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Beryllium and the formation of the Thick Disk and of the Halo

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Abstract. We use Beryllium to investigate star formation in the early Galaxy. Be has been demonstrated to be a good indicator of time in these early epochs. By analyzing the so-far largest sample of halo and thick disk metal poor stars, we find a clear scatter in Be for a given value of [Fe/H] and [O/H]. The scatter is very pronounced for Halo stars, while it is marginal for thick disk stars. Our halo stars separate in the [α/Fe] - Be diagram, showing two main branches: one indistinguishable from the thick disk stars, and one with lower [α/Fe] ratio. The stars belonging to this branch are characterized by highly eccentric orbits and small perigalactic radius (R_{min}). Their kinematics are consistent with an accreted component.

Keywords. Stars: Abundances, Galaxy: Halo, Galaxy: Disk

1. Introduction

Beryllium has a unique nucleosynthesis: is neither a product of stellar nucleosynthesis nor created in detectable amounts by standard homogeneous primordial nucleosynthesis (Thomas *et al.* 1993). Its single long-lived isotope, ^{9}Be, is a pure product of cosmic-ray spallation of heavy (mostly CNO) nuclei in the interstellar medium (Reeves *et al.* 1970)

Early theoretical models of Be production in the Galaxy assumed the cosmic-ray composition to be similar to the composition of the interstellar medium (ISM). In this scenario, Be is produced by accelerated protons and α-particles colliding with CNO nuclei of the ISM (Meneguzzi & Reeves 1975; Vangioni-Flam *et al.* 1990; Prantzos *et al.* 1993), resulting in a quadratic dependence of the Be abundance with metallicity. However, observations of Be in metal-poor stars (Rebolo *et al.* 1988; Gilmore *et al.* 1992; Molaro *et al.* 1997a; Boesgaard *et al.* 1999) found a slope equal or close to one between log(Be/H) and [Fe/H], and just slightly higher for log(Be/H) and [O/H]†. Such slopes argue that Be behaves as a primary element and its production mechanism is independent of ISM metallicity. Thus, the dominant production mechanism is now thought to be the collision of cosmic-rays composed of accelerated CNO nuclei with protons and α-particles of the ISM (Duncan *et al.* 1992; Vangioni-Flam *et al.* 1998).

As a primary element and considering cosmic-rays to be globally transported across the Galaxy, one may expect the Be abundance to be rather homogeneous at a given time in the early Galaxy. It should have a smaller scatter than the products of stellar nucleosynthesis (Suzuki *et al.* 1999; Suzuki & Yoshii 2001). Thus, Be would show a good

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† $[A/B] = \log\,[N(A)/N(B)]_\star - \log\,[N(A)/N(B)]_\odot$

correlation with time and could be employed as a cosmochronometer for the early stages of the Galaxy (Beers *et al.* 2000; Suzuki & Yoshii 2001).

Pasquini *et al.* (2004, 2007) tested this suggestion deriving Be abundances in turn-off stars of the globular clusters NGC 6397 and NGC 6752. The Be ages derived from a model of the evolution of Be with time (Valle *et al.* 2002) are in excellent agreement with those derived from theoretical isochrones. Moreover, the Be abundances of these globular cluster stars are similar to the abundances of field stars with the same metallicity. These results strongly suggest the stellar Be abundance to be independent of the environment where the star was formed and support the use of Be as a cosmochronometer.

Pasquini *et al.* (2005) extended the use of Be as a measure of time to a sample of 20 halo and thick disk stars and investigated the evolution of the star formation rate in the early-Galaxy. Stars belonging to the two different kinematic components identified by Gratton *et al.* (2003a) seem to separate in a log(Be/H) vs. [O/Fe] diagram. Such separation is interpreted as indicating the formation of the two components to occur under different conditions and time scales.

