The Light Elements and Their Evolution
IAU Symposium, Vol. 198, *2000*
L. da Silva, M. Spite, J. R. de Medeiros, eds.

The Galactic Evolution of Beryllium

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Abstract. The abundance of beryllium has been determined in unevolved stars over a range metal abundances in order to enhance our understanding of the chemical evolution of our Galaxy, cosmic-ray theory, and cosmology. Observations of 27 stars have been made with Keck I with HIRES at high spectral resolution (45,000) and high signal-to-noise ratios (60 - 110 typically). We find a remarkably linear relationship between log N(Be/H) and [Fe/H] with a slope of 0.96 (±0.04). Similarly, the relationship between log N(Be/H) and [O/H] is linear with a slope of 1.45 (±0.04). Beryllium increases at the same rate as Fe, but much faster than O. This provides constraints for and insights into models of Galactic chemical evolution. There is some evidence for an intrinsic spread in Be at a given [O/H] or [Fe/H]. There is no evidence of a plateau in Be at the lowest metallicities down to log N(Be/H) = −13.5.

1. Introduction

Unlike the heavier elements which are formed by nuclear fusion reactions in the interiors of stars at high–temperatures, Be is destroyed in stellar interiors. Instead of being formed by fusion of lower mass nuclei, it is widely accepted that Be is created by the breaking up of heavier nuclei in spallation reactions. There are interactions of high energy cosmic rays ($H\&He_{CR}$) with abundant elements like C, N, O in the interstellar gas (CNO_{ISM}) as first proposed by Reeves, Fowler, & Hoyle (1970); whether these interactions take place in the immediate vicinity of supernovae or in the general interstellar gas is not completely clear. In the early Galaxy, there was little CNO_{ISM} but plenty of CNO_{CR} and this reaction was of greater *relative* importance then than now (Yoshii, Kajino & Ryan 1997). The evolution of the abundance of Be should reflect the production of CNO and cosmic rays and thus mirror the production of massive stars (which contribute the O atoms) and supernovae.

The determination of the amount of Be in the most metal-poor stars (expected to be the oldest stars), may reveal if any Be has been synthesized in the Big Bang. The standard model of Big Bang nucleosynthesis (BBN) produces only a little Be: ($N(Be)/N(H) = 10^{-17}$). But models that include inhomogeneities in the early universe could produce a different mixture of light elements than that in the standard models (see the review by Malaney & Mathews 1992).

Several papers have been published on Be abundances in halo stars including Rebolo et al. (1988), Ryan et al. (1991), Gilmore, Edvardsson, & Nissen (1991), Ryan et al. (1992), Gilmore et al. (1992), Boesgaard & King (1993), Molaro et al. (1997), Boesgaard et al. (1999a). The relationship between log N(Be/H) and [Fe/H] appears to have a slope of 1, indicating that the environment for the spallation reactions is the vicinity of supernovae (SNII) with freshly minted CNO nuclei rather than the ambient interstellar medium.

We have observed stars with [Fe/H] values down to −3.0 to search for a Be plateau which might indicate a BBN component of Be. In the most metal-poor stars the Be II lines are expected to be very weak so spectra with high resolution and high signal-to-noise (S/N) were needed. We have observed Be in stars with an array of metallicities to investigate the Galactic evolution of Be. To this end we have also determined O abundances in these stars (Boesgaard et al. 1999b) and thus have a consistently determined data set of Be and O abundances in halo stars. The Be abundances could be determined to a precision of ±0.1 dex.

2. Observations

The Be II resonance lines are at 3130.420 and 3131.065 Å in the ultraviolet (UV) spectral region accessible from the ground. For our Be observations we used the HIRES spectrometer (Vogt et al. 1994) on the Keck I telescope. To maximize the UV flux we have made observations as close as possible to the lowest air mass for each star. The resolution of the spectra is ~45,000 (FWHM = 3 pixels) with an effective dispersion of 0.022 Å pix^{-1}. The signal-to-noise ratios were typically 60 - 110 per pixel.

We have spectra of 22 metal-poor stars. We also took exposures of the daytime sky (as a solar spectrum) and of three disk stars for comparison with the halo stars. For our faintest and most metal-poor star, BD -13 3442, our total integration time was 11 hours for a S/N of 130.

3. Data Analysis

Standard echelle reductions were carried out within the IRAF routines. In order to co-add the spectra from different times of night or from different nights/runs the cross-correlation techniques in IRAF were used to determine the spectral shifts. The continua were fit quite easily for the lowest metallicity stars since the blending features in this crowded spectral region are so weak. The spectra of these stars could be used to help identify the continuum high points in the stars with progressively stronger atomic and molecular features.

We invested much effort in the determination of the stellar parameters so they are as self-consistent as possible. The temperature indicators used are (b-y), (V-K), and (R-I). We applied corrections for interstellar reddening where needed. The values for [Fe/H] were taken from high spectral resolution determinations in the literature. These were 1) corrected to a solar value of log N(Fe/H) + 12.0 = 7.51 (Anders & Grevesse 1989), and 2) corrected for the temperature difference between the published values and our scale. One of the methods we employed to find gravities was to use published detailed analyses which used ionization balance to find log g.

