

# Beryllium in Extremely Metal Deficient Stars

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## ABSTRACT

The very low metal stars ( $[\text{Fe}/\text{H}] \sim -3.0$ ) were formed in the earliest days of the Galaxy. Spallation reactions, the main progenitor of Be, are tied to the rate of supernovae. Therefore, the abundance of Be in low metal, older stars is a tracer of massive star formation within our galaxy. There is also evidence of a possible primordial Be plateau at very low metallicities, a result of some inhomogeneous Big-Bang models. We analyze high S/N HIRES spectra of 13 very low metal stars in order to determine the history of Be abundance and explore the possible Be plateau. We determine stellar parameters of our sample spectroscopically, using equivalent widths of FeI and FeII lines. Our results indicate that the relationship between Be and  $[\text{Fe}/\text{H}]$  continues to lower metallicities, with no indication of a plateau. Our results also seem to indicate that the relationship between Be and  $[\text{Fe}/\text{H}]$  and Be and  $[\text{O}/\text{H}]$  have similar slopes, which would indicate similar formation processes for Be and O, possibly SN II's.

## 1. Introduction

The history of Be in our galaxy is tied to multiple areas of astronomy. Recent observations suggested the possibility of a Be plateau at very low  $[\text{Fe}/\text{H}]$  (Primas et al. 2000a, 2000b). This would be similar to the Spite lithium plateau. The Li plateau in older stars is due to nucleosynthesis of Li during the Big Bang. Some non-homogeneous models of the Big Bang would lead to the synthesis of a large enough amount of Be that a similar plateau could be detected in the oldest stars. Another possible cause could be the creation of Be through spallation reactions in contained superbubbles created by multiple supernovae (Parizot and Drury 2000) or near hypernovae (Fields et al. 2002, Nakamura et al. 2006). Enrichment of

the ISM in Be by such processes early in the history of the galaxy could result in a detectable plateau.

The lowest metal stars ( $[\text{Fe}/\text{H}] < -3.0$ ) were formed early in the evolution of the Galaxy. By tracing the abundance of beryllium in these old stars, insight can be gained into the chemical history of the Galaxy. Be is formed mainly through spallation reactions, which was proposed by Reeves, Fowler & Hoyle (1970) and further described by Meneguzzi, Audouze & Reeves (1971). This happens either as the early generations of massive stars eject C and O in supernovae, which then collide with baryons and spall into Be, or as high energy cosmic rays interact with C, N and O atoms in interstellar gas. This means that abundances of Be in old stars provides a way to trace the earliest generations of massive stars.

## 2. Observations and Data Reduction

The Be II resonance line located in the UV spectral region at 3130.421 and 3131.065 Å was used to determine the Be abundances. High signal to noise and high resolution are required to assess the Be doublet due to the weak, blended nature of the Be spectral region. The High Resolution Echelle Spectrograph (HIRES) instrument on the Keck I telescope achieves the necessary requirements: it has high enough resolution and the light collecting power of a 10 m telescope, which allow observations of the preferentially faint stars in our metal-poor sample. Observations were carried out over several nights using the blue cross-disperser, which has a spectral range of approximately 3000 to 6000 Å. The HIRES ccd is composed of three chips, one each for UV (on which the Be doublet is located), green and red wavelengths, with excellent quantum efficiency in the UV, making exposure times manageable. G64-37 was observed with HDS on Subaru, which has a similar but smaller wavelength range, with a maximum of  $\sim 4500$  Å. G64-37 was reduced by Boesgaard & Novicki (2006)

HIRES data reduction was carried out using the MAKEE pipeline and standard IRAF routines. Excessive cosmic ray strikes were removed using the LACosmic routine described in Van Dokkum 2001. The MAKEE pipeline was used to flatten, extract and wavelength calibrate the spectrum from each individual exposure. IRAF was used to co-add multiple exposures of the same star and to fit continua to each combined, calibrated spectrum.

Table 1 shows observations of the stars analyzed in this project with V band magnitudes, total exposure time and S/N near the Be doublet pixel range.

### 3. Data Analysis

The data were analyzed using IRAF and MOOG, a stellar synthesis program (Snedden 1973). Equivalent widths of spectral lines were measured using IRAF routines. MOOG was used for two purposes: stellar parameter determination and abundance determination. MOOG’s “abfind” driver was used to measure the metallicity,  $[\text{Fe}/\text{H}]$ , and determine  $T_{eff}$  and the surface gravity,  $\log g$ , of the stars in our sample, the “synth” driver was used to create synthetic spectra in order to measure Be and O abundances.

