Harvey R. Butcher

Age of the elements via stellar spectroscopy: Struggles with atomic spectra and transition probabilities

ABSTRACT

A program to develop a stellar cosmochronometer based on radioactive decay is described, with emphasis on the laboratory data needed to remove remaining uncertainties.

INTRODUCTION

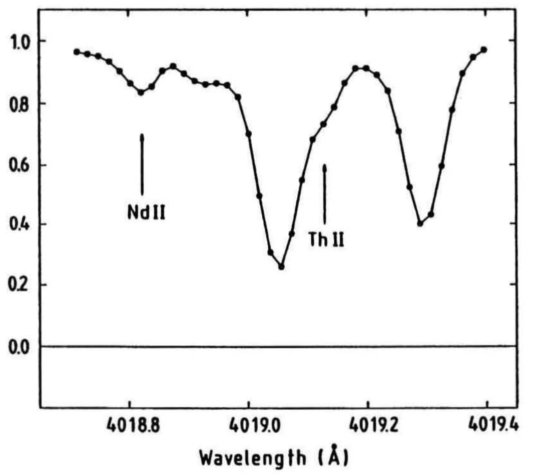
It should be possible in principle to explore the origin of the elements as well as the chemical evolution of the Galaxy by observing the abundances of various species in stellar spectra. It is believed that dwarf stars like the Sun exhibit surface compositions identical to that of the interstellar gas from which they formed. Study of stars of this type as a function of stellar age should, therefore, yield a detailed picture of the chemical history of the Galaxy. And to the extent that nucleosynthesis has been an on-going phenomenon in the Galaxy, this history may provide clues to the actual sites of element synthesis.

To develop these possibilities requires observation and interpretation of absorption lines in stellar spectra. To estimate abundances, knowledge of the physical state of stellar atmospheres must be combined with the relevant atomic and molecular line parameters measured in the laboratory. Over the past several decades a great deal of preliminary work has been done in this field. It has become clear on the one hand that the basic idea of using stellar observations for these purposes is sound, but on the other that the situation is complex and unlikely to be unravelled easily. So for example, in the disc of the Galaxy one sees gradients in the abundances of C, N, and O, which are almost certainly due to hydrogen burning reaction products from inside stars. But one also finds at any given age significant variations in the absolute abundance levels of the heavier elements -- arguing for inefficient mixing of the interstellar gas together with continuing element production, but at the same time no detectable variation of relative abundances of elements which would be expected to show large variations -- that is, unless mixing is very efficient or only small amounts of synthesis have occurred since early epochs. No convincing explanation is available for such apparent contradictions.

It has also become clear that many of the key elements to be analyzed have only weak lines occurring in crowded regions of stellar spectra, which cannot be studied without excellent laboratory data on all lines present in their vicinity.

A good example of the latter situation is the subject of this contribution. Butcher (1987) has proposed that the techniques of radioactive decay chronometry might be extended to the whole Galaxy, by observing the abundances of the long lived but radioactive element thorium (14 Gyr half-life) in stars of various ages. There are three or four potentially unblended lines of thorium in stellar spectra (Hauge and Sørli 1973; Holweger 1980), but only the strongest -- at 4019.129 Å -- has reliable enough laboratory data on its expected strength to warrant detailed study. To circumvent the many difficulties in analyzing the atmospheres of solar type dwarf stars, it was proposed that a nearby line of neodymium be used to normalize the thorium abundance. The figure displays the 4019 Å region in a typical solar type star. Both the thorium and neodymium lines are unsaturated and derive from the dominant ion throughout the atmospheres of these stars. The lines also have nearly identical excitation potentials. The ratio of their line strengths is therefore proportional to the Th/Nd abundance ratio to within 2% over a stellar temperature range of 4500 to 6500 K.

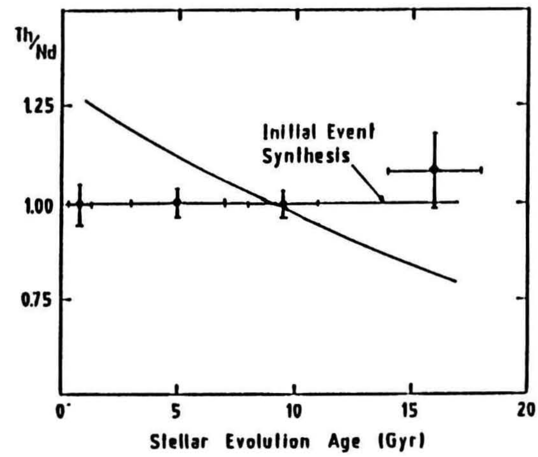
A reliable Th/Nd stellar cosmochronometer would provide constraints on galactic evolution and nucleosynthesis complementary to the existing Solar System chronometers (primarily the uranium and thorium isotope ratios). The observed Th/Nd ratio in a given star results from an integration of destruction and production processes in the Galaxy, as well as radioactive decay, up to the epoch of the stellar birth. Therefore, even though one has only a single decay to use, examination of stars of different ages effectively samples these processes at several points in the history of the Galaxy. Such



