Measurement of stellar age from uranium decay

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The ages of the oldest stars in the Galaxy indicate when star formation began, and provide a minimum age for the Universe. Radioactive dating of meteoritic material[1] and stars[2] relies on comparing the present abundance ratios of radioactive and stable nuclear species to the theoretically predicted ratios of their production. The radioisotope ^{232}Th (half-life 14 Gyr) has been used to date Galactic stars[2–4], but it decays by only a factor of two over the lifetime of the Universe. ^{238}U (half-life 4.5 Gyr) is in principle a more precise age indicator, but even its strongest spectral line, from singly ionized uranium at a wavelength of 385.957 nm, has previously not been detected in stars[4–7]. Here we report a measurement of this line in the very metal-poor star CS31082–001[8], a star which is strongly overabundant in its heavy elements. The derived uranium abundance, $\log(\mathrm{U/H}) = -13.7 \pm 0.14 \pm 0.12$ yields an age of 12.5 ± 3 Gyr, though this is still model dependent. The observation of this cosmochronometer gives the most direct age determination of the Galaxy. Also, with improved theoretical and laboratory data, it will provide a highly precise lower limit to the age of the Universe.

We are currently undertaking a large programme of high-resolution spectroscopy—at the ESO Very Large Telescope and UVES[9] spectrograph—of extremely metal-poor stars selected primarily from the Ca II HK survey of ref. 8. The star CS31082–001(V-band magnitude $V = 11.7$) has been identified as very metal-poor (T.C.B. *et al.*, manuscript in preparation). One of us (the observer, V.H.) has noted that this star is similar to another well studied very metal-poor star, CS22892–052[6,10,11], in that it exhibits a large enhancement (relative to iron) of elements formed by the neutron-capture r-process. High-resolution spectroscopic observations of CS22892–052 had allowed a precise measurement of ^{232}Th from the 401.9-nm line, but based on the abundance of this slowly decaying species, the age of this star remained fairly uncertain: 15.6 ± 4.6 Gyr (ref. 4).

Moreover, the newly discovered star CS31082–001 exhibits considerably less contamination of the atomic line spectrum by molecular bands of CH and CN than does CS22892–052. The Th II line at 401.9 nm is also unusually strong and clear of contaminants; in fact, a total of 14 Th II lines are detected, 11 of which were selected for measurement. Only the 401.9-nm line has previously been accurately measured in a stellar spectrum, and 10 additional lines in CS31082–001 appear to be first detections. More importantly, the strongest U II line is clearly detected (Fig. 1). We note that no lines are seen at this wavelength in the stars HD115444[4] or HD122563, which have atmospheric parameters and iron abundance similar to those of CS31082–001, removing any doubt that the line we see is indeed due to U II. To illustrate the quality of our data, a one-hour integration at a resolving power of $R = 70{,}000$ yields typical signal-to-noise (S/N) ratios of 150 at 385 nm, and 250–300 at 650 nm. The region of the U II line is currently covered by eight such individual spectra. Other lines of U II are below 1 mÅ in equivalent width in our spectra, and blended with stronger lines.

Using available visual and infrared photometry and the detailed spectroscopic constraints from our own observations, the best model atmosphere for CS31082–001 has the parameters effective temperature $T_{\mathrm{eff}} = 4{,}825$ K, gravity $[g(\mathrm{cm\,s^{-2}})]$ log $= 1.5 \pm 0.2$, and microturbulence $\xi_{\mathrm{micro}} = 1.8 \pm 0.2\,\mathrm{km\,s^{-1}}$. Thermal non-equilibrium effects should be unimportant for Th II and U II, as these elements are virtually fully ionized and the observed transitions come from the ground level or from a very low excitation level. We then derive the following abundances (on the scale where $\log\epsilon(\mathrm{H}) = 12$): $\log\epsilon(\mathrm{Fe}) = 4.60 \pm 0.06$, $\log\epsilon(\mathrm{Os}) = 0.49 \pm 0.10$; $\log\epsilon(\mathrm{Ir}) = 0.40 \pm 0.12$, $\log\epsilon(\mathrm{Th}) = -0.96 \pm 0.03$, and $\log\epsilon(\mathrm{U}) = -1.70 \pm 0.10$. The quoted errors are the standard deviation on the mean abundance from at least three lines when available, otherwise they are estimates from the S/N ratio of the spectrum. They do not include systematic errors on oscillator strengths, which are extremely difficult to assess. For U we recomputed the partition functions of U I, U II and U III from the tables of energy levels in ref. 12, and adopted the oscillator strength from the laser-induced fluorescence measurements of ref. 13.

The iron abundance of CS31082–001 is about 1/800 of that of the Sun, while the heaviest detected stable elements, Os and Ir, are about 1/9 as abundant as in the Sun. CS31082–001 is exceedingly rich in spectral lines from most or all of the heavy elements, and a detailed discussion of the individual elements and the process(es) by which they were formed will be reported elsewhere (R.C. *et al.*, manuscript in preparation).

