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NEUTRON-EXPOSURE VARIATIONS IN MS AND S STARS, AND THE IMPLICATIONS FOR *s*-PROCESS NUCLEOSYNTHESIS

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ABSTRACT

High-resolution, near-infrared spectra have been obtained for 34 stars of types MS and S along with 14 M giants used as comparison stars. Equivalent width measurements of spectral lines arising from the heavy *s*-process species La II and Nd II, relative to the lighter *s*-process species Y II, indicate a large range of neutron exposures (which describe the *s*-process abundance distributions) in the MS and S stars. The indicated range of mean neutron exposures is approximately $\tau_0 \approx 0.1$–0.6 mb^{-1}. The solar system *s*-process distribution is characterized by $\tau_0 = 0.26$ mb^{-1}, near the middle of the distribution seen in the MS and S stars, and may be the result of a mixture of material with differing values of τ_0. The observed variations in the neutron exposure are in qualitative agreement with what is expected from the ^{13}C(α, n)^{16}O neutron source operating in low-mass asymptotic giant branch stars. The overall enhancement of *s*-process elements observed in the MS and S stars indicates that they are substantial contributors to the Galactic production of *s*-process nuclei.

Subject headings: nucleosynthesis — stars: abundances — stars: S-type

I. INTRODUCTION

Red giants have long been recognized as sites for the synthesis of the *s*-process heavy nuclei. The dramatic discovery of Tc in S stars (Merrill 1952) and marked overabundances of heavy elements in these and other types of red giants (Boesgaard 1970) demand that the *s*-process operates in these stars. The distribution of the *s*-process abundances in the solar system has been analyzed repeatedly in order to define the conditions under which the *s*-process operates in stellar sites. It has generally been presumed that the solar system mix of *s*-process nuclei was synthesized in red giants. In this study we validate this presumption by showing that the abundance distributions of *s*-process nuclei in MS and S stars resemble the solar distribution.

Analysis of the solar system distribution of *s*-process abundances provides estimates of conditions under which they were synthesized. For example, Howard *et al.* (1986) find that the solar system *s*-process nuclei were formed at a site with a mean neutron density $N_n = 1.1^{+0.6}_{-0.3} \times 10^8$ cm^{-3}, a temperature $T_9 = 0.27 \pm 0.03$, and a mean neutron exposure $\tau_0 = 0.26 \pm 0.01$ mb^{-1}. The neutron exposures are taken to follow an exponential distribution, $\rho(\tau) \propto \exp(-\tau/\tau_0)$, where $\tau = \int n_n v \, dt$, v is the neutron velocity, and the integral is taken over time. Howard *et al.* (1986) suppose that the neutrons are released during thermal pulses (see below); the above parameters correspond to a pulse duration $t_p \approx 450^{+250}_{-150}$ yr. Käppeler *et al.* (1982) find similar parameters. Our goal here is to show that the solar system value of τ_0 is representative of the *s*-process elements synthesized in MS and S stars.

Iben (1975*a*, *b*), Truran and Iben (1977), and Iben and Truran (1978) studied, in great detail, *s*-process nucleosynthesis in model intermediate-mass stars evolving through the thermally pulsing asymptotic giant branch (AGB) phase of stellar evolution. These investigations suggested that stars in the mass range $M \sim 3$–$8\ M_\odot$ were the primary source of the *s*-process species from approximately Sr through to Pb, and the reaction ^{22}Ne(α, n)^{25}Mg was the major source of neutrons. This particular neutron source was able to reproduce the solar system *s*-process abundance distribution. Ulrich (1973) demonstrated that an exponential distribution of neutron exposures could result from repeated *s*-process events with some fraction of material remaining from one event to the next and being successively irradiated by neutrons. Such repeated exposures in a single star occur in an AGB star undergoing He-shell flashes, or thermal pulses, as first investigated by Schwarzschild and Härm (1965).