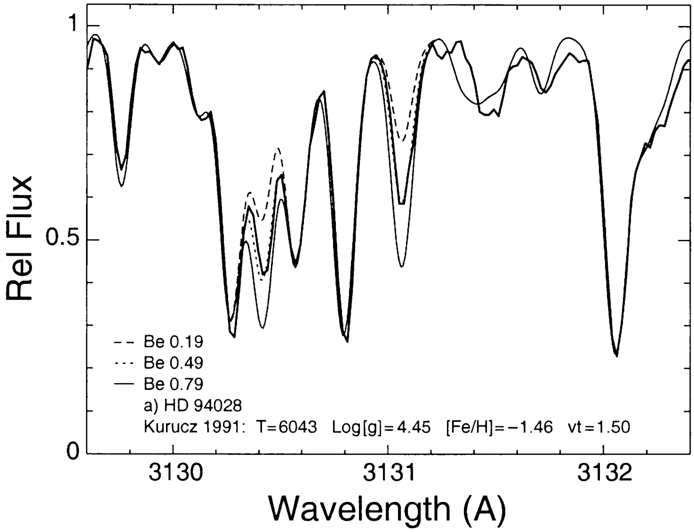

Figure 1. An example of the spectrum synthesis fit for HD 94028. They heavy solid line is the observed spectrum. The three syntheses are different from each other by factors of 2. Log N(Be/H) = −11.81: long dash; −11.51: dots; −11.21: light solid line. The best fit is −11.51.

4. Abundance Determinations

We have determined abundances from both spectrum syntheses and from the measured equivalent widths of Be II lines. In each method the results from the weaker, less blended line at 3131 Å are to be preferred. Kurucz (1993) model atmospheres have been used throughout.

For the equivalent width method we treated the λ3131.065 Be II line as a blend with 11 other atomic and molecular lines between 3131.015 and 3131.116 Å from the line list of King, Deliyannis & Boesgaard (1997) as weak possible blends. The spectrum synthesis calculations have been modified to include the effect of enhanced O. Our study of O abundances in these same stars (Boesgaard et al. 1999b) has enabled us to specify the O abundance. The agreement between the abundances determined by the equivalent width method and the spectrum synthesis method is very good. Figure 1 shows an example of the spectrum synthesis of HD 94028. The fit is excellent. This is significant because this star lies above the best fit in the Be vs Fe and Be vs O diagrams; it may indicate that there is an intrinsic spread in Be at a given Fe.

5. Results

The key results of this work are the trends of Be with Fe and with O. Figure 2 shows the relationship between log N(Be/H) +12.00 and [Fe/H]. The line

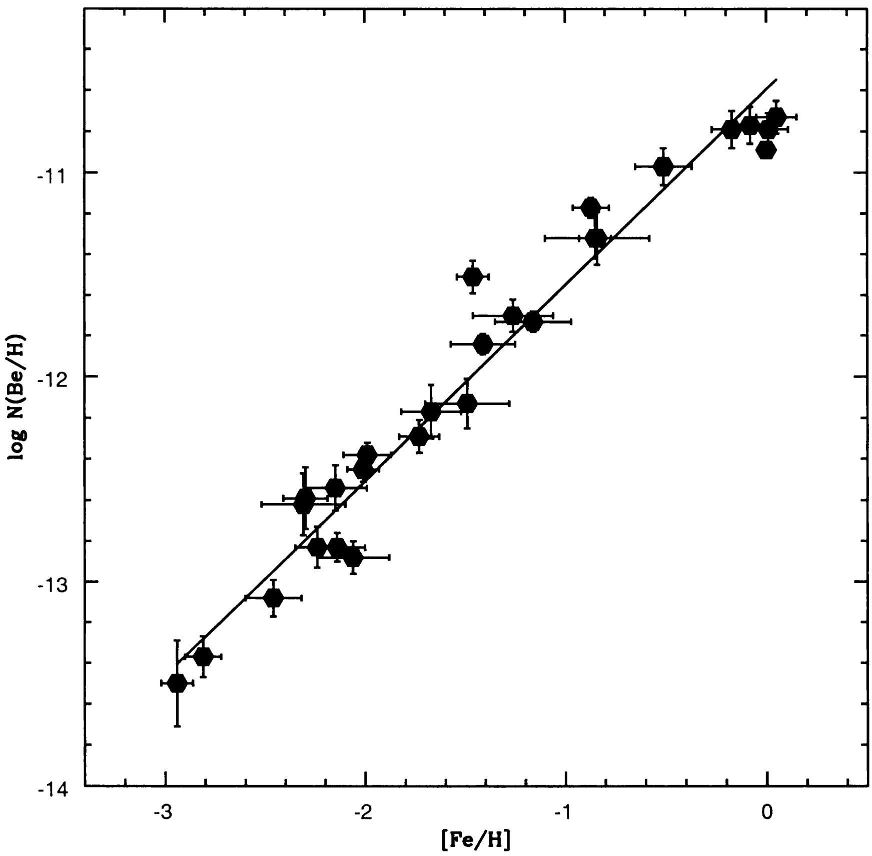

Figure 2. Beryllium abundances as log N(Be/H) vs [Fe/H] for the Keck observations. The line is the fit taking the error bars in both quantities into account.

