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Nucleosynthesis Clocks and the Age of the Galaxy

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Abstract.
Nucleocosmochronology involves the use of the abundances of radioactive nuclear species and their radiogenic decay daughters to establish the finite age of the elements and the time scale for their formation. While there exist radioactive products of several specific nucleosynthesis mechanisms that can reveal the histories of these mechanisms, it is the long lived actinide isotopes ^{232}Th, ^{235}U, and ^{238}U, formed in the r-process, that currently play the major role in setting the time scale of Galactic nucleosynthesis. Age determinations in the context of Galactic chemical evolution studies are constrained by intrinsic model uncertainties. Recent studies have rather taken the alternative approach of dating individual stars. Thorium/europium dating of field halo stars and globular cluster stars yields ages on the order of 15±4 Gyr. A solid lower limit on stellar ages is available as well, for stars for which one both knows the thorium abundance and has an upper limit on the uranium abundance. For the cases of the two extremely metal deficient field halo stars CS 22892-052 and HD 115444, lower limits on the nuclear age of Galactic matter lie in the range 10-11 Gyr. Th/U dating of the star CS 31082-00 gives an age of 12.5±3 Gyr. Observations of thorium and uranium abundances in globular cluster stars should make possible nuclear determinations of the ages of clusters that can be compared with ages from conventional stellar evolution considerations.

1. Introduction

Nuclear chronometers have played an historically important role in the determination of the ages of our solar system and our Milky Way Galaxy, thus providing important lower limits on the age of the Universe itself. The critical long lived nuclear radioactivities were long ago identified to be ^{187}Re ($\tau_{1/2}$=4.5x10^{10} years), ^{232}Th ($\tau_{1/2}$=1.4x10^{9}), ^{235}U ($\tau_{1/2}$=7.0x10^{8}), and ^{238}U ($\tau_{1/2}$=4.5x10^{9}), all of which are products of the *r*-process of neutron capture synthesis Burbidge *et al.* 1957; Cameron 1957).

While interesting age constraints can be obtained on the basis of "model independent" chronometric considerations (see, e.g. Meyer & Schramm 1986), most determinations of the age of the Galaxy to date have been obtained in the context of models of Galactic chemical evolution (see, e.g. the review by Cowan, Thielemann, & Truran 1991a). Such models can be used to explore the sensitivities of the ages thus obtained to the star formation and nucleosynthesis history of Galactic matter. The Re/Os chronometer is of particular concern in this regard, both because the ^{187}Re decay rate is temperature sensitive (a factor when ^{187}Re is recycled through stars) and because both r-process and s-process contributions may be important.

In this paper we will concentrate on recent age determinations for individual stars, built upon the use of thorium and uranium related chronometers. Since the available data is associated with extremely metal-poor stars, formed during the very earliest stages of Galactic evolution, dating of such stars is entirely equivalent to dating of the Galaxy as a whole.

2. r-Process Nucleosynthesis Considerations

While the general nature of the r-process of neutron capture synthesis and its contributions to the abundances of heavy elements in the mass range from beyond the iron peak through thorium and uranium is generally understood (Cowan, Thielemann, & Truran 1991b), many of the details remain to be worked out. Of particular concern is the very fact that the astrophysical site in which the r-process occurs remains unidentified. Both meteoritic data (Wasserburg, Busso, & Gallino 1996) and stellar abundance data (e.g. the robust consistency of the heavy (A $\gtrsim$ 140) r-process abundance patterns in the most extreme metal deficient stars with that of solar system matter) suggest the likelihood of two distinct r-process environments responsible, respectively, for the mass regions A $\lesssim$ 140 and A $\gtrsim$ 140. The heavy element patterns in low metallicity stars strongly imply that at least the production of r-process nuclei in the heavy element region is associated with stars of short lifetimes (e.g. massive stars and/or supernova Type II).

Excellent reviews of r-process nucleosynthesis through the years have been provided by Hillebrandt (1978), Cowan, Thielemann & Truran (1991b), and Meyer (1994). Promising studied sites for the synthesis of the r-process isotopes in the mass range A $\gtrsim$ 140 include: (1) the high-entropy, neutrino heated, hot bubble associated with Type II supernovae (Woosley *et al.* 1994; Takahashi, Witti, & Janka 1994); (2) the ejection and decompression of matter from neutron star-neutron star mergers (Lattimer *et al.* 1977; Freiburghaus *et al.* 1999); and

(3) the ejection of neutronized matter in magnetic jets from collapsing stellar cores (LeBlanc & Wilson 1970). Note that all three of these mechanisms are tied to environments provided by the evolution of massive stars (and associated Type II supernovae) of short lifetimes ($\tau \lesssim 10^8$ years), compatible with their presence in the oldest stellar populations of our Galaxy.