#### 3.1. Stellar Parameters

Stellar parameters are needed to generate the stellar models used for spectral synthesis and abundance determination. Several Fe I and II lines fall within the range of the HIRES ccd and can be used to determine  $[\text{Fe}/\text{H}]$ ,  $T_{eff}$  and  $\log g$ , using a method similar to Stephens (1999). Microturbulence,  $\mu$ , has a negligible effect on any of the measurements in this project, so a standard value of 1.5 km/s was used in all models. Equivalent widths of 28 FeI and 10 FeII lines on the green and red chips of the HIRES ccd as well as 3 FeI lines from the UV chip near the Be doublet.

Using an initial estimate for the stellar parameters and the measured equivalent widths, MOOG’s “abfind” driver was then used to calculate an Fe abundance for each line, as well as an average  $[\text{Fe}/\text{H}]$  from the equivalent widths. MOOG also calculates the slope of each line’s calculated abundance vs. its excitation potential (EP). If the temperature is correct, there should be no trend of abundance with EP. Figure 1 shows a plot of abundance vs. EP at two different temperatures for a star from our sample: there is a trend at 6000 K, which is too low, versus 6350 K which is approximately the  $T_{eff}$  of the star.  $T_{eff}$  calculated from a spectrum tends to be a bit lower than calculations based on color indices (king, carney reference?).  $T_{eff}$  can be adjusted and the abundances recalculated until there is no trend and  $T_{eff}$  is correct.

If the  $\log g$  is correct for a given star, the  $[\text{Fe}/\text{H}]$  measured from the FeI and FeII lines should agree. If the abundances do not agree, the value of  $\log g$  can be adjusted and the abundances recalculated with MOOG. For the purposes of this project, MOOG was run iteratively by first calculating the abundance from FeI lines, adjusting the temperature accordingly and subsequently calculating the abundance from FeII and comparing the two sets of abundances. The value for  $\log g$  is adjusted and the process can then be run iteratively between FeI and FeII abundances until  $[\text{Fe}/\text{H}]$ ,  $T_{eff}$  and  $\log g$  are calculated. The stellar parameters used to calculate abundances are shown in the second, third and fourth columns

of Table 2.

### 3.2. Abundance Determination and Errors

Once stellar parameters were calculated for each star, they were used to define models for MOOG’s “synth” driver. The synthetic models, coupled with a line list (slightly modified from Boesgaard et al. 1999b) generate a synthetic spectrum, which can then be compared to the data. As an example, the synthesis of the Be region of G206-34 is shown in figure 2. The difficulty in determining  $A(\text{Be})$  can be seen in figure 3, which shows a comparison of a very metal poor star from our sample (at about 1/750 solar) and one of much higher metallicity (about 1/10 solar). The Be abundances calculated for each star, except for G268-32 and G10-4 are listed in Table 2. Unfortunately, the Be spectral regions for G268-32 and G10-4 appear to lack observable Be lines due to blending caused by an as yet undetermined source.

Four reliable lines that fall on the UV chip were used to calculate the O abundance of each star using the “synth” driver as well. One of these lines falls within the Beryllium synthesis region, just redward of the Be line at 3130, the three others are further in the red at 3139 Å, 3140 Å and 3167 Å. Generally the O abundance agreed with the initial abundance calculated in the Be region, so those values are listed in Table 2.

Error in abundance determinations is a result of error in the stellar parameters as well as the accuracy of the synthesis fits. Errors in the abundances were determined by adjusting the stellar parameters  $[\text{Fe}/\text{H}]$ ,  $T_{eff}$  and  $\log g$  to see how it affected the abundance calculation.  $\log g$  has the largest effect on the Be lines of any of the stellar parameters. For instance, a change in  $T_{eff}$  in  $\pm 100$  K results in a change in  $A(\text{Be})$  of  $\pm 0.03$  and a change in  $[\text{Fe}/\text{H}]$  of  $\pm 0.3$  dex results in a change in  $A(\text{Be})$  of  $\pm 0.01$ . However, a change in  $\log g$  of  $\pm 0.3$  results in a change of about  $\pm 0.15$  dex in  $A(\text{Be})$ . The combination of these errors as well as the spectrum synthesis results in an error in  $A(\text{Be})$  of about  $\pm 0.2$  dex.

