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GALACTIC CHEMICAL EVOLUTION: AN ANALYTICAL MODEL

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RESUMEN

Este trabajo se refiere a las abundancias de hierro, oxígeno y elementos de partículas α en estrellas del halo galáctico y de los discos grueso y delgado, donde ha habido un gran progreso observacional en los años recientes; un modelo sencillo de evolución química de la galaxia puede ser ajustado muy bien a los modelos de supernovas de Thielemann, Nomoto y sus colegas.

ABSTRACT

This work relates to abundances of iron, oxygen and α-particle elements in stars of the galactic halo and thick and thin disks where there has been great observational progress in recent years; a simple galactic chemical evolution model can be fitted quite well to the supernova models of Thielemann, Nomoto and their colleagues.

Key words: **GALAXY: EVOLUTION — ISM: SUPERNOVA REMNANTS — NUCLEAR REACTIONS, NUCLEOSYNTHESIS, ABUNDANCES — STARS: ABUNDANCES**

1. INTRODUCTION

The theory of galactic chemical evolution (GCE) attempts to combine ideas on the end-products of stellar evolution with ideas on the formation and evolution of galaxies in order to understand the distribution of chemical elements in the interstellar medium and stellar populations. As this involves many uncertainties, I prefer to adopt the approach pioneered many years ago by M. Schmidt, L. Searle & W. Sargent, B. Tinsley, R. Larson, D. Lynden-Bell, D. Clayton and others, which is to parameterize the problem as simply as possible and to treat it analytically. This is somewhat unfashionable nowadays, but it has the advantage that one can immediately see which parameters are the important ones and where the uncertainties lie, which is not always the case in elaborate numerical models. The approach has been described in somewhat more detail by Pagel (1994).

The main ingredients of GCE models are: initial conditions, end-products of stellar evolution (cf., Woosley, Langer, & Weaver 1993; Thielemann, Nomoto, & Hashimoto 1995; Maeder 1992, 1993; Renzini & Voli 1981; Käppeler et al. 1990; Nomoto, Thielemann, & Yokoi 1984; Thielemann, Nomoto, & Yokoi 1986), initial mass function (e.g., Kennicutt 1983; Scalo 1986; Kroupa, Tout, & Gilmore 1991), star formation rates or laws (Schmidt 1959; Kennicutt, Tamblyn, & Congdon 1994; Sommer-Larsen 1995), and the galactic context. The latter concerns the nature of the region to be considered, its environment and history, e.g., whether it has evolved in a closed box or has been subjected to inflows and/or outflows as in dynamical collapse models. Following Tinsley (1980) I shall treat the region of interest as a cylinder through the Sun perpendicular to the galactic plane, although Gilmore has recently pointed out that a "solar sausage" would be a better picture. The relationship between different stellar populations is an important input into GCE models.

2. INSTANTANEOUS RECYCLING AND DELAYED PRODUCTION APPROXIMATIONS

Analytical treatments have traditionally used the instantaneous recycling approximation, in which the stellar-dependent ingredients can be summarized in a few parameters, namely the yields (as defined by Searle & Sargent 1972) for various elements and the lock-up fraction which is assumed to be constant, and they have been roundly criticized for doing so, basically because instantaneous recycling gives a poor picture of recycling from intermediate and low-mass stars and cannot account for the systematics of iron abundance relative to oxygen and α-particle elements, which are generally believed to arise from the major contribution to solar iron abundance from supernovae type Ia (SN Ia) which have a significant evolution time (Tinsley 1979; Matteucci & Tornambé 1987). However, as long as the gas fraction is not too small, it does give a fair account of typical SN II products like oxygen and magnesium, and for metal-deficient stars born too early to have been affected by SN Ia it works for the iron group as well. Where it breaks down is, obviously, when SN Ia do contribute and thus lead to time and hence metallicity dependences of primary-element ratios like α/Fe or O/Fe, which has been known from observations for a very long time (cf. Aller & Greenstein 1960; Wallerstein 1962; Gasson & Pagel 1966; Conti et al. 1967). Pagel (1989a) introduced a "delayed production approximation" in which the star formation rate at time t in chemical evolution equations is simply replaced by the star formation rate at time $t - \Delta$, where Δ is some constant, i.e., the current death-rate, and the outcome then depends on a prompt yield p_1, a delayed yield p_2 and the dimensionless product $\omega\Delta$ where ω is just the transition probability per unit time for gas to be locked up in stars, and is of order $(3\ \mathrm{Gyr})^{-1}$.

