Beryllium in the Ultra-Lithium-Deficient, Metal-Poor Halo Dwarf, G186-26¹

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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 $T > 5900$ K and $[\text{Fe/H}] < -1.0$ that are ultra-Li-deficient. We have looked for Be in the very low metallicity star, G 186-26 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 $[\text{Fe/H}] = -2.7$, G 182-26 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: stars: abundances; stars: evolution; stars: late-type; subdwarfs; stars: individual (G 186-26); stars: Population II; Galaxy: halo

1. Introduction

Although nearly all metal-poor dwarf and turn-off stars with $T_{\text{eff}} > 5600$ K and $[\text{Fe/H}] \lesssim -1.3$ show similar Li abundances, there are a few such stars which seem to be ultra-deficient 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 (BBN) (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),

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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 $A(\text{Li}) \ (= \log N(\text{Li}/\text{H}) + 12.00)$ is near 2.2, but “the plateau” seems to have both a temperature and a metallicity dependence, e.g. Novicki (2005); those results are consistent with the results of Thorburn (1994) and Ryan et al. (2001a) in terms of both the coefficients of the dependencies and the sample size. For HD 97916 at 6124 K the upper limit on $A(\text{Li})$ is $<1.2$. The extreme halo star, G 186-26, was found to be Li deficient by Hobbs, Welty, & Thorburn (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 value, $A(\text{Li})_p$. Do they represent a true dispersion in the plateau? Do they indicate greater Li depletion and are thus sign-posts of general (more mild) Li depletion in all or most of the plateau stars? If all plateau stars have undergone some depletion, then $A(\text{Li})_p$ 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, 2002) 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: $\sim 2.5 \times 10^6$ K for Li and $\sim 3.5 \times 10^6$ 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, Deliyannis & Demarque 1992, hereafter PDD92).

The nine ultra-Li-deficient are not a uniform group. Four of them are single-line spectroscopic binaries (Carney et al. 2001); three of those four plus one other have measurable rotation velocities, while two (including G 186-26) have very sharp lines with only upper limits on $v \sin i$ (Elliott & Ryan 2005); three or four (including G 186-26) are single stars (Ryan et al. 2001a). There seem to be no peculiarities in composition that characterize all
of them (e.g. Spite et al. 1993, Norris et al. 1997; Elliott & Ryan 2005).

In this letter we report on the Be abundance of one of the warmest and most metal-poor of the ultra-Li deficient stars, G 186-26. The value of A(Li) for this star is $<1.1$ and [Fe/H] = $-2.8$ (Thorburn 1994).

2. Observations and Analysis

The spectra for G 186-26 were obtained on one night in 2003 May 27 (UT) with the high-dispersion spectrograph (HDS) at the Subaru 8.2 m 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 0.7 x 4.4 arcsec and the binning was 2 x 2. There are two EEV-CCDs covering 2048 x 4100 pixels (pixel size = 13.5 µ) 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 (per pixel) of 98 at 3130 Å. The spectral resolution is $\sim$50,000 or 0.062 Å. The dispersion is 0.0187 Å pix$^{-1}$ and the resolution element is 3.3 pix. 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 wavelength calibrated from the Th-Ar spectra. The two exposures were combined and the continuum was determined. Since G 186-26 has a metallicity of 500 times below solar, there is little blending and the continuum placement was straight-forward.

The stellar parameters for G 186-26 have been determined by Novicki (2005). We used the photometric indices of $(b - y)_0$, $(V - K)_0$, and $(R - I)_0$ and the calibrations of Carney (1983) to determine the effective temperature, $T_{\text{eff}}$. (The $(b - y)$ values are from Shuster & Nissen (1988), $(V - K)$ from Alonso et al. (1994) and Carney (1983), the $(R - I)$ from Eggen (1979).) A weighting of 4:2:1 was used for $T_{\text{eff}}(b - y)_0$: $T_{\text{eff}}(V - K)_0$: $T_{\text{eff}}(R - I)_0$. (For G 186-26 the reddening is negligible and was ignored: $E(b - y) = 0.011$.) The three temperatures are 6196 K, 6181 K, and 6256 K with a weighted mean of 6200 K $\pm 25$ K, but we use $\pm 40$ K as a more realistic estimate of the uncertainty. For comparison Alonso et al. (1996) find a weighted mean of 6428 K from H, J, K 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 (e.g. 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, $(b-y)_0$ and $c_0$, to estimate log $g$ via the Yi, Demarque & Kim (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 G 186-26 are $T_{\text{eff}} = 6200 \pm 40$ K, log $g = 4.48 \pm 0.20$, [Fe/H] = $-2.71 \pm 0.12$, 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; http://verdi.as.utexas.edu/moog.html). 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 G 186-26. 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 G 186-26; 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 G 186-26 with the same synthesis as in Figure 1. The value for A(Be) of $-1.58$ was selected as the expected initial Be abundance (see §3.2). The uncertainty in the Be abundances that is due to the uncertainties in the stellar parameters is $\pm 0.09$.

