VLT Observations of Beryllium in a Globular Cluster:

a clock for the early Galaxy and new insights into Globular Cluster formation

The first-ever measurement of the beryllium content in two stars of a globular cluster obtained with UVES at the VLT shows that beryllium can be used as a powerful cosmochronometer to date the oldest stars. In this way we estimate that the globular cluster NGC 6397 formed 0.2–0.3 Gyrs after the onset of star formation in the Milky Way. Assuming that this started shortly after the Big Bang (13.7 Gyrs ago according to WMAP), and the subsequent "dark ages" which are thought to last about 0.2 Gyr, the NGC 6397 stars were therefore born ~13.2–13.3 Gyrs ago, a result which is consistent with the age of the cluster as independently derived from main sequence fitting. This consistency would indicate a remarkable agreement between stellar evolution, cosmic-ray nucleosynthesis and cosmology. The UVES spectra prove as well that the gas which formed the stars must have gone through CNO processing in the protocluster cloud before their formation.

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Dating stars, in particular the oldest ones, is one of the challenges for stellar astronomers. By dating them, we can, for instance, test evolutionary theories and set lower limits to the age of the Galaxy and of the Universe. The most common approach to dating involves the determination of a star's age, that is, the time elapsed from its birth to the present.

We present here an orthogonal perspective, investigating if it is possible for the oldest stars to provide a reliable measurement of the time elapsed between the beginning of star formation in the Galaxy and the birth of these objects.

In order to achieve this goal we need a tracer which, at least in the early Galaxy, was growing steadily (possibly slowly) and homogeneously, not suffering from inhomogeneities which may have been present, given the limited time available for an efficient mixing to occur.

Such a tracer is ^{9}Be. Unlike most elements, which are produced either in stars or by big bang nucleosynthesis, in fact, ^{9}Be (together with B and the ^{6}Li isotope) can only be produced in the interstellar medium by Galactic Cosmic Rays (GCRs) through the spallation of heavier nuclei, such as carbon, oxygen and nitrogen (Reeves et al. 1970). In the early Galaxy, Be was produced by energetic particles generated in SN explosions and transported globally on a Galactic scale; its abundance is predicted to increase uniformly with time, showing less scatter than the products of stellar nucleosynthesis such as Fe or O. The dominant spallation process is expected to be the so called "primary" process, where Be is produced by the collisions of accelerated C,N,O nuclei in Galactic Cosmic Rays with interstellar medium (ISM) protons and α-particles. This process is called primary because it is expected to lead to a linear dependence of Be on metallicity. A tight trend between Be and metallicity has been confirmed observationally down to [Fe/H] ≅ –3.3 in metal-poor field halo stars (Gilmore et al. 1992, Molaro et al. 1997, Boesgaard et al. 1999). This makes Be a potentially powerful "cosmic clock" for dating the first stages of Galactic halo evolution (Suzuki et al. 2001).

To test Be as a cosmic clock it is necessary to measure Be in stars which can be dated independently. In this respect stars in old globular clusters, such as NGC 6397, are ideal candidates, because their ages can be determined in a reliable way through, for instance, main sequence fitting and stellar evolutionary theory, and they have been shown to be formed within ~1 Gyr after the Big Bang (Gratton et al. 2003).

However, the search for Be poses several challenges, because the only available Be lines are the Be II resonance doublet at 313.1 nm. This wavelength is very close to the atmospheric cut-off at 300 nm and the terrestrial atmosphere heavily absorbs the incoming radiation, making observations very challenging. In addition, the Be lines are very weak and the spectral region around them very crowded, so that high spectral resolution is necessary.

The high UV efficiency of UVES at the VLT telescope Kueyen has opened a new possibility, allowing for the first time the detection of Be in two turn-off (TO) stars in NGC 6397. It is essential to reach the cluster TO because these stars are the most suitable for Be analysis; in fact it must be borne in mind that Be may be destroyed in the stellar interiors at temperatures above ~3.5 million K, that is at temperatures about 1 million K higher than the more fragile Li. Previous studies of this cluster (Bonifacio et al. 2002)

