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FIRST DETECTION OF PLATINUM, OSMIUM, AND LEAD IN A METAL-POOR HALO STAR: HD 126238

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ABSTRACT

Using the Goddard High Resolution Spectrograph (GHRS) of the *Hubble Space Telescope* (*HST*), we have detected the very heavy elements osmium, platinum, and lead in the metal-poor ([Fe/H] = −1.7) giant HD 126238, the first such detections of these elements in a Galactic halo star. Os and Pt are synthesized predominantly via rapid neutron captures (i.e., the *r*-process), and this nuclear region defines one of the three major *r*-process peaks identified in solar system material. Within the error limits, the elemental abundances of Os and Pt are consistent with solar system abundances scaled to the metallicity of HD 126238. Element-by-element comparisons of the data from *HST* and from ground-based data demonstrate, for the first time, the operation of the *r*-process for all of the elements from Ba to Pt in the progenitor (or progenitors) of this halo star. The newly determined Pb abundance, predominantly produced in slow neutron captures (i.e., the *s*-process) for solar material, can best be explained as resulting from a combination of *s*- and *r*-process nucleosynthesis contributions, prior to the formation of HD 126238. The *s*-process fraction is likely to have been generated only from the most massive stellar sites of the *s*-process.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: individual (HD 126238) — stars: Population II

1. INTRODUCTION

Elemental abundance patterns in Galactic halo stars are now providing important clues to the chemical evolution and early history of the Galaxy. In particular, observations of the very heavy elements can be used to determine the characteristics of objects that may have preceded the current generation of Population II stars and produced their observed heavy elements. Comparisons of the abundance patterns in these very metal-poor stars with younger, more metal-rich stars, can be employed to help determine the early chemical evolution of the Galaxy (see, e.g., Wheeler, Sneden, & Truran 1989).

Very heavy elements (better described as neutron-capture or *n*-capture elements) are those with atomic numbers $Z > 30$ that are synthesized by slow and/or rapid neutron captures on Fe-peak seeds (the so-called *s*- and *r*-processes). Optical observations, along with theoretical arguments, have shown that the *n*-capture abundance patterns found in the most extremely metal-deficient halo stars ([Fe/H] ≤ -3)[5] exhibit an *r*-process origin (Spite & Spite 1978; Truran 1981; Sneden & Parthasarathy 1983; Sneden & Pilachowski 1985; Gilroy et al. 1988; Sneden et al. 1988; Gratton & Sneden 1994; Sneden et al. 1994; Cowan et al. 1995; Sneden et al. 1996b). The observations further show that the relative abundances of the elements barium through dysprosium in these metal-poor stars are consistent with solar system *r*-process abundances (Cowan et al. 1995). The observed presence of this *r*-process signature also strongly suggests the occurrence of *r*-process nucleosynthesis in a stellar generation preceding that of the halo stars (Cowan et al. 1995). However, there are many questions that remain to be answered. First, despite considerable theoretical effort, the astrophysical site of *r*-process nucleosynthesis remains to be identified (Cowan, Thielemann, & Truran 1991a). While Type II supernovae have been suggested as a likely site, it is not clear whether high-mass (i.e., ~25 $M_\odot$) or low-mass (i.e., ~10 $M_\odot$) supernova progenitors could have been responsible for this synthesis (see Mathews, Bazan, & Cowan 1992).

