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Early star formation in the Galaxy from beryllium and oxygen abundances

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Abstract. We investigate the evolution of the star formation rate in the early Galaxy using beryllium and oxygen abundances in metal poor stars. Specifically, we show that stars belonging to two previously identified kinematical classes (the so-called "accretion" and "dissipative" populations) are neatly separated in the [O/Fe] vs. log (Be/H) diagram. The dissipative population follows the predictions of our model of Galactic evolution for the thick disk component, suggesting that the formation of this stellar population occurred on a timescale significantly longer (by a factor ~5–10) than the accretion component. The latter shows a large scatter in the [O/Fe] vs. log (Be/H) diagram, probably resulting from the inhomogeneous enrichment in oxygen and iron of the protogalactic gas. Despite the limitation of the sample, the data suggest that the combined use of products of spallation reactions (like beryllium) and elemental ratios of stellar nucleosynthesis products (like [O/Fe]) can constrain theoretical models for the formation and early evolution of our Galaxy.

Key words. stars: abundances – stars: age, late-type – Galaxy: halo – Galaxy: thick disk

1. Introduction

In a recent paper (Pasquini et al. 2004), we presented the first detection of beryllium in two turnoff stars of the globular cluster NGC 6397, and tested the theoretical proposal that Be could be used as a cosmochronometer for the earliest stages of evolution of the Galaxy. The rationale behind this suggestion is that Be is produced only by spallation reactions of Galactic cosmic rays on interstellar medium nuclei, and if Be was produced by the primary process (see e.g. King 2002), the evolution of Be was a global process occurring on a Galactic scale (Beers et al. 2000; Suzuki & Yoshii 2001), rather than a local process like the production and subsequent ejection of heavy elements by supernovae (SNe). At any time, the abundance of Be is thus expected to be characterized by a scatter around the mean value significantly smaller than that of typical products of stellar nucleosynthesis like e.g. Fe or O, making Be a more reliable chronometer than [Fe/H] or [O/H]. For example, according to the stochastic model of Suzuki & Yoshii (2001), at a Galactic age of 0.2–0.4 Gyr the spread in log (Be/H) is about 0.5 dex, whereas the spread in [Fe/H] is more than twice this value. This theoretical prediction was the main justification for the use of Be as a clock for the early Galaxy in Pasquini et al. (2004). In this paper we extend this approach to a sample of halo and thick disk stars, using the Be abundance as an "equivalent" time scale. In particular, we test the usefulness of Be as a cosmic clock showing that two previously identified kinematical classes of low-metallicity stars likely formed over significantly different time scales. In this spirit, we attribute most of the scatter in the data, especially at low values of log (Be/H), to an intrinsic spread in O and Fe abundances, rather than Be. This is an idealization, of course, and we expect some intrinsic scatter to be present in the Be abundance as well.

2. The sample

The stars of our sample satisfy two main requirements: (1) their Be, Fe and O photospheric abundances are known, and computed in an homogeneous way, and (2) they belong to one of the two kinematical classes identified by Gratton et al. (2003, hereafter G03). The first kinematical class is composed by a rotating inner population with a galactic rotation velocity larger than 40 km s^{-1} and an apogalactic distance of less than 15 kpc. This was called by G03 the *dissipative collapse* component because it broadly corresponds to the classical Eggen et al. (1962) dissipative collapse population, and includes stars from the classical thick disk and the classical halo. The second kinematical class is composed by non rotating or counter rotating stars, and contains mainly stars of the classical halo. It was called the *accretion* component, because it can be roughly identified with the accreted population first proposed by Searle & Zinn (1978) to explain the formation of the halo. These two components differ not only in their kinematical properties, but also in their chemical composition (see G03).

The abundances of Be, O, and Fe for the stars of our sample were taken from Boesgaard et al. (1999, hereafter B99). To guarantee a homogeneous choice of the stellar parameters and derived abundances we did not include stars from other compilations. We extracted from this sample a metal poor subsample with [Fe/H] < -0.5 to focus only on the earliest phases of Galactic chemical evolution ($t \lesssim 3$ Gyr). Also, we eliminated stars cooler than 5500 K and checked that no evolved star was included in our sample. Cool stars and giants show Li abundances clearly depleted, indicating that this element has been burned or diluted (Li and Be are destroyed in stellar interiors by proton reactions above temperatures ~2.5 and 3.5×10^6 K, respectively).

