Galactic Cosmochronometry from Radioactive Elements in the Spectra of Very Old Metal-Poor Stars

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Abstract

In a short review of neutron-capture elemental abundances in Galactic halo stars, emphasis is placed on the use of these elements to estimate the age of the Galactic halo. Two prominent characteristics of neutron-capture elements in halo stars are their large star-to-star scatter in the overall abundance level with respect to lighter elements, and the dominance of r-process abundance patterns at lowest stellar metallicities. The r-process abundance signature potentially allows the direct determination of the age of the earliest Galactic halo nucleosynthesis events, but further developments in r-process theory, high resolution spectroscopy of very metal-poor stars, and in basic atomic data are needed to narrow the uncertainties in age estimates. Attention is brought to the importance of accurate transition probabilities in neutron-capture element cosmochronometry. Recent progress in the transition probabilities of rare earth elements is discussed, along with suggestions for future work on other species.

1. Introduction

The very heavy radioactive elements thorium and now uranium have been detected in metal-poor stars that almost surely were born soon after the initial formation of our Galaxy. The most abundant isotopes of these and almost all other elements with atomic numbers $Z > 30$ are created almost exclusively in neutron bombardment reactions. The comparison of Th and U abundances to those of lighter stable neutron-capture (n-capture) elements may in principle be used to derive age estimates for the Galactic halo.

Much progress has been made in recent years in radioactive element cosmochronometry, leading to reported metal-poor star age estimates in the range of 11–16 Gyr. But uncertainties in these estimates are still large (typically ± 3 Gyr). If this Galactic age technique is to rival other more indirect age indicators, further work is needed in many areas: identification of suitable candidate metal-poor stars, acquisition of stellar spectra with the requisite resolution and signal-to-noise, derivation of accurate stellar atmosphere models, theoretical prediction of n-capture element production, and determination of reliable atomic transition parameters for as many n-capture species as possible. In this review we first sketch the general trends in n-capture element abundances in metal-poor stars, and outline the basic techniques of Th & U age assessments in stars. After briefly touching on desired advances in stellar observations, spectrum analysis, and element predictions, we concentrate on discussing the application of state-of-the-art atomic transition parameters for n-capture elements to questions of the age and chemical history of the Galaxy.

2. Abundance Trends for n-Capture Elements in Halo Stars

Halo stars will be considered here to be those with metallicities $[\mathrm{Fe/H}] \leq -1.5$, where we adopt standard stellar spectroscopic definitions that $[\mathrm{A/B}] \equiv \log_{10}(\mathrm{N_A/N_B})_{\mathrm{star}} - \log_{10}(\mathrm{N_A/N_B})_{\odot}$, that $\log \epsilon(\mathrm{A}) \equiv \log_{10}(\mathrm{N_A/N_H}) + 12.0$, for elements A and B, and that stellar metallicity may be (arbitrarily) assigned to the [Fe/H] value of a star. The $[\mathrm{Fe/H}] \leq -1.5$ metallicity limit mostly avoids questions of contamination of true Galactic halo stars by members of the thick disk populations. For halo stars, the dominant characteristics of n-capture element distributions are the large star-to-star scatter in their bulk levels compared to Fe-peak elements, and their non-solar detailed abundance ratios.

The great variation in overall n-capture abundances with respect to lighter elements is now firmly established [1–4], but with the benefit of hindsight one can see evidence for this effect in much earlier published works. For example, pioneering high resolution studies [5-6] of the bright very metal-poor ($[\mathrm{Fe/H}] \simeq -2.7$) giant HD 122563 found $[\mathrm{Eu/Fe}] \simeq -0.4$, but

HD 115444, a star with only slightly smaller metallicity ([Fe/H] $\simeq$ –2.9) was found [7] to have [Eu/Fe] $\simeq$ +0.7. As more very metal-poor stars have been studied, it has become clear that the range in [n-capture/Fe-peak] is at least two orders of magnitude from star-to-star (e.g., see Figures 14 and 15 in [2]). The reality of the scatter can be easily demonstrated by comparisons of spectra of stars with similar metallicity and atmospheric parameters but different amounts of n-capture elements (e.g. Figure 3 of [4]). So far no obvious correlation of variable n-capture abundance level with other stellar characteristic has emerged. In particular, knowing the [Fe/H] value for a particular halo star apparently gives one no immediate insight into its n-capture abundances.

Not established yet is the metallicity regime at which the large variations first appear in [n-capture/Fe-peak]. The n-capture elements exhibit little star-to-star scatter in high metallicity ([Fe/H] $\geq$ –1.0) disk stars [8], but certainly significant scatter is evident for stars with ([Fe/H] < –2.0). This scatter provides some of the most convincing evidence for the effects of "local" nucleosynthesis events in an apparently poorly mixed early Galactic halo interstellar medium.

Not only do overall n-capture levels vary from star-to-star, but their abundance distribution in a given star is often very different than in the solar system. These elements are almost exclusively produced in neutron bombardment reactions, but the fusion conditions can vary widely. In the so-called s-process, the neutron flux is weak enough so that nuclei unstable to β-decay reactions will have sufficient time to do so between successive neutron captures. Synthesis of the n-capture nuclei proceeds on well-defined paths along the valley of β stability. Alternatively in the other extreme labeled the r-process, a huge but short-lived neutron flux temporarily overwhelms β-decays, driving nuclei out to the "neutron drip line"; subsequent β-decays after shutoff of the neutron source move the nuclei back toward the valley of β stability. However, some nuclei are much more easily (sometimes exclusively) synthesized in the s-process, while others are more abundantly built by the r-process. This leads to sometimes strikingly different total elemental abundance distributions from these two types of synthesis events.