## 4. Results and Discussion

The Be abundances calculated in our project are shown in figure 4, as well as Be abundances from several other references, cited in the figure caption. Our results seem to continue the same trend of  $[\text{Be}/\text{Fe}]$  to lower metallicities, within the errors. The possible nucleosynthesis of Be in the Big Bang has been discussed by several authors (Alibes et al. 2002, Boyd et al. 1989, Jedamzik and Rehm 2006, Malaney and Fowler 1989). In only the most optimistic of inhomogeneous BB cosmologies is their enough Be produced to observe using

current methods. Our results do not seem to indicate a Beryllium plateau at very low metallicities, as has been recently suggested by primas et al. (2000a). Analyzing stars of even lower metallicities might provide further information, but observations become very time consuming, due to the faintness of stars at such low metallicities.

There is the possibility of an overabundance of Be for stars of a given metallicity, but the results as plotted in figure 5 seem to indicate that there is no overabundance or dispersion, within the errors. There are two stars analyzed in this project that were previously considered by Primas et al. (2000a, 2000b), LP815-43 and G64-12. The values of  $A(\text{Be})$  calculated from our data are slightly lower than Primas’: for LP815-43 we calculated  $A(\text{Be})=-1.25$ , Primas et al. calculated  $A(\text{Be})=-1.09$  and for G64-12 we calculated  $A(\text{Be})=-1.35$ , Primas et al. calculated  $A(\text{Be})=-1.15$ . Primas et al. adopt higher temperatures for their stellar models, which would lead to generally higher abundances. The parameters used in this project were determined spectroscopically and fit the data well. When the stellar parameters from Primas (2000a) were applied to our data,  $A(\text{Be})$  was found to be about -1.25, but other spectroscopic features in the Be region did not fit the data as well as with our parameters.

$A(\text{Be})$  vs.  $[\text{Fe}/\text{H}]$  and  $A(\text{Be})$  vs.  $[\text{O}/\text{H}]$  are plotted in figure 6 along with linear least-squares fits to each. The slopes of these two lines would seem to indicate that at very low metallicities, Be and O underwent similar amounts of formation. Since O is formed by Type II supernovae of massive stars and Be can be formed in the vicinity of Type II supernovae this would imply that Be was formed mainly in the vicinity of those SNe at very low metallicity. Boesgaard et al. (1999a) determine slopes for  $A(\text{Be})$  vs.  $[\text{Fe}/\text{H}]$  of 0.96 and  $A(\text{Be})$  vs.  $[\text{O}/\text{H}]$  of 1.45, as opposed to the slopes from this project of 0.75 and 0.73 respectively. They note that if Be is formed in the vicinity of Type II supernovae, the slope of  $A(\text{Be})$  vs.  $[\text{O}/\text{H}]$  should be 1, if it is formed in the ISM it should be 2. The difference between the results from this paper and Boesgaard (1999a) is likely due to the fact that this project only considers stars of very low metallicity and because the stellar parameters were determined spectroscopically rather than via color indices as in Boesgaard et al.

## 5. Conclusion

Be and O abundances in 13 very metal deficient stars from  $[\text{Fe}/\text{H}]$  -3.66 to -2.42 were calculated from high S/N, high resolution spectra from HIRES on Keck I. Stellar parameters were calculated using equivalent widths of FeI and FeII lines and used in the determination of those abundances. Be abundances were calculated using the BeII doublet at 3130 and 3131. O abundances were calculated using 4 OH lines in the UV. The stellar synthesis program MOOG was used to calculate both stellar parameters and elemental abundances.

The Be abundances calculated seem to indicate that the trend of  $A(\text{Be})$  continues to lower metallicities, with no indication of a Be plateau. The similar trends of Be with Fe and of Be with O seem to indicate that at very low metallicities Be and O may have undergone similar formation processes, possibly in the neighborhood of SN II's. Since O atoms are formed mainly by SN II's and those same SN II's form energetic CNO particles that create Be, if that is indeed the formation mechanism they would have similar slope, having formed at similar rates. Boesgaard et al. (1999) seems to indicate that this is likely not the case at higher metallicities, however.

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Table 1. Beryllium Observations

Star	R.A.	Dec.	V	[Fe/H]	Exp. min.	S/N
LP 651-4	02 44	−05 26	12.0	−2.70	65	86
G 75-56	03 00	−05 57	11.9	−2.42	232	116
BD +3 740	05 01	+04 06	9.8	−2.85	60	167
BD +20 2030	08 16	+19 41	11.2	−2.38	60	122
BD +9 2190	09 29	+08 38	11.2	−3.07	120	110
BD +1 2341p	09 40	+01 00	10.5	−2.78	40	139
BD -13 3442	11 46	−14 06	10.4	−3.00	80	183
G 64-12	13 40	−00 02	11.5	−3.40	210	121
G 64-37	14 02	−05 39	11.1	−3.00	270	87
G 206-34	18 35	+28 41	11.4	−3.07	105	101
LP 752-17	19 25	−11 56	11.9	−2.53	60	73
LP 815-43	20 38	−20 25	10.9	−2.91	90	91
G 275-4	23 07	−23 52	12.2	−3.66	190	75

