URANIUM-THORIUM COSMOCHRONOLOGY.

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Introduction: Observations of the cosmic microwave background, local and distant type Ia supernovae, and galaxy clusters constrain very precisely the values of the four parameters governing the age of the Universe. The most recent estimates give $(\Omega_k,\Omega_\Lambda,\Omega_m)\approx(0,0.73,0.27)$ [1,2] and $H_0\approx72$ km.s^{-1}.Mpc^{-1} [3], corresponding to an age of 13.7±1.7 Gy [2,4]. The age of the solar system ($T_\odot$) is well constrained from meteorite measurements at 4.567.2±0.6 Gy [5]. The age of the Milky Way must lie between these two ages but is very poorly constrained. Four approaches can be used to estimate this value.

(*i*) White dwarfs are remnants of stars lower than 8 $M_\odot$ in mass. They radiate energy into space and therefore become less luminous with time. Comparison with theory gives ages for the oldest white dwarfs in the Galaxy of approximately 8-14 Gy [6].

(*ii*) Globular clusters are clusters of stars of different masses formed simultaneously. As the cluster ages, stars of lower masses exhaust their hydrogen fuel and leave the main sequence in the Hertzsprung-Russell diagram, providing a useful chronometer. Globular clusters impose a minimum age for the Galaxy of 10.4 Gy [7].

(*iii*) The U/Th (^{238}U/^{232}Th) ratio was recently measured in the spectra of a low metallicity halo star (LMHS), CS 31082-001 [8,9]. These two nuclides are produced by the *r*-process, presumably in supernovae, and their abundances in CS 31082-001 were not modified by nucleosynthesis after formation of the star. The difference between the ratio measured at present in the spectra of this star ($R^{8/2}$) and the production ratio ($P^{8/2}$) only reflects free decay,

$$R^{8/2}_{CS\,31082-001} = P^{8/2} \times \exp\left(\frac{T}{\tau_2} - \frac{T}{\tau_8}\right)$$

If the U/Th production ratio is known and the U/Th ratio in the LMHS is measured, then it is possible to calculate the age T.

(*iv*) The U/Th ratio in the interstellar medium at solar system birth measured in meteorites [10] depends on the history of nucleosynthesis and decay during galactic chemical evolution (GCE). The simplest model of all assumes that the Galaxy contained its full inventory of matter at its formation, that the rate of star formation is proportional to the gas density, and that newly synthesized matter is instantaneously recycled back into the ISM [11,12]. Under the assumptions of the simple closed-box model, the ratio of ^{238}U/^{232}Th in the ISM at solar system birth is given by,

$$R^{8/2}_{SS} = P^{8/2} \times \frac{\tau_8}{\tau_2}\left(\frac{1-e^{-T_{SS}/\tau_8}}{1-e^{-T_{SS}/\tau_2}}\right)$$

Here T_{SS} represents the age of the Galaxy at solar system formation ($T_{SS}=T-T_\odot$). Again, if the production ratio is known, then it is possible to derive the age of the Galaxy, and vice-versa.

The last two radiometric methods depend on the estimation of the ^{238}U/^{232}Th production ratio. This value is poorly constrained, as there are no neighbor stable nuclides to anchor *r*-process model predictions and *r*-process calculations use nuclear physics models to infer the properties of nuclides far from the valley of β-stability. Recently, two groups independently estimated the U/Th production ratio and its uncertainty. Schatz *et al.* [13] estimated a ratio of 0.603±0.139 while Goriely and Arnould [14] proposed a more conservative range from 0.298 to 0.980. Given the fact that actinide nucleosynthesis can only be anchored to nuclides that are 30 mass units below, it is difficult to assess the precision and accuracy of the predicted U/Th ratio, which is crucial to the determination of galactic ages. A usual procedure is to use galactic chemical evolution (*iv*) to constrain the production ratio and inject it in (*iii*) to retrieve an age for the LMHS [9,14]. There is however a circularity in this approach as an age is assumed in (*iv*) to constrain the production ratio in (*iii*) which is then used to retrieve an age using another method. Here, I show that constraints based on meteorites and LMHS can be combined to calculate independently the production ratio P and the age of the Milky Way T.

Open nonlinear GCE and the intersection approach: The two approaches based on meteoritic abundances and observations of LMHS give relationships between the production ratio and the age. In both cases, a longer presolar galactic history requires a higher production ratio to balance the more extensive decay of the actinides. What is crucial is that the relationships are not identical and the intersection between the two curves can therefore be used to calculate P and T. The reason why the two relationships are not identical is due to the fact that for LMHS, which formed early, the inventory of actinides is acquired at the formation of the Galaxy and they then only decay, while in the case of GCE, actinides decay but are constantly replenished by newly synthesized matter. If a closed-box model is used as described in (*iv*), then the intersection between the two curves is at T=17.9 Gy and P=0.76. These values do not compare favorably with independent estimates. However, it has been long known that the simple closed-box model presented in (*iv*) fails to reproduce several astronomical observations, notably the G-dwarf metallicity distribution [15-17]. High velocity clouds containing low metallicity gas are seen being accreted by the Galaxy. If infall of such low metallicity material is taken into account, then it is possible to devise GCE models that reproduce the most recent determinations of the G-dwarf metallicity distribution. Dauphas *et al.* [18] developed an algorithm that allows, for a given age of the Galaxy, to calculate the parameters of a non-linear open GCE model that reproduces the present total surface density, the present gas/star ratio, the solar metallicity at solar system birth, and the G-dwarf metallicity distribution. When these parameters and their uncertainties are known, it is straightforward to compute the U/Th production ratio required to explain the observed meteoritic abundances. This procedure can be repeated for any given age between 10 and 20 Gy. The result of this numerical calculation is presented in Fig. 1. It is easy to derive the uncertainty ellipsoid of the intersection of the two curves and then calculate the marginal probability densities for both P and T.