The elements osmium, iridium, and platinum ($Z = 76$–78) are produced predominantly in *r*-process nucleosynthesis. This nuclear mass region defines one of the three major *r*-process peaks identified in the solar system *r*-process abundance pattern. In solar material, the total abundance in this *r*-process peak is approximately 10 times larger than the abundances of the *r*-process element Eu, which has already been measured in a number of the metal-poor stars (see Gilroy et al. 1988; Gratton & Sneden 1991, 1994). Moreover, both the *r*- and the *s*-process contribute substantially to the abundances of most of the heavy elements (Ba–Dy) that are spectroscopically accessible in the visual spectral range, in contrast to the nearly pure *r*-process origin of osmium, iridium, and platinum. Thus, the detection of the Os-Ir-Pt *r*-process peak in halo stars would demonstrate unambiguously that *r*-process nucleosynthesis contributed to the entire very heavy element mass range in early Galactic history. In addition, the very occurrence of *r*-process elements all the way through platinum in the oldest (most metal-deficient) stars in our Galaxy will have consequences for Galactic age determinations based upon nucleochronology (Cowan et al. 1991a, b). Since the *r*-process is the nucleosynthesis mechanism that is responsible for the synthesis of the critical nuclear chronometers in the uranium-thorium element region (a nuclear region nearby to the Os-Ir-Pt peak), it will be important to establish that their production occurred at time zero of the Galaxy.

In contrast to the suspected supernova origin for the *r*-process, the *s*-process elements, including lead ($Z = 82$), probably are formed during the late stages of stellar evolution in lower mass stars with relatively long stellar lifetimes (Meyer

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[5] We employ standard spectroscopic notation throughout: $[A/B] \equiv \log_{10}(N_A/N_B)_{star} - \log_{10}(N_A/N_B)_\odot$, and $\log \epsilon(A) \equiv \log_{10}(N_A/N_H) + 12.0$, for absolute number density abundances of elements A and B.

1994). We still are not certain of the relative levels of production of *r*-process and *s*-process nucleosynthesis products as a function of Fe metallicity. The data clearly establish the existence of depletions in the abundances of the designated *s*-process elements, such as barium, relative to iron, in stars of very low Fe/H (Wheeler et al. 1989). There is evidence, however, for the production of *s*-process elements in stars of metallicities as low as [Fe/H] = −2.5 to −2 (Mathews & Cowan 1990; Mathews, Bazan, & Cowan 1992). It is particularly significant that this abundance evolution occurs prior to the entry of the major component of iron (presumably from Type Ia supernovae) at a metallicity of [Fe/H] > −2. Lead forms part of the solar system *s*-process peak near mass number 210. The abundance determination of this element can be used to ascertain the timescale between the death of the progenitor stars and the formation of the halo stars. A comparison of the *s*-process abundance levels between stars of different metallicities (and presumably ages) can also be used to constrain the mass range of stars that can produce such elements.

The dominant atomic transitions for the elements Os, Ir, and Pt are not accessible to ground-based telescopes, thus preventing their detection until now. A couple of Pb I transitions (λλ4058, 3683) exist in the near-UV, but they are weak and blended in the Sun and have never been detected in metal-poor stars. But each of these elements has several strong transitions in the 2600–3100 Å spectral region. Therefore, to attempt to identify and trace these elements back to early Galactic epochs, we have acquired high-resolution spectra of two metal-poor stars at selected UV wavelengths with the *Hubble Space Telescope* (*HST*) and Goddard High Resolution Spectrometer (GHRS). The relatively bright stars HD 126238 and HD 122563, with [Fe/H] = −1.7 and −2.7, respectively, were chosen both because of their spread in metallicities and because they had been well studied with ground-based high-resolution spectra (Gilroy et al. 1988; Gratton & Sneden 1994). In this Letter we report the first detections of the elements osmium, platinum, and lead in HD 126238 and discuss the implications in terms of nucleosynthesis and Galactic chemical evolution.

2. OBSERVATIONS AND ABUNDANCE ANALYSIS

During *HST* cycle 5, we obtained GHRS spectra of HD 126238 of three spectral regions containing low excitation neutral species transitions of Pt, Ir, Os, and Pb. These followed acquisition of similar spectra of HD 122563 in *HST* cycle 4. Only such transitions of these elements have detection possibilities in cool, metal-poor stars, for strong transitions of singly ionized species are located too far in the UV, and high-excitation neutral species lines are simply too weak. A detailed discussion of spectrograph parameters, reduction procedures, and analysis techniques is deferred to a second paper (Sneden et al. 1996a). Briefly, the GHRS (whose operating characteristics have been discussed extensively by Gilliland et al. 1992) was configured with the low-order grating G270 and the "small science" spectrograph entrance aperture. For each observation a substepping pattern of four slightly shifted grating positions per detector diode was employed. The spectra each spanned wavelength ranges of approximately 46 Å, and had central wavelengths of 2832, 2913, and 3059 Å. The resolving power of each reduced spectrum was $R \simeq 32{,}000$ as determined by inspection of calibration lamp spectra, and the signal-to-noise ratio was S/N ∼ 70.