Table 2. Stellar Parameters

Star	$T_{eff}$ (K)	log g	[Fe/H]	[O/H]	A(Be)
LP 651-4	6218	4.32	−2.70	−1.93	−1.12
G 75-56	6000	4.06	−2.42	−1.83	−0.78
BD +3 740	6048	4.16	−2.85	−2.43	−1.17
BD +20 2030	6350	4.82	−2.38	−1.83	−0.70
BD +9 2190	5900	4.14	−3.07	−2.78	−1.55
BD +1 2341p	6275	4.28	−2.78	−2.18	−1.10
BD -13 3442	5900	4.10	−3.00	−2.53	−1.25
G 64-12	6028	4.20	−3.40	−2.63	−1.35
G 64-37	6000	4.02	−3.00	−2.48	−1.42
G 206-34	5940	4.12	−3.07	−2.23	−1.20
LP 752-17	5750	4.14	−2.53	−2.23	−0.56
LP 815-43	6268	4.34	−2.91	−2.23	−1.25
G 275-4	5762	4.16	−3.66	−2.93	−1.60

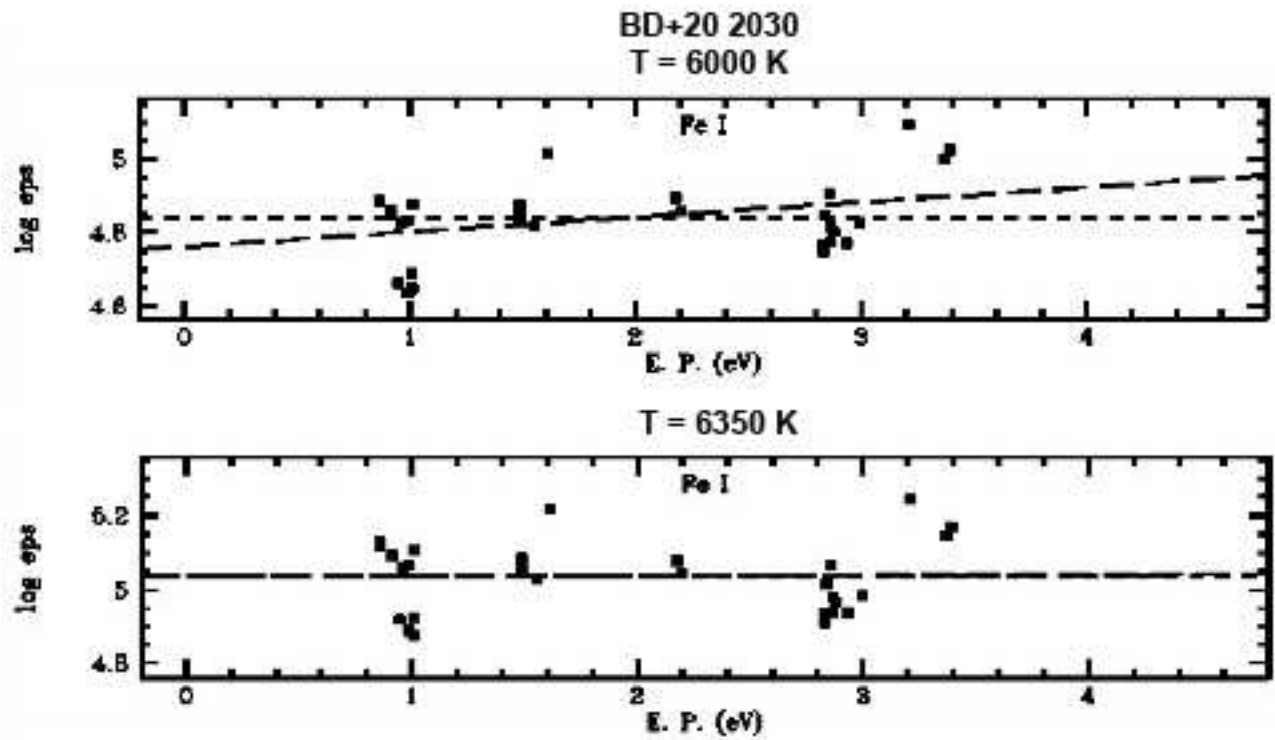


Fig. 1.— Plots of excitation potential vs. Fe abundance used in the calculation of  $T_{eff}$ . The top plot shows a positive trend of abundance with excitation potential, meaning the temperature is too high. The temperature has been adjusted to the proper value in the bottom plot.