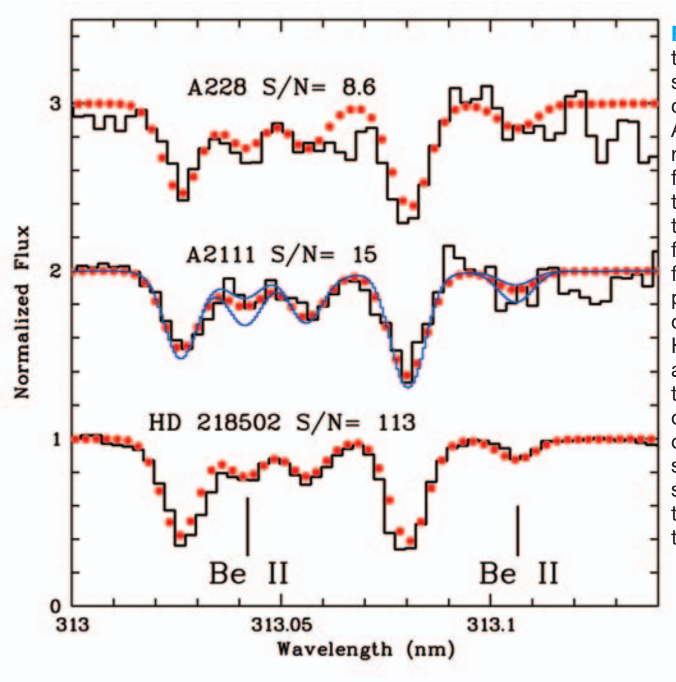

Figure 1: UVES spectra of the two turn-off stars of the Globular cluster NGC 6397: A2111 and A228. The red dots are the best-fitting synthetic spectra which correspond to Log(Be/H)= −12.27 for A228 and −12.43 for A2111. For comparison, the spectrum of the bright halo star HD 218502, whose atmospheric parameters are close to those of the NGC 6397 turn-off stars, is also shown. The best fit synthetic spectrum for this star corresponds to Log(Be/H)=–12.36.

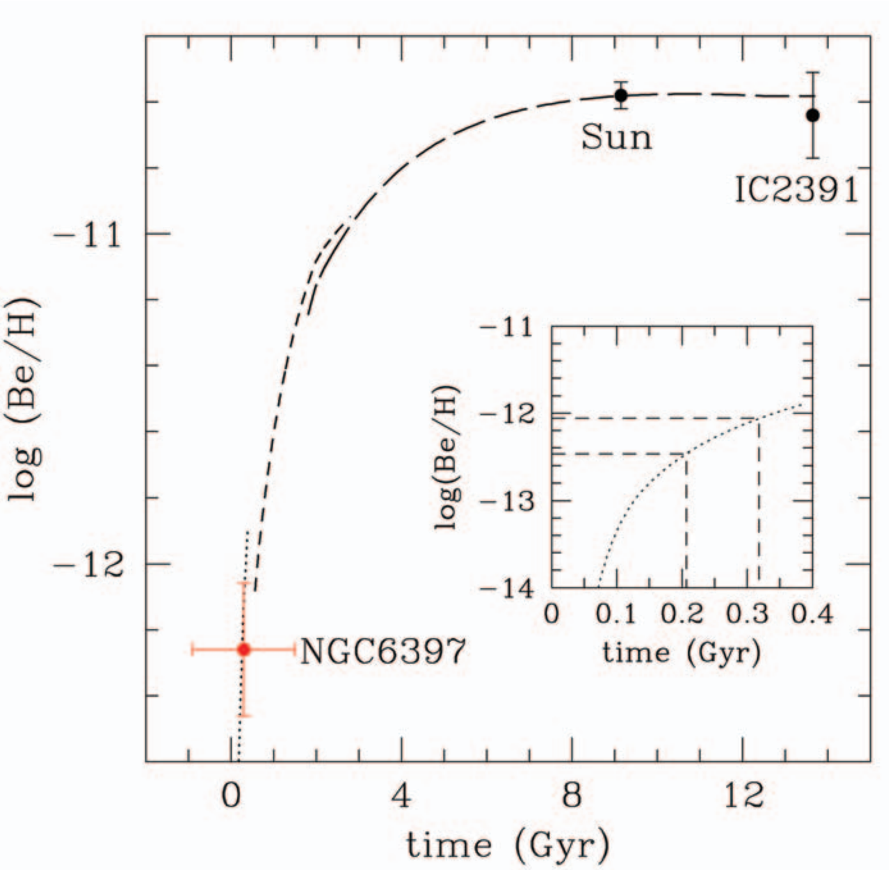

Figure 2: Evolution of Be with time in the Galaxy according to a three-zone Galactic chemical evolution model (Valle et al. 2002). The three curves refer to the halo, thick disc, and thin disc. The data points show the Be abundance in the young open cluster IC 2391 (age 50 Myr), the Sun (age 4.55 Gyr), and the globular cluster NGC 6397 (age 13.4±0.8 Gyr). The model result is normalized to the solar meteoritic abundance. The inset illustrates the use of Be as a "cosmic clock" to constrain the formation of NGC 6397. The horizontal lines corresponds to the 1σ contours around the measured Be abundance. The cluster birth is constrained to the first 0.2–0.3 Gyr after the onset of star formation in the Galactic halo.

have shown that these TO stars have an abundance of Li as high as the primordial value. Since this more fragile element is at its original level, then, *a fortiori*, Be has not been depleted in their atmospheres. Conversely, brighter subgiants in the same cluster show clear evidence of Li dilution. Even if NGC 6397 is the second closest cluster, its TO is still relatively faint, placed at an apparent magnitude of V~16. This means that a jump of almost 3 magnitudes with respect to the faintest star previously observed for Be abundance determination was necessary. Even with UVES and the VLT it has been necessary to expose each star for 10.5 hours.

