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The Age of the First Nucleosynthesis in the Galaxy

R .CAYREL[1], V. HILL[1], M. SPITE[1], F. SPITE[1], P. FRANÇOIS[1], E. DEPAGNE[1], B. NORDSTRÖM[2], J. ANDERSEN[2], B. PLEZ[3], B. BARBUY[4], T. BEERS[5], P. BONIFACIO[6], P. MOLARO[6], and F. PRIMAS[7]

(1) GEPI, Observ. de Paris-Meudon, France
(2) Astron. Observ., Copenhagen, Denmark
(3) GRAAL, Univ. de Montpellier II, France
(4) IAG, Univ de São Paolo, Brazil
(5) Michigan State Univ., USA
(6) Osserv. Astron.di Trieste, Italy
(7) ESO, Germany

Abstract

The observation of extremely metal-poor stars makes possible to obtain the epoch of formation of the first elements produced by massive supernovae, or hypernovae. The classical way of obtaining stellar ages (isochrone fitting) is unfortunately not applicable at present, as the distances of these stars are not known with enough accuracy. Dating by decay of radio-elements is another path, which has been renewed by the observation of uranium in the yellow giant CS 31082-001. We discuss the prospects opened by this discovery, and recent theoretical works triggered by this new opportunity.

1.1 Introduction

A Large program, named "Galaxy Formation, Early Nucleosynthesis, and the First Stars" was run at ESO, Paranal with the VLT-UVES telescope-spectrograph combination, in order to determine accurate abundances of a sample of stars of the Beers-Preston-Shectman Survey, (Beers, Preston & Shectman 1992) all with metallicities $-4.0 < [Fe/H] \leq -2.8$. The main objective (cf. Monique Spite talk) was to identify the imprint left by the explosions of the first supernovae in the photospheric compositions of low-mass stars formed in their environment, and still observable today in the galactic halo. As it is today a day of celebration, I wish to emphasize the monumental impact of the work accomplished by the three people who have carried out this survey. The careful examination of more than a million of prism-objective spectra has actually opened our main window on what happened in the early days of the Milky Way, as exemplified by McWilliam et al. 1995, in a cornerstone paper. I am inviting you to give a standing ovation to these three scientists, to whom so many of us, in this room, are heavily indebted. (Ovation...).

George Preston and myself have a common strategy in the study of the early Universe. Instead of making sure that we observe the early Universe in observing sources at high redshift, we try to find fossilized traces of this early Universe, as nearby as possible. This "as nearby as possible" means in practice a few kiloparsecs, very metal-poor halo stars found in the Beers-Preston-Shectman survey. The inconvenience is that we still have to demonstrate that these object are quite old. The advantage is that we gain about 32 magnitudes by observing at a few kpc, instead of 10 to 13 light-Gyr. Not a trifle!

A key point is to identify what can be fossilized. For example, we may consider as fossilized the chemical composition of the interstellar matter, once it has been isolated from the background in the envelope of a low-mass star. Although a few people consider that the surface composition may have been modified by accretion, we argue that the flow of matter at the surface of a star, when existing, has always been seen the other way, i.e. mass loss. Another argument is that most of our chemical analyses concern giant stars, for which the mass of the convective zone is an important fraction of the total mass of the star, so that any reasonable amount of accretion would be drastically diluted. Another advantage of analyzing giant stars is that the effect of microscopic diffusion which may alter the surface composition of a star having a thin convective zone, is erased when the star becomes giant. Actually in giants, the main danger does not come from outside, but from inside. Giant stars are submitted to dredge-up episodes, fairly well identified in the theory of stellar evolution. If we avoid the very evolved asymptotic giant branch objects, the first dredge up affects only specific elements, as the isotopes ^{12}C,^{13}C, and ^{14}N. So the majority of element ratios can be considered as representative of the galactic gas, when the star was born.

The gross features of the kinematical properties of old stars can also be considered as fossilized. The angular momentum of a halo star with respect to the galactic center for example, is fairly difficult to modify. The mere fact that *all* old stars have a kinematics with characteristic features (low angular momentum, high scatter in the 3 components of the velocity shows that these features have not been greatly altered by the accretion of gas during the life of the Galaxy. Actually the eccentricity of a stellar orbit is an adiabatic invariant.

We shall now turn our attention to the problem of getting the actual age of the stars *presumed* to be very old, just because they are very metal-poor.