In solar-system material, a few easily observed elements appear to have been created predominantly by one process or the other, while others seem to be due to a mix of r- and s-processes. The breakdown by synthesis process has been studied by several groups [9,10,4], and in Figure 1 we summarize the solar-system r-process fractional contributions to n-capture elements, adapted from [4]. It is clear from this figure that in the rare-earth element domain, spectroscopically observable elements such as Ba, La, and Ce were predominantly produced in the s-process, while Eu, Gd, and Dy were synthesized by the r-process.

Assessment of the relative r- and s-process contributions to n-capture elements in stars has until recently mostly been a matter of deriving values of [Ba/Eu], using this ratio to make general conclusions about the entire n-capture element domain. In doing so, it has been long established [11] that [Ba/Fe] is often (usually?) negative at least for stars with [Fe/H] < -2. This has led to the conclusion that r-process synthesis dominated early Galactic production of the n-capture elements. Significant exceptions to this general trend are known to exist in the discovery of carbon-rich metal-poor stars that have high ratios of [Ba/Eu], probably indicative of s-process activity in prior evolved intermediate mass stars that was transfered to the stellar companions observed today (e.g. [12]). These are interesting stars but are beyond the scope of this review.

Recent detailed spectroscopic studies of some halo stars with sub-solar [Ba/Eu] values have established that at least among elements with Z $>$ 56, the abundances of all of the observable stable elements are consistent with the same sort of r-process nucleosynthesis pattern seen in solar-system material (e.g. [13-18]). This abundance distribution is seen so often that possibly nature may know "only one" way to both synthesize n-capture elements in conditions of very high neutron flux *and* expel them into the interstellar medium. The full r-process cannot be reproduced in laboratory conditions, and is difficult to model theoretically. Moreover, the astrophysical site of the r-process is still not known, although suggestions are not lacking (Type II supernovae [19-21]; neutron star mergers [22]; explosive He burning in massive stars [23]). The repeated pattern of the solar system abundance r-process distributions in very metal-poor stars provides a severe constraints on the entire r-process production and distribution scenario.

A dominant r-process abundance set of n-capture elements observed in a star's atmosphere cannot have been created in the interior of that star; the explosive nature of the r-process precludes it. Thus, the most r-process-rich stars not only have obtained their n-capture elements from a local synthesis event, but that event in some way (not well established at present) probably was associated with some aspect of the formation of a neutron star or black hole in a supernova explosion. An interesting observational test might be a radial velocity variability study of the most r-process-rich stars, in order to search for unseen compact object companions to these stars. For example, the extremely r-process-rich very metal-poor giant CS 22892-052 [15,16] has sinusoidal radial velocity variations with an apparent period of 128 days [24]. This is very suggestive of the presence of a companion object, but unfortunately no mass for the secondary can be estimated from the data available at present. Indeed, since the semi-amplitude of the radial velocity variations is only 1.0 km s^{-1} [24], the suggested orbital motion of CS 22892-052 is in need of confirmation.

Further discussion on the mechanics of r-process synthesis will not be pursued here; see [25] and [26] for further discussion. Instead the next section discusses cosmochronometry from comparisons between abundances of stable and radioactively decaying n-capture elements.

3. Stellar Ages from Abundances of Thorium and Uranium

In principle it is straightforward to apply techniques of Th & U cosmochronometry to a star whose n-capture elements were created in a single prior synthesis event. First, one must derive accurate abundance of Th, and if possible U also. Then these abundances need to be compared to those created in the original synthesis event, via

$$N_{\rm X,now}/N_{\rm X,creation} = exp(-t/\tau(X)_{\rm mean})$$

For example, $\tau(\mathrm{Th})_{1/2}$ = 14.0 Gyr, and after translation to a mean lifetime,

$$N_{\rm Th,now}/N_{\rm Th,creation} = exp(-t/20.3Gyr)$$

A similar equation would be written for U, with $\tau(\mathrm{U})_{1/2}$ = 4.5 Gyr.

Unfortunately, the geologist's method for establishing $N_{\rm X,creation}$ from measuring the total parent+child elemental abundance cannot be employed here. The chief decay product of Th and U is Pb, which is very difficult to observe spectroscopically. More importantly, Pb does not just grow from Th and U decay, but in fact is a direct product of the s- and r-processes. Therefore unfortunately the initial abundances of Th and U must be estimated indirectly. Since U has been detected in only one r-process-rich star to date (see below), the usual technique for a star with a measured Th abundance is to determine abundances for as many lighter stable n-capture elements as possible, and then to extrapolate this abundance pattern out to Th. The first attempt in this manner [27] was done for disk stars, employing only Nd as a comparison element. Since Nd is a product of both s- and r-processes, and since the Th abundance in a high metallicity disk star is a complex integration over multiple synthesis events and thus various decay time scales, most subsequent investigations (e.g. [28]) have concentrated on at least using "pure" r-process products such as Eu to compare with Th.

There is some inherent uncertainty in using a stable element nearly 30 atomic numbers away from Th and U when attempting to probe stellar ages. Thus, several studies have attempted to push the known n-capture abundance range out to the "third n-capture peak", Os–Pb. These are the heaviest stable elements and are much closer in nuclear mass to Th and U than, for example, the rare-earth elements. As mentioned in the previous section, some detailed spectroscopic investigations of very metal-poor giant stars (CS 22892-052 [16], HD 115444 [17], BD+17^{o}3248 [29], and $\simeq$20 other halo giants with metallicities [Fe/H] $\leq$ –1.6

[18]) have yielded observed abundance distributions that are very good matches to the solar system r-process-only abundances. This suggests that one may extrapolate the solar system curve out to the actinide element domain to establish the zero-decay-age Th abundance for these stars. Doing this yields implied ages in the range 11–16 Gyr. The $\simeq$5 Gyr range is large enough to be consistent with more indirect methods for Galactic age estimates, such as globular cluster color-magnitude diagram modeling.