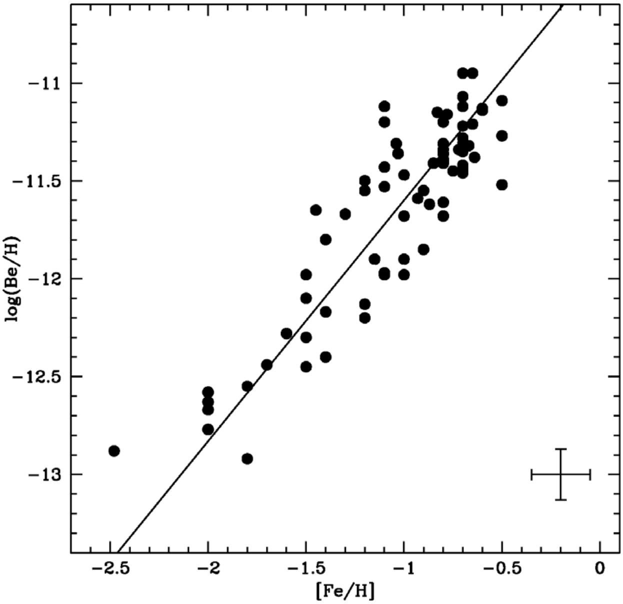

Figure 1. Be abundance vs. [Fe/H] for the sample stars. The linear relationship is clear, but a substantial scatter is present.

We present the analysis of an unprecedentedly large sample of halo and thick disk stars, and further investigate the use of Be as a cosmochronometer and its role as a discriminator of different stellar populations in the Galaxy.

2. The Sample and Analysis

The sample stars were selected from the compilation by Venn *et al.* (2004) of several abundance and kinematic analyses of Galactic stars available in the literature. Using the available kinematic data, Venn *et al.* (2004) calculated the probabilities for each star to belong to the thin disk, the thick disk, or the halo. A total of 90 stars were selected for this work; 9 of them have higher probability of being thin disk stars, 30 of being thick disk stars, 49 of being halo stars, and 2 have 50% probabilities of being halo or thick disk stars. We simply assume a star to belong to a certain kinematic group when the probability of belonging to that group is larger than the probability of being in the other two groups. Our aim being to compare stars of different populations but of similar abundances, we tried to maximize the metallicity overlap between the two sub-samples. The halo stars range from [Fe/H] = −2.48 to −0.50 and the thick disk stars from [Fe/H] = −1.70 to −0.50, although strongly concentrated in [Fe/H] $\geqslant -1.00$.

Spectra for all stars were obtained using UVES, (Dekker *et al.* 2000) fed by UT2 of the VLT. The resolving power of these spectra varies between 40,000 and 80,000 and the S/N ratio varies between 100 and 450 in the blue arm.

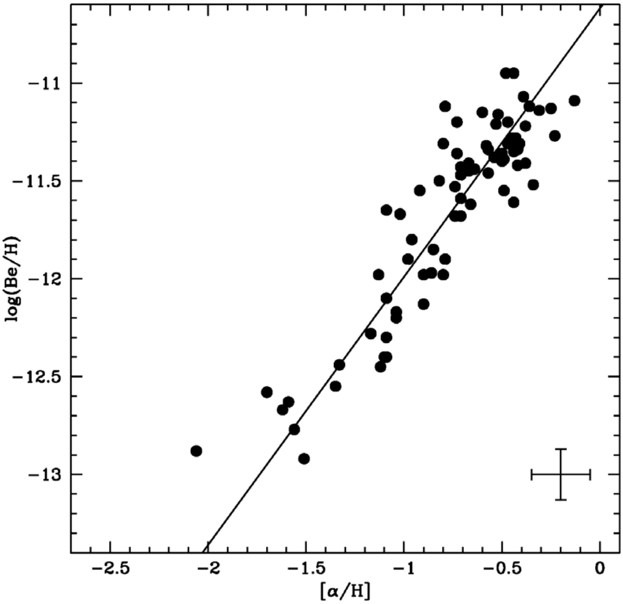

Figure 2. Be abundance vs. $[\alpha/H]$ for the sample stars. The linear relationship is clear, but a substantial scatter is present.