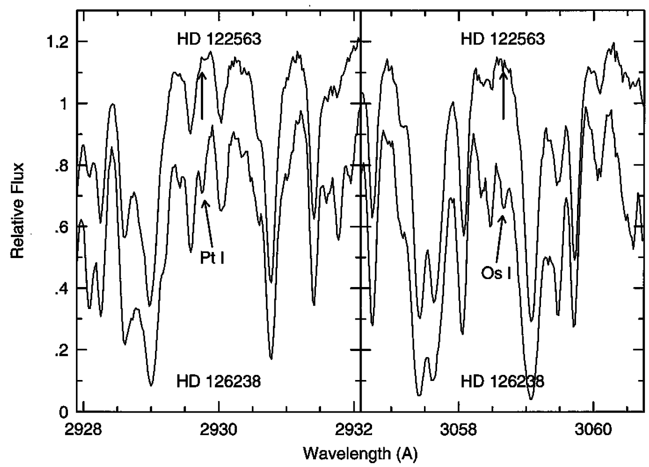

FIG. 1.—Comparison of GHRS spectra of HD 122563 and HD 126238 in the spectral region near Pt I λ2920 and Os I λ3059. The relative flux scale is correct for HD 126238, while that of HD 122563 has been shifted vertically for display purposes.

On these spectra we detected two Os I lines (λλ2838.61, 3058.65), two Pt I lines (λλ2929.79, 3064.71), and one Pb I line (λ2833.05) in HD 126238. None of these transitions was visible on our HD 122563 spectra. We illustrate this in Figure 1, comparing an Os I and a Pt I line in the two stars. Similar plots of the other features show the same difference between the two stars. We were unable to detect the presence of Ir I in HD 126238; a strong predicted line at 2924.79 Å may be present in our spectrum, but it is too blended to allow a detection claim here.

We derived abundances for Os, Pt, and Pb in HD 126238 by comparing the observed spectra with synthetic spectra generated in the following manner. We employed the analysis code of Sneden (1973), taking as input a model atmosphere computed with the MARCS code (Gustafsson et al. 1975) from the parameters of Gratton & Sneden (1994) ($T_{\rm eff} = 4979$ K, log $g = 2.50$, [M/H] = −1.7, $v_t = 1.5$ km s^{-1}), and an atomic and molecular line list from the Kurucz (1991) compendium. Transition probabilities for the features of interest came from lab analyses: for Os I, Kwiatkowski et al. (1984) and Corliss & Bozman (1962) scaled to Kwiatkowski et al. (1984); for Pt I, Ramanujam & Andersen (1978), Gough, Hannaford, & Lowe (1982), Lotrian & Guern (1982); and for Pb I, Penkin & Slavenas (1963). While we would have liked to detect these elements in the more metal-poor HD 122563, the nondetections allowed us to gauge the influence of potential contamination of the Os I, Pt I, and Pb I transitions by lines of other species. We thus used the HD 122563 spectra as templates, modifying the transition probabilities of surrounding features to produce acceptable synthetic/observed spectrum matches first for HD 122563 ($T_{\rm eff} = 4590$ K, log $g = 1.17$, [M/H] = −2.7, $v_t = 2.3$ km s^{-1}; Gratton & Sneden 1994), and then applying the modified line lists to HD 126238.

