BERYLLIUM IN THE ULTRA–LITHIUM-DEFICIENT, METAL-POOR HALO DWARF G186-26

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ABSTRACT

The vast majority of low-metal halo dwarfs show a similar amount of Li; this has been attributed to the Li that was produced in the big bang. However, there are nine known halo stars with $T_{\text{eff}} > 5600$ K and $[\text{Fe/H}] \leq -1.3$ that are ultra–Li-deficient. We have looked for Be in the very low metallicity star G186-26, at $[\text{Fe/H}] = -2.71$, which is one of the ultra–Li-deficient stars. This star is also ultra–Be-deficient. Relative to Be in the Li-normal stars at $[\text{Fe/H}] = -2.7$, G186-26 is down in Be by more than 0.8 dex. Of two potential causes for the Li deficiency—mass transfer in a pre–blue straggler or extra rotationally induced mixing in a star that was initially a very rapid rotator—the absence of Be favors the blue straggler hypothesis, but the rotation model cannot be ruled out completely.

Subject headings: Galaxy; halo — stars: abundances — stars: evolution — stars: individual (G186-26) — stars: late-type — stars: Population II — subdwarfs

Online material: color figures

1. INTRODUCTION

Although nearly all metal-poor dwarf and turnoff stars with $T_{\text{eff}} > 5600$ K and $[\text{Fe/H}] \leq -1.3$ show similar Li abundances, there are a few such stars that seem to be ultradeficient in Li. The discovery by Spite & Spite (1982) of a plateau in the Li abundances in metal-poor stars has been followed by much research to determine Li in many additional ancient halo stars and to derive the primordial Li abundance produced by big bang nucleosynthesis (e.g., Thorburn 1994; Bonifacio & Molaro 1997; Ryan et al. 1999, 2000; Meléndez & Ramírez 2004). In fact, in the follow-up work to the initial paper by Spite & Spite (1982), Spite et al. (1984) discovered a Li-deficient star, HD 97916, with a Li abundance at least an order of magnitude below the plateau. The plateau value of $A(\text{Li}) = \log N(\text{Li}/H) + 12.00$ is near 2.2, but “the plateau” seems to have both a temperature and a metallicity abundance at least an order of magnitude below the plateau. The value of $A(\text{Li}) = \log N(\text{Li}/H) + 12.00$ is near 2.2. But the “plateau” seems to have both a temperature and a metallicity abundance at least an order of magnitude below the plateau. The plateau value of $A(\text{Li}) = \log N(\text{Li}/H) + 12.00$ is near 2.2, but “the plateau” seems to have both a temperature and a metallicity abundance at least an order of magnitude below the plateau. The value of $A(\text{Li}) = \log N(\text{Li}/H) + 12.00$ is near 2.2, but “the plateau” seems to have both a temperature and a metallicity abundance at least an order of magnitude below the plateau.

The extreme halo star G186-26 was found to be Li-deficient by Hobbs et al. (1991). Additional Li-deficient metal-poor stars have been discovered by Hobbs & Mathieu (1991), Thorburn (1994), and Ryan et al. (2001b). There are now nine known halo dwarfs with $[\text{Fe/H}] < -1.1$, all having $T_{\text{eff}} > 5980$ K.

These “ultra–Li-deficient” stars are important in estimating the primordial Li abundance, $A(\text{Li})_{\text{p}}$. Do they represent a true dispersion in the plateau? Do they indicate greater Li depletion and thus represent signposts of general (more mild) Li depletion in all or most of the plateau stars? If all plateau stars have undergone some depletion, then $A(\text{Li})_{\text{p}}$ is higher than the currently measured value, with concomitant implications for cosmology, such as the baryon-to-photon ratio, $\eta$.