1.2 Age from Isochrones

The subject will be quickly closed, as we shall see. Isochrones for star in the metallicity range we consider here (-4.0 < [Fe/H] < -2.8 are not flourishing in the literature, but the problem is not there (A. Chieffi computed a few very metal poor stellar tracks at our request). The problem is that, even assuming that the theoretical isochrones are perfect, and that the star is favorably located in the subgiant area, an error in the absolute magnitude of 0.1 mag results in an error of 1 Gyr in the derived age. This corresponds to an error of 5 per cent on the distance. At 3 kpc this, in turn corresponds to an error of 17 μas on the parallax. We have to wait the SIM or GAIA space missions for reaching this accuracy, without forgetting that the metallicity has to be known with an accuracy of 0.15 dex not to spoil the former values. We have to wait from 7 to 15 years before we get the results of these missions...

1.3 Age from Radioactive Decay

Until February 2002 , the only radioactive element used for cosmochronology has been thorium. Butcher 1987 for galactic disk stars, then François et al. 1993, for old halo stars. This last attempt led to rather unconclusive results. Later Sneden et al. 1996, were more successful with the very metal-poor star CS 22892-052, ([Fe/H]=-3.1), which was found to be extremely enhanced in *r*-process elements, fact greatly improving the visibility of Th and Eu lines. The time Δt elapsed since the formation of the *r*-process elements is derived from the equation:

$$\Delta t = 46.7(\log(\mathrm{Th}/\mathrm{Eu})_0 - \log(\mathrm{Th}/\mathrm{Eu})_{\mathrm{obs}}) \quad (1.1)$$

where $(\mathrm{Th/Eu})_0$ is the production ratio of Th and Eu, before the matter is trapped in the envelope of the star, and $(\mathrm{Th/Eu})_{obs}$ the observed value, now. The numerical coefficient 46.37 is the time in Gyr corresponding to a radioactive decay of Th (actually ^{232}Th) by a factor of 10. The difficulty is of course to evaluate the production ratio. We refer the reader back to the discussion in Cowan et al. 1999 for this tricky problem. The method is based on the assumption that the neutron exposure which has produced the ratio $(\mathrm{Th/Eu})_0$ must reproduce the ratios of all other stable *r*-process nuclides of the solar system. In short this assumes a kind of universal production ratios for the *r*-process elements. One was encouraged to do so, because the abundance ratios in the solar system and in CS 22892-052, and in another *r*-process element-enriched star were extremely similar. However, some warnings were given by theoreticians (Goriely & Clerbaux 1999) that the ratio of actinides to lower mass *r*-process elements could vary strongly, although maintaining the same ratios within the $56 < Z < 82$ atomic numbers. Actually it possible to produce the light nuclei in the solar proportions, without producing much thorium or uranium, which need much higher entropies.

1.3.1 The Case of CS 31082–001

The argument was shifted from the theoretical to the observational ground with the discovery of a new *r*-process element-enriched star, CS 31082-001, (again from the Beers-Preston-Shectman survey!) which showed another actinide, ^{238}U (Fig. **??**), also solar ratios of the *r*-process elements with $56 < Z < 82$, but with the two actinides U and Th strongly enhanced with respect to the lighter *r*-process elements (Cayrel et al. 2002, Hill et al. 2002). Other relations become available when U is measurable:

$$\Delta t = 14.8(\log(\mathrm{U}/\mathrm{Eu})_0 - \log(\mathrm{U}/\mathrm{Eu})_{\mathrm{obs}}) \quad (1.2)$$

$$\Delta t = 21.8(\log(\mathrm{U}/\mathrm{Th})_0 - \log(\mathrm{U}/\mathrm{Th})_{\mathrm{obs}}) \quad (1.3)$$

At first, it is tempting to use equation (**??**), which takes full advantage of the shorter decay time of ^{238}U (4.47 Gyr) than that of ^{232}Th (14.05 Gyr). But, as emphasized by J. Truran (2002), equation (**??**) is likely to be a better choice, because the prediction of the production ratio ^{238}U/^{232}Th is much more robust than that of other ratios, taking into account the great similarity in the mass-models of these two nearby nuclides. A beautiful confirmation of this statement, came with a paper by Wanajo et al. (2002), who studied the formation of the *r*-process elements in the neutrino wind of a core-collapse type II supernova. They studied the formation of the the *r*-process elements as a function of the initial electron fraction Y_e of the very dense and very hot plasma, for various pair of elements, and the corresponding effect on the derived age for CS 31082-001. We reproduce part of their results in table **??** and **??**. The stability of the production ratio of U/Th is striking.