Recently, several lines of evidence suggest that lower mass stars may be the primary producers of the *s*-process species. In particular, studies by Aaronson and Mould (1985) of S and C stars in clusters in the Magellanic Clouds suggest that for $M \gtrsim 3\ M_\odot$, AGB evolution is truncated by severe mass loss before the onset of thermal pulses. Also, surveys of carbon stars in the Magellanic Clouds by Blanco and McCarthy (1981) demonstrate that many low-mass stars with $M \sim 1\ M_\odot$ undergo efficient dredge-up of processed material on the AGB. Recent calculations and models of low-mass ($M \sim 1\ M_\odot$) AGB evolution by Iben and Renzini (1982*a*, *b*) and Iben (1983) now indicate that the dredge-up of material that has been exposed to repeated thermal pulses may occur in these low-mass stars. In these lower masses, however, the peak temperatures during thermal pulses may not be sufficient to drive the reaction ^{22}Ne(α, n)^{25}Mg as a neutron source, and the competing lower temperature reaction ^{13}C(α, n)^{16}O will occur (Iben 1983). In addition, Mathews *et al.* (1986) find that the neutron densities found in the higher mass stellar models are too high to fit the solar system *s*-process abundances, while lower mass models ($M \lesssim 3\ M_\odot$) provide a better fit. Unfortunately, even the low-mass AGB models fail to reproduce adequately the solar system *s*-process abundance distribution (Malaney 1987; Malaney and Boothroyd 1987). The discrepancy is quite serious and leads Malaney and Boothroyd (1987) to conclude that AGB stars *are not* the site of the *s*-process and alternative sites must be considered. For similar reasons, Iben (1986) has proposed that accretion from a normal star onto a white dwarf in a binary system could lead to *s*-processing on the surface of the white dwarf, and perhaps be the major site for the *s*-

process. Clearly, observations of the nature of the *s*-process in AGB stars are needed, not only to compare to the solar system *s*-process abundances, but as future guidelines with which to test AGB theory. The physics which occurs during the thermally pulsing AGB phase is very complicated, and recent theoretical attempts at AGB nucleosynthesis (Hollowell 1987) will be aided by observations.

In our Galaxy, those stars which show evidence of the dredge-up of *s*-process and ^{12}C-rich material are the MS and S stars (Smith and Lambert 1985, 1986) and the C stars (Utsumi 1985; Lambert *et al.* 1986). Estimates of the luminosities of the S stars (Keenan 1954; Eggen 1972) and their space distributions (Stephenson 1984) suggest that the majority of these stars are of low mass ($M \lesssim 2\ M_{\odot}$). A similar result is obtained for the C stars (Dean 1976) and SC stars (Catchpole and Feast 1985). Since these low-mass stars are numerous and exhibit substantial enhancements of the *s*-process elements (Smith and Lambert 1985, 1986; Utsumi 1985), they may be expected to have been major contributors to the solar system *s*-process abundances. Here we report on the enhancements of selected heavy elements and the neutron exposures for a sample of 34 MS and S stars.

II. OBSERVATIONS

Our data consist of Reticon spectra obtained with the coudé spectrograph of the McDonald Observatory's 2.1 m telescope. The spectra have a resolution of 0.2 Å and cover the wavelength region 7430–7530 Å, one of several wavelength intervals used by Smith and Lambert (1985, 1986). This region is relatively free from molecular line blanketing except for the very coolest stars, of which none are included in our sample.

Spectral lines representing both light and heavy *s*-process species were chosen: Y II λ7450.32, La II λ7483.48, and Nd II λ7513.73. In addition, lines of Fe-peak elements were chosen with equivalent widths similar to those of the *s*-process lines: these lines are Cr I λ7462.37 and Fe I λ7507.30. Lines of singly ionized Fe-peak elements were unavailable. However, a comparison of neutral lines of Fe and Cr with ionized lines of Y, La, or Nd is insensitive to the adopted effective temperature and surface gravity. At temperatures and gravities characteristic of giants of spectral type M6 ($T_{\rm eff} \approx 3200$ and $\log g \approx 0.0$), La II and Nd II are the dominant species in the line-forming regions, along with Fe I and Cr I, while Y II still represents about 50% of yttrium atoms. At the higher temperatures and gravities characteristic of spectral type M0 ($T_{\rm eff} \approx 3800$ K and $\log g \approx 1.0$), La II, Nd II, and Y II are the dominant ionization state in line-forming regions along with Fe I (still), while Cr I represents about 50% of all chromium atoms. The sensitivities to temperature and gravity of the particular lines used here are all in the same sense and roughly similar in magnitude (see Table 4 of Smith and Lambert 1985 for predicted changes in line strengths for various species as functions of changes in $T_{\rm eff}$, surface gravity, and microturbulent velocity). In short, simple equivalent width ratios of an *s*-process line to Fe I or Cr I are expected to provide a first-order estimate of *s*-process enhancement. Such an approach is presented in this study. A detailed abundance analysis of a subset of the MS and S stars studied here will follow.