There are some important uncertainties to keep in mind in this kind of exercise. First, the age computation involves an exponential, so that any small error in the observed Th abundance translates to a large age error. Second, it is not easy to conclusively establish that the extrapolation of the solar system abundance distribution to Th is correct for the r-process events that occurred in the early Galaxy. Indeed some have argued [30] that the production of Th is sensitive to many details of the synthesis event, and is difficult to predict even with knowledge of the abundances of many lighter elements. On the other hand, investigation of nuclear models [25] suggests that the production of Th is not alterable at will, and in fact is reasonably the same for realistic simulations of r-process synthesis events.

A major new observational development has been the detection [31] of not only Th but also U in the very metal-poor giant CS 31082-001. The Th/U production ratio probably can be estimated with much greater reliability than can Th/Eu or similar ratios of Th with respect to lighter stable elements (see [29] for further discussion of this point). The observed Th/U ratio in CS 31082-001 (which should be sensitive function of age, given the very different decay rates of Th and U), is consistent with an age of 12-13 Gyr for this star [31]. This agreement with the Th-based ages for other metal-poor stars is encouraging, but detection of U in more stars would obviously be welcome.

Since the present review emphasizes the observational aspects of radioactive element cosmochronometry, detailed discussion about theoretical predictions of Th and U abundances will be deferred to other papers (e.g. [32]). Given the difficulty in making r-process predictions from laboratory data, and the enormous range in n-capture abundance levels in metal-poor stars, radioactive element cosmochronometry probably will be shown to yield reliable ages of Galactic halo stars only when the distribution of the entire range of n-capture elements is understood in a large number of stars over the entire halo metallicity range.

A future goal of r-process observational studies will be to discover whether or not significant exceptions to the solar-system r-process abundance pattern exists in halo stars. The exceptions, or possibly lack thereof, will empirically establish the limits that nature imposes on r-process production in the Galaxy. If the solar-system pattern pattern extends over all stable heavy n-capture elements in r-process-rich stars, then abundances of unstable Th and U may be compared with confidence to *any* of the stable elements with $Z > 56$ in cosmochronometry studies. If the pattern is often broken, only comparisons of Th and U to the closest neighboring stable elements in the periodic table can yield age estimates with confidence. In the next sections we will discuss two aspects of this problem: obtaining the stellar spectra, and improving the laboratory data of important n-capture species.

4. Candidate Stars for Cosmochronometry

Since the goal is to use stellar abundances of thorium and uranium to derive radioactive decay-based ages for the Galaxy, samples of stars are needed with the following characteristics: (a) birth epochs as near as possible to the formation of the Galaxy; (b) evolved evolutionary states; (c) relatively high abundance ratios of n-capture elements to those of the Fe-peak; and (d) apparent brightness large enough to permit the requisite spectra to be acquired.

Galactic halo stars provide the obvious target sample, but there may exist a significant age range in the general halo field population. Color-magnitude diagram analysis can provide age estimates for stars that are members of clusters, but this is not possible for field stars. Metallicity and kinematics are observationally the best stellar age surrogates, and so major surveys have concentrated in these areas. Metallicities for nearby halo stars have been determined in a large survey [33] of high proper motion stars. Parallaxes exist for many of these stars, yielding the definite advantage of the ability to compare abundance characteristics with kinematics. However, these stars are most often relatively unevolved main sequence dwarfs, turnoff stars, and subgiants. As such, they have relatively high gravities, and thus have narrow, high density atmospheres that produce weak-lined spectra that favor transitions of neutral atoms over the ionized species that account for the majority of n-capture element lines in the visible spectral domain.

Giants should be better candidates for detections of Th and U in halo stars, because they have deep, low density atmospheres that produce much stronger ionized line spectra than do the higher gravity stars. A Galactic pole region objective prism survey ([34] and references therein) has provided an appropriate (and very large) sample of low metallicity giants far out into the Galactic halo. This stellar database is now being explored at medium and high spectral resolution to elucidate the abundance trends over a range of metallicities. Most attention to date has centered so far on stars with $[Fe/H] < -2.5$ in this sample, since higher metallicity domains have been studied extensively with target lists of more nearby (and brighter) field halo giants (e.g. [35])

Of the Galactic pole giant star sample, only low metallicity stars with “super-solar”

n-capture elemental abundances are suitable for Th and U age estimates. The reason is simply that only those stars with [n-capture/Fe-peak] $\gg 0$ AND [n-capture/C] $\gg 0$ can produce Th II and U II features that are significantly stronger than the large number of contaminating lines that surround them. We illustrate this effect in Figure 2, which shows the spectrum of the 4019.12 Å Th II line in the Sun and four metal-poor giants. The figure notes not only the stellar [Fe/H] metallicity but also the [Eu/Fe] value, standing as a simple measure of the overall [n-capture/Fe-peak] level. The 4019 Å line is by far the strongest Th II line in cool stars, but unfortunately it is part of a complex atomic and molecular feature blend, which probably includes lines of V I, Mn I, Fe I, Fe II, Co I, and Ni I [28,36], perhaps Tb II and/or Ce II [15], and ^{13}CH [37]. Absorption from the Th II line is visible in the solar spectrum displayed at the bottom of this figure, but it comprises only a small fraction of the total feature at this wavelength. Very accurate Th abundances may not easily be determined from the solar photospheric spectrum.

The Th II line cannot detected at all in the halo giant HD 122563 (Figure 2, top spectrum), which has been the subject of numerous abundance analyses. This star has an underabundance not only of Eu as indicated in the figure, but of all of the heavier n-capture elements ([17], and references therein). That paper showed through comparisons of synthetic and observed Th II spectra that the entire 4018.9–4019.3 Å absorption can be accounted for without invoking the presence of the Th II line. The n-capture-rich stars shown as the middle three spectra of Figure 2 (HD 115444 [17]; BD+17^{o}3248 [18,29]; CS 22892-052, [15,16]) have clearly detected Th II lines. However, even in these cases the Th II absorption is not isolated, and significant contamination still exists. Particular attention needs to be paid to the ^{13}CH lines in C-rich stars such as CS 22892-052; in some cases the ^{13}CH absorption can overwhelm the rest of the components of the 4019 Å blend [37].