Out of the original 26 stars in the sample of B99 only 20 are left; 4 were eliminated because too metal rich, 1 because too cool (HD 103095), one (BD-13 3442) because no accurate kinematic parameters were available. We used the abundances obtained with the King scale, given in Tables 2 and 5 of B99. Since all data necessary for our work were published in B99, they are not reproduced here. For a few stars not present in the sample of G03, the association to the accretion or the dissipative component was established with the kinematical parameters derived by Fulbright (2002). In summary, twelve stars belong to the accretion group, eight (HD 19445, 76932, 94028, 134169, 184499, 201889, BD +26 3578, BD +23 3912) to the dissipative component.

3. The model of Galactic evolution

We recall briefly the key features of the model of Galactic evolution adopted in this work to interpret the observational data summarized in the previous section. The model follows the coupled evolution of three regions in the Galaxy, labelled *halo*, *thick disk*, and *thin disk* (*multizone* treatment), characterized by different star formation rates and hence exhibiting distinct chemical properties (for a more detailed discussion see Ferrini et al. 1992, 1994). In the framework of this model, Valle et al. (2002) computed the production of Li, Be, and B nuclei in the Galaxy resulting from spallation reactions induced by Galactic cosmic rays. According to Valle et al. (2002), the production of Be is dominated by spallation of cosmic-ray protons onto ISM heavy nuclei, mostly O nuclei. At very early times, when the ISM metallicity is very low, an important contribution to the production of Be can be provided by spallation of CNO nuclei directly coming from SN ejecta. The relative weight of this process depends however on poorly constrained quantities like the CNO abundance in SN ejecta and the SN rate at very early times.

As for the stellar production of Fe and O, the heavy elements considered in this paper, our model follows the nucleosynthesis prescriptions of Woosley & Weaver (1995) and Thielemann et al. (1996) for SNeII and SNeI, respectively. A detailed discussion of the evolution of these elements in our model of Galactic evolution can be found in Travaglio et al. (1999). The model abundances of Fe and O have been converted into abundances relative to the Sun adopting $\log A(\mathrm{Fe}) = 7.50$ (Grevesse & Sauval 1999) and $\log A(\mathrm{O}) = 8.69$ (Allende Prieto et al. 2001).

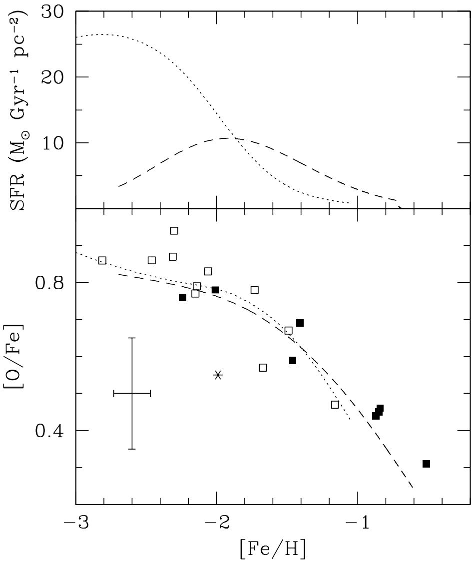

Fig. 1. *Upper panel*: the SFR for the halo and the thick disk (*dotted* and *dashed curves*, respectively), plotted as function of [Fe/H]. *Lower panel*: [O/Fe] vs. [Fe/H] diagram for our sample stars (*filled squares*: dissipative component; *empty squares*: accretion component). An *asterisk* denotes the position of the chemically peculiar star HD 74000, belonging to the accretion component. The median absolute abundance error bar is given. Note that the uncertainty in the relative abundances will be smaller. The abundance ratios predicted by our model for the halo and the thick disk are shown by the *dotted* and *dashed curves*, respectively.

4. Results

In Fig. 1 we show the [O/Fe] vs. [Fe/H] diagram for our sample stars, representing the two populations with different symbols (cf. Fig. 3 of G03), and the abundance ratios predicted by our model for the halo and the thick disk. The upper panel shows the star formation rate (SFR) of the model for the two zones, as function of [Fe/H] (we use the SFR to represent the number of long-living stars formed at that value of metallicity). The predictions of our model for the halo and the thick disk appear to follow a very close evolution in the [O/Fe] vs. [Fe/H] diagram. Our sample shows the same characteristics discussed by G03 for a larger sample, namely a larger scatter of the accretion component with respect to the dissipative component, and a slightly higher [O/Fe] ratio for the latter at fixed metallicity. No clear separation exists between the two groups, with the obvious exception that the dissipative component dominates the metal rich tail of the distribution.