The 4019 Å region in a solar type star.

effects as astration (causing loss of matter to the system via incorporation in low mass, long lived stars; also the modification of abundances by nuclear processes in successive generations of stars) and infall of extra-galactic material (which effectively dilutes in later epoch stars the quantity of material synthesized early in the life of the Galaxy, perhaps to the point even that it cannot be detected in Solar System matter) can be directly examined by investigating very old and very young stars, and requiring that the Solar System uranium and thorium isotopic data and the Th/Nd stellar data yield consistent results. In particular, because the Solar System data do not effectively constrain evolutionary models having large ages (Meyer and Schramm 1986; Fowler and Meisl 1986), whereas the Th/Nd stellar data are especially sensitive in this case, it seems very important that the proposed Th/Nd chronometer be developed to the point where it can provide reliable information on the age and evolution of the Galaxy.

First observations of the Th/Nd ratio in stars of all ages were also presented by Butcher (1987). As shown in the figure, no variation of the ratio was detected within the experimental errors in that data. This result was then combined with Solar System data to constrain the age of the Galaxy to no more than 11 or 12 Gyr, independently of whether synthesis occurred in a more or less single event at early epochs or over an extended period lasting the entire history of the Galaxy.



Mean values of Th/Nd vs. stellar age. The horizontal solid line is the predicted behavior for element production concentrated at early epochs. The sloping solid line is the predicted relation for continuous synthesis at a constant rate throughout the lifetime of the Galaxy. The horizontal error bars indicate the spread in ages of stars in the point.

This age disagrees, however, with our best estimates for the ages of the globular clusters as based on stellar evolution theory (e.g. VandenBerg 1983). The most metal poor clusters should have the most reliable age estimates (because they are least susceptible to errors in the opacity parameters), but they also yield the largest ages, and one must naturally suspect that there might be something wrong with the Th/Nd analysis.

The various problems which could be compromising that analysis are summarized in the following section. Then, that laboratory data which at present seem most necessary for the analysis are listed.

MAJOR UNCERTAINTIES

Four likely areas for error in the Th/Nd analysis may be cited:

(1) The relative r- and s-process contributions at element synthesis to the abundances of Nd and Th.

Thorium is thought to be synthesized only in the r-process, while in the Solar System neodymium has roughly equal contributions from the r- and s-processes (Howard etal 1986). Because the s-process appears to require the presence of seed nuclei, whereas the r-process does not (but see also Clayton 1988, and Malaney and Fowler 1989), one naturally expects the relative contributions from the two processes to evolve systematically with epoch in the Galaxy (cf Clayton 1987; Mathews and Schramm 1988). That they do not, at least in the disc of the Galaxy (Lambert 1987; Butcher 1975; Butcher 1988), is a puzzle of the first order, but fortunate for the Th/Nd analysis. For extremely metal deficient stars in the galactic halo, s-process abundances do seem to vary between stars (Spite and Spite 1978; Sneden and Parthasarathy 1983; Sneden and Pilachowsky 1985). The Th and Nd lines in these stars will be exceedingly weak, but if they are ever measured, it will be possible to correct for non-solar s-process contributions to Nd by also measuring other s- and r-process abundances similar to Nd in atomic mass (eg. Ba, Eu, Gd, etc). Similarly, one can, at least in principle, measure high and low mass r-process species (eg. Eu and Os) in stellar spectra, to test and correct for evolutionary variation in the shape of the r-process abundance curve. This uncertainty, therefore, is unlikely to be a serious one, unless the derivation of the required abundances cannot be made because of inadequate laboratory data on the spectra in question.

(2) The stellar age estimates.

If the largest ages used in the Th/Nd analysis are overestimated, then the derived total age of the Galaxy may be underestimated. This possibility is potentially a serious one, because at present the only stars which can be studied have relatively strong lines and orbits characteristic of stars confined to the disc of the Galaxy. They cannot therefore be said to belong to the halo population, which is generally agreed to contain the oldest stars.