Finally, the spectra displayed in Figure 2 demonstrate that in almost all cases the Th II line will attain a central depth of $\leq$10%. This weakness combined with the complexity of the contaminant features mandates the acquisition of high resolution (R $\lambda/\Delta\lambda > 40{,}000$), high signal-to-noise (S/N > 100) if reliable Th abundances are to be obtained from the 4019 Å line. Other Th II lines, e.g. 4086.6 Å, are detectable if the Th abundance is very large, but they are all weaker and have their own line contamination problems.

The observational situation for U is even more difficult. The only reasonably strong U II line in most cool stellar spectra, 3859.6 Å, lies in the middle of the strong CN blue system Δv = 0 sequence. Therefore the U II line will be totally obliterated in most spectra of cool stars. The presence of this line in CS 31082-001 (Figure 1 of [31]) is a happy but probably rare conjunction of very low metallicity ([Fe/H] = –3.1), effectively absent CN bands near 3860 Å, and extreme overabundances of all elements with Z $\geq$ 56 (e.g., [Os,Ir/Fe] $\sim$ +2.0).

5. Atomic Transition Data

Until very recently, n-capture abundance analyses had to use very scattered laboratory transition probabilities for many species, and several important transitions had no reliable gf values at all. Moreover, the necessary hyperfine and isotopic structure information needed to derive reliable abundances from strong (saturated) lines was sparse. Happily, several atomic physics groups are now publishing extensive data for especially the rare earths, and in the process bringing the transition parameters to the level required by the new high resolution stellar spectra.

In this section we will discuss some of these new data, and suggest some needs for future work in this area. Pending publication of the full abundance results for CS 31082-001 [31], the r-process-rich ultra-metal-poor giant CS 22892-052 is the halo star with the most detections of n-capture elements. Nearly all other metal-poor stars are likely to yield fewer detections. and the combination of element detections in CS 22892-052 [16] and HD 115444 ([17]) should cover nearly all n-capture elements that are likely to be analyzed in metal-poor star spectra. We concentrate on those species discovered in those two stars.

The discussion of new atomic data will emphasize the new results of the Wisconsin group, but excellent data are being published by other atomic physics teams as well. A good survey of literature data for lines arising from lowest energy states of n-capture species (often those lines that are most easily observed) is given in [38]. The reader is urged to consult that discussion for many elements. Some further comments, and attempts to reconcile some conflicting literature gf data are in [15]. Consulting these and other sources can give an idea of which species have well-established gf scales and which need work.

As an opening example of the recent improvements in data for ionized rare earths, consider the case of Ce II. The combination of experimental lifetime measurements and theoretical calculations have produced [39] a very extensive set of gf values for Ce II. This species is potentially interesting because in solar-system material Ce, like Ba, is predominantly a product of the s-process. But Ba II presents only 4–5 very strong transitions and a couple of very weak ones for abundance analyses, whereas Ce II lines of moderate strength can be found throughout the entire near UV to visible spectrum. We "tested" the reliability of the new gf's by applying them to the spectra of CS 22892-052 [16] and BD+17^{o}3248 [29]. Equivalent width measurements were made only for easily identified lines in these spectra, and abundances were derived in the manner described in the papers on these stars. The abundances derived for each Ce II line in the two stars are shown in Figure 3, plotted as functions of wavelength (plots with respect to line excitation potential, gf, or equivalent width revealed no trends in abundances with respect to these quantities). The key point shown in this figure is the very small line-to-line scatter (σ = 0.06–0.07) in the abundances.

For comparison, the study of CS 22892-052 [15] with lower quality spectra and transition probabilities only employed nine Ce II lines, and the resulting line-to-line abundance scatter, $\sigma = 0.16$, was more than double the present values.

The Ce II data demonstrate the necessity of having transition probability data for many lines of a species that at least have the internal consistency to yield stellar abundances with small line-to-line scatter. Then for those stars with many measurable lines of a species, the average elemental abundance values can be meaningfully employed to address larger issues, in particular to compare the observed abundances with theoretical nucleosynthesis predictions. This can be accomplished for stars with large [n-capture/Fe] ratios, which present rich spectra of the n-capture elements. Just as importantly, the existence of internally consistent gf sets allow the derivation of accurate abundances in stars with lower n-capture element levels; such stars often may exhibit only a few detectable transitions of a species.

The Wisconsin atomic physics group has been gathering lifetime data and very high resolution (Fourier transform) spectra for several rare earth elements, combining these data to produce gf values and hyperfine/isotopic parameters for many lines of neutral atoms and their first ions. These data are then applied to the solar spectrum to try to improve the (sometimes poorly determined) photospheric abundances of these elements. The most recent efforts have yielded extensive new atomic data for La II [40], Eu II [41], and Tb II [42]. In Figure 4 we summarize the solar abundance results using these data; see the papers for descriptions of the analysis techniques, which typically involved matching synthetic and observed solar spectra. The line-to-line abundance scatters are satisfactorily small ($\sigma \simeq 0.04$) for La and Eu, but not so for Tb. The problem for Tb lies not in the atomic data but in the extreme weakness of all Tb II transitions in the solar spectrum. There appear to be no useful lines of Tb II beyond 4000 Å, and only three very weak, partially blended lines in the crowded near-UV solar spectrum. Even so, this new photospheric Tb abundance is in much closer accord with the meteoritic value [43] than previously estimated. For all three of these rare earth elements, the consistently small negative offset, averaging -0.06 dex, of the solar photospheric abundances with respect to meteoritic abundances is not well understood and deserves further study.