There are at least two possible origins for the Li deficiencies. Ryan et al. (2001a, 2002) argue that the original Li is reduced by the mechanism that operates in blue straggler stars, primarily a mass transfer event or a stellar merger, but in “blue stragglers to be.” Pinsonneault et al. (1999, 2000) propose that stellar mixing caused by rotation has lowered Li in the plateau and has produced larger Li depletions in some fraction of the stars that were originally the most rapid rotators. (Ryan et al. [2001a] rule out diffusion and a Hyades-like Li dip as explanations for the severely Li-deficient halo stars.) These two hypotheses have different implications for the Be content of the ultra–Li-deficient stars. In the blue straggler model, the star would undergo substantial internal mixing and/or mass transfer, which would destroy both Li and Be completely, as atoms of both elements would be in environments where the temperatures are high enough to destroy them: $\sim 2.5 \times 10^5$ K for Li and $\sim 3.5 \times 10^5$ K for Be. (Mass transferred from an evolved giant would also be diluted in Li and Be.) In the rotationally induced mixing model, Li may be partly or completely destroyed, while Be may be totally or partly preserved (Pinsonneault et al. 1992, hereafter P92).

2. OBSERVATIONS AND ANALYSIS

The spectra for G186-26 were obtained in one night on 2003 May 27 (UT) with the high-dispersion spectrograph (HDS) at the 8.2 m Subaru Telescope on Mauna Kea (Noguchi et al. 2002). We used the blue collimator and blue cross-disperser with the standard HDS setup: StdUb. Our slit was 0.77 $\times$ 4.4, and the binning was 2 $\times$ 2. There are two EEV CCDs covering 2048 $\times$ 4100 pixels (pixel size 13.5 $\mu$m), corresponding to a wavelength coverage of 2970–4640 Å. Calibration exposures were taken of the bias, halogen lamps for flat-fielding, and Th-Ar comparison spectra. We obtained two integrations of 50 minutes each of this $V = 10.82$ star, for a total signal-to-noise ratio (S/N) of 98 pixel$^{-1}$ at 3130 Å. The spectral resolution is $\sim$50,000, or 0.062 Å. The dispersion is 0.0187 Å pixel$^{-1}$, and the resolution...
element is 3.3 pixels. Both resonance lines of Be ii at 3130.416 and 3131.064 Å appear in two different orders of the spectrum, and we analyzed both separately, but the flux in the order where the Be ii lines are centered is 8.5 times that in the lower order. Standard data reduction procedures were used. After division by the normalized flat field, scattered light and cosmic-ray events were removed. The spectra were traced and extracted and then wavelength-calibrated from the Th-Ar spectra. The two exposures were combined, and the continuum was determined.

Since G186-26 has a metallicity of 1/500 solar, there is little blending, and the continuum placement was straightforward.

The stellar parameters for G186-26 have been determined by Novicki (2005). We used the photometric indexes (b − y)h, (V − K)h, and (R − I)h, and the calibrations of Carney (1983) to determine the effective temperature, Teff. (The b − y values are from Schuster & Nissen [1988], V−K from Alonso et al. [1994] and Carney [1983], and R−I from Eggen [1979].) A weighting of 4 : 2 : 1 was used for T(x)(b−y)h, T(x)(V−K)h, T(x)(R−I)h. [For G186-26 the reddening is negligible and was ignored: E(b−y) = 0.011.] The three temperatures are 6196, 6181, and 6256 K with a weighted mean of 6200 ± 25 K, but we use ±40 K as a more realistic estimate of the uncertainty. For comparison, Alonso et al. (1996) found a weighted mean of 6428 K from HJK photometry for this star. We have found six values for [Fe/H] in the literature from high-resolution, high-S/N determinations. These have been normalized to the same scale [i.e., to solar log N(Fe/H) = 7.51] and averaged. Two lower resolution results have been included also. The final weighted mean for [Fe/H] is ±2.71 (Novicki 2005). We used Strömgren photometry, (b − y)h, and cy, to estimate log g by means of the Yi et al. (2004) 10 Gyr isochrone for Y = 0.23. This gives a value of 4.48, and we estimate the uncertainty as 0.20 dex. (The 13 Gyr isochrone gives log g of 4.44, which would result in a smaller Be abundance by 0.018 dex, so our value of 4.48 is a conservative choice.) The microturbulent velocity was taken to be 1.5 km s−1, the typical value for low-metal stars according to Magain (1987). Our parameters for G186-26 are Teff = 6200 ± 40 K, log g = 4.48 ± 0.20, and [Fe/H] = −2.71 ± 0.12, which are in good agreement with those of Thorburn (1994), Norris et al. (1997), and Akerman et al. (2004).