It is interesting to note that for the value of $Y_e = 0.3975$ the three ratios (U/Th, U/Eu and Th/Eu) lead to the same age, 14.1 Gyr, proving that there is no inconsistency between the ratios.

1.4 Accuracy of the U/Th Cosmochronometer

It is not enough to have a robust chronometer, we need an accurate chronometer. Let us first note that without the work of our colleague physicists of Lund Observatory, the

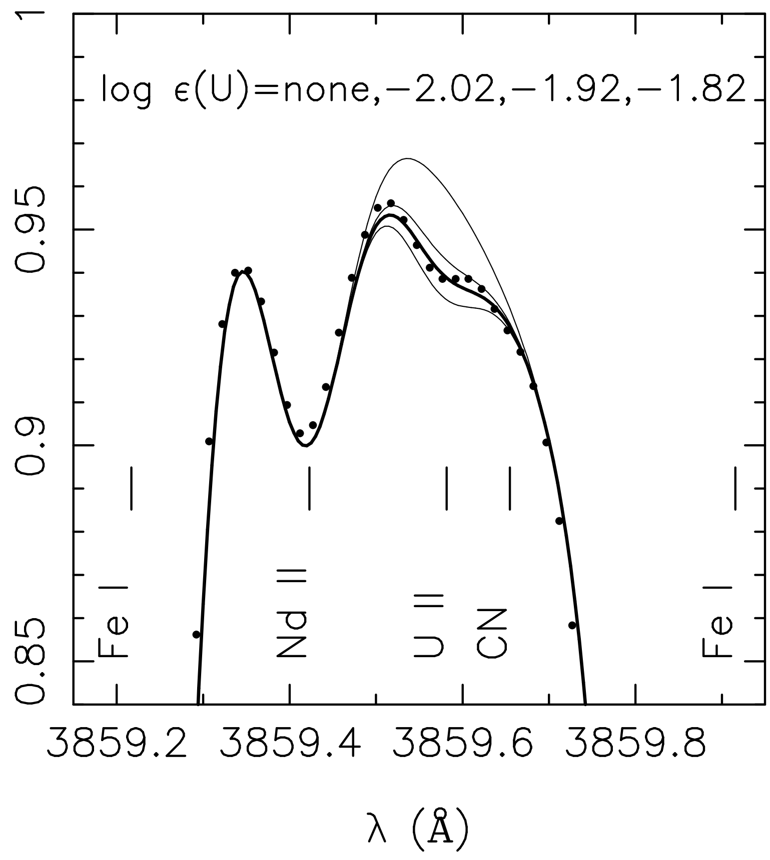

Fig. 1.1. The U II line at 3859.47 Å in the spectrum of CS 31082-001. The S/N ratio is 350

Table 1.1. *Production ratios for the pairs U/Th, U/Eu and Th/Eu as a function of* Y_e

Y_e	$\log(U/Th)_0$	$\log(U/Eu)_0$	$\log(Th/Eu)_0$
0.39	-0.29	-0.11	0.18
0.40	-0.29	-0.24	0.05
0.41	-0.29	-0.40	-0.11
0.42	-0.31	-0.89	-0.58
0.43	-0.32	-1.24	-092

age claimed for the actinides in CS 31082-001 would not be 14.1 but 9.7 Gyr! The observed abundance ratio involves the oscillator strengths of the lines of U II and Th II used in the analysis. Thanks to an accurate remeasurement of all these lines (the most crucial one being the only measurable line of U II at 3859.57 Å) by Lundberg 2001, and Nilsson et al. 2002a, 2002b, by lifetime and branching ratios measurements, our "observed" ratio of U/Th has

