sists mainly of *molecular clouds*. The so-called Great Molecular Clouds (GMC) are individual objects of great interest and the problems of their origin are not less intriguing than those of stellar clusters. But at the moment our knowledge of them is very superficial. Great efforts are necessary.

But GMC clouds form only one of the components of interstellar matter.

The other components are connected with the general structure of the Galaxy as a whole as well as with external influences on the Galaxy. We are only beginning to understand their role in the Galaxy.

My talk, as I mentioned, reviewed only some aspects of the problems of galactic and intergalactic research and reflects mostly my personal views and interests, the interest of a theoretician. May I repeat here what I have said in my welcome to this school:

The real essence of our knowledge of the Universe is contained in the observational data. The role of the theory is to systematize the data and to connect them logically between themselves and with the data from other sciences.

Galactic Chronometry with the Coudé Echelle Scanner

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Introduction

I have recently proposed that observations of the radioactive nucleus 232 Th in stars may be used to derive a new kind of galactic chronometer (*Nature,* vol. 328, pp. 127–131, 1987). The extraordinary performance of the Coudé Echelle Spectrometer on La Silla has played a central role in making possible the difficult observations required. I congratulate the ESO staff on producing such an outstanding instrument.

The idea is simple – if G-dwarf stars sample a well-mixed interstellar medium in the Galaxy at the time of their birth, and if the compositions of their atmospheres have not changed since birth except for radioactive decay, then the abundances of radioactive species in these stars will represent an integration of element production and destruction (via radioactive decay, astration and possibly dilution) in the Galaxy, up to the moment of stellar birth, followed by free decay still observed today. If one can develop a sample of stars with accurately known ages, then one has a record of the history of nucleosynthesis, at least for thorium and the r-process elements, which may help resolve the model dependencies inherent in using solar system data alone. That is, solar system material provides an integration of element production and destruction activity up to 4,6 Gyr ago; observations of radioactive species in the oldest stars known will yield an integration over only a short period at the beginning of the Galaxy; and data on the youngest stars give an integration over the whole galactic history.

Thorium has several faint absorption lines in the solar spectrum, and the strongest of these, at 4019.129 Å, even has an accurately measured transition probability (Andersen and Petkov, *Astron. Astroph.* **45,** 237–238, 1975).

When combined with the measured line strength, this probability yields the same abundance for thorium as found in meteorites. The line, therefore, appears to be largely unblended and a good candidate for use in setting up a chronometer based on thorium. It should also be remarked that the element thorium has only one long-lived isotope, 232 Th, so that measurement of the elemental abundance is expected also to give the isotopic abundance of interest.

The Chronometer

Figure 1 shows the region around Th II 4019.129 Å in alpha Cen B, one of the stars in my final sample. The thorium line is seen to appear in the wing of a stronger line, which turns out to be a blend of a Fe I and a Ni I line. Also indicated is a nearby absorption line of neodymium, Nd II 4018.823 Å. This line has a lower level excitation only 0.05 eV above that of Th II 4019.129, and neodymium has a first ionization potential close to that of thorium. Both lines are, therefore, from the dominant ion throughout late-type stellar atmospheres, and will behave with temperature and pressure essentially identically. Furthermore, both lines are unsaturated in G-dwarf spectra, so that their strength ratio is proportional to the abundance ratio of these two elements, and is largely unaffected by unknown or poorly estimated stellar atmospheric properties. And finally, it is important that there exist two rather good continuum points, at 4018.66 and 4019.67 Å, in the near vicinity (see for example the high resolution but compacted plots of the solar spectrum displayed in Figure 5 of Rutten and van der Zalm, *Astron. Astrophys. Suppl. Ser.* **55,** 143–161, 1984). Because the lines are so close together in wavelength and are bracketed by good continuum points, the ratio of their strengths may be determined with considerable reliability.

The proposed chronometer is the ratio of the strengths of these two lines. This ratio has the property that it can be measured to high accuracy. Whether it will in the end provide a useful and reliable chronometer depends on the details of the measurement errors and on the reality of a crucial assumption.

