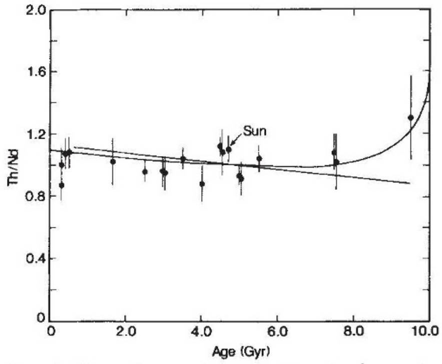

Fig. 1 The observations by Butcher[1] on the abundance ratio, Th/Nd, for 19 stars including the Sun plotted vs the age of the stars adjusted to the age of the Galaxy given in ref. 2. The curve is a theoretical calculation based on the nuclear cosmochronology described in ref. 2.

at the accepted age of 4.6 Gyr. The theoretical curve calculated as described above has been normalized to Th/Nd = 1 at the age of the Sun with $f = 1.40$. It will be noted that the curve fits the observations reasonably well. It must be conceded that Butcher's data can be fitted with other values of f, S_E and t_0. This can be understood simply because the mean lifetime of ^{232}Th is so long, about 20 Gyr. At the same time I think it fair to emphasize that the agreement shown in Fig. 1 is based on a chronological model[2] presented in the literature before Butcher's observations were published. That model used a range of mean lifetimes, 1.0 Gyr for ^{235}U, 6.4 Gyr for ^{238}U, as well as 20 Gyr for ^{232}Th.

Faced with my timescale, the astute reader will question how the published ages for Butcher's stars can be high by a factor of 2 both by his calculations and by mine. The published ages come in the main from the time required for a star in a globular cluster to reach the main-sequence red giant turnoff point in the Hertzsprung–Russell diagram. I think that a possible solution of the problem has been given by Clayton[9] and Willson, Bowen and Struck-Marcel[10]. These authors introduce early main-sequence mass loss for stars and the latter authors state, "We conclude that it is possible that no stars in our Galaxy are older than 7–10 × 10^9 yr old." If stars are more massive when they first form they convert their primordial hydrogen into helium very quickly and thus reach the main-sequence red giant turn-off point when their central hydrogen is consumed much sooner than given by canonical calculations. I have summarized[2] many other observations that agreed with a Galaxy age of 10 Gyr.

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BUTCHER REPLIES — Professor Fowler's enthusiasm for my result is gratifying, especially so because I was once a student of his. Let me emphasize, however, that the correct treatment of s- and r-process abundances in models for the chemical evolution of the Galaxy is very uncertain. What seems to have been established[1] is that the ratio of these abundances does not vary more than the measurement error—the best to date being about 25 per cent — among stars of all ages, as long as the absolute heavy element abundance level is greater than about 3 per cent of its solar value. How this result may be reconciled with major ongoing stellar synthesis in an evolving galaxy is unclear. There do exist, of course, stars with even smaller metal abundances, and in these stars one does observe variations in the relative amounts of r- and s-process elements. One imagines that such stars are evidence for a period early in the Galaxy before much nucleosynthesis has occurred, but how they relate in time to other, indistinguishably old stars with higher abundances may only be guessed at. It is fortunate that for the timescale discussion, which uses stars with abundances high enough to show the thorium line, the problem of different synthesis possibilities for neodymium does not seem to matter.

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SIR—There is no contradiction between Butcher's[1] Th/Nd ages for the oldest stars of about 11–12 Gyr and the results of stellar evolution, when the diffusion of helium is taken into account. The evolution of stars of low mass is accelerated by the diffusion of helium towards the centre[2,3]. When this process is omitted, the ages are overestimated. At a nominal age of 16 Gyr as calculated by classical methods[4] (omitting diffusion), the actual age[2,3] is about 25 per cent less, or 12 Gyr. This reduces the evolutionary ages in Butcher's sample (minus at most one standard deviation) to lie within the range of his nucleochronological results. It is in fact quite encouraging that Butcher's ages are as young as they are; otherwise one would have to invoke some mechanism to slow the evolution of these stars. Meridional circulation could do so by mixing them if they were rapid rotators, but Butcher's own data belie this unless the stars rotate much more rapidly inside than on their surfaces or have spun down quite recently.

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BUTCHER REPLIES — Noerdlinger brings to our attention one of several plausible mechanisms for reducing the maximum ages of stars as deduced from stellar evolution calculations. This idea has not yet been tested against the helioseismological data which are not available, so it is hard to see that it is clearly preferable to other age-reducing possibilities. Another suggestion that has received considerable discussion recently, proposes that solar-mass stars in reality were substantially more massive as they arrived on the main sequence, but then suffered a period of extensive mass loss. Such stars would then have burnt significant amounts of their core hydrogen very quickly, and would appear rather older than they really are[1]. There might be observable signatures of this process, in the distribution of main-sequence stars versus mass for example, but at present no convincing evidence one way or the other has been presented to decide the matter. Finally, it has been recognized for some time that even the standard models used for computing stellar evolution can produce substantially younger ages than those reported as best estimates. by adjusting the detailed chemical composition, the description of convection and the distance scale, maximum ages as young as 10 Gyr may be obtained[2].

Determining which of these ideas may apply to the real world, and which are red herrings, may have to await the new generation of very large optical telescopes, when high-quality, high-resolution spectra and detailed asteroseismological data can be obtained for relatively faint stars.

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