All the heavy elements in a star as metal-poor as CS31082–001 were likely to have formed during a very short interval early in the history of the Galaxy itself[14,15]. The abundance ratio, r, between a radioactive and a stable comparison species observed Δt Gyr after production is then $\rho = \rho_0[\exp(-\ln 2 \times \Delta t/t_{1/2})]$, where ρ_0 is the initial production ratio and $t_{1/2}$ is the half-life of the radioactive isotope.

In order to determine an absolute radioactive decay age, the initial production ratio is needed. Such ratios are predicted by theoretical nucleosynthesis models, validated by requiring that the

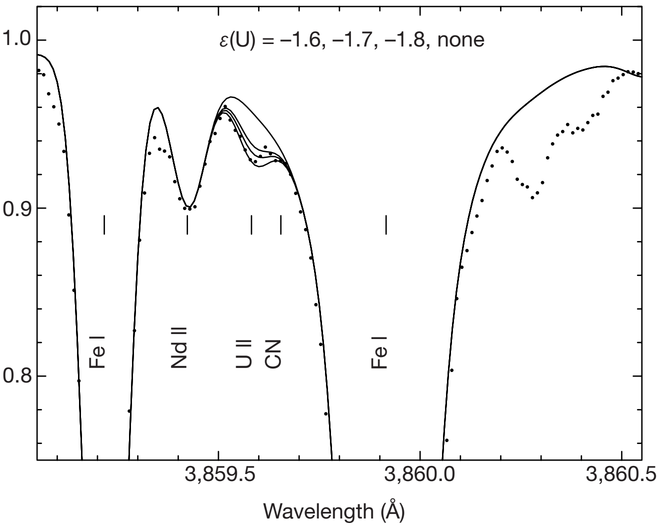

Figure 1 The spectrum of CS31082–001 around the U II line at 385.959 nm. The synthetic spectra (solid lines) were computed with the stellar atmospheric parameters given in the text, and for the three U abundances indicated, adopting an oscillator strength $f = 0.053$ for the line (ref. 13). The observed spectrum (data points) was obtained in four hours, for a total S/N ratio of 300.

predicted abundance ratios for all stable r-process elements in a neighbouring range of mass numbers should be identical to those observed in the star and in the Solar System[4,16]. The accuracy of a predicted ratio depends both on the adopted nuclear physics model and on the degree to which different production sites yield similar results. The latter has generally been found to be the case for previously studied r-process enhanced stars, but further work is needed to verify it in detail for CS31082–001.

Both theoretical and observational uncertainties should be minimal for elements as close as possible to each other in atomic number. Thus, Os and Ir should be the best stable reference elements in CS31082–001 for the radioactive species ^{232}Th and ^{238}U (any ^{235}U has decayed to insignificance long ago). From the half-lives of ^{232}Th and ^{238}U (14.05 and 4.468 Gyr, respectively), Δt as a function of the logarithmic decay of Th and U is:

$$\Delta t = 46.7[\log(\mathrm{Th}/r)_0 - \log(\mathrm{Th}/r)_{\mathrm{obs}}] \qquad (1)$$

$$\Delta t = 14.8[\log(\mathrm{U}/r)_0 - \log(\mathrm{U}/r)_{\mathrm{obs}}] \qquad (2)$$

$$\Delta t = 21.8[\log(\mathrm{U}/\mathrm{Th})_0 - \log(\mathrm{U}/\mathrm{Th})_{\mathrm{obs}}] \qquad (3)$$

where Δt is expressed in Gyr, r is a stable third-peak r-process element (here Os or Ir), and the terms such as $(\mathrm{Th}/r)_0$ are the initial production ratios for each pair of species.

Equations (1) and (2) highlight the importance of adding U to the battery of Galactic chronometers: an error of 0.1 dex in a Th abundance propagates as a time equal to the age of the Solar System, neglecting other sources of error. But equation (3) shows that U and Th can be used in concert, with little loss in formal precision but with important overall advantages: the initial production ratio $(\mathrm{U}/\mathrm{Th})_0$ is in principle much less affected[17] by theoretical uncertainties than any of the individual $(\mathrm{U}/r)_0$ because of the proximity of the two elements in their mass numbers. We note that the observational accuracy of (U/Th) is better than for U or Th alone, because errors coming from the choice of model atmosphere parameters largely cancel out.

The observed value of log(U/Th) in CS31082–001 is –0.74 ± 0.15. Here our error estimate includes 0.1 dex reflecting astrophysical observational errors, and 0.12 dex for the uncertainty on the oscillator strength of the U II 385.96-nm line. We only have to introduce an estimate of $\log(\mathrm{U}/\mathrm{Th})_0$ in equation (3) to derive the age of CS31082–001. This is done in Table 1, where we have given the reference used for the value of the production ratio. We have also explored the use of the ratio of U to stable elements. As explained above, it is safest to choose a reference element as heavy as possible (that is, close in mass number to U and Th). Table 1 gives the corresponding results using production ratios for Os and Ir from ref. 4. Any age between 11.1 and 13.9 Gyr is compatible with the various determinations associated with their error bars. We consider the median value 12.5 Gyr as our best present estimate for the age of CS31082–001, with a conservative standard error of 3 Gyr. When increased by 0.1–0.3 Gyr (refs 14, 15), these values give the age of the Galaxy, which is in turn a lower limit to the age of the Universe.