3. Results and Interpretation

It can be seen from Figures 1 and 2 that the spectrum of G 186-26 is consistent with no Be present in the stellar atmosphere, but we suggest an upper limit on A(Be) of $-2.00 \pm 0.09$ 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 G 64-12, 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 G 186-26 with Be abundances for other stars at its metallicity. Our Figure 3 shows the Be abundance limit of G 186-26 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, i.e. they have normal Be abundances. They also all have
normal Li plateau abundances. Our A(Be) 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.

3.1. Blue Straggler

Ryan et al. (2001) 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 turn-off 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 M 67 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 4 of the 5 Li-deficient field blue stragglers that they studied are single-lined spectroscopic binaries.

Pritchet & Glaspey (1991) conclude 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 where they would 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 G 186-26. The Carney et al. (1996) 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 $\sim 0.9$ km s$^{-1}$. There are no signs of double lines in our spectra.
If there has been mass transfer from a former AGB star onto G 18-6-26, it would have left composition signatures. In particular, Sneden, Preston & Cowan (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 G 18-6-26, with \([\text{Ba/Fe}] = 0.35\). 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 G 18-6-26. Norris et al. (2001), Stephens & Boesgaard (2002) and Fulbright (2002) all find that such an overabundance of \([\text{Ba/Fe}]\) is extremely rare at this low \([\text{Fe/H}]\).

Support for the blue straggler model for the ultra Li-deficient stars comes from the apparent lack of Be in G 18-6-26. Additional support for this comes from the super-solar content of neutron-capture elements. However, there is no evidence that G 18-6-26 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 \(\sim 3.5 \times 10^6\) K. Therefore, abundances of Be in the ultra-deficient Li halo stars could provide a clue about the efficiency of internal mixing. That is, if Be is found to be present in the ultra-Li deficient stars, that 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 PDD92. According to the standard models, there is no Be depletion (their Tables 3A and 3B). The models which 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 PDD92 models. Therefore, we have examined the latest “Yale” isochrones (Yi et al. 2004) appropriate for our star’s \([\text{Fe/H}]\), \(\log g\), and effective temperature to find the mass for G 186-26. The 13 Gyr isochrone gives a mass of 0.735 M\(_{\odot}\). Tables 5A, 5B, and 5C in PDD92 show the expected depletion for Li and Be for \(Z = 0.0001\) for 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 on A(Li) by Thorburn (1994) is consistent at $<1.1$ dex. The initial value for Be can be found from the relationship between A(Be) and [Fe/H] for the iron abundance in G 186-26 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 $-2.0$ 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 PDD92 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 PDD92 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 which 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: (1) They are analogs to blue stragglers which have lost surface Li through binary mass-transfer or mergers. (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, G 186-26. This star has [Fe/H] = $-2.71$, $T_{\text{eff}} = 6200$, and A(Li) < $-1.1$. Our Subaru/HDS spectrum has a spectral resolution of $\sim 50,000$ and S/N of 98 in the Be II spectral region near 3130
A. An upper limit for A(Be) 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 G 186-26 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 Be. 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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Fig. 1.— The synthetic spectrum in the Be region for G 186-26. 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 PDD92 calculations (−1.58) and the dotted line is a factor of 2 more Be and the dashed dotted is a factor of 4 more Be. The upper dotted line is our upper limit, A(Be) = −2.00, but see Figure 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). G 186-26 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.
Fig. 2.— Like Figure 1 of G 186-26, but zoomed in on the Be II lines.
Fig. 3.— The trend of Fe and Be showing the Be upper limit for G 186-26 as the solid triangle with Li-normal stars. Open squares are from Primas et al. (2000a, 2000b); open circles are from Boesgaard et al. (1999), Boesgaard (2000), Stephens et al. (1997).
Fig. 4.— Radial velocities measured for G 186-26 by Carney et al. (1994). Latham et al. 2002 find no evidence for binarity in the star. The line is simply the least squares fit through the data and is not meant to imply that there is an increase in the radial velocity over time.