For cosmochronometry studies, one is of course concerned with the state of Th II and U II transition data, which fortunately appear to be reasonably well established for critical features of these species. The Th II 4019 Å line was studied in [44], and the U II 3859 Å transition probability has been reconsidered in [45]. More extensive lab studies of other Th II transitions would be useful, as they become detectable in the most r-process-rich stars [31].

In spite of the recent progress, some species relevant to cosmochronometry still need attention. Several neutral atoms of the so-called "third n-capture peak" have only a few trustworthy gf's, and frustratingly those transitions tend to occur in the UV ($\lambda < 3200$ Å) spectral domain, difficult to observe and to model. A couple ionized species of rare earths have poorly understood transition probabilities, and as an example consider data for Nd II in BD+17°3248. In Figure 5 the well-determined abundances of La and Eu (computed with the new atomic data discussed above) are displayed in the top panel, and results of abundance computations for Nd with three different sets of published gf values are shown in the other panels. The gf values of [46] and [4] are derived from experimental data, while those of [48] adoptions or corrections of the values in the literature. It is easily seen that none of these atomic data sets produce satisfactory abundance results for Nd in BD+17°3248, and the large σ values appear to be unrelated to the number of lines used in the analyses. An attempt to reconcile the gf-scales of [46] and [47] in [15] produced equally unsuitable results. This species clearly deserves a new laboratory analysis.

Aside from the problem of Nd II, we recommend renewed attention to neutral atomic lines of the Os–Pb element group and elements in the range $41 \geq Z \geq 48$; both of these sets of elements are just now beginning to be spectroscopically accessible in metal-poor stars, and often the transition data are older and less extensive than the data for the rare earths.

6. Summary

Establishing an age for the Galactic halo from observations of Th and U transitions in metal-poor stars demands progress in a number of areas. We have emphasized here that obtaining abundances for the radioactive elements for this task is only one part of the problem. Greater understanding of the production of the whole range of n-capture elements is essential, and this task cannot be accomplished without the best possible astronomical spectra of n-capture-rich halo stars and continuing progress on laboratory data. Nucleosynthesis theory can be confronted only at the level of accuracy that can be established by abundance analyses. Improving atomic data and stellar spectra go jointly forward in this endeavor.

We are pleased to thank the US National Science Foundation for its support of this work, most recently through grants AST-9987162 to C.S., AST-9819400 to J.E.L., and AST-9986974 to J.C.C.

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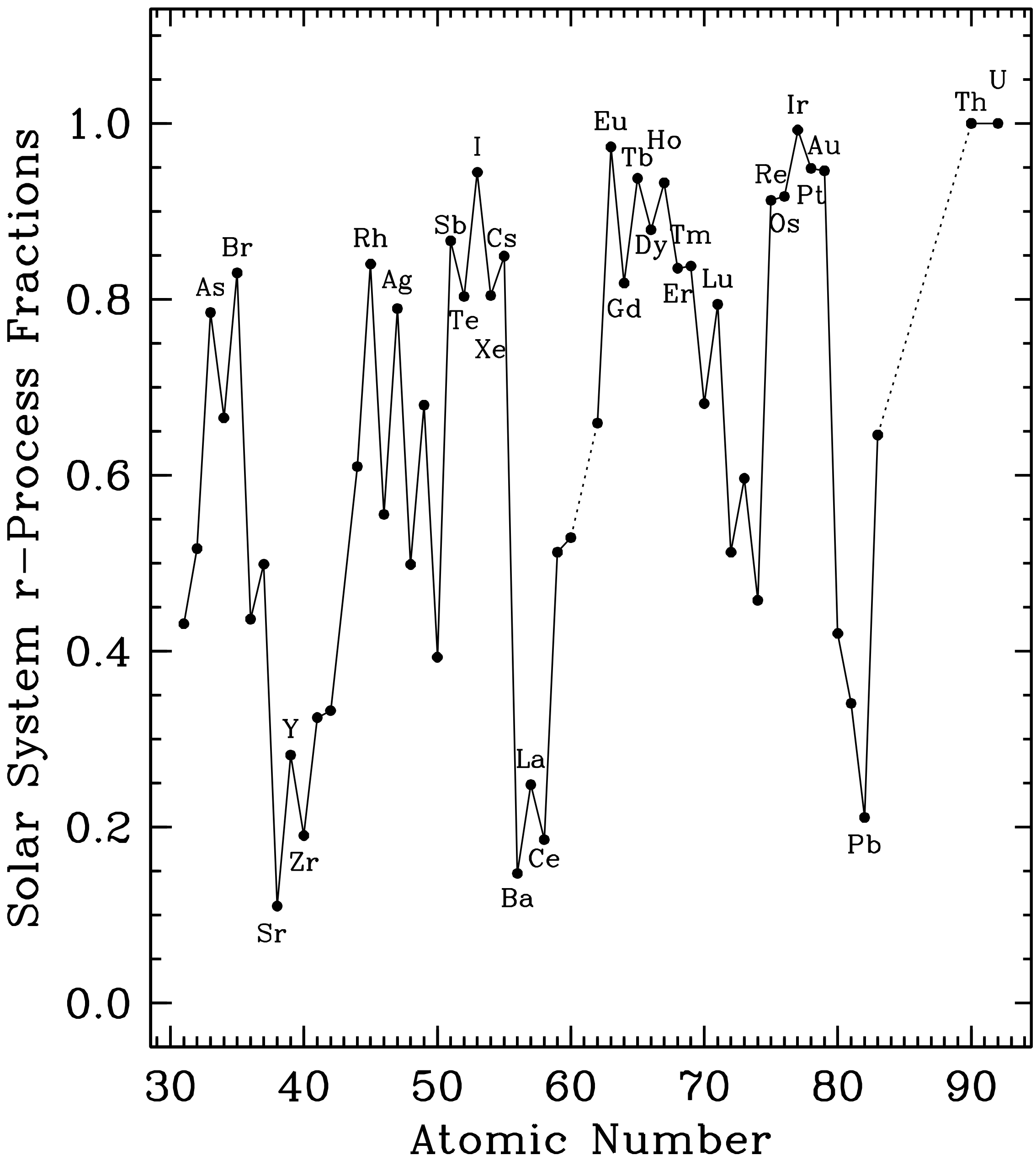

Fig. 1.— Fractions of solar system n-capture abundances due to r-process synthesis. The data are taken from [4]. Element symbols are written only for those elements with r-process fractional contributions >70% or <30%.