3. "SIMPLE" AND INFLOW MODELS

The "Simple" model assumes a closed box, well mixed, with constant yields, starting from pure gas with primordial composition. This model has long been known to be in conflict with the distribution function of abundances of long-lived stars in the solar neighborhood, the classic "G-dwarf problem" (van den Bergh 1962; Schmidt 1963; Pagel & Patchett 1975). Solutions proposed include the following:

1. No problem because the older stars have migrated away (Grenon 1989, 1990).
2. Larger yields at low metallicities (Schmidt 1963; Maeder 1992).
3. Prior enrichment from the halo or preferably the bulge (Köppen & Arimoto 1990).
4. Inflow associated with a gradual formation of the disk involving accretion of unprocessed (or less processed) material. This is the most interesting solution because it can be related to models of formation of the Galaxy by dynamical collapse and it readily accommodates the small tail of metal-weak stars that does exist, representing both the halo and the metal-weak extension of the thick disk. Analytical formulations have been given by Lynden-Bell (1975), Clayton (1985) and others; I have found Clayton's formalism particularly convenient.

4. RECENT DEVELOPMENTS

So far, main-stream GCE models for the solar neighborhood have used the idea of inflow in some form, inspired by notions of the formation of the Galaxy by dynamical collapse which go back to the classic works of Eggen, Lynden-Bell, & Sandage (1962) and Larson in the 1970's. Since then, various complications have emerged, e.g., identification of the "thick disk" (Gilmore & Reid 1983) which was missed in the proper motion catalogues used by ELS (although long known to B. Strömgren as "Intermediate Population II") and the suggestion by Searle & Zinn (1978) that some or all of the halo comes from mergers of dwarf galaxies or small fragments accumulated over a long period of time. The halo and the disk (including the thick disk) have distinct dynamical properties, as is revealed in plots of rotation velocity against metallicity (Carney, Latham, & Laird 1990; Nissen & Schuster 1991), but overlap in either coordinate taken separately. The distributions of specific angular momentum in the halo and bulge are similar to each other, but very different from that of the thin or thick disk (Wyse & Gilmore 1993). Thus the old idea of a gradual collapse leading through the halo to a subsequent disk phase no longer seems plausible; rather, the halo and the disk seem to have gone their separate ways. At the same time, more extensive surveys of proper motion stars (Sandage & Fouts 1987; Carney et al. 1990; Nissen & Schuster 1991) and kinematically unbiased objective-prism surveys (Norris, Bessell, & Pickles 1985; Morrison, Flynn, & Freeman 1990; Beers & Sommer-Larsen 1995) have revealed an ever-increasing degree of overlap in metallicity between the thick disk and the halo. In particular, Beers & Sommer-Larsen have found that about 30 % of metal-deficient stars within 1 kpc of the galactic plane having $-\infty <$ [Fe/H] ≤ -1.5, as well as essentially all stars with $-1.0 \leq$ [Fe/H] ≤ -0.5, belong to the thick disk dynamically. Thus the evolution of the solar neighborhood seems to have begun from primordial abundances, without any prior contribution from halo gas, and a pure disk model should therefore cover all metallicities including those previously ascribed to the halo. Unfortunately it is not known yet whether there are actually chemical differences between disk and halo stars with the same metallicity!