All the selected stars have previous abundance analyses. We decided to adopt the atmospheric parameters, effective temperature ($T_{\rm eff}$), surface gravity (log g), microturbulence velocity (ξ), and metallicity ([Fe/H]), as determined by the previous studies.

As Be abundances are calculated from lines of the ionized species, log g is the most relevant parameter for the analysis. Our sample stars are relatively bright and nearby, therefore we used Hipparcos parallaxes (ESA 1997) to estimate gravity. Apart from eight stars that show a significant (larger than 0.28 dex) difference between spectroscopic and astrometric gravities, the agreement is excellent.

After cleaning the sample for double line spectroscopic binaries, contaminated spectra and Be-depleted stars, we are left with 39 halo stars, 28 thick disk stars, and 9 stars classified as thin disk.

For most stars kinematic data was available, and for a few objects we have computed the orbits, following Gratton *et al.* (2003a).

3. Results

Figures 1 and 2 show Be abundance vs. [Fe/H] and [α/H] for the stars. The scatter, in particular in the [Fe/H] diagram, is evident. The linear relationships give:

$$Log(Be/H) = -10.37 + 1.23[Fe/H]$$
$$Log(Be/H) = -10.62 + 1.37[\alpha/H]$$

Is this scatter real or does it just reflect the abundance uncertainties? A statistical analysis shows that the scatter is significant, but the level of significance depends strongly on the assumed uncertainties. To support the hypothesis of a real scatter, we find it very convincing to directly compare the spectra of pairs of stars with similar overall stellar parameters and abundances, but different Be abundance, as given in Figure 3. Only the Be doublet substantially differs from star to star, while the rest of the spectra overlap.

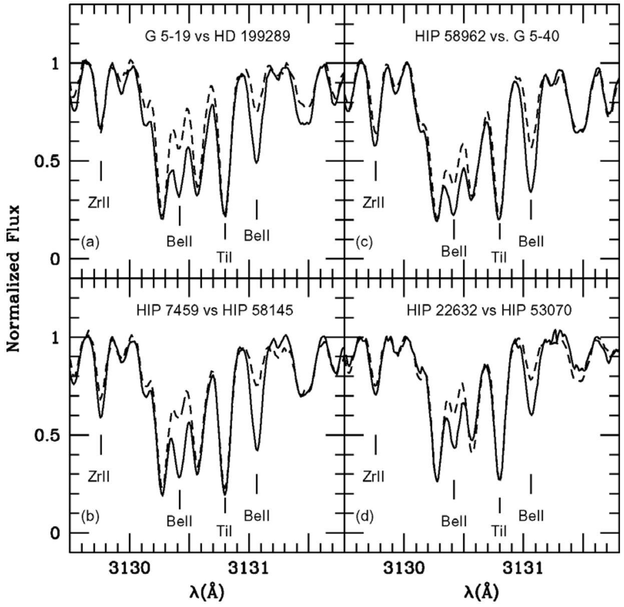

Figure 3. Comparison of spectra of couples of stars with similar parameters, but different Be content.

Once the reality of the scatter has been established, we shall consider its possible causes. In general, we can think of at least two concepts: the first is that the spread is induced by local effects. We know that this may happen, as proposed to explain the exceptionally Be-rich star HD106038 (Smiljanic *et al.* 2008). A second possibility is that the spread is due to the presence of a composite population. If stars with the same metallicity belong to different populations, they were formed at a different time in the Galaxy, therefore their Be abundance should be naturally different. If we divide the sample stars in thick disk and halo components, we find indeed, that while the spread among the thick disk stars is minimal, the halo component is dominating the whole scatter. This might be the signature of a composite or complex halo formation.

Figure 4 shows the Halo and Thick Disks stars in the [α/Fe] vs. Be diagram. Pasquini *et al.* (2005) proposed that this diagram represents star formation rate as function of time. In the same figure the models used in that work are shown. Interestingly, the halo component looks composite, with two quite distinct branches: one branch has high Be and high [α/Fe] and is indistinguishable from the thick disk stars. The other branch is well represented by the halo model and is characterized by a low [α/Fe] ratio.