3. Dating Individual Stars

The direct determination of the ages of individual stars has recently become possible, with the availability of thorium (and most recently uranium) abundances for halo stars. A distinct advantage of this approach is the elimination of uncertainties associated with our imperfect knowledge of the star formation, stellar evolution, and associated nucleosynthesis histories of galaxies, which are a necessary ingredient of chemical-evolution-based models of nucleocosmochronology. There remain. of course, the uncertainties associated with the nuclear properties of heavy actinide nuclei, which dictate the relative levels of production of ^{232}Th, ^{235}U, and ^{238}U in nucleosynthesis sites, and with the character of the astrophysical r-process itself. For example, a critical question associated with the use of the Th/Eu ratio as a chronometer is the robustness of the reproduction of the solar system r-process pattern over the mass range $130 \lesssim A \lesssim 238$. We should also note that the use of such age determinations for individual stars (particularly the Th/U chronometer) may be *effectively* constrained to low metallicity ([Fe/H] $\lesssim$ -2.5), r-process enriched ([r-process/Fe] $\gtrsim$ 1) stars like CS 22892-052, CS 31082-001, and HD 115444.

3.1. Th/Eu Dating

The detection of thorium and the determination of its abundance in the extremely metal deficient halo field star CS 22892-052 first made thorium dating possible (Sneden *et al.* 1996). In this case, due to the absence of knowledge of the uranium abundance, it is necessary to utilize some stable r-process product. The choice of europium here is a relatively obvious one, since both isotopes of Eu are produced almost exclusively by the r-process.

Data regarding Th and Eu is now available for a number of stars in the halo and in globular clusters. This data is collected in our Table 1. The ages were determined with the assumption that the "theoretical" r-process production ratio was $(\mathrm{Th/Eu})_{theory} = 0.51$. Note that the mean Thorium/Europium age for these stars is 13.6 Gyr, with a spread consistent with the intrinsic observational uncertainty of approximately $\pm$ 4 Gyr.

A critical question concerning the use of the Th/Eu chronometer is the robustness of the r-process abundance pattern over a range of mass number $A \approx 140$-238. The abundance patterns in this mass number range for the two extremely metal deficient stars CS 22892-052 and HD 115444, displayed in Figure 1, both show a remarkable agreement with the solar system r-process abundance distribution. The quoted abundance level for the star CS 31082-001 (Hill *et al.* 2001), however, is distinctly different from those for the other stars in Table 1 (where we do not quote a Th/Eu age for this star). It is important to examine this behavior for other halo and globular cluster stars to more firmly establish the limits of confidence of the Th/Eu chronometer. We emphasize that we believe

TABLE 1

Thorium/Europium Ages for Individual Stars

Object	[Fe/H]	logϵ_{Th}	logϵ_{Eu}	Δ	(Th/Eu)	τ_*
CS22892-052	-3.1	-1.57	-0.91	-0.66	0.22	16.8
HD 115444	-3.0	-2.23	-1.63	-0.60	0.25	14.4
HD 115444	-3.0	-2.21	-1.66	-0.55	0.28	12.1
HD 186478	-2.6	-2.25	-1.55	-0.70	0.20	18.9
HD 108577	-2.4	-1.99	-1.48	-0.51	0.31	10.1
M92 VII-18	-2.3	-1.94	-1.45	-0.49	0.32	9.4
BD +8 2856	-2.1	-1.66	-1.66	-1.16	0.32	9.4
K341 (M15)	-2.4	-1.47	-0.88	-0.59	0.25	14.4
K462 (M15)	-2.4	-1.26	-0.61	-0.65	0.22	16.8
CS31082-001	-3.0	-0.96	-0.70	-0.26	0.55	-

References: (1) Sneden *et al.* 2000a; (2) Westin *et al.* 2000; (3) Johnson & Bolte 2001; (4) Sneden *et al.* 2000b; Hill *et al.* 2001.

that the Th/Eu chronometer (or perhaps a Th/Pt chronometer) will generally be a more commonly available tool for the dating of halo stars than Th/U - and thus that we should work hard to confirm its reliability.