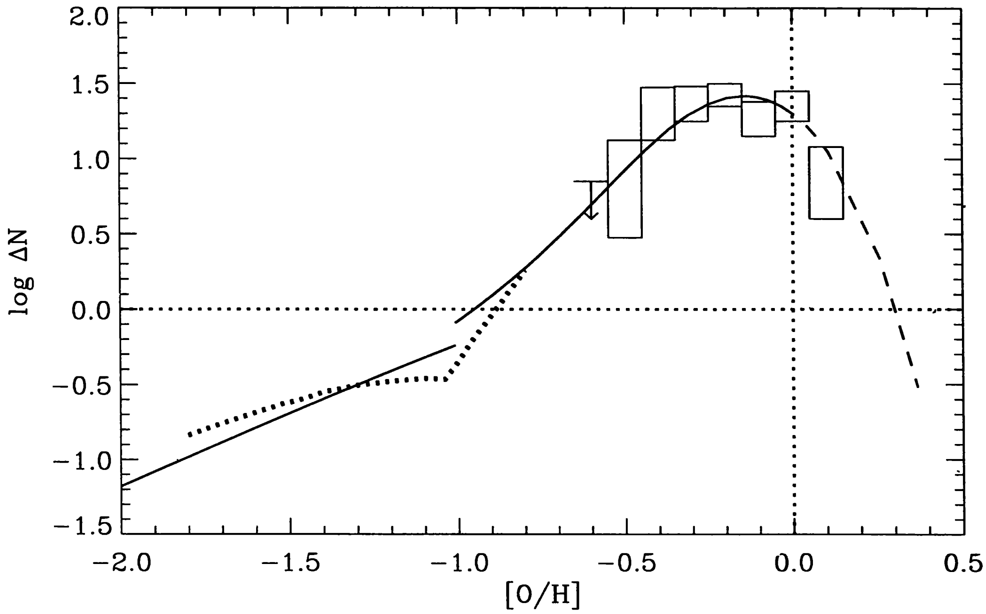

Fig. 1. Oxygen ADF for 132 G-dwarfs in the solar cylinder. Boxes show observed numbers with error limits after Sommer-Larsen's (1991) rediscussion of data derived originally by Pagel & Patchett (1975), and the dotted curves on the left of the diagram show the extension to the metal-weak thick disk after Beers & Sommer-Larsen (1995). The solid curve shows the ADF from our model assuming a present-day gas fraction of 0.11; the broken curve on the right shows a hypothetical extension to lower gas fractions.

Another development that encourages a new look at the chemical evolution of the Galaxy is the monumental study of abundances in disk stars by Edvardsson et al. (1993) in which some very clear patterns emerge for the behavior of various element/iron ratios as a function of [Fe/H] for [Fe/H] ≥ -1 or so, clearer than from the data that were available to Wheeler, Sneden, & Truran (1989) in their classic discussion. The patterns can be extended to lower metallicities (halo and metal-weak thick disk) using a variety of data from the literature which display rather more scatter, presumably due to some combination of real effects with larger uncertainties in the determinations. In an investigation recently completed in collaboration with Grazina Tautvaišienė from Vilnius, Lithuania, we have concentrated our attention on oxygen, α-particle elements, iron and r-process elements, which we believe can be reasonably understood in terms of a model with constant yields and time delays (Pagel & Tautvaišienė 1995). For elements affected by the s-process, the situation is more complicated and we are still thinking about it.

The distinctive features of our model are designed to fit the abundance distribution function (ADF) for oxygen (computed in instantaneous recycling) shown in Figure 1. The main body of G-dwarfs is fitted by a model of Clayton's "standard" type with his k-parameter equal to 3 and with a final mass equal to 7 times the initial mass. That initial mass, however, is allowed to evolve according to the "Simple" model up to [O/H] $= -1.0$ so as to fit Beers & Sommer-Larsen's low-metallicity tail. The star formation rate is assumed to be proportional to the mass of gas, with a coefficient $\omega = 0.3$ Gyr^{-1} in the solar neighborhood (with an age of 15 Gyr) and $\omega = 0.45$ Gyr^{-1} in the inner galactic disk (with an age of 16.5 Gyr), leading to the age-metallicity relations for disk stars shown in Figure 2. The overall fit is good, but the scatter is real and large and requires a separate discussion.