TABLE 1

ATOMIC-LINE DATA

λ (Å)	Species	χ (eV)	Observed Equivalent Width Range (mÅ)
7450.32.........	Y II	1.74	30–140
7462.37.........	Cr I	2.90	150–250
7483.48.........	La II	0.13	100–450
7507.30.........	Fe I	4.41	80–150
7513.73.........	Nd II	0.92	20–140

In Table 1 we list the spectral line data along with the ranges of equivalent widths observed in the sample of stars studied. Because of space limitations we do not include the measured equivalent widths and the stars observed, although the measurements are available upon request. In total, 34 stars of type MS and S are included and are from the catalog by Stephenson (1984). Spectral types were also from Stephenson (1984) and include 14 stars of type MS and 20 of type S. Seven stars studied previously by Smith and Lambert (1985, 1986) are included in this sample: HR 363, HR 1105, HR 1556, HR 3639, HR 6702, HR 8062, and HR 8714. In addition, 14 normal stars from types K5–M6 analyzed by Smith and Lambert (1985, 1986) are adopted as a "control group" spanning the range of $T_{\rm eff}$ and luminosity covered by the MS and S stars.

III. ANALYSIS

The enhancement of a heavy *s*-process element (La or Nd) relative to a lighter one (Y) is a measure of the neutron exposure (τ). Our earlier study (Smith and Lambert 1986) of four MS and three S stars suggested that the mean neutron exposure, τ_0, increased from MS to S stars. This possible trend is further investigated using Figure 1, where we plot the equivalent width ratio of the La II/Cr I lines against the ratio Y II/Fe I. In the M giants, the Cr I line is nearly as strong as the La II line (which is typically quite strong, as can be seen from Table 1), and these two lines are ratioed to minimize microturbulence effects. The Y II and Fe I lines are much weaker and, hence, less affected by microturbulence. Even though the M giants presented in Figure 1 span a range in $T_{\rm eff}$ from about 3200 to 3900 K and a range in surface gravity of a factor of 30, the track that they form is a very tight one. This demonstrates that variations due to $T_{\rm eff}$, surface gravity, or microturbulence are largely canceled out. The MS and S stars, collectively, show greatly enhanced Y II lines, and, since the temperatures and gravities of these stars overlap those of the M stars (Augason 1987), a true enhancement of Y/Fe is indicated. A comparison of the La II line in the MS relative to the S stars reveals that, on average, the line is stronger in the S stars than in those of type MS. The stars with the greatest enhancements of La tend to be the S stars. Lanthanum is a heavy *s*-process element and requires a larger neutron exposure than is needed for an element such as Y in order to produce a significant enhancement. Next to the seven stars studied by Smith and Lambert (1986), which are plotted in Figure 1, we show their derived values of τ_0 (in mb^{-1}) for these stars, and, indeed, the larger values of τ_0 are associated with larger La II/Cr I line ratios. These values of τ_0 were determined using five elements; Sr, Y, Zr, Ba, and Nd.

As the particular La II line used here is quite strong and suffers from large hyperfine splitting, it is not an ideal candidate for quantitative analysis. The Nd II line, on the other hand, is much weaker and, along with the Y II line, is more reliably used in a quantitative comparison with predictions from model atmospheres. In Figure 2 we present the Nd II/Fe I

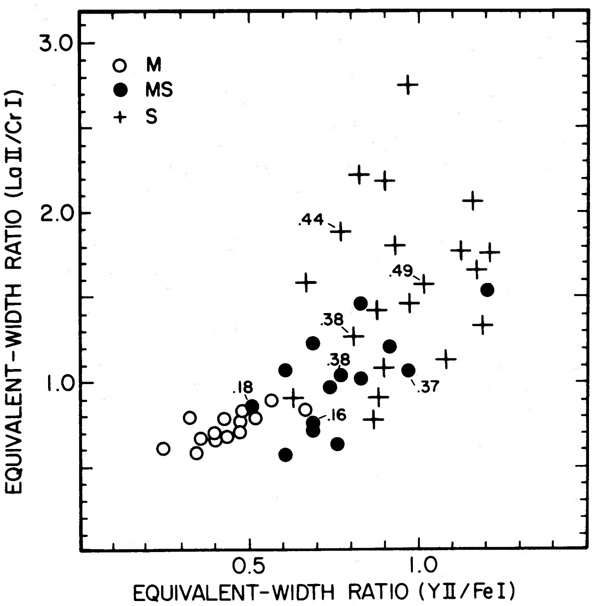

FIG. 1.—Observed equivalent width ratios of La II/Cr I vs. Y II/Fe I in the M, MS, and S stars. Derived neutron exposures (in mb^{-1}) for the seven stars studied by Smith and Lambert (1986) are indicated.