The Be abundance was determined using spectrum synthesis with the program MOOG, version 2002 (Sneden 1973). The stellar parameters were used to generate a model atmosphere using the Kurucz (1993) grid of models. All elements except Be and O are reduced by the same amount as [Fe/H]. The O abundance matters, as there are many blending OH lines in the Be ii spectral region. We have used the value of [O/Fe] = +0.49 derived for this star by Akerman et al. (2004). Figure 1 shows the spectrum synthesis fit for Be in our combined spectrum of G186-26. Neither of the two Be ii resonance lines is present. Shown for comparison in Figure 1 is the Li-normal star BD +3 740, which has normal Be for its temperature and [Fe/H], both of which are similar to those parameters for G186-26; this spectrum is from Boesgaard et al. (1999) but has been reanalyzed with the latest version of MOOG. Figure 2 shows an enlarged view of the Be ii lines in G186-26 with the same synthesis as in Figure 1. The value A(Be) = −1.58 was selected as the expected initial Be abundance (see § 3.2). The uncertainty in the Be abundances due to uncertainties in the stellar parameters is ±0.09.

### 3. RESULTS AND INTERPRETATION

It can be seen from Figures 1 and 2 that the spectrum of G186-26 is consistent with an absence of Be in the stellar atmosphere, but we suggest an upper limit on A(Be) of −2.00 ± 0.09 dex. As Figure 1 shows, we have detected Be ii lines in BD +3 740 at 6227 K and [Fe/H] = −2.81 and derive A(Be) = −1.37. Furthermore, Primas et al. (2000a) show the presence of Be in G64-12, a star with a similar temperature (6400 K) and even lower metallicity, [Fe/H] = −3.28, with A(Be) = −1.15.

We compare our upper limit on Be for G186-26 with Be abundances for other stars at its metallicity. Figure 3 shows the Be abundance limit of G186-26 in the context of Be detections in other metal-poor, Li-normal stars as a function of metallicity. The stars below [Fe/H] of −0.9 appear to fall on the same Fe-Be trend, considering the scatter in the Be abundances at a given Fe; that is, they have normal Be abundances. They also all have normal Li plateau abundances. Our A(Be) upper limit, −2.0, is less than other such stars at this metallicity by 0.8 dex. Allowing for the ±0.12 uncertainty in [Fe/H], it is lower by 0.7–0.9 dex.

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**Fig. 1.**—Synthetic spectrum in the Be region for G186-26. The small squares are the data. The solid line corresponds to our line list predictions for the Kurucz model for this star for no Be. The short-dashed line corresponds to the Be abundance expected from the P92 calculations (−1.58); the dotted line is a factor of 2 more Be, and the dash-dotted line is a factor of 4 more Be. The upper dotted line is our upper limit, A(Be) = −2.00, but see Fig. 2 for more clarity. The lower part of the figure is a spectrum of a star with normal Li and normal Be, BD +3 740 (displaced, but on the same scale). G186-26 and BD +3 740 have similar temperatures and metallicities. For such metal-poor stars, the stronger Be ii line λ3130 is a better abundance indicator than λ3131. [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 2.**—Same as Fig. 1 for G186-26, but zoomed in on the Be ii lines. [See the electronic edition of the Journal for a color version of this figure.]
from Boesgaard et al. (1999), Boesgaard (2000), and Stephens et al. (1997).

Squares are from Primas et al. (2000a, 2000b); circles are from Boesgaard et al. (1999), Boesgaard (2000), and Stephens et al. (1997). [See the electronic edition of the Journal for a color version of this figure.]