A Crucial Assumption

To have a useful chronometer, it is necessary to be able to compare the abundance of the radioactive species at synthesis, which is normally a quantity predicted theoretically, with the observed abundance. For the U-Th data in meteorites, for example, one can estimate the relative production ratios of 232 Th, 235 U, and 238 U, rather accurately, because they are very close to each other in atomic mass and in a mass range expected to exhibit a relatively smooth variation of abundance with mass in the r-process. Nevertheless, a major source of uncertainty in applying U-Th data in the solar system for chronometry are the uncertainties in the production ratios.

The situation in the stellar case is, in principle, much, much worse. Thorium

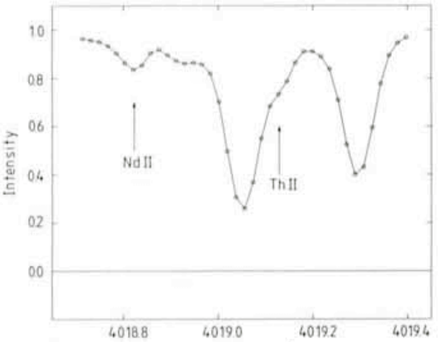

Figure 1: *CES spectrum of α Cen B in the region of Th II 4019.129 Å. The thorium and neodymium lines used to form the chronometric quantity Th/Nd are indicated.*

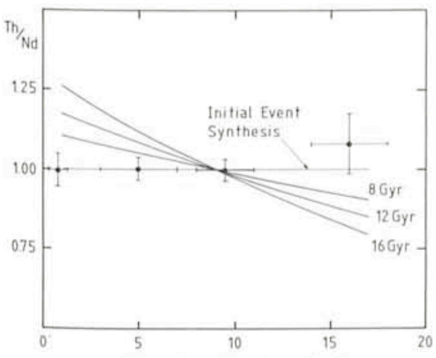

Figure 2: *Variation of normalized Th/Nd with stellar age. Individual data points have been combined here to show the statistical weight of the whole data set. Also shown are two models for the predicted variation of Th/Nd. The initial event model supposes that essentially all thorium and neodymium were synthesized before the sample stars formed; it predicts constant Th/Nd vs. age, and fits the data well. The second model supposes that net element production has proceeded continuously and at a constant rate over all time. The stellar ages are on Van den Berg's scale, but the latter model is shown assuming three different total timescales, as indicated, stretched to overlay the data points appropriately. Total durations of synthesis above about 10 Gyr in this model are seen to be excluded.*

is produced during fission cycling of the r-process. Neodymium also partakes in this cycling, but is probably also produced in the very short-lived process responsible for the lighter r-process nuclei. Its abundance, therefore, could very well evolve over time if the contributions to r-process synthesis vary. Furthermore, neodymium isotopes derive nearly 50% of their abundance in the solar system not from the r-process, but from the s-process. The r-process is generally believed to have occurred in explosions, probably supernovae, whereas the s-process is seen to take place in red giant stars. There is every reason to suppose, therefore, that the ratio of r-process to s-process abundances will evolve over time and place in the Galaxy. If they do, the Th/Nd chronometer will be compromised, because it will be difficult to disentangle that evolution from the production and decay history of thorium. That is, for all but the oldest stars the observed Th/Nd ratio results from an integration of production and destruction activity over extended periods, and it therefore will not be easy to separate uniquely the effects of variations in the s-process contribution to neodymium in one model for the history of synthesis, from no variations in a different model.

Fortunately, the situation is not hopeless. It has been known for some time that the abundances of the s-process elements barium and strontium, and the r-process element europium, do not vary among dwarf stars in the solar neighbourhood, at least for stars having metallicities greater than about 3% of solar. The best measurements to date limit any such variation to certainly no more than about 25% (Butcher, *Ap. J.* **199,** 710–717, 1975; Lambert, *Astrophys. Astr.* **8,** 103–122, 1987). Hence in any star having strong enough lines for the thorium line to be measurable, the contribution to the neodymium abundance from the s- and r-processes has been sensibly constant over all time. And when it becomes possible to observe thorium in very metal deficient stars, it will be possible to apply a correction to account for any r/s evolution, because such stars are all very old and hence represent an integration of only a very brief period. They will not therefore produce uniqueness problems in the analysis.