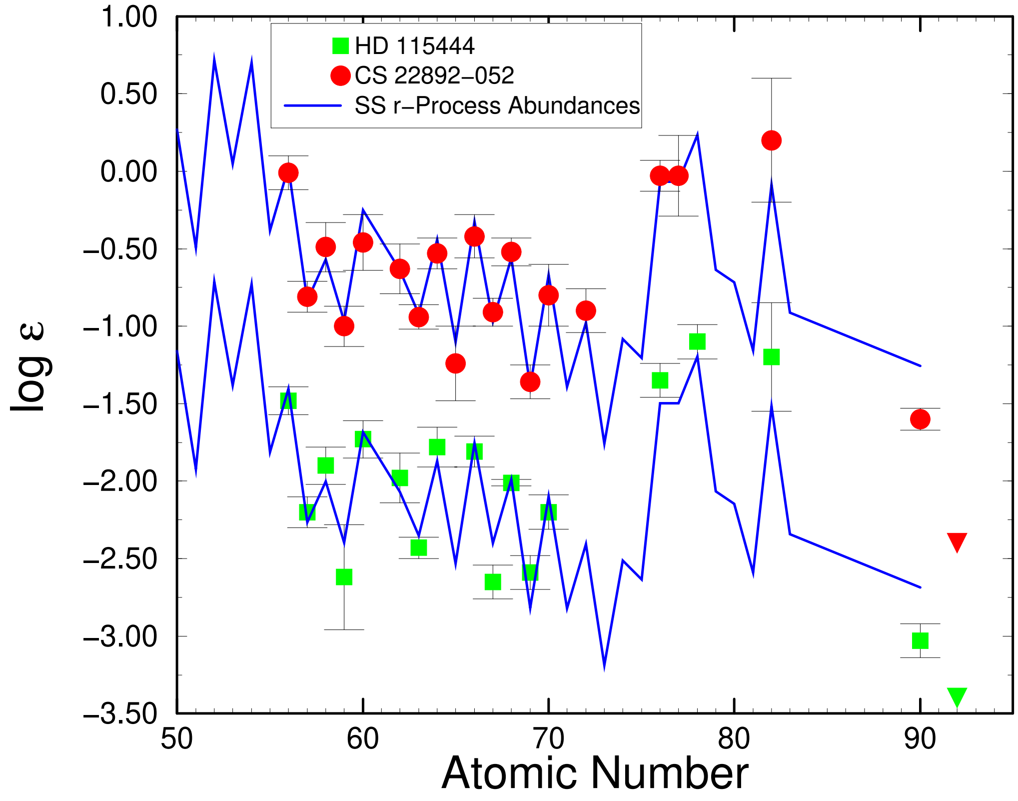

Figure 1. Abundance comparisons between HD 115444 (filled squares) and CS 22892–052 (filled circles). The abundance values for HD 115444 have been vertically displaced (arbitrarily by -0.8) for display purposes. The upside-down triangles are upper limits on the uranium abundances. The solid lines are scaled solar system r-process only abundance distributions.

3.2. Th/U Dating

When available, it is understood that the Th/U chronometer will give age determinations for which the nuclear uncertainties and astrophysical uncertainties may be smaller than those for the Th/Eu chronometer. Theoretical calculations of r-process nucleosynthesis can be employed to provide estimates of for example the ^{232}Th/^{238}U and ^{235}U/^{238}U ratios. Early model predictions for these so-called production ratios typically show rather wide dispersion (Cowan, Thielemann, & Truran 1987). However, more recent theoretical determinations (e.g. Möller, Nix, & Kratz 1997; see also Cowan *et al.* 1999) are now available.

Recently Cayrel et al. (2001; see also their contribution to this conference volume) have discovered that the ultra metal poor star CS 31082-001 ([Fe/H] $\sim$ –

3) has even larger n-capture abundance levels than does CS 22892-052. Most interesting is their detection of *many* transitions of Th II and the strongest U II line; the combined abundances of two radioactive elements (with different half-lives) yields an "age" of the neutron-capture elements in this star of $\sim$13 Gyr. But they also report an *observed* [Th/Eu] ratio that is much larger than in CS 22892-052. This abundance ratio in CS 31082-001 would imply an age of only a few Gyrs, obviously inconsistent with this star's metallicity and halo membership (see, e.g. the data cited in our Table 1). It is clear that many more Eu and Th abundances need to be determined for halo stars, in order to make some sense of this issue.

We also wish to note, however, the *even upper limits on the uranium abundance* allow firm and interesting lower limits on the age of the Galaxy. Figure 2 displays the exponential dependence of the age of a star as a function of the observed Th/U ratio. Here we assume that ^{238}U dominates ^{235}U, and therefore show only ages greater than 5 Gyrs. The green region indicates the range of allowed r-process Th/Eu production ratios (Cowan, Thielemann, & Truran 1987). Lines of constant log(U/Th) are displayed. An upper limit on U/Th excludes the lower left half of the plane. We note that the upper limits on the uranium abundances for the two stars CS 22892-052 and HD 115444 allow lower limits on the ages of these stars, respectively, of 10 and 11 Gyr.

