely the star formation rate per unit mass is 1-10% of that in the solar vicinity,
- a strong galactic wind develops when the thermal energy of the gas equates the binding energy of the gas. The rate of gas loss is assumed to be several times the star formation rate (between 5 and 15 times).

An example of the predictions of Lanfranchi & Matteucci (2003) standard model is shown in Fig. 4.

As one can see from Fig. 4, the predicted [α/Fe] ratios show a clear change in slope followed by a steep decline, in agreement with the data. The change in slope corresponds to the occurrence of the galactic wind which starts emptying the galaxy of gas. In such a situation the star formation starts to decrease as does the production of the α-elements from massive stars, whereas Fe continues to be produced since its progenitors have long lifetimes. This produces the steep slope: the low star formation efficiency coupled with the galactic wind, which decreases further the star formation rate. In this situation, the time-delay model predicts an earlier and steeper decline of the [α/Fe] ratios, as already discussed.

Therefore, we can conclude that the time-delay model can account for the chemical properties of both the Milky Way and the dwarf spheroidals of the Local Group and that the data suggest that the star formation rates in these latter systems were lower than in the Milky Way.

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