line ratio versus the Y II/Fe I line ratio. As in Figure 1, the M stars define a relatively small region of the diagram, with the majority of the MS stars showing enhancements of the Y II line with no corresponding increase in the Nd II line. The S stars, on the other hand, show enhancements of Y II along with large variations in the strength of the Nd II line which, like La II, arises from a heavy *s*-process element. Although there is overlap between the two types, the strongest enhancements of La and Nd tend to be found in the S stars. Some overlap is not surprising, since the boundary between types MS and S in spectral classification is not a simple, precise one. Again, as in Figure 1, we show the derived values of τ_0 for the seven stars studied by Smith and Lambert (1986). Also, in Figure 2, we present theoretical equivalent width ratios from a series of model atmospheres and predicted abundance patterns compiled from Malaney's (1987) calculations for *s*-process nucleosynthesis; these predictions differ slightly from previously published values by Cowley and Downs (1980) owing to more recent determinations of neutron-capture cross sections and a more complete reaction network. The model atmospheres are from Johnson, Bernat, and Krupp (1980), and the temperatures, gravities, and microturbulent velocities were chosen to be representative of the stars from Smith and Lambert (1985, 1986); these values of $T_{\rm eff}$, log g, and microturbulent velocity are respectively (*a*) 3800 K, 1.5, 2.0 km s^{-1}, (*b*) 3400 K, 1.0, 2.0 km s^{-1}, and (*c*) 3200 K, 0.0, 2.5 km s^{-1}. Equivalent widths were predicted using a modified version of the LTE spectrum synthesis code from Sneden (1974). The predicted *s*-process abundances from Malaney (1987) were diluted by a factor of 10^3 with material of normal, i.e., solar, composition. This "mixing factor" is typical of what is found from the detailed analyses of Smith and Lambert (1985, 1986). Thus, the predicted equivalent width ratios in Figure 2 represent a mixture of solar composition material ($\tau_0 \approx 0.3$) and additional processed material described by the appropriate model value of τ_0. For example, the model labeled by $\tau_0 = 0.1$ represents solar composition material plus 1 part in 10^3 of processed material described by $\tau_0 = 0.1$; the resultant mixture of heavy elements will not be represented by either a solar mixture or material with only $\tau_0 = 0.1$. In a usual abundance analysis, it is necessary to "remove" the underlying, presumed solar, initial composition in order to extract the neutron exposure of the added, processed material (for example, see Smith and Lambert 1986). In Figure 2 we avoid this inversion and

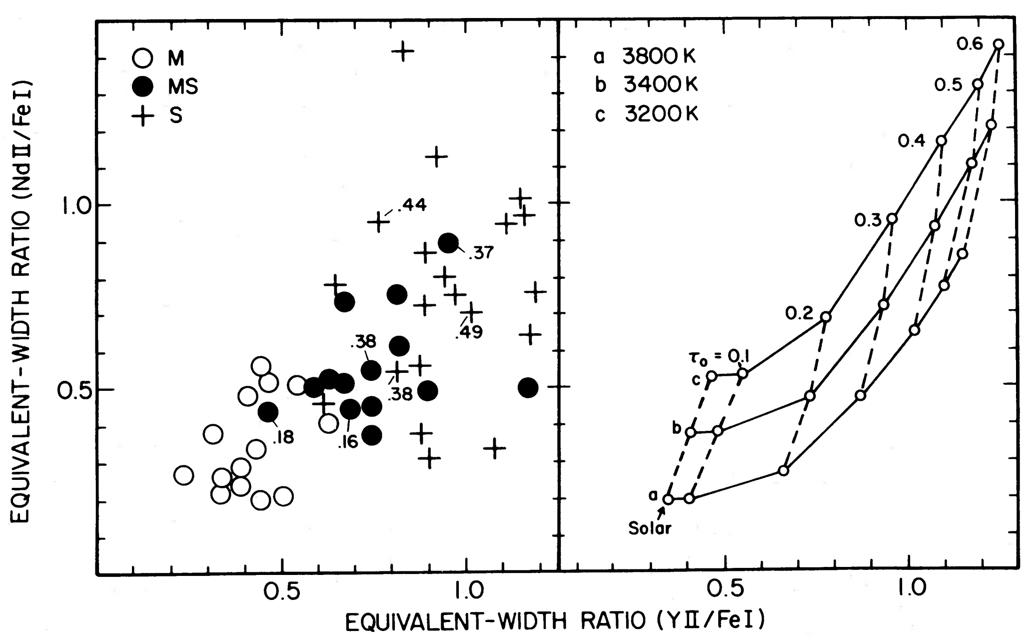

FIG. 2.—Observed equivalent width ratios of Nd II/Fe I vs. Y II/Fe I in the M, MS, and S stars, along with the neutron exposures derived for the seven stars from Smith and Lambert (1986). The right-hand panel shows predicted ratios from three model atmospheres of differing $T_{\rm eff}$ with an initial solar *s*-process composition (indicated by the solar arrow), followed by models with enhanced *s*-process abundances characterized by an increasing mean neutron exposure (in mb^{-1}).