The stars in the analysis do, however, have rather large and apparently reliable trigonometric parallaxes, and can be placed on the H-R diagram with some confidence. When this was done, the three stars HR 1136, HR 3018, and HR 5699 all have ages above 15 Gyr. The first object has a perfectly normal disc-like galactic orbit as well as solar abundances, and is also cool enough that the theoretical isochrones are converging as they approach the Hayashi limit; its age is clearly uncertain at the 25% level. The remaining two stars, however, are each moderately metal poor and have high enough space motions that they must be considered as being intermediate between the disc and halo populations. And they are not so evolved that they cannot be reliably placed in the H-R diagram. Taking conservative error estimates on their parallax measurements, on their photometry, and on their overall heavy element abundances, one can only conclude that they are indeed as old as the halo proper. On the other hand, with only two stars of this type, even though they were not selected primarily on the basis of their age (rather because they were the most metal poor dwarfs having some chance of yielding a result with present equipment), one cannot yet be entirely confident that they are representative of the earliest epochs of the Galaxy.

(3) The detailed spectrum model used to fit to the observational data and derive the Th and Nd line strengths.

Because the Th line used in the analysis is located in the wing of a blended line of Fe and Ni, its precise measurement depends on having very accurate wavelengths for those lines. In addition, its strength is influenced, at roughly the two percent level, by the damping parameter for the Fe line in the blend. Inconsistencies in the reported wavelengths for these lines lead to an uncertainty in the equivalent width of the Th line in the solar spectrum of some 20%. Investigation of any potential contamination of the Th line by comparing its expected and measured strengths cannot therefore be made yet. Fortunately, Learner, Thorne and colleagues at Imperial College, London, report elsewhere at this conference that they have made the necessary measurements, so it is now possible to repeat the analysis with much improved wavelengths. A quantitative estimate of the precision required for the Fe line's damping parameter will also be derivable as part of this re-analysis.

(4) The purity of the Th line.

If the Th line is contaminated by some line of a stable element of unknown strength, its variation due to radioactive decay will be diluted and a young age will be incorrectly inferred. A contamination of 10% was assumed in the original analysis, but several workers have proposed a higher contamination (Holweger 1980; Aldering 1987; Whaling and Lawler 1988), of up to 30% and by a weak line of Co I at 4019.13 Å.

Aldering has kindly calculated synthetic spectra for the region around 4019 , with and without a 30% contamination by Co I, and covering a temperature range of 4000 - 7000 K. Over the temperature range of the stars studied to date (4700 - 6300 K), he predicts for zero contamination a 2% variation of Th/Nd, but over 40% for a contribution from the Co I line to the measured equivalent width in the solar spectrum of 30%. The observed scatter of the data, with one caveat and excepting that for HR 3018 (which has a substantially higher estimated error), is well explained by a constant Th/Nd ratio with an 8% standard deviation. It therefore seems highly unlikely that the contamination of the Th line equivalent width measurement in the Sun is as much as 30%. A value of 10% is certainly permitted, however, and the numbers of stars at the extremes of temperature are few, so the matter cannot be said yet to have been resolved in a completely satisfactory way.

The caveat mentioned above is that there is in the data as they now stand a dependence of the Th line strength on the stellar velocity width parameter. That is, the stars with the narrowest lines, HR 509 and HR 5460, yielded slightly larger Th/Nd ratios than the rest of the sample. Because they are neither the oldest, youngest, hottest, or coolest stars in the sample, these points have simply been corrected in a plausible manner for the subsequent analysis. The best fit model spectrum to the data for these stars also showed deviations significantly above the noise, however, from which one can only conclude that the model spectrum needs improvement, especially as regards the relevant wavelengths. Now that this can be done, it will soon be possible to comment more reliably on the likely contamination, at least as estimated from the variation of the Th/Nd ratio with stellar temperature.

LABORATORY DATA NEEDED

The discussion above indicates that the following atomic line data will be essential, or at the least very helpful, in establishing a reliable Th/Nd chronometer.

(i) Precise relative wavelengths for the Th II, Ni I, Fe I, and Nd II lines. With this information it should be possible to improve the model spectrum for fitting to the stellar spectra, thereby to derive a reliable equivalent width for the Th line in the solar spectrum and test for the level of contamination, and to eliminate the increased Th/Nd ratio at small velocity broadenings. Luckily, the ICL group has reported greatly improved values for some of these wavelengths at this meeting.

(ii) The damping parameter for the Fe I 4019.04 Å line, which is expected to be larger than that for any other line in the vicinity. If this parameter is as large as or larger than estimated from the calculations of Warner (1967; 1969), accurate knowledge of its value will significantly improve the resulting chronometer.