4. Conclusions

We draw the following conclusions from our overview of considerations of nuclear chronometer dating:

- (1) The important nuclear chronometers ^{232}Th, ^{235}U, and ^{238}U are r-process products.

- (2) The observations of r-process abundance patterns in the oldest ([Fe/H] $\lesssim$ -2.5) halo stars serve to confirm the identification of the r-process site with massive star environments and to convince us that we are dating the history of stellar activity in our Galaxy.

- (3) The robustness of the r-process mechanism for the production of nuclei in the region A $\gtrsim$ 140 is reflected in the extraordinary agreement (see Figure 1) of the stellar abundance patterns with the solar system r-process abundances (even at metallicities so low that at best only a few supernovae can have contributed). *The remarkable star CS 22892-052, at [Fe/H] = -3.1, exhibits a pure r-process pattern in the mass range A $\gtrsim$ 140, but at an abundance level [r-process/Fe] $\approx$ +1.5.*

- (4) Ages (and/or age constraints) for individual halo field stars or globular cluster stars can be obtained (in principle) from Th/Eu and Th/U, when the abundances of these nuclear species are known.

- $\rightarrow$ Th/Eu dating of the two well studied stars CS 22892-052 and HD 115444 give an average age chronometric age $\tau_* \sim 15.6 \pm 4.6$ Gyr.

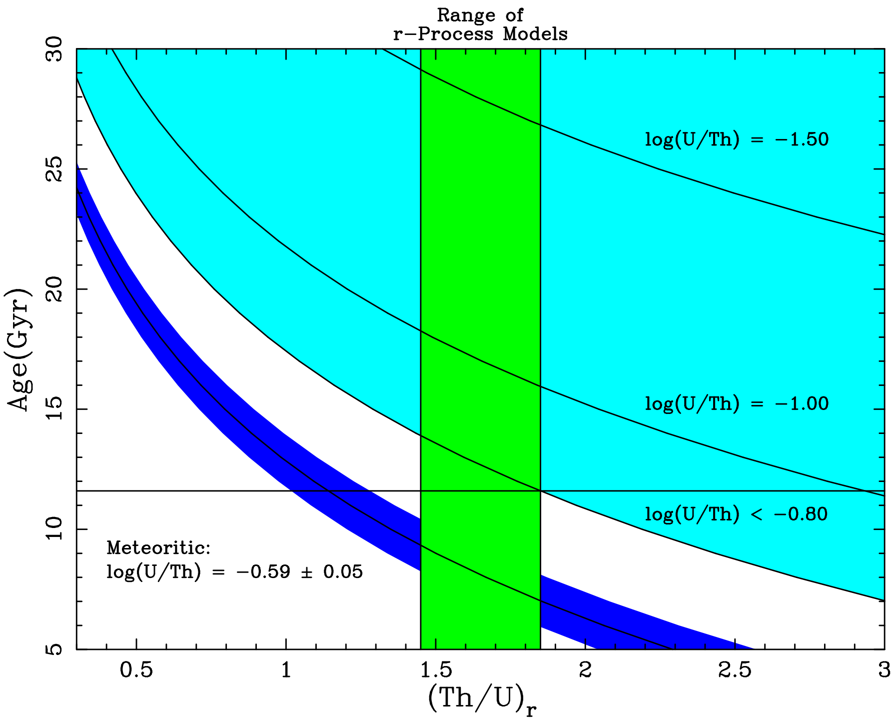

Figure 2. Stellar ages as a function of the Th/U ratio. Shown is the exponential dependence of the observed Th/U abundance on the age of the system. We assume that 238 dominates 235, and therefore only show ages greater than 5 Gyrs. Lines of constant log U/Th ratios are shown in the plane of Age vs. 232/238 seed ratio. An upper limit on U/Th excludes the lower left half of the plane. A measurement of U/Th is restricted to a narrow band as is the case with meteoritic observations (Anders & Grevesse 1989).

- $\rightarrow$ Upper limits on the Uranium abundances for these two stars provide lower limits on their ages $\tau_* \gtrsim$ 10-11 Gyr.
- (5) While both thorium and uranium abundance determinations for individual halo stars will continue to accumulate, it seems likely that uranium abundances will become available for only a small fraction of those for which thorium abundances are known. Continued efforts to place the Th/Eu (or perhaps Th/Pt) chronometer on a firm basis are thus critical to our ability to date the various components of our Galactic halo population.

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