The Data

A series of spectra were taken at the CAT and CES on La Silla, during 2–6 Sept. 1983 and 3–7 April 1985. Study of model and real data showed that spectral resolutions of at least 100,000 and preferably twice that would be required to be able to adequately measure the inflection that is the thorium line. For reasons of observing efficiency the CES was set to R = 100,000. The efficiency of the spectrometer is not optimal at 4000 Å, and with the 1,872 channel Reticon detector and integration times of up to 11 hours, the faintest star for which a S/N of several hundred could be obtained was about V = 6,5 mag. The instrument performed very well, except for some difficulty in obtaining a reliable instrumental profile using the blue laser (that is, the derived profile seemed to be a function of how saturated the line core became on the detector). Given the obvious importance of knowing with some accuracy and precision just what the instrumental profile is for a given measurement, I suggest that a careful study of known absorption line spectra, such as of an absorption cell, should be made. Perhaps then the saturation problems I encountered can be alleviated.

Results

It proved possible in the end to acquire data on 18 G-dwarf and several giant stars with narrow enough lines. These data have been analysed by fitting a model spectrum of the region to the individual spectra, of which there are typically two or three per star. The differences between the best-fit model spectra and the data are taken to give a measure of the noise in the line strength estimates, and I have argued that the resulting scatter in the data points about their mean is to be understood entirely as due to this noise. If that is so, then individual points may be appropriately summed to display the total statistical weight of the data set.

Such a display is given in Figure 2. Each of these data points is the average of 3 to 7 stars. The horizontal error bars give the range in age of the stars in each point (but also a rough estimate of the reliability of the age estimates), and those in the vertical direction the one sigma uncertainty in Th/Nd for the point.

The age estimates for the sample stars, except for the four youngest stars, are derived from trigonometric parallaxes (being all bright stars, the quality of the parallax data is quite reasonable), available broad band photometry, and the isochrones of Van den Berg (*Ap. J. Suppl. Ser.* **58,** 711, 1985). It is these isochrones which have given globular cluster ages above 15 Gyr, although there is now some suggestion that for large (factors of five) overabundances of oxygen in the most metal poor clusters, the maximum ages may be reduced to 14 Gyr (McClure et al., *Astron. J.,* **93,** 1144–1165, 1987).

In Figure 2 are also indicated the predictions of two extreme models for the history of synthesis, namely a single event at the beginning (initial spike model), and continuous synthesis at a constant net rate. It is evident that the initial spike model fits the data very well, whereas there is no support for any model with constant net production, even when it is assumed that the stars may be correctly ordered by age but with an incorrect total age scale. If the thorium line is contaminated by no more than 10% (a value of 20% seemingly ruled out by various tests reported in the *Nature* paper), then a two sigma upper limit on the total duration of synthesis in the latter model is less than 10 Gyr.

On the other hand, these data provide no independent age limit in the initial spike model. Any total age always yields a uniform composition at any given epoch in this case. But then the solar system U-Th data provide a sensitive limit, namely 11 Gyr maximum, with preferred values 2 or 3 Gyr less (see Fowler and Meisl, in *Cosmogonical Processes,* Arnett et al. eds., 83–100, VNU Utrecht, 1986; and Meyer and Schramm, in *Nucleosynthesis and its Implications on Nuclear and Particle Physics,* Audouze and Mathieu eds., 355–362, Reidel 1986, for discussion of results from models with synthesis peaked at early epochs). So combining stellar and solar system data constrains the total age scale, with the stellar thorium observa-