3.1. Blue Straggler

Ryan et al. (2001a) pose a question about the blue straggler phenomenon, which essentially is, why should the processes that form blue stragglers be limited only to those stars that have masses above the turnoff for main-sequence stars? Those higher mass stars are apparent because of their unusual colors—too bright and too blue for their ages. The phenomenon involving mass transfer and mergers could be at work in lower mass, sub-turnoff stars as well. Peculiar colors would not be the signature of this behavior, but Li depletion would result. For example, blue stragglers examined for Li in M67 by Pritchet & Glaspey (1991) have no detectable Li. Hobbs & Mathieu (1991) found no Li line in blue stragglers in the two halo field stars they studied. Those two stars were “known” blue stragglers before they were on the list of the nine ultra–Li-deficient stars. Carney et al. (2005) find that four of the five Li-deficient field blue stragglers that they studied are single-lined spectroscopic binaries.

Pritchet & Glaspey (1991) concluded that the blue straggler formation must be due to binary coalescence, binary mass transfer, or other deep mixing. Such stars would be thoroughly mixed. All three light elements, Li, Be, and B, would be destroyed in this scenario, as all the atoms of these elements would be subjected to temperatures at which they could be destroyed by nuclear reactions. Preston & Sneden (2000) argue that most field blue stragglers are produced by mass transfer events because collisions are less common in the field than in clusters. The former-giant primary that transfers the mass would deposit Li-depleted deep-envelope material onto the current primary. Our measurement of A(Be) and Thorburn’s (1994) measurement of A(Li) show that both Li and Be are severely depleted, if present at all. We may be observing a star that is a blue straggler to be. It does not have the mass to have evolved beyond the main sequence, yet it has the signature of a coalesced binary or mass transfer in its Li and Be deficiencies.

Latham et al. (2002) did not find a period for G186-26. The Carney et al. (1994) radial velocity measurements show a variation from −317.78 to −323.19 km s⁻¹, for a range of 5.41 km s⁻¹ with measurement errors of ±0.71 to ±1.89 (or ±0.98, the mean internal error). Their 43 measurements with error bars over 3220 days are shown in Figure 4. Four additional measurements by Latham et al. (2002) some 3300 days later, spanning 139 days, center around −322.6 km s⁻¹ with errors of −0.9 km s⁻¹. There are no signs of double lines in our spectra.

If there has been mass transfer from a former asymptotic giant branch star onto G186-26, it would have left composition signatures. In particular, Sneden et al. (2003) have shown that blue stragglers would have overabundances of the s-process elements, Sr, Ba, and Pb. Norris et al. (1997) found an overabundance of Ba in G186-26, with [Ba/Fe] = 0.35. Abundances of many elements in six ultra–Li-deficient halo stars were reported by Elliott & Ryan (2005); they find that Sr is overabundant by +0.5 dex and Ba by +1.0 dex in G186-26. Norris et al. (2001), Stephens & Boesgaard (2002), and Fulbright (2002) find that such an overabundance of [Ba/Fe] is extremely rare at this low [Fe/H]. Support for the blue straggler model for the ultra–Li-deficient stars comes from the apparent lack of Be in G186-26. Additional support for this comes from the supersolar content of neutron-capture elements. However, there is no evidence that G186-26 is a binary star, but it may be a coalesced binary.

3.2. Rotation

Although all the Li abundances in the ultra–Li-deficient stars are upper limits, the presence of Be could indicate that rotationally induced mixing has occurred but not down to internal temperatures as high as 3.5 × 10⁶ K. Thus, abundances of Be in ultradeficient Li halo stars could provide a clue about the efficiency of internal mixing: If Be is found to be present in ultradeficient Li stars, it would imply that the Li depletion is likely to be due to mixing caused by high initial angular momentum.

The effect of rotationally induced mixing on the Li and Be abundances in halo stars was first addressed by P92. According to the standard models, there is no Be depletion (their Tables 3A and 3B). The models that track the instabilities due to spin-down and angular momentum loss do predict depletion of both Li and Be. These authors address whether there is a range in initial rotation rates (i.e., in initial angular momentum) that results in a range in Li at the present epoch. Since Li is destroyed at shallower layers than Be, this mixing mechanism should produce less Be destruction than Li destruction, unless mixing is deep enough to deplete both elements substantially.