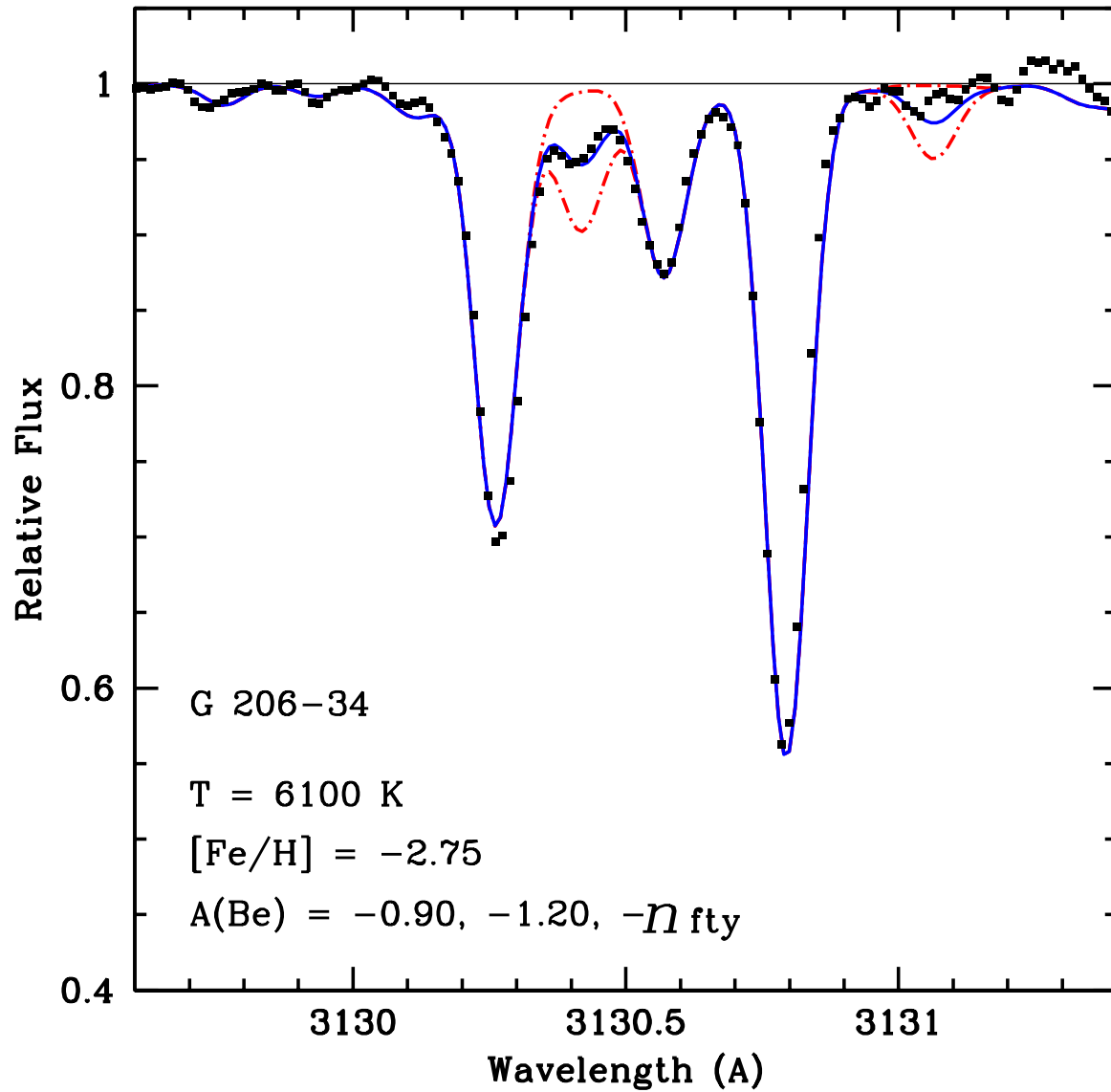


Fig. 2.— Example of a output from MOOG’s “synth” driver. The Be abundance is calculated from the doublet in the spectral region above. The OH feature in the region is used as a preliminary estimate at the O abundance.