The observed spectra in the region around the BeII lines are shown in Figure 1, together with the best-fit synthetic spectra. Thanks to the high resolution (R=45,000) and signal-to-noise ratio (8.5 and 15) of the spectra, the two Be II lines are clearly detected and measurable in both stars. The resulting abundance is very similar for both stars, and we obtain log (Be/H) =–12.35±0.2 (where errors include uncertainties in the adopted gravity). The log (Be/H) retrieved is in excellent agreement with that of field stars with similar [Fe/H] abundances. In the same figure the spectrum of a brighter field star is also shown, which has parameters similar to the targets and is used as a control star.

The measured Be abundance of the two targets is plotted in figure 2, together with the time evolution of Be resulting from a model of chemical evolution following the enrichment of three different regions in the Galaxy, coupled by mass flows: the halo, the thick disk and the thin disk (Valle et al. 2002). The other data point in the Figure shows the Be abundance in the Sun and in the young open cluster IC 2391, an indicator of the present-day value. In this Figure, star formation in the Galaxy is assumed to start 13.7 Gyr ago. This value represents the age of the Universe (time elapsed from the Big Bang) according to WMAP (Bennet et al. 2003). A more realistic age of the galaxy should take into account the time interval between the Big Bang and the epoch of re-ionization. The best estimate for this interval is 0.18 Gyr (WMAP data), well within the errors on the age estimate of NGC 6397.

The inset in Fig. 2 shows the halo evolution of Be on a finer time scale, with the two horizontal lines limiting the 1σ range of Be abundance in NGC 6397. This plot emphasizes the possible use of Be as a "cosmic clock": the measured value of Be indicates that the formation of NGC 6397 occurred about 0.2–0.3 Gyr after the onset of star formation in the Galactic halo. Given the uncertainty in the model assumptions, it is safe to conclude that the birth of the stars composing NGC 6397 took place within the first ~0.5 Gyr of halo evolution, in agreement with the main-sequence dating of the cluster. In fact under the previous assumptions, the "Beryllium age" retrieved for the cluster is 13.45 Gyr, which is in very good agreement with the absolute age of 13.4 ± 0.8 ± 0.6 Gyr, recently derived on the basis of the main sequence fitting method with standard isochrones (Gratton et al. 2003). Although the almost exact coincidence between the two "ages" is fortuitous, the combination of

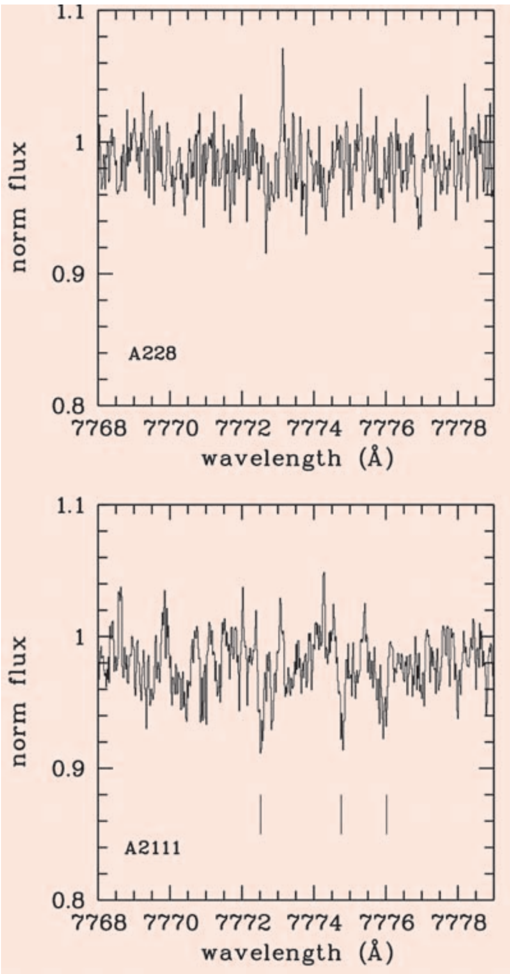

Figure 3: UVES spectra of the two NGC 6397 stars in the region of the Oxygen triplet. The two stars have identical stellar parameters but clearly different line strengths; their O abundances differ by almost 0.6 dex.