We have tried to determine the amount of Li and Be depletion that is predicted for our star by the P92 models. Therefore, we examined the latest “Yale” isochrones (Yi et al. 2004) appro-
priate for our star’s [Fe/H], log g, and effective temperature to find the mass for G186-26. The 13 Gyr isochrone gives a mass of 0.735 Mᵍ are tables 5A–5C of P92 show the expected depletion for Li and Be for Z = 0.0001 and three values of the initial angular momentum. We looked at Table 5C primarily, in order to find the largest Li and Be depletions. From our interpolation we find Li depleted from the initial value by −1.21 dex and Be by −0.40 dex, compared with at least −0.8 dex in G186-26. If the initial Li is 2.2 dex (like the current plateau value), the present value would be 1.0 dex. The measured limit by Thorburn (1994) is consistent at (Li) < 1.1 dex. The initial value for Be can be found from the relationship between (A(Be)) and [Fe/H] for the iron abundance in G186-26 of [Fe/H] = −2.71. From Figure 5 of Boesgaard et al. (1999) and Figure 10.3 of Boesgaard (2004), we find the initial Be was about −1.18 dex, and thus the current value would be −1.18 + −0.40 = −1.58 for A(Be). Figures 1 and 2 show this value in the spectrum synthesis, as well as 2 and 4 times more Be than that. −2.00 (2.6 times less Be), and zero Be. Although no Be gives the best fit, an upper limit of −2.00 dex is consistent with the noise seen in the continuum and the overall fit of the synthesis. We note there are uncertainties in the initial Be assumed for this star and for the amount of Be depletion from the models.

Newer models and observations on this issue have been discussed by Pinsonneault et al. (1999, 2002). Pinsonneault et al. (2002) explain that the early models of P92 did not take into account that there could be a saturation effect in the loss of angular momentum for the rapidly rotating stars. They state that the amount of Li depletion could not be as large as the P92 rates. This would likely reduce the amount of Be depletion also. The hypothesis that the ultra–Li-deficient stars were originally part of a group of very rapidly rotating stars that have now spun down, along with some destruction of Li and Be, is not easy to reconcile with such a low upper limit on A(Be). This issue of Be abundances should be readdressed with modern models.

4. SUMMARY AND CONCLUSIONS

The nature of the ultra–Li-deficient metal-poor stars has been the subject of several papers and is relevant for the determination of the value of primordial Li. Two leading hypotheses for the Li deficiencies are that (1) they are analogs to blue stragglers that have lost surface Li through binary mass transfer or mergers, and that (2) they are the descendents of a subset of stars with initial rapid rotation that have depleted Li by rotationally induced mixing during spin-down through their evolution. In the blue straggler idea, there would be complete destruction of both Li and Be. If extra mixing resulted from rotation, much of the Li would be destroyed, but little or no Be. Thus, Be acts as a discriminator between these two hypotheses because it is less fragile than Li.

We have made observations of Be in a Li-deficient, very metal-poor halo star, G186-26. This star has [Fe/H] = −2.71, T_eff = 6200 K, and (A(Fe)) < −1.1. Our Subaru HDS spectrum has a spectral resolution of ∼50,000 and S/N of 98 in the Be i spectral region near 3130 Å. An upper limit for A(Fe) is −2.00. The data support the blue straggler hypothesis over rotation. A coalesced binary and mass transfer episodes could result in the observed deficits of Li and Be.

For G186-26 the blue straggler analog fits well, but it is necessary to look at Be in other ultra–Li-deficient, low-metal stars. To more fully evaluate the rotation hypothesis, new model predictions should be done for beryllium. Elliott & Ryan (2005) have shown that there are no commonalities in other abundances, but four of their six stars have measurable rotational velocities; perhaps rotation plays a role in these stars.

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