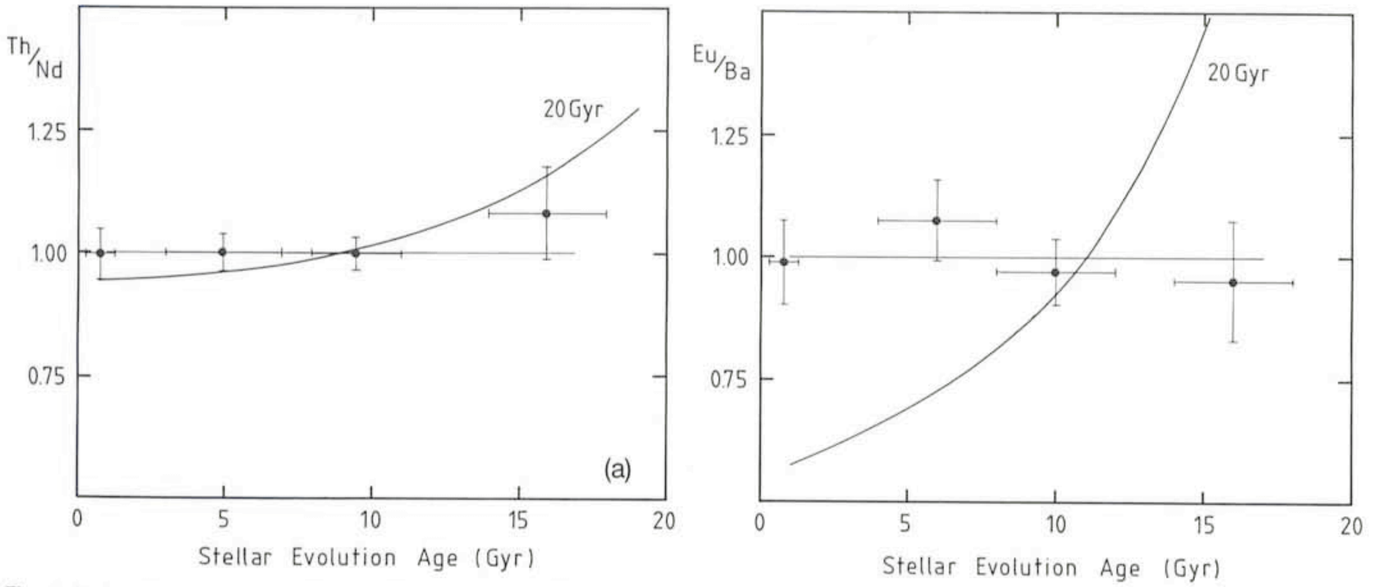

Figure 3: *Comparison of Clayton's galactic evolution model with stellar abundance results. This model assumes the r-process is a primary process, whereas the s-process is secondary. The resulting evolution of the neodymium abundance (52 % s-process and 48 % r-process in the solar system) compensates for the decay of thorium for ages above 15 Gyr, as seen in (a). The model predicts the europium (91 % r-process in the solar system) to barium (84 % s-process) ratio results displayed in (b), however, which is clearly inconsistent with existing measurements of these elements in the sample stars.*

tions limiting the constant rate model and the meteoritic data the initial spike model.

For models mid-way between the extremes, some sensitivity is lost in either case, and maximum ages of 11–12 Gyr are acceptable within both stellar and meteoritic constraints. But it remains the case that the best-fit model has synthesis concentrated in a single period at the beginning of the Galaxy (or before).

Potential Problems

The reliable use of Th/Nd for galactic chronometry rests on two assumptions that are still not fully verified. The first is that the thorium line at 4019.129 Å is not contaminated by more than, say, 10 %; any much greater contamination would make the chronometer too sensitive to the exact amount of contamination. I suggested that none of the tests I made would have distinguished blending due to a line from a low lying level of an ion of an r-process element, and proposed that Tb II 4019.14 might be a candidate contaminator at the 10 % level. Unfortunately, the spectrum of Tb II has never been fully analyzed, and I understand now that the line in question may in fact not really exist. But Holweger (*Observatory,* **100,** 155–160, 1980) has pointed out that Co I 4019.126 Å probably should be considered a candidate contaminator at this level. It is clear that a definitive discussion of the contamination question awaits further investigation.