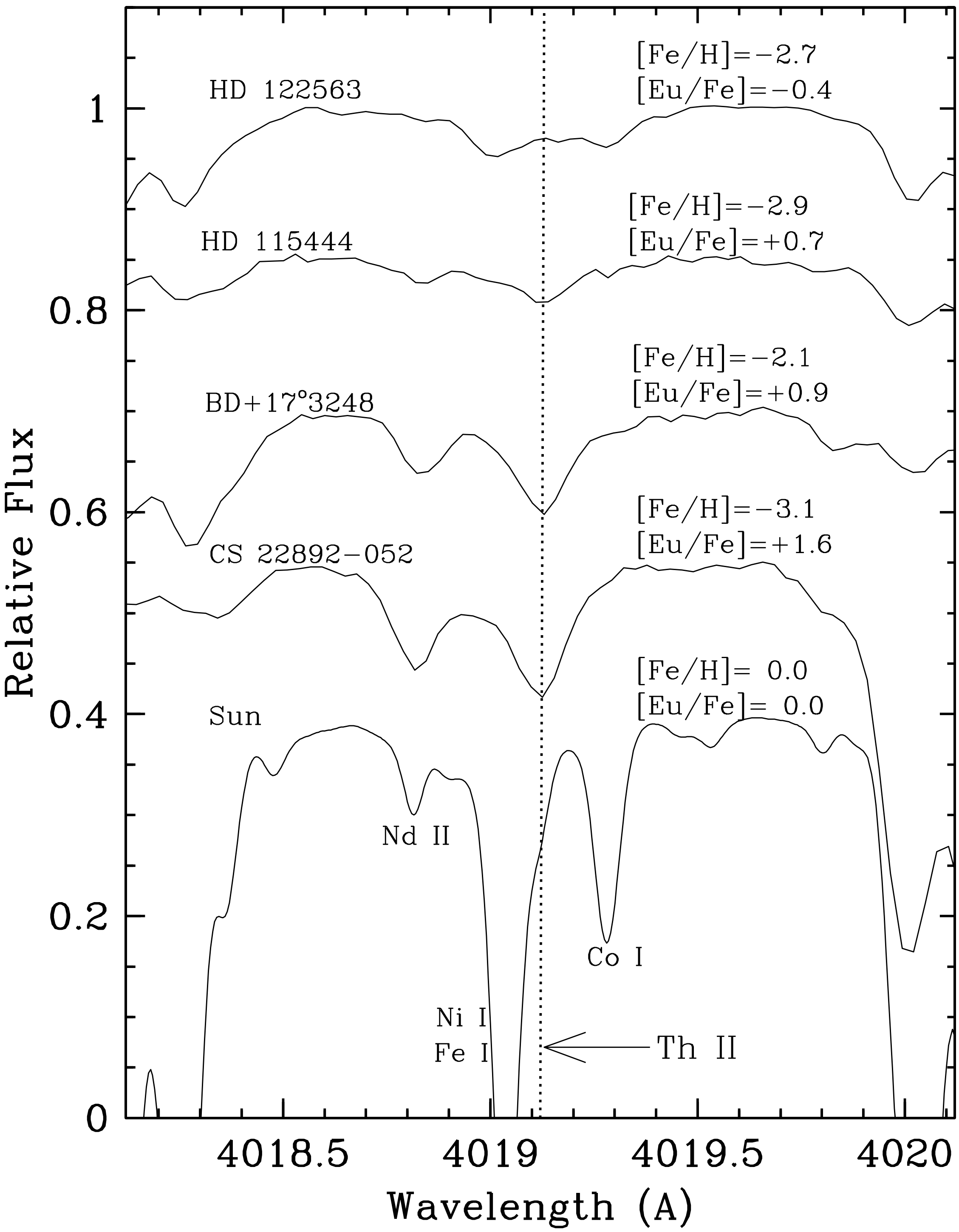

Fig. 2.— Spectra of the Th II 4019.12 Å line in the Sun and four very metal-poor stars. The spectrum sources are: HD 122563 and HD 115444, [17]; BD+17^{o}3248, [29]; CS 22892-052, [16]; and the Sun, [49]. The [Fe/H] and [Eu/Fe] values of the four stars are also taken from these papers. The wavelength of the Th II line is marked with a dotted line, and a few other atomic features are also labeled.