Suggested abundances for HD 126238 from our syntheses are log ϵ(Os) = +0.3 ± 0.3, log ϵ(Pt) = +0.6 ± 0.3, and log ϵ(Pb) = +0.2 ± 0.3. The uncertainties in these abundances arise mainly from continuum placement and other feature contamination uncertainties in these crowded spectral regions. It would be extremely difficult to determine proper continuum

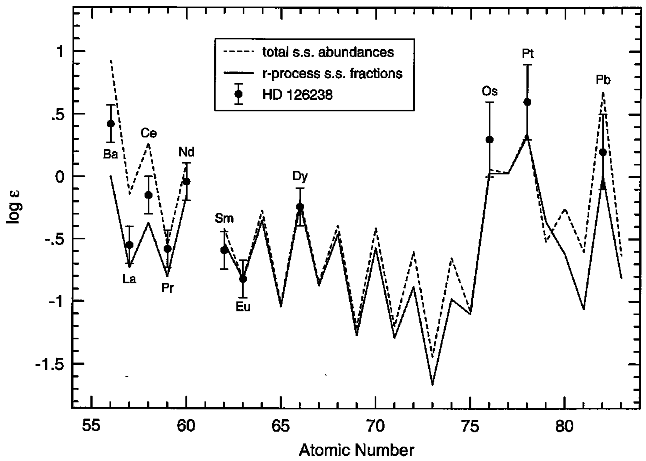

FIG. 2.—Comparison of ground-based and *HST* observations with total solar (*dashed line*) and *r*-process-only (*solid line*) abundances.

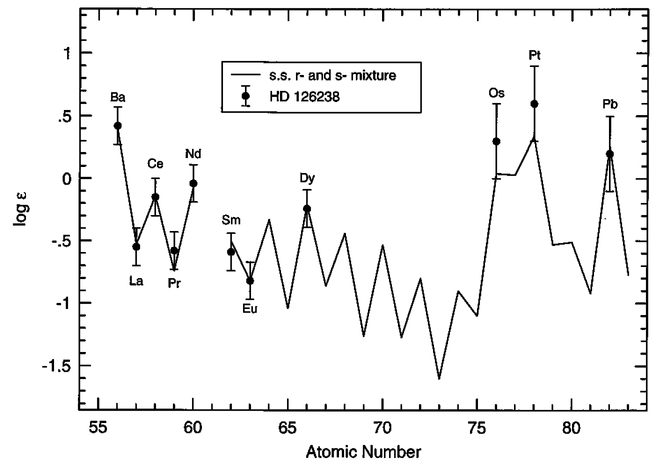

FIG. 3.—Comparison of ground-based and *HST* observations with an abundance curve of solar *r*-process plus 20% of the total *s*-process abundances.

levels for our spectral regions in a solar metallicity star, but the severe metal deficiencies of our stars considerably weaken their UV line blanketing (e.g., compare the program star spectra in the right-hand panel of Figure 1 with the solar flux spectrum of Kurucz et al. 1984). Moreover, Gustafsson et al. (1980) showed that the UV flux of HD 122563 down to 2300 Å could be quite adequately accounted for by the models and line data (which have been greatly extended in the Kurucz 1991 database that we employ) available at the time of their study. This increases our confidence that the UV line spectra are reasonably well understood in our cool, very metal-poor giants. A more detailed discussion of the construction of the synthetic spectrum line lists, with assessment of the level of contamination on our lines by other spectral features, will be given by Sneden et al. (1996a).