Table 1.2. *Ages derived from the three pairs for CS 31082-001*

Y_e	age(U/Th) Gyr	age(U/Eu) Gyr	age(Th/Eu) Gyr
0.39	14.1	15.5	18.7
0.40	14.1	13.6	12.6
0.41	14.1	11.2	5.1
0.42	13.7	4.0	-16.8
0.43	13.5	-1.2	-32.7

line

moved from -0.74 dex to -0.94 dex, a shift of 4.4 Gyr on the age.The new oscillator strengths are likely exact to 12 per cent, but there are other sources of error, of course. The line of U II (cf. Figure **??**) is very weak, blended, and in an uncomfortable region of the spectrum, where the continuous opacity is in great part due to Rayleigh scattering. A. Schuster had already shown in 1905 that it is necessary to know the exact proportion of scattering in the continuum and in the line to compute correctly such a line. So it is necessary to go to NLTE for this line, and for the Th II lines as well. We estimate that an error of 0.05 dex (12 %) is very difficult to beat there, even with a very high S/N ratio. Finally the age depends on the accuracy of the production ratio $(U/Th)_0$. It is difficult to estimate this uncertainty, but we believe that progresses are under way, and that the help of the new Institute for Nuclear Astrophysics, and experimental results from the the expected upgrade of the Darmstadt accelerator, may bring new precious constraints on the nuclides ^{232}Th and ^{238}U. Right now we are stuck with an uncertainty of the order of 2.5 Gyr. If the errors on $(U/Th)_0$ and $(U/Th)_{obs}$ can be both contained to be less or equal to 0.05 dex, the error bar on the age of the nucleosynthesis of U and Th can be brought down to 1.5 Gyr.If lead (Pb) can be observed further improvements are possible.

1.5 Stellar Ages versus Cosmology and Concluding Remarks

Figure **??** shows how the ages of CS 3182-001, and of the globular clusters (Chaboyer 2002) compared with the time of first stellar formation, very recently obtained from an analysis of one year of observations of the Cosmic Microwave Background by the satellite WMAP (Spergel et al. 2003). It is very encouraging that three ages, obtained by completely different methods, overlap, as they do in Figure **??**. But the error bars on the ages of the globular clusters, and on the age of the uranium star are desperately large, compared with the accuracy on the age of the first stellar formation (reionization of the Universe) from WMAP. The steps for greatly improving the accuracy on the age of the globular clusters are already taken, with a specific program proposed by Chaboyer for the SIM satellite. For the uranium/thorium ages an important program for finding more of them is also under way, the LP 170.D-0010 "Nucleo-chronometric age dating of the oldest stars", with Norbert Christlieb as PI. This program which is a quick search for stars with enhanced *r*-process elements ,will definitively qualify the U/Th chronometer, if all XMP stars for which U and Th are measurable gives very similar ages. The gain in statistical accuracy will be roughly $\sqrt{(n)}$ if n stars are found, but this will not take care other sources of errors. For example, if we use an oscillator strength good at 12 per cent, but we are at one end of the interval,

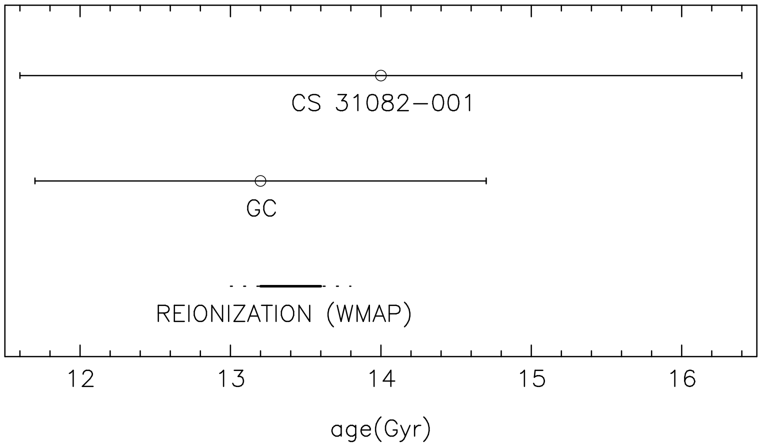

Fig. 1.2. Comparison of the age of reionization from WMAP, with the age of globular clusters (Chaboyer 2002), and the age of CS 31082-001. For reionization from WMAP, the full line represents the duration of the reionization, and the dotted line the uncertainty of 0.2 Gyr on the age of the Universe

we shall have a systematic error of 1.1 Gyr on our ages. The same remark is valid for the value of $(U/Th)_0$, or on the continuous opacity, or on the source functions used in the line in the continuum, or in the other lines blending the uranium line. So a parallel effort has to be made to reduce these other kind of errors, in order to average, in Christlieb's LP, good values, and not wrong values.

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