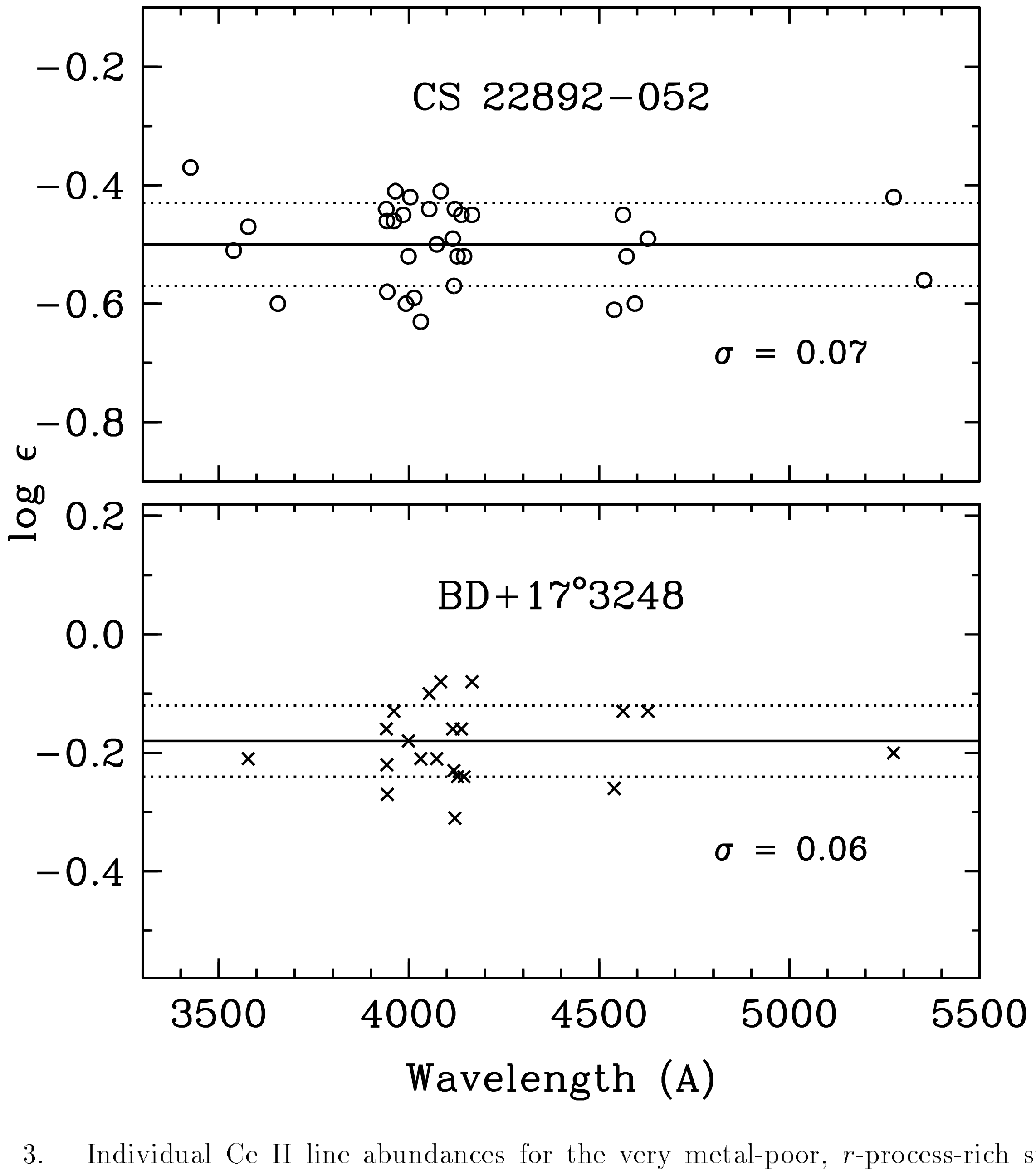

Fig. 3.— Individual Ce II line abundances for the very metal-poor, r-process-rich stars CS 22892-052 (top panel) and BD+17^{o}3248 (bottom panel). The gf values for the transitions are taken from [39], and the stellar spectra employed in the analysis were those cited in Figure 2. For each star the mean Ce abundance is shown as a solid horizontal line. The sample standard deviation value σ is both written in the figure panel and shown as dotted lines displaced from the mean abundance line.