The second area of uncertainty is the constancy of the thorium to neodymium ratio during synthesis. Of course, the data suggest that the initial event model is to be preferred, so that if negligible amounts of on-going s-process synthesis have occurred, then the data are fully consistent. It is only on the major synthesis at all epochs model, such as would be relevant if synthesis were directly tied to star formation, that the uncertainty becomes a matter for concern.

Several workers have proposed that the conclusion of a young age for the Galaxy is easily refuted, by simply taking account of a plausibly separate evolution of s-process and r-process abundances over time. Shown in Figure 3, for example, is a model due to Clayton (*Nature,* **329,** 397–398, 1987) which postulates a gradually increasing contribution from the s-process. The fit to the Th/Nd data is quite good, even for a galactic age of 20 Gyr. But I have been able to assemble Eu/Ba ratios for most of my sample stars, and display these data together with the prediction of Clayton's model. Here even though the Eu/Ba data are not as good as for Th/Nd, it is evident that the model fails. Mathews and Schramm (submitted to *Ap. J.* Letters) have also constructed a complicated galactic evolution model based on a varying s-process production. They claim that their model fits the Th/Nd data for ages up to 15 Gyr. This model is displayed in Figure 4, and their claim for Th/Nd is again seen to be correct. However, the model also cannot produce constant Th/Nd and simultaneously constant Eu/Ba, as is evident in the second part of the figure.

Simple schemes for compromizing the Th/Nd chronometer, therefore, run afoul of even existing data. It will be of considerable interest, of course, to determine observationally just how constant the ratios of r- to s-process abundances really are, and for the halo stars to find the corrections needed to the neodymium abundance for those stars ultimately to be usable for this sort of chronometry.

Speculation

Finally, I would like to communicate the following, deliberately provocative, speculation.

The so-called G-dwarf problem – that the distribution of metallicities among dwarf stars cannot be reproduced with simple galactic evolution models having synthesis closely tied to star formation – has traditionally been explained by supposing that infall of primordial material must have been important (although other schemes, such as metal-enhanced star formation, have occasionally also been proposed). The Th/Nd data suggest that synthesis peaked at early epochs is the right model, in which case the G-dwarf problem, as well as the metallicity gradients seen in the Galaxy, may be due to some other phenomenon than ordinary stellar nucleosynthesis.

I wonder, therefore, whether the generally accepted picture of continuous star-formation-linked synthesis, fixed up via mechanisms which are plausible but for which there is no real positive evidence to fit the metallicity distribution results, has any claim to preference over the initial spike model. For the latter, some mechanism will have to be found to account for the metallicity gradients, but this deficiency must be weighed