The situation is, however, quite different in Fig. 2, showing the observational data and the model results in the [O/Fe] vs. log (Be/H) diagram (the Be abundance of the model has been normalized to the solar (meteoritic) value as in Pasquini et al. 2004). The most interesting feature of Fig. 2 is the significant separation of the halo and thick disk tracks, especially for high

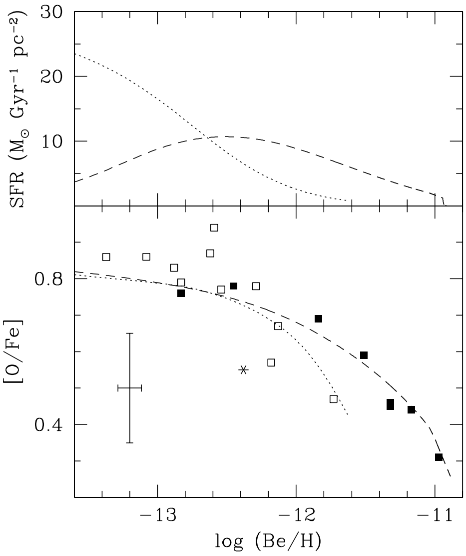

Fig. 2. *Upper panel*: the SFR for the halo and the thick disk (*dotted* and *dashed curves*, respectively) as function of log (Be/H). *Lower panel*: [O/Fe] vs. log (Be/H) diagram for our sample stars (same symbols and line types as in Fig. 1). Notice the good agreement between the thick disk model and the dissipative component.

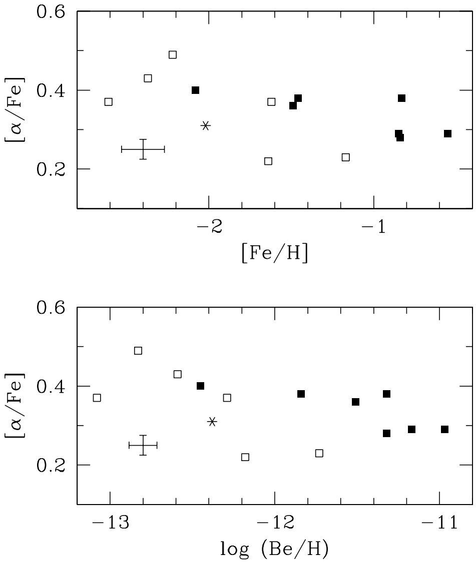

Fig. 3. Diagram of [α/Fe] vs. [Fe/H] and log (Be/H), where α is the average of the abundances of Mg, Ca, Si, and Ti (same symbols as in Figs. 1 and 2).

values of log (Be/H), and a corresponding separation in the accretion and dissipation components. Stars belonging to the dissipative component, in particular, define in this diagram a sequence characterized by little or no scatter that closely follows the thick disk track. The halo track of the model, on the other hand, for high values of log (Be/H) defines the upper envelope of the distribution of stars belonging to the accretion component, but at lower values of log (Be/H) the scatter in the data cannot be accounted by our deterministic model of Galactic evolution. The large spread in the abundances probably reflects the inhomogeneous enrichment of the halo gas.

Since oxygen is produced by core-collapse (type-II) SNe, while iron is also significantly produced by merging-binary (type-I) SNe evolving on a longer timescale, the oxygen-to-iron ratio is an indicator of the time variation of the star formation rate at any epoch. The abundance of Be, on the other hand, provides a good measure of the time elapsed after the onset of star formation in the Galaxy, as proposed by Beers et al. (2000), Suzuki & Yoshii (2001) on the basis of stochastic models of chemical evolution, and empirically demonstrated by Pasquini et al. (2004).