Figure 3 shows the same two age-metallicity relations from the model, plotted against relative zinc abundances measured in high red-shift absorption-line systems by Pettini et al. (1994). Here the lengths of the horizontal lines representing each data point represent the possible range in age of the universe (in units of its present age t_0) between an open model and an Einstein–de Sitter model and the horizontal placement of the curves is somewhat arbitrary. Some of the objects are readily fitted by this model, but it is also clear that the evolution of quasars, on the one hand, and of dwarf galaxies on the other, has been on totally different time-scales. One might guess that the damped Lyman-α systems that appear here are a mixture of proto-spirals destined to become like our own Galaxy and dwarf systems.

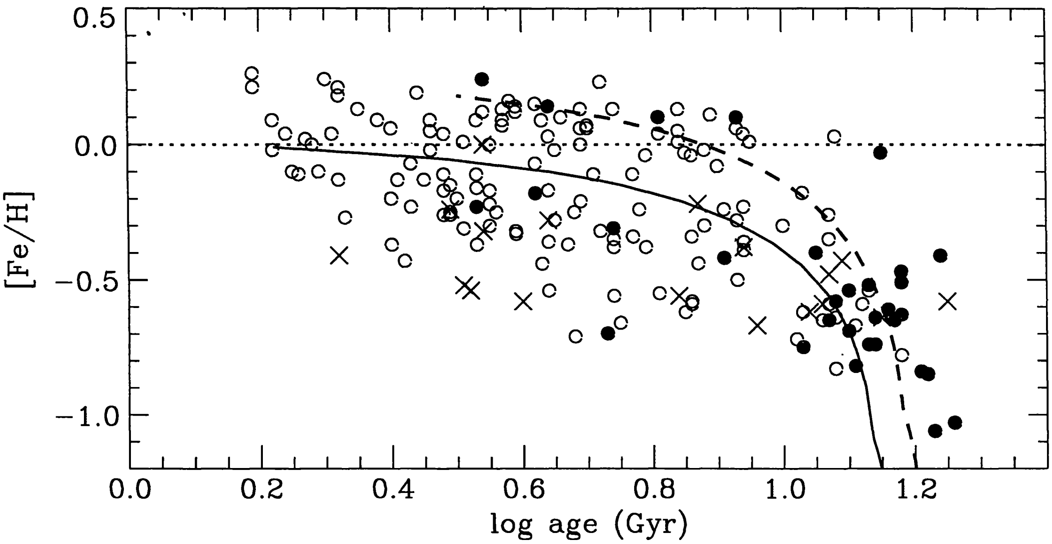

Fig. 2. Age-metallicity relations from our model, full-drawn curve for the solar neighborhood and broken curve for the inner galactic disk. Crosses, open and filled circles show corresponding data from Edvardsson et al. (1993) for stars with mean galactocentric distances $\geq$ 9 kpc, 7 to 9 kpc and $\leq$ 7 kpc respectively.