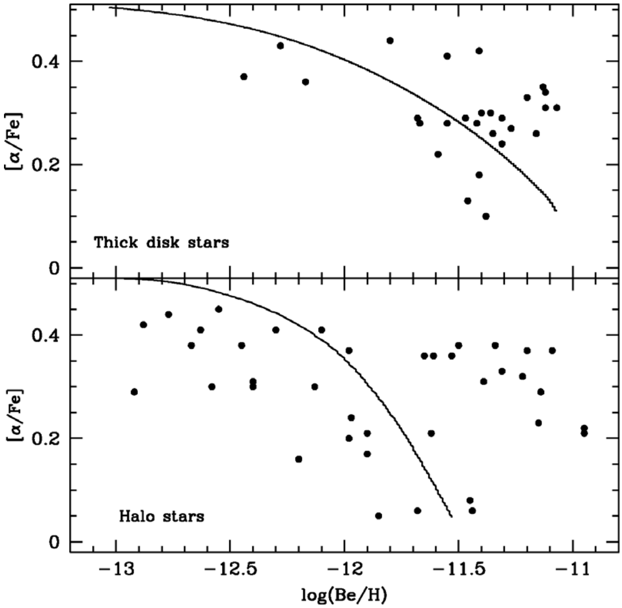

Figure 4. [α/Fe] vs. Be diagram for Halo and Thick disk stars, separately. This diagram can be interpreted as Star formation rate vs. Time. Superimposed are the models used by Pasquini *et al.* (2005) for the Halo and the Thick Disk. The halo seems composite, with a component at high Be and high [α/Fe] indistinguishable from thick disk stars , and a component with low [α/Fe].

If we look at the low [α/Fe] stars in more detail, they all have a similar kinematics: very low galactic rotation and orbits which reach a small perigalactic distance R_{min}. These kinematics could be compatible with an accreted component.

The hypothesis that these low [α/Fe] stars might belong to a specific population is confirmed by the fact, shown in Figure 5, that they distribute along the same line in the Fe vs. Be diagram. In conclusion, while we cannot prove that these low [α/Fe] stars are accreted, we have several indications that they separate from the other halo and thick disk stars. It is, on the other hand, also interesting that the high Be, high α stars do not show any chemical peculiarity with respect to the thick disk stars, even when a peculiar element such as Be is considered; this similarity in composition would lead us suppose a common origin.

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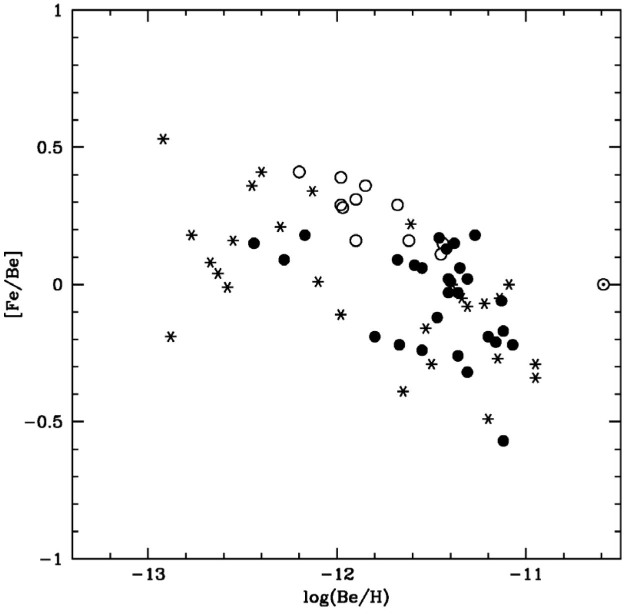

Figure 5. [Fe/Be] vs. Be for the sample stars. Open circles indicate the low [α/Fe] stars. They lie in a small range and along a sequence, suggesting a common origin.

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