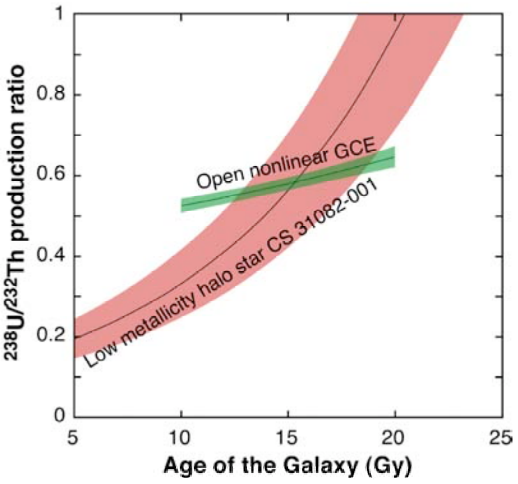

Fig.1. Intersection between the curves corresponding to the "U/Th production ratio-age of the Galaxy" relationships based on the low metallicity halo star CS 31082-001 (red) [8,9] and an open nonlinear GCE model (green) [18]. Uncertainties are 1σ.

The inferred U/Th production ratio is $0.571^{+0.037}_{-0.031}$ and the age of the Milky Way is $14.5^{+2.8}_{-2.2}$ Gy (68 % confidence intervals). These two estimates are in complete agreement with results obtained using independent approaches (see introduction). The U/Th production ratio can be used to constrain nuclear physics models and refine predicted productions of other actinides that also play important roles in cosmochronology (^{235}U, ^{244}Pu, and ^{247}Cm). The age of the Universe expressed in units of the Hubble time ($1/H_0$) depends directly on the three cosmological parameters Ω_k, Ω_m, and Ω_Λ, through Friedmann's equation. Bahcall *et al.* [1] noted that $\Omega_k+\Omega_m+\Omega_\Lambda=1$ and that the evolution of the Universe could therefore be represented in a triangular diagram. The age of the Universe can also be represented in such a diagram and the lower bound imposed by the radiometric age of the Galaxy can eventually be used to constrain the cosmological parameters (Fig. 2).

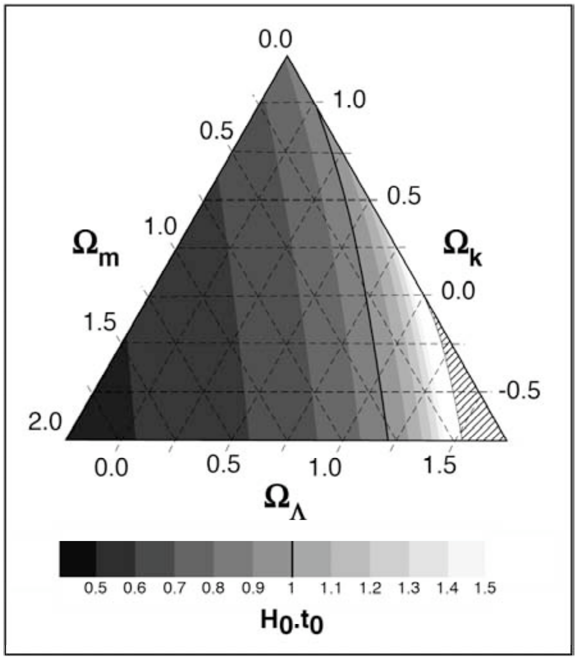

Fig.2. Cosmic ages mapped in the cosmic triangle. Ages are expressed in units of the Hubble time ($1/H_0$=13.8 Gy). The hatched region corresponds to models with no Big-Bang. The heavy line corresponds to universes with ages equal to the Hubble time.

References: [1] Bahcall N.A. *et al.* (1999) *Science 284*, 1481. [2] Spergel D.N. *et al.* (2003) *ApJSS 148*, 175. [3] Freedman W.L. *et al.* (2001) *ApJ 553*, 47. [4] Lineweaver C.H. (1999) *Science 284*, 1503. [5] Amelin Y. *et al.* (2002) *Science 297*, 1678. [6] Hansen B. (2004) *Phys. Rep. 399*, 1. [7] Krauss L.M. & Chaboyer B. (2003) *Science 299*, 65. [8] Cayrel R. *et al.* (2001) *Nature 409*, 691. [9] Hill V. *et al.* (2002) *A&A 387*, 560-579. [10] Chen J.H. *et al.* (1993) *LPSC XXIV*, 277. [11] Clayton D.D. (1988) *MNRAS 234*, 1. [12] Pagel B.E.J. (1997) Nucleosynthesis & Chemical Evolution of Galaxies, Cambridge University Press. [13] Schatz H. et al. (2002) *ApJ 579*, 626. [14] Goriely S. & Arnould M. (2001) *A&A 379*, 1113. [15] van den Bergh S. (1962) *AJ 67*, 486. [16] Schmidt M. (1963) *ApJ 137*, 758. [17] Nordström B. (2004) *A&A 418*, 989. [18] Dauphas N. (2003) *Nucl. Phys. A719*, 287c.