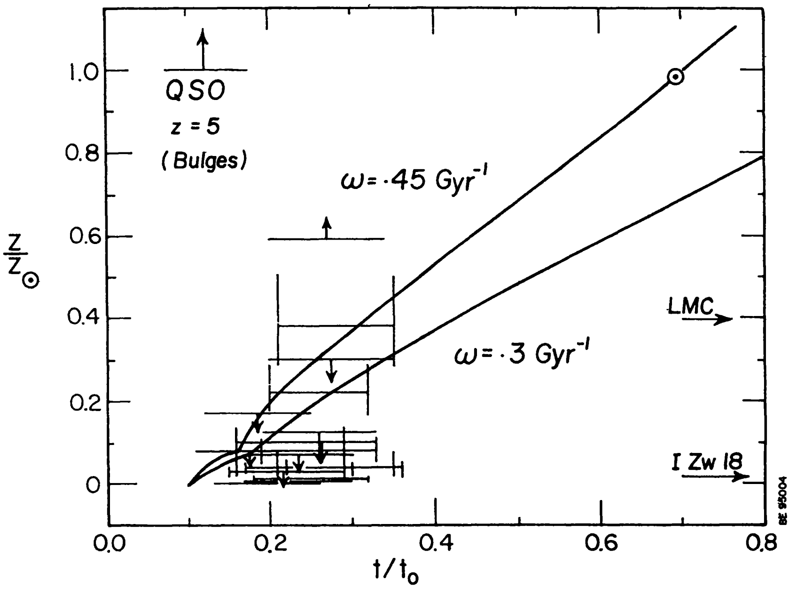

Fig. 3. Age-metallicity relations from the model (as in Fig. 2) compared with abundances in high red-shift absorption-line systems and other typical objects.

TABLE 1

YIELDS AND TIME DELAYS

El.	$p_1/Z_\odot$	$p_2/Z_\odot$	$\omega\Delta$ $R_m \geq 7$ kpc	$\omega\Delta$ $R_m < 7$ kpc
O	0.70	0.00	—	—
Mg	0.88	0.00	—	—
Si	0.70	0.12	0.4	0.6
Ca	0.56	0.18	0.4	0.6
Ti	0.70	0.12	0.4	0.6
Fe	0.28	0.42	0.4	0.6
Eu	0.08	0.66	0.008	—