3. RESULTS AND DISCUSSION

In Figure 2 we plot the Os, Pt, and Pb abundances determined here and other *n*-capture element abundances derived by Gratton & Sneden (1994) versus atomic number *Z*. Solar system abundances, taken from Anders & Grevesse (1989) and Anders & Ebihara (1982), have been superimposed on the observations. Employing the *s*-process cross section measurements of Käppeler et al. (1989), we determined, by summing over all the stable isotopes, the solar elemental abundances arising from both the *r*-process and the *s*-process (see also Cowan et al. 1995). The deconvolution of the solar system abundances into strictly *r*-process fractions is shown in Figure 2 as a solid line. We have scaled both this curve and the total solar system curve vertically to match the observed abundance of the element Eu, produced mostly in the *r*-process. Osmium and platinum, as noted earlier, are also produced mostly in the *r*-process (92% and 95%, respectively), and thus the total solar curve and the *r*-process curve virtually overlap for those elements. Within the error limits, these two elements in HD 126238 are in solar proportions, confirming previous suggestions that the *r*-process elements are always produced in relative solar proportions (Gilroy et al. 1988; Cowan et al. 1995). The previous work, however, was based solely upon elements in the mass range near 130–150. This is the first time we have been able to confirm the operation of the *r*-process in the mass range near 200, a major *r*-process peak observed in the solar system abundance distribution.

Some elements (notably Ba, La, and Ce) shown in Figure 2 deviate significantly from the solar *r*-process distribution. Such elements are produced predominantly via the *s*-process in solar system material. But the total solar abundance distribution (with the full *s*-process signature) overproduces these elements. A better fit to all of the observed data is obtained by taking some fraction of the total solar *s*-process abundances and adding it to the solar *r*-process distribution. We multiplied the solar *s*-process elemental distribution that we had obtained by 20% (retaining the relative elemental differences) and added the resulting *s*-process abundances to the total *r*-process abundances; the results are shown in Figure 3. We have again vertically normalized this predicted curve to the observed europium abundance in HD 126238. As the figure illustrates, over a wide range in atomic number, the abundances from both the *HST* data and the ground-based data are well fitted by the predicted curve. While Os and Pt are little affected by the addition of any *s*-process contribution, the abundances of Ba, Ce, La, and particularly Pb clearly show some, but not the total solar, *s*-process contribution.

Our results clearly demonstrate the full operation of the *r*-process in the progenitor stars of HD 126238. Previous results, based upon even more metal-poor stars, have suggested the existence of massive progenitors for the *r*-process early in the history of the Galaxy (Cowan et al. 1995). While the observations reported here are consistent with that suggestion, with a metallicity of [Fe/H] = −1.7 and only one star, it is not possible to constrain the masses of those progenitors. Our results also suggest that at this metallicity, whatever time that relates to in the Galaxy, the onset of the *s*-process has already occurred. On the other hand, the comparisons between the predicted curves and the measured abundances in HD 126238 suggest that the majority of the *s*-process contributions could not have occurred prior to the formation of this halo star. While there are several possible explanations, we would argue that the simplest is that at the time of the formation of HD 126238, only the most massive of the stellar *s*-process sites has had time to evolve. While the mass range of the stellar *s*-process sites is uncertain, an upper limit of 3 $M_\odot$ has been suggested (Meyer 1994). Considering only the contribution from stars in this mass range would imply a minimum of $\sim 3 \times 10^8$ yr (Iben 1967) between the formation of the progenitor star (or stars) and the formation of the halo star

HD 126238. A more precise estimate would require a detailed knowledge of the total stellar mass range for the *s*-process, the individual nucleosynthetic yield for each star, and the detailed history of that star formation over the lifetime of the Galaxy. None of these are currently well determined.

More *HST* observations need to be made to extend and generalize our results for this halo star. In particular, stars with lower metallicity need to be observed to look for only *r*-process contributions and to find the actual initiation of the *s*-process. Also observations of higher metallicity stars will be needed to see the increasing contribution of the *s*-process to Galactic abundances. Chemical evolution models suggest the onset of this *s*-process buildup is also related to the timescale for Galactic disk formation. A comparison of the *s*-process abundances between two (or more) halo stars may therefore provide information concerning whether the Galactic disk collapse was sudden or gradual. Further comparisons between the relative and absolute (with respect to iron) levels of the abundances of the heaviest neutron-capture elements in stars of various metallicities will also indicate something about the distribution of supernovae and chemical mixing, and thus tell us much more about the early history of our Galaxy.

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