(iii) The transition probability of the Th II 4019.129 Å line. The Aarhus group (Simonsen et al 1988) have measured the lifetime of the upper level of this transition to very high accuracy, but the relevant branching ratio from this level remains uncertain at the 10% or more level. A convincing comparison of the predicted and measured equivalent widths of the line in the Sun cannot be made, and hence the contamination estimated, until this measurement is pinned down.

(iv) Transition probabilities for three other measurable absorption lines of Th II in the solar spectrum, at 3675, 3741, and 4086 Å (Hauge and Sørli 1973; Holweger 1980). Predicted strengths for these lines, together with accurate wavelengths relative to nearby stronger features, would make it possible to include them in the analysis, and thereby strengthen confidence in the final conclusions.

(v) An accurate transition probability for the potential contaminator line, Co I 4019.126 Å, relative to another Co I line nearby in wavelength and unblended in stellar spectra. A good candidate line for this purpose is Co I 4011.08 Å, although the Co I blend 4019.29 + 4019.30 Å might also be a possibility. Both of these lines, as well as any others proposed, should be examined carefully for blending, of course, before the proposed test is made (the 4019.3 Å blend has been difficult to fit in some of the author's stellar spectra without inclusion of a blend of unknown origin in the spectrum model). If an appropriate Co I line can be found, it should be possible to ascertain the contamination by Co I 4019.13 Å, independently of uncertainties in the absolute equivalent width of the Th line.

(vi) Line strength determinations for other potential blends at the position of Th II 4019.129 Å. Kurucz and Peytremann (1975) give numerous possible contaminators. Most of these can be ruled out by the Th/Nd vs stellar temperature test, or by the ratio in s-process enhanced stars (cf Butcher 1987). The only remaining serious candidate for an undetected contaminator is Tb II 4019.12 Å, which, being from a predominantly r-process element, may not have been detected in any of the tests carried out so far. Unfortunately, the spectrum of Tb II has never been fully analyzed, so that the term classification and lower level of 4019.12 Å are not known. Prof Klinkenberg reported privately at this meeting that the line of terbium at 4019.12 Å in his spectra is in fact a blend of a Tb I and Tb II line. The suggestion, therefore, is that the Tb II line is unlikely to be of significant strength in stellar spectra.

REFERENCES

Aldering, G.S. 1987, unpublished.

Butcher, H. 1975, *Ap.J.*, **199**, 710.

Butcher, H. 1987, *Nature*, **328**, 127.

Butcher, H. 1988, *ESO Messenger*, Nr 51, p 12.

Clayton, D.D. 1987, *Nature*, **329**, 397.

Clayton, D.D. 1988, *Mon.Not.R.ast.Soc.*, **234**, 1.

Fowler, W.A., and Meisl, C.C. 1986, in "Cosmological Processes," p 83, Arnett et al eds, VNU Science Press, Utrecht.

Hauge, Ø., and Sørli, H. 1973, *Solar Physics*, **30**, 301.

Holweger, H. 1980, *Observatory*, **100**, 155.

Howard, W.M., Mathews, G.J., Takahashi, K. and Ward, R.A. 1986, *Ap.J.*, **309**, 633.

Kurucz, R.L., and Peytremann, E. 1975, SAO Special Report, no. 362.

Lambert, D. 1987, *Astrophys.Astr.*, **8**, 103.

Malaney, R.A. and Fowler, W.A. 1989, *Mon.Not.R.ast.Soc.*, **237**, 67.

Mathews, G.J. and Schramm, D.N. 1988, *Ap.J.*, **324**, L67.

Meyer, B.S. and Schramm, D.N. 1986, *Ap.J.*, **311**, 406.

Simonsen, H., Worm, T., Jessen, P., and Poulsen, O. 1988, *Physica Scripta*, **38**, 370.

Sneden, C. and Parthasarathy, M. 1983, *Ap.J.*, **267**, 757.

Sneden, C. and Pilachowski, C.A. 1985, *Ap.J.*, **288**, L55.

Spite, M. and Spite, F. 1978, *Astr.Astrophys.*, **67**, 23.

VandenBerg, D.A. 1983, *Ap.J.Suppl.*, **51**, 29.

Warner, B. 1967, *Mon.Not.R.ast.Soc.*, **136**, 381.

Warner, B. 1969, *Observatory*, **89**, 11.

Whaling, W., and Lawler, J.E. 1988, unpublished.

AUTHOR'S ADDRESS

Kapteyn Astronomical Institute
P.O. Box 800
9700 AV Groningen
The Netherlands