The accuracy of this uranium dating technique is at present limited by incomplete knowledge of a few critical physical data, in particular oscillator strengths and production ratios of the elements produced by the r-process. Further laboratory and theoretical work should enable progress on both these issues, as should the detection of additional stars with enhanced abundances of r-process elements, similar to CS31082–001. Such work, already in progress, should allow the full potential of the uranium chronometer to be realized. □

Table 1 Ages derived for CS31082–001 as a function of production ratios

Element pair	log (production ratio)	Ref.	log (observed ratio)	Derived age (Gyr)
U/Th	–0.255	4	–0.74 ± 0.15	10.6 ± 3.3
U/Th	–0.10	17	–0.74 ± 0.15	14.0 ± 3.3
U/Os	–1.27	4	–2.19 ± 0.18	13.6 ± 2.7
U/Ir	–1.30	4	–2.10 ± 0.17	11.8 ± 2.5

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1. Tilton, G. R. in *Meteorites and the Early Solar System* (eds Kerridge, J. F. & Matthews, M. S.) 249–258 (Univ. Arizona Press, Tucson, 1988).
2. Butcher, H. R. Thorium in G-dwarfs as a chronometer for the Galaxy. *Nature* **328,** 127–131 (1987).
3. François, P., Spite, M. & Spite, F. On the galactic age problem: Determination of the [Th/Eu] ratio in halo stars. *Astron. Astrophys.* **274,** 821–824 (1993).
4. Cowan, J. J. *et al.* *r*-process abundances and chronometers in metal-poor stars. *Astrophys. J.* **521,** 194–205 (1999).
5. Westin, J., Sneden, C., Gustafsson, B. & Cowan, J. J. The *r*-process enriched low-metallicity giant HD 115444. *Astrophys. J.* **530,** 783–799 (2000).
6. Sneden, C. *et al.* Evidence of multiple *r*-process sites in the early Galaxy: New observations of CS 22892-052. *Astrophys. J.* **533,** L139–L142 (2000).
7. Sneden, C. & Cowan, J. J. The age of the Galaxy from thorium cosmochronometry. *Rev. Mex. Astron. Astrophys.* (in the press); also preprint astro-ph/0008185 at ⟨http://xxx.lanl.gov⟩ (2000).
8. Beers, T. C., Preston, G. W. & Shectman, S. A. A search for stars of very low metal abundance. II. *Astron. J.* **103,** 1987–2034 (1992).
9. D'Odorico, S. *et al.* The performance of UVES, the echelle spectrograph for the ESO VLT, and highlights of the first observations of stars and quasars. *Proc. SPIE* **4005,** 121–130 (2000).
10. McWilliam, A., Preston, G. W., Sneden, C. & Searle, L. Spectroscopic analysis of 33 of the most metal-poor stars. II. *Astron. J.* **109,** 2757–2799 (1995).
11. Sneden, C. *et al.* The ultra-metal-poor, neutron-capture-rich giant star CS 22892-052. *Astrophys. J.* **467,** 819–840 (1996).
12. Blaise, J. & Wyart, J.-F. *Tables Internationales de Constantes Sélectionnées* Vol. 20, *Energy Levels and Atomic Spectra of the Actinides* (Univ. Pierre et Marie Curie, Paris, 1992).
13. Chen, H.-L. & Borzileri, C. Laser induced fluorescence studies of U II produced by photoionization of uranium. *J. Chem. Phys.* **74,** 6063–6069 (1981).
14. Argast, D., Samland, M., Gerhard, O. E. & Thielemann, F.-K. Metal-poor halo stars as tracers of ISM mixing processes during halo formation. *Astron. Astrophys.* **356,** 873–887 (2000).
15. Chiappini, C., Matteucci, F., Beers, T. C. & Nomoto, K. The earliest phases of Galaxy formation. *Astrophys. J.* **515,** 226–238 (2000).
16. Pfeiffer, B., Kratz, K. -L. & Thielemann, F.-K. Analysis of the solar-system *r*-process abundance pattern with the new ETFSI-Q mass formula. *Z. Phys. A* **357,** 235–238 (1997).
17. Goriely, S. & Clerbaux, B. Uncertainties in the Th cosmochronometry. *Astron. Astrophys.* **346,** 798–804 (1999).
18. Fouqué, P. *et al.* An absolute calibration of DENIS (Deep Near Infrared Southern Sky Survey). *Astron. Astrophys. Suppl.* **141,** 313–317 (2000).

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Generic mechanism for generating a liquid–liquid phase transition

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Recent experimental results[1] indicate that phosphorus—a single-component system—can have a high-density liquid (HDL) and a low-density liquid (LDL) phase. A first-order transition between two liquids of different densities[2] is consistent with experimental data for a variety of materials[3,4], including single-component systems such as water[5–8], silica[9] and carbon[10]. Molecular dynamics simulations of very specific models for supercooled water[2,11], liquid carbon[12] and supercooled silica[13] predict a LDL–HDL critical point, but a coherent and general interpretation of the LDL–HDL transition is lacking. Here we show that the presence of