merely compare the equivalent widths in real stars with models which mimic the hypothesized AGB dredge-up. Although the real stars will certainly exhibit more variety than our simple model, the trend of Y II/Fe I and Nd II/Fe I with increasing τ_0 tracks the M, MS, and S stars quite well, beginning with a solar composition for the M stars and ever-increasing *s*-processing for the MS and S stars.

Could the MS, S, and C stars be major contributors to the production of Galactic *s*-process elements and, in particular, to the solar system distribution of *s*-process nuclei? When the neutron exposures (τ_0), the overabundances, and the rates of return to the interstellar medium are examined, the answer is yes.

The seven MS and S stars from Smith and Lambert (1986) have derived values of τ_0 ranging from about 0.15 in some MS stars to 0.50 in some S stars, with a mean $\tau_0 = 0.34$. Results from Utsumi (1985) suggest that most C stars have $\tau_0 \gtrsim$ 0.5–0.6. The enlarged sample presented here is spread across this range, confirming that the previous selection of stars were typical of the O-rich AGB stars. This range encompasses and is approximately centered on the solar value $\tau_0 = 0.26$ (Howard *et al.* 1986). Käppeler *et al.* (1982) find a best fit to the solar distribution with two components; a "main" component with $\tau_0 = 0.30 \pm 0.1$ and a "weak" component with $\tau_0 = 0.06 \pm 0.01$. The latter component would not be easily detected in our survey because the Y, La, and Nd enhancements would be very small. Such "mild" *s*-processing might be most readily detected through Co overabundances (Smith and Lambert 1987). The observations suggest that the solar system *s*-process distribution could arise from a mixture of MS, S, and C stars.

The enhanced *s*-process abundances in these stellar envelopes will be returned to the interstellar medium through steady winds and the ejection of planetary nebulae. Schönberner and Weidemann (1981) and Schönberner (1981), using observations of the central stars of planetary nebulae, argue that most precursor stars of planetary nebulae have $M \lesssim 3$ $M_\odot$. Recently, Mazzitelli and D'Antona (1986) demonstrated that for stars up to an initial mass of 3 $M_\odot$, extensive and rapid mass loss during the AGB phase can account for the peak in the white dwarf mass spectrum near 0.6 $M_\odot$. Thus, these lower mass stars probably return a substantial fraction of their mass back into the interstellar medium. As discussed earlier, the MS, S, and C stars tend to be associated with these lower mass stars. Thus, the MS, S, and C stars will give rise to planetary nebulae and return their enriched *s*-process material back into the interstellar medium. Based upon the rate of planetary nebula formation and the mass yield per nebula, Tinsley (1978) shows that if the excess abundance of an element in the precursor star of a planetary nebula relative to its interstellar value is greater than about 7 ($X_{PN}/X_{ISM} \gtrsim 7$), then planetary nebulae will be the dominant contributor of that element to the interstellar gas. For the S stars, the *s*-process elements have excess abundances a factor of 4–6 over the solar value, while the MS stars exhibit a factor of 2–3. In the C stars, Utsumi (1985) finds *s*-process excesses of a factor of about 5–10. These *s*-process overabundances are very close to the value needed by Tinsley (1978) to make these objects the dominant source of *s*-process nuclei in the Galaxy.

The results here indicate that a mixture of stars of type MS, S, and C can account for the "main" component of *s*-process elements in the solar system. The rather large range in neutron exposure exhibited by these stars is in qualitative agreement with what is expected from the $^{13}C(\alpha, n)^{16}O$ neutron source operating in low-mass AGB stars (Iben 1983). The "weak" *s*-process component with $\tau_0 = 0.06$ is probably not explained by these stars; one speculation might be that the "weak" component could be the contribution from $^{22}Ne(\alpha, n)^{25}Mg$ operating in more massive stars. A careful survey of supergiants would be of interest. The very mild *s*-processing found in *o* Cet by Dominy and Wallerstein (1986) may indicate that Mira variables play a significant role in the "weak" *s*-process component.

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