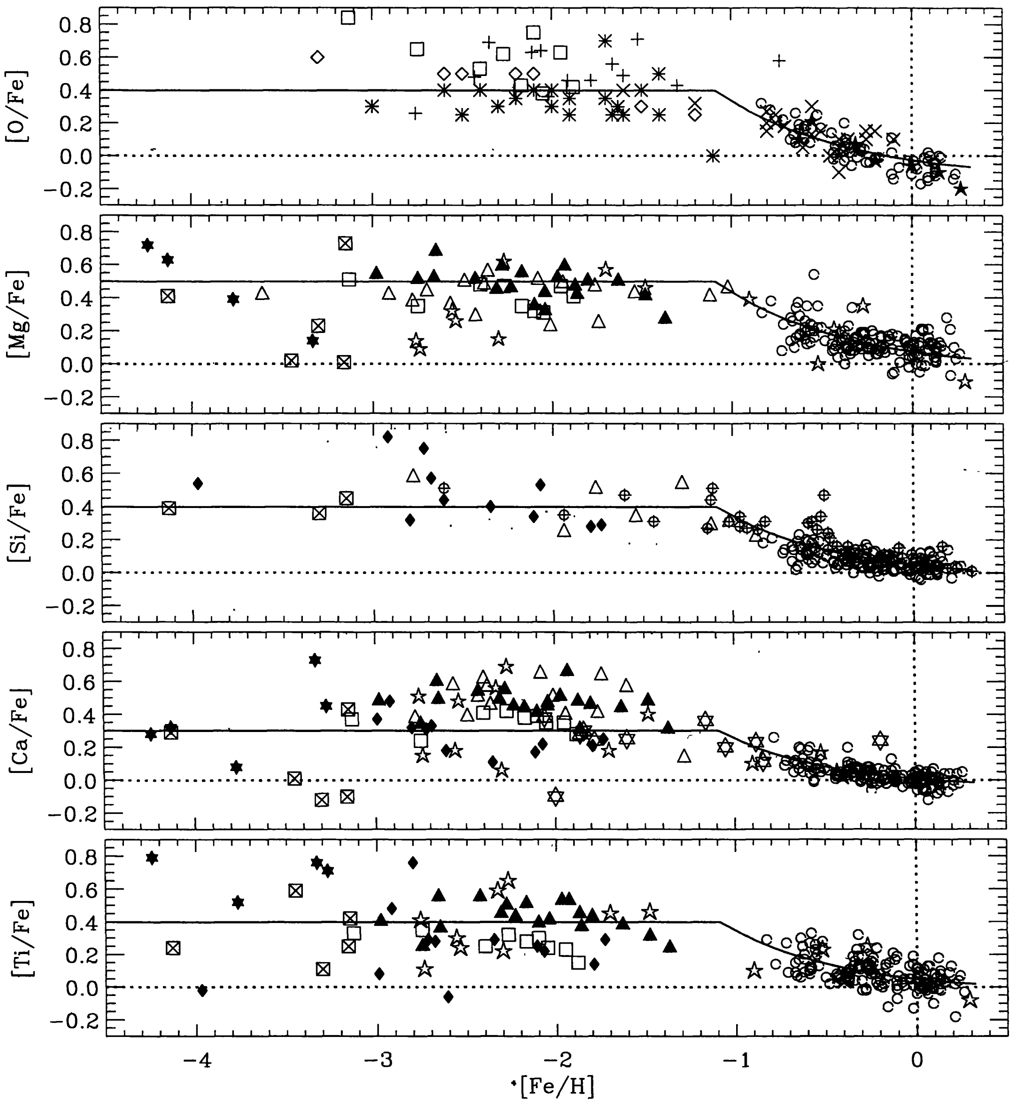

Fig. 4. Abundance ratios relative to iron plotted against metallicity [Fe/H] for nearby disk stars and extension to [Fe/H] = −4.5. Symbols indicate various data sources: *open circles*, Edvardsson et al. (1993) for $R_m \geq 7$ kpc; *crosses*, Barbuy & Erdelyi-Mendez (1989); *asterisks*, Barbuy (1988); *open squares*, Nissen et al. (1994); *"plus" signs*, King 1993; *open diamonds*, Bessell et al. (1991); *filled 5-cornered stars*, Kyröläinen et al. (1986); *open 5-cornered stars*, Tautvaišenė & Straižys (1989); *filled triangles*, Magain (1989); *open triangles*, Magain 1987; *crosses in squares*, Primas et al. (1994); *filled 6-cornered stars*, Norris et al. (1993); *"plus" signs in circles*, François (1986); *filled diamonds*, Gratton & Sneden (1988); *"stars of David"*, Hartmann & Gehren (1988).

Our fits to element/element ratios are based on ad hoc yields (p_1 prompt and p_2 with a time-delay Δ) given in Table 1. The values of $\omega\Delta$ for the elements from Ca to Fe represent an actual time delay Δ of 1.3 Gyr for SN Ia with ω values of 0.3 and 0.45 Gyr^{-1} in the solar neighborhood and in the inner galactic disk respectively, while the $\omega\Delta$ value for Eu represents a time-delay Δ of 27 Myr for the low-mass Type II (or related) supernovae that seem to be the best candidates for the r-process (Mathews, Bazan, & Cowan 1992). However, these Δ values must be regarded as quite rough, because of uncertainty about ω and its constancy.

Figure 4 shows the fit of our model to data for the solar neighborhood and for the halo and metal-weak thick disk. For [Fe/H] ≥ -1 there seems to be a good fit with little ambiguity, whereas for lower metallicities the scatter of the observational data is significant and we have had to make somewhat arbitrary choices based on the parameters that give the best fit to the disk stars. Thus our model does not allow for a continuous increase in [O/Fe] towards the lowest metallicities, such as has recently been claimed rightly or wrongly by King (1994).