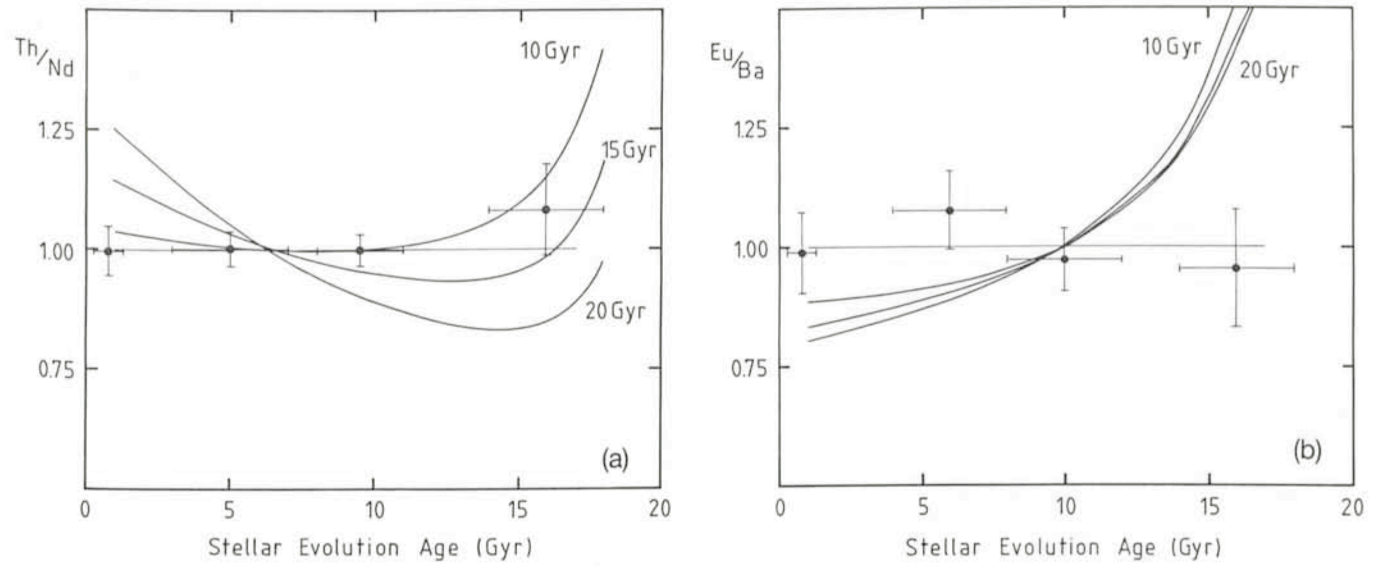

Figure 4: *Comparison of a galactic evolution model due to Mathews and Schramm with stellar abundance data. This model supposes that the r- and s-processes occur in stars of different masses, so that a gradual change in the contribution ratio for neodymium is predicted which will compensate thorium decay for ages up to 15 Gyr. The predicted Th/Nd ratio vs. age is shown in (a) for this model and three maximum ages. In (b) is shown the prediction for the stable r- and s-process elements, europium and barium. It is clear that such simple models will always have trouble providing nearly constant Eu/Ba and at the same time constant Th/Nd, unless the total age is so short that thorium has not had time to decay substantially in even the oldest stars.*

against the absence of a convincing mechanism in the traditional scenario for producing significant metallicity variations without altering the ratio of r- to s-process abundances. I suggest that all available data fit the initial spike model as well as they fit the synthesis in normal stars idea. One is then left in the amusing situation of having stars making helium, but with the vast majority of the helium around us having been produced in the Big Bang, and of supposing that although stars clearly make new elements via nuclear reactions, the majority of the heavy elements were made by some process preceding or accompanying the formation of the Galaxy. The short-lived radioactivities found in solar system material would then have their origins in such minor on-going synthesis as has taken place, and only a few species, such as the CNO isotopes, will have had their abundances measurably altered via stellar evolution.

What might the initial process be? A most exciting possibility has recently been proposed. Models concerning the quark-hadron phase transition in the Big Bang suggest that inhomogeneous conditions may have resulted during the epoch relevant to primordial nucleosynthesis (Applegate and Hogan, *Phys. Rev.*, **D 35,** 1151, 1985; Malaney and Fowler, preprint). In such conditions it appears possible to generate not only the light nuclei, but also to bridge the mass gap at atomic number 8, to produce heavy elements all the way up to U and Th. The very first generation of stars following the Big Bang would then have been responsible for the s-process elements seen in halo stars. Here is a plausible mechanism for synthesizing the r-process radioactivities which are used for cosmochronology in a single initial event. I for one will be following further studies of this idea with gleeful anticipation!

High Resolution CASPEC Observations of the z = 4.11 QSO 0000-26

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Introduction

The QSO Q0000-26 is a newly discovered object with an emission redshift of 4.11 and a continuum magnitude at ~ 6000 Å of around 17.5. The QSO was discoverd as part of a programme to detect bright (m(R) $\lesssim$ 18.5), high redshift (z $\gtrsim$ 3.5) QSOs using IIIa–F objective prism plate material taken with the UK 1.2-m Schmidt telescope at Siding Spring in New South Wales, Australia (Hazard and McMahon 1985). Q0000-26 was observed and confirmed as a high redshift QSO during an observing run on the Anglo-Australian Telescope in August last year. Fortunate timing of a run immediately following on the ESO 3.6-m telescope meant that we were able to collect the high resolution data we present here only a few days after the object was discovered.