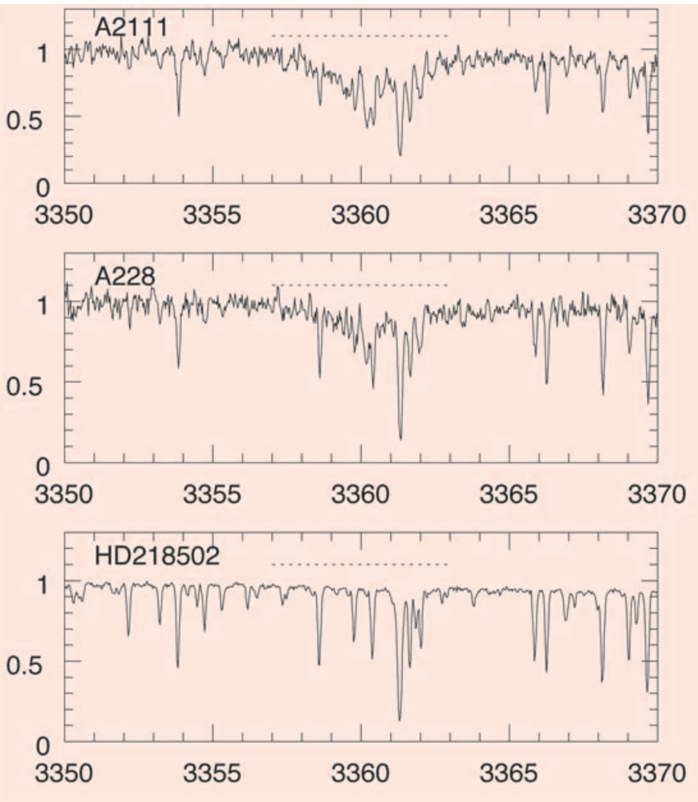

Figure 4: UVES spectra of the two NGC 6397 stars and of the comparison field star HD218502 in the region around the NH band at 336 nm. The band is very well pronounced in the two globular cluster stars, while it is virtually absent in the reference star, indicating the strong N overabundance in the NGC 6397 stars.

the evolutionary and of the Be age clearly show that the halo of the Galaxy must have formed shortly after the Big bang.

More exciting results about the Cluster

Many Globular Clusters show peculiar patterns in their chemical composition, which are not observed among field stars and are therefore clearly related to the peculiar Globular Cluster environment. Although this anomaly was first discovered more than 30 years ago, no clear answer yet exists for its origin. The superb UVES spectra, thanks to the combination of resolving power, signal to noise and spectral coverage, add some significant new results on this topic. In addition to the Beryllium lines, we also observed important bands of Nitrogen in the UV and the Oxygen triplet in the near infrared.

While the rest of the elements show an impressively constant value in NGC 6397 stars, our spectra show that the two observed stars have a difference of up to 0.6 dex in their O abundance, and a rather high N content ([N/Fe]~1.3) with respect to field stars of similar metallicity. We also confirm that the average oxygen level is low with respect to that of field stars of similar metallicity, as found by Gratton et al. 2003.

Figures 3 and 4 shows the spectra around the Oxygen triplet and the NH regions respectively. In figure 3 the difference in the Oxygen line strength among the two stars is evident, while in figure 4 the comparison between the two cluster stars and the similar field star HD218502 shows clearly how much stronger the NH band in the cluster stars is with respect to the field object.

This abundance pattern suggests that the stars of NGC 6397 were either formed from, or partially polluted by, material bearing the signature of the products of stellar nucleosynthesis, such as that occurring in massive asymptotic giant-branch (AGB) stars (Ventura et al. 2002). In this phase, stellar material is processed at very high temperatures (~10^8 K) where O is effectively burnt to N in the CNO cycle and then returned to the ISM by mass loss. This process could explain both the low O and the high N values observed, while most other elements would conserve their previous abundances. However, at the high temperatures characterizing AGB nucleosynthesis, Li and Be are completely destroyed. The normal Pop II stars level of Li observed in NGC 6397 (Bonifacio et al. 2002) could have been restored during this AGB phase because Li is predicted to be produced by AGB stars and could be brought to the surface from the interior through the so called Cameron-Fowler mechanism: convective cells bring up to the surface freshly synthesized Li before it is destroyed. Of course this hypothesis requires a remarkable fine-tuning between Li production and destruction. However the special nature of ^{9}Be means that this element cannot be synthesized in stars, but that it is only destroyed during the AGB phase, and our observations therefore seem to be at variance with this picture. Thus, our detection of Be rules out the possibility that a considerable fraction of the gas of the protocluster was processed by a previous generation of AGB stars, unless the gas was processed extremely early in these stars and immediately released back to the ISM, where it was exposed to the Galactic Cosmic Rays.

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