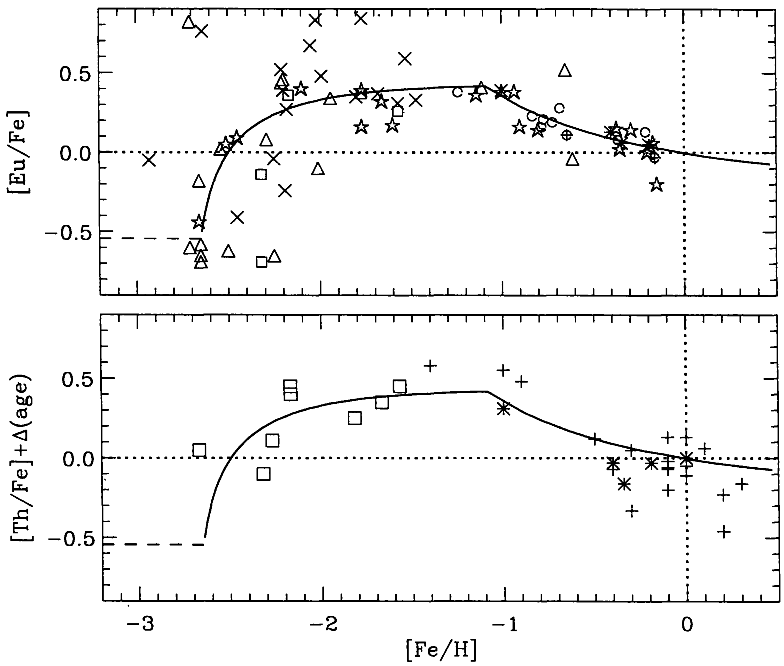

Fig. 5. Europium and thorium to iron ratios plotted against metallicity. Symbols represent various data sources: *5-cornered stars*, Gratton & Sneden (1994); *open triangles*, Luck & Bond (1985); *crosses*, Gilroy et al. (1988); *open circles*, Tautvaišenė, in preparation; *"plus" signs*, Morell et al. (1992); *asterisks*, da Silva et al. (1990); *open squares*, François, Spite, & Spite (1993).

Such a trend might be expected from deficiencies in the instantaneous recycling approximation at very early times, when only the most massive SN II have evolved, but it could equally be masked by a dispersion in ages. Observations of [FeIII] lines in dwarf HII galaxies (Thuan, Izotov, & Lipovetsky 1995) fit our model very well as far as the data go, i.e., down to [Fe/H] = -1.8. Our ad hoc yield ratios p_1/p_2 for iron, silicon and calcium are in excellent agreement with those of SN Ia and SN II computed theoretically by Thielemann, Nomoto, & Hashimoto (1995) as reported in Tsujimoto (1993) for relative supernova rates of 1 to 5 for type Ia/type II, which is in good agreement with direct observation (van den Bergh & McClure 1994) and with the conclusion already drawn by Tsujimoto on the basis of solar abundances. There is a discrepancy for titanium (also present in the solar abundances) which must reflect a deficiency in the current nucleosynthesis models, where Ti is underproduced in SN II.

Figure 5 shows our fits to the r-process elements Eu and Th, the thorium data having been shifted upwards by small amounts to allow for radio-active decay after Pagel (1993) and the fit (with or without these shifts) is remarkably good. Some of the scatter in [Eu/Fe] could well be real, in view of the existence of the remarkable r-process star CS 22892-052 (Sneden et al. 1994), but the fit to the data of Gratton & Sneden (1994), which are probably the best, is very close.

In conclusion, we believe that we have identified effects of galactic chemical evolution involving simple time delays on a number of element:element ratios involving hydrostatic and explosive nucleosynthesis in core-collapse and Type Ia supernovae, and that the theoretical models of Thielemann, Nomoto, & Hashimoto fit the data very well, apart from titanium. The general idea of a small time delay for the r-process also appears to work well. Edvardsson et al. give results in addition for a number of other elements such as Na, Al and elements affected by the s-process. Their galacto-chemical history looks more complicated and will be the subject of future work that we plan.

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