Thus, despite the limited sample, the correspondence of the two stellar populations, identified by G03 on purely kinematic grounds, with the two components of the model of Galactic evolution, separated solely on the basis of their different star formation histories, supports the idea that the formation of the two populations took place under significantly different conditions: an inhomogeneous, rapidly evolving "halo phase" for the accretion population, and a more chemically homogeneous, slowly evolving "thick disk phase" for the dissipative population. As an indication, in our model the SFR in the halo has a peak around $t \approx 0.06$ Gyr and lasts for about 0.1 Gyr (full width at half-maximum), whereas the SFR in the thick disk has a peak around $t \approx 0.3$ Gyr, and lasts for about 1 Gyr.

5. Discussion

Although the separation of the two stellar populations shown by Fig. 2 suggests a close association between kinematical properties and star formation history, the identification of the two kinematical groups with the two components of our Galactic model should be taken with caution. In fact, the dissipative component identified by G03 also includes halo stars with kinematical properties similar to those of the thick disk. Also, the use of the [O/Fe] ratio as an indicator of the variation of the star formation rate is questionable, as the determination of the O abundance is known to be affected by a number of uncertainties (see e.g. the discussion in Barbuy et al. 2001). In principle, a diagram of any α element other than O vs. log (Be/H) should present characteristics similar to Figs. 1 and 2, since all α-elements have a common origin in the pre-supernova stages of massive stars. We show in Fig. 3 the stars of our sample for which the [α/Fe] ratio was determined by G03, as function of [Fe/H] (also from G03) and log (Be/H). Here, α is the *average* of the abundance ratios of Mg, Si, Ca, and Ti relative to Fe. Despite the larger scatter evident in the "combined" abundances, and the reduced sample, a significant separation between the two populations is still discernible, especially in the [α/Fe] vs. log (Be/H) diagram, lending support to our conclusions based on the [O/Fe] ratio.

A feature evident in Figs. 1 and 2 that cannot be reproduced by our deterministic model of Galactic evolution is the large scatter in chemical abundances shown by the accretion population. One should keep in mind, however, that the amount of intrinsic scatter present in such a small sample is difficult to assess, since peculiar abundances of just a few stars may strongly influence the conclusions. For instance, one of the stars most deviating from the model, HD 74000 (shown by an asterisk in our figures), is known to have a peculiar, N-rich composition (see e.g. Laird 1985). Some scatter in the accretion component, however, could be due to spatial inhomogeneities present in the halo gas.

The halo formation picture emerging from this work favours an accretion component formed by a short burst plus a component formed in a long-lasting dissipative process. This is at odds with the canonical picture which predicts a very short ($\sim 10^8$ yr) dissipative collapse (Eggen et al. 1962) and a rather slow accretion ($\sim 10^9$ yr, Searle & Zinn 1978). Recent simulations based on ΛCDM modelling (Bekki & Chiba 2001, Samland & Gerhard 2003) however suggest that the classical, non rotating halo was formed early by the disruption of small clumps, and imply a rather long timescale (up to ~2 Gyr) for the phase of dissipative collapse. This picture is at least in qualitative agreement with our findings. In addition a star formation process taking place in small clumps may provide a natural explanation for the α/Fe deficiency observed. Small mass clumps would in fact not be able to produce many high mass SNae and/or to retain their ejecta, leading to a net lower oxygen abundance in the stars which formed there.

We should however keep in mind that our analysis is affected by several uncertainties. First, our knowledge of the early evolution of galactic cosmic ray and their confinement is fairly incomplete. In particular, the results of our model can strictly be applied only to the solar neighborhood, whereas it is possible that some halo stars have formed at very large Galactocentric radii characterized by a lower cosmic ray flux and therefore a lower production of Be and heavy elements. In our sample there is not evidence for a gradient in Be and only one star has a maximum radius above 20 kpc; the sample is too small to derive any conclusion in this respect. The absence of an [α/Fe] gradient in the halo (Venn et al. 2004) is in this respect reassuring, but this possibility should be properly tested before it can be excluded. Second, our identification of the the outer non rotating component with the accreted halo, and the rotating inner component with the dissipative thick disk depends sensitively on the adopted kinematical criteria. For example, with the criteria of Venn et al. (2004) only 4 of our stars would be classified as disk objects.

The broad picture outlined in this paper should be confirmed and refined on the basis of a large, statistically significant sample of stars with well defined kinematical properties and accurate abundance determinations. Such a database could, in addition, be used to discriminate different models of Galactic chemical evolution. Stellar groups proposed to belong to accretion episodes from external galaxies (Navarro et al. 2004) could also be studied in a similar fashion.

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