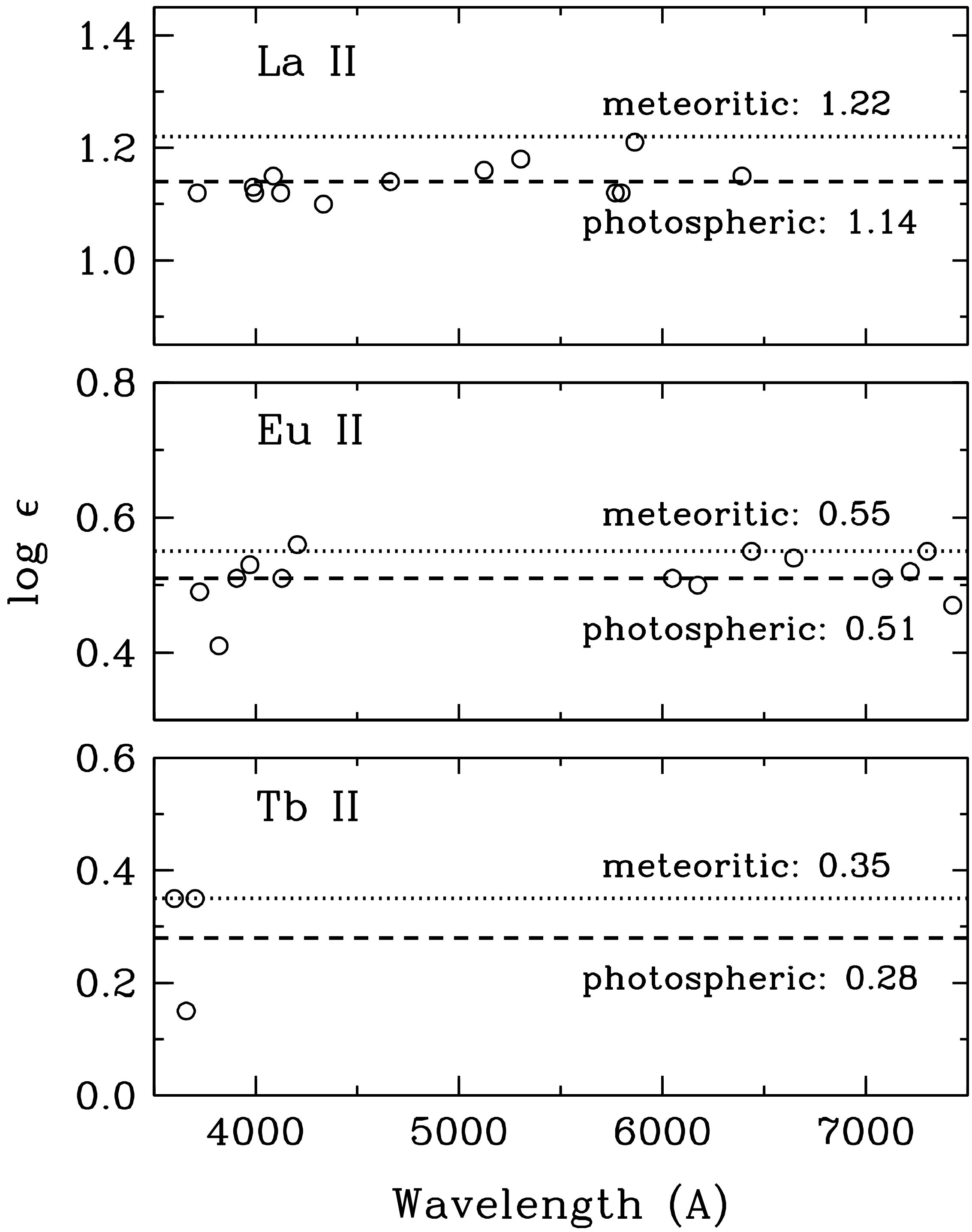

Fig. 4.— Solar photospheric abundances from individual lines of La II, Eu II, and Tb II, using the new atomic data described in the text. The photospheric abundances written in the figure panels are also indicated by dashed lines. For comparison, the meteoritic values recommended by [43] are shown as dotted lines.

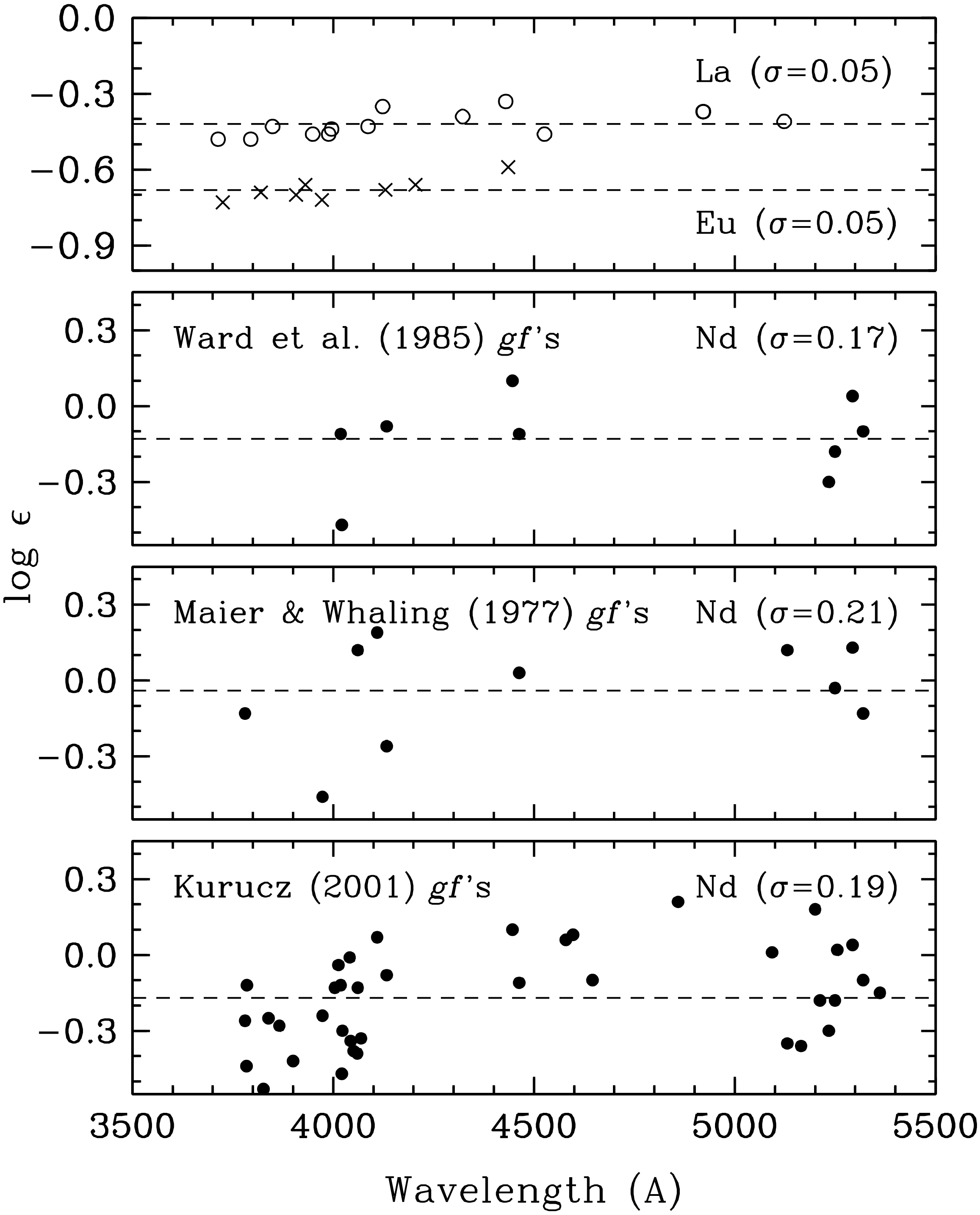

Fig. 5.— Abundances of La II, Eu II, and Nd II in BD+17°3248. In the top panel, individual line abundances for La and Eu are shown as open circles and $\times$ symbols, the mean abundances are shown as dashed lines, and the σ values are noted. These abundances have been generated using the atomic data of [40,41]. The other three panels show the same kinds of data for Nd II lines in BD+17°3248, adopting three different sets of transition probabilities.