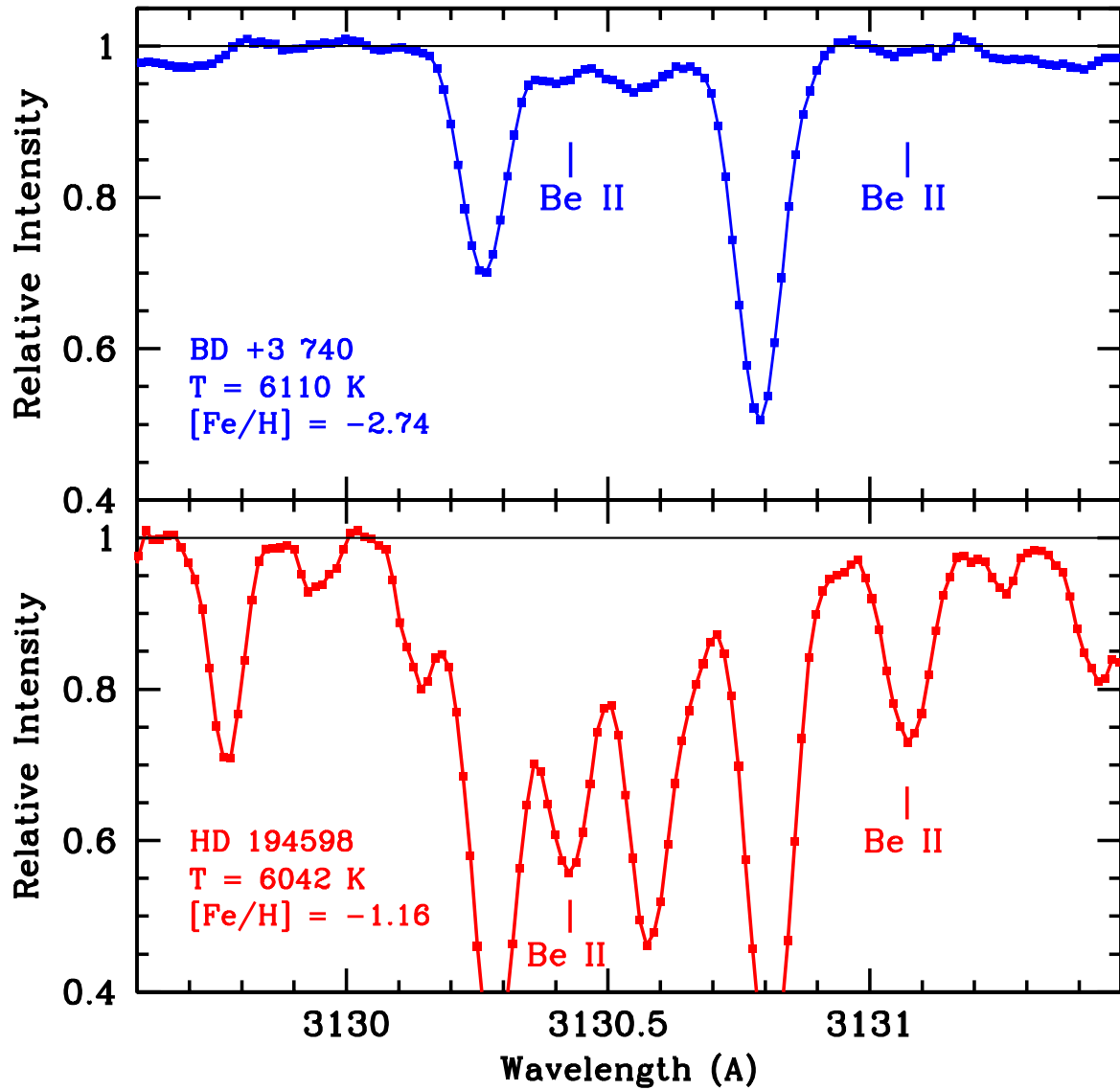


Fig. 3.— The Be region of a star from our sample of very metal-poor stars compared to a star of much higher metallicity. Both the Be doublet and the OH feature are much reduced at low metallicities, necessitating the high signal to noise of our observations.

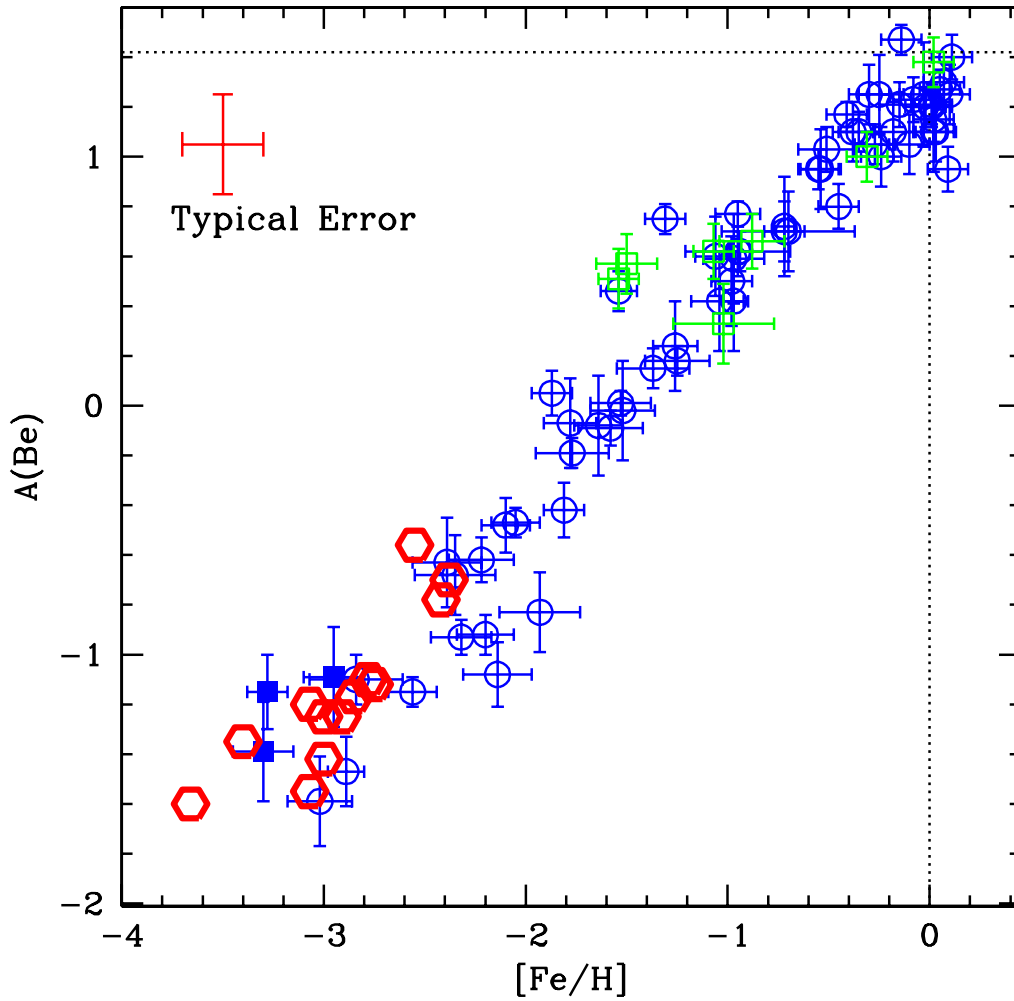


Fig. 4.— The plot above shows current data with our results added as red hexagons, as well as a typical error range. Our abundance determinations generally follow the current trend of  $A(\text{Be})/[\text{Fe}/\text{H}]$ . The results do not seem to indicate a Beryllium plateau at low metallicities a possibility discussed in Primas et al. (2000a) Analyzing stars of even lower metallicities might provide further information, but observations become very time consuming, due to the faintness of stars at such low metallicities. Blue circles are data from Boesgaard et al. (1999, 2000, 2004), Blue squares are from Primas et al. (2000a, 2000b). Green points are from Boesgaard & Novicki (2006). The dotted horizontal line is the meteoritic Be Abundance,  $A(\text{Be})=1.42$ . The plot below shows another way of visualizing the Beryllium abundance, with  $[\text{Be}/\text{Fe}]$  rather than  $A(\text{Be})$ . The points from this study are red squares.

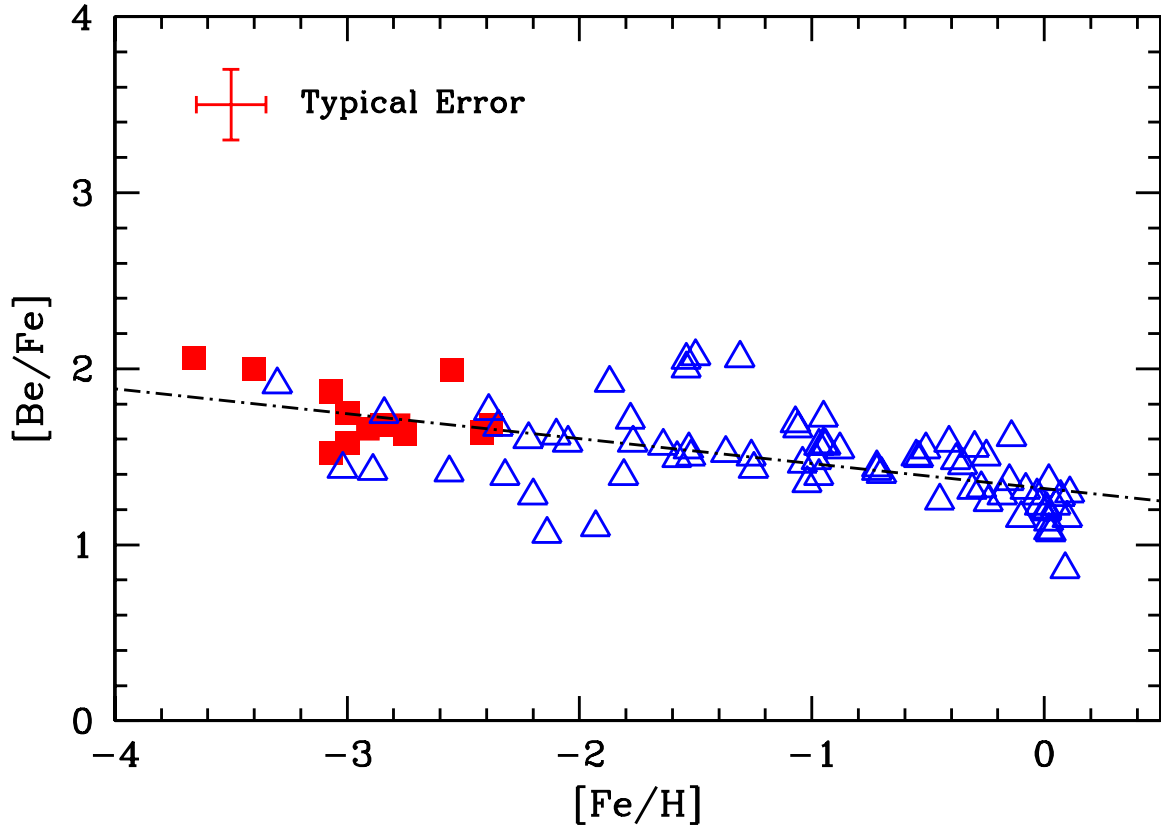


Fig. 5.— The above figure shows the trend of Be with metallicity plotted differently. The stars in this project extend the known trend of  $[Be/Fe]$  to lower metallicities within the errors. If there is an overabundance of Be for a given Fe in a particular star, it could be due to local enrichment from excessive spallation due to formation in a superbubble (Parizot & Drury 2000) or near a hypernova (Fields 2002).

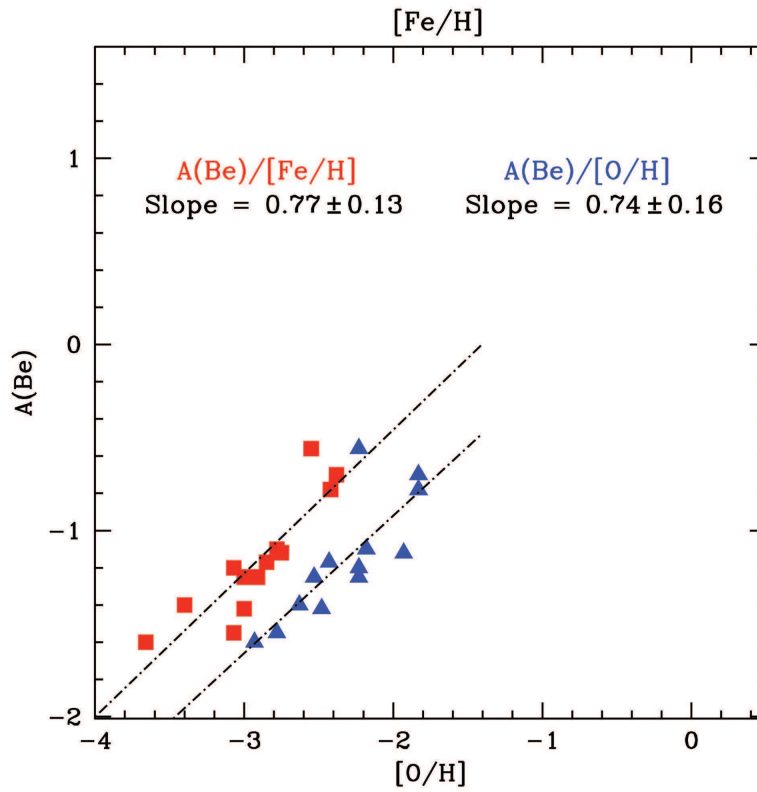


Fig. 6.— The above plot shows the trend of Be with both Fe and O plotted on the same axes. The result is difficult to interpret, but the similar slope would seem to indicate that O and Be at very low metallicities underwent similar amounts of formation.