through the points is a least squares fit which takes the errors in both coordinates into account. The equation for the line is:

$$\log N(Be/H) = 0.96\ (\pm 0.04)\ [Fe/H]\ -10.59\ (\pm 0.03).$$

The slope is ~1. As the Galaxy ages, Be and Fe increase together over three orders of magnitude in [Fe/H]. This is rather remarkable since they are formed by such different nucleosynthetic processes. Note that there is no indication of a plateau in the low metallicity, low Be corner of this plot. That is, there is no evidence for Big Bang-produced Be.

We know that there is some intrinsic spread in Be at the metallicities of solar-type stars (Boesgaard & King 1993, Boesgaard et al. 1999a) and we may be seeing some evidence of that here at lower metallicities, e.g. at [Fe/H] ~−1.5 and ~−2.2. One star stands out above the line at −1.46, −11.51; this is HD 94028 and, as mentioned above, the spectrum synthesis is excellent (see Figure 1). When this star is compared to HD 219617 at −1.49, −12.15, which has the

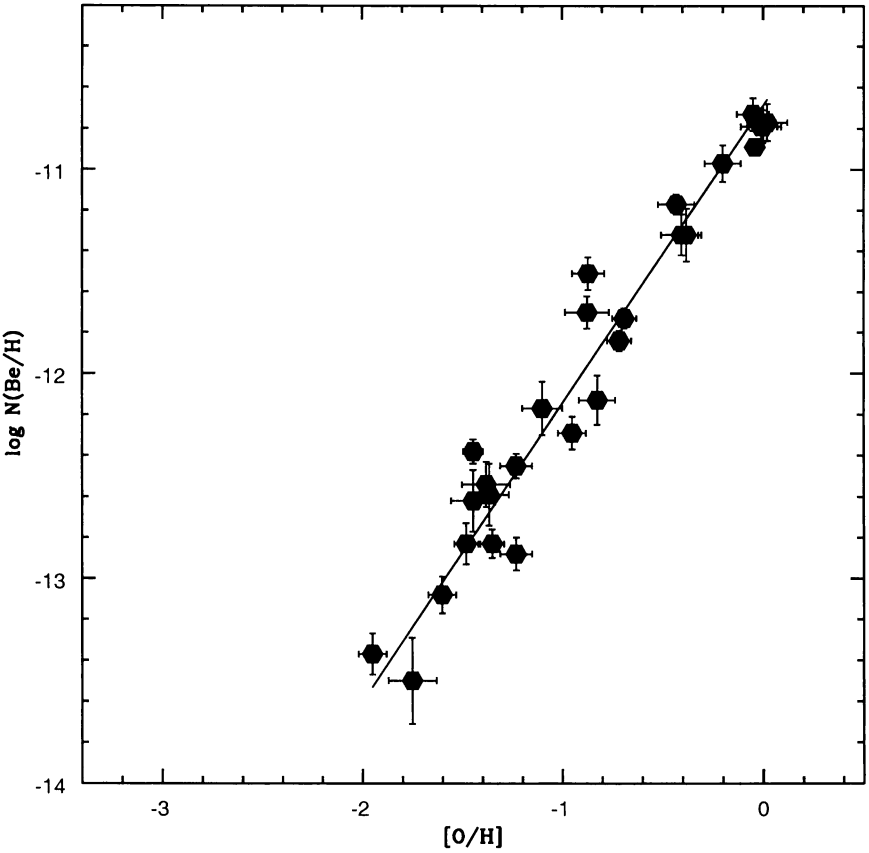

Figure 3. Beryllium abundances as log N(Be/H) vs [O/H] for the Keck observations. The line is the fit taking the error bars in both quantities into account.

same metallicity, temperature and log g, the difference in Be is large: a factor of 4.4, well beyond the errors.

Since Be is produced by spallation with CNO nuclei, it is important to examine the relationship between Be and O. We have determined O abundances from these same spectra and stellar parameters (Boesgaard et al. 1999b). Figure 3 shows the trend of Be with O; the line through the data points takes into account the errors in both quantities. Again, these are straight-line correlations, represented by

$$\log N(Be/H) = 1.46\ (\pm 0.04)\ [O/H]\ -10.69\ (\pm 0.04).$$

The relationship between Be and O is well-represented by a single straight line with a slope of 1.45. As O increases 100-fold, Be increases by 800 times.

We have made additional observations of Be in metal-poor stars with the 4-m at CTIO and with the Canada-France-Hawaii 3.6-m telescope (Deliyannis et al. 1995). The resolutions were 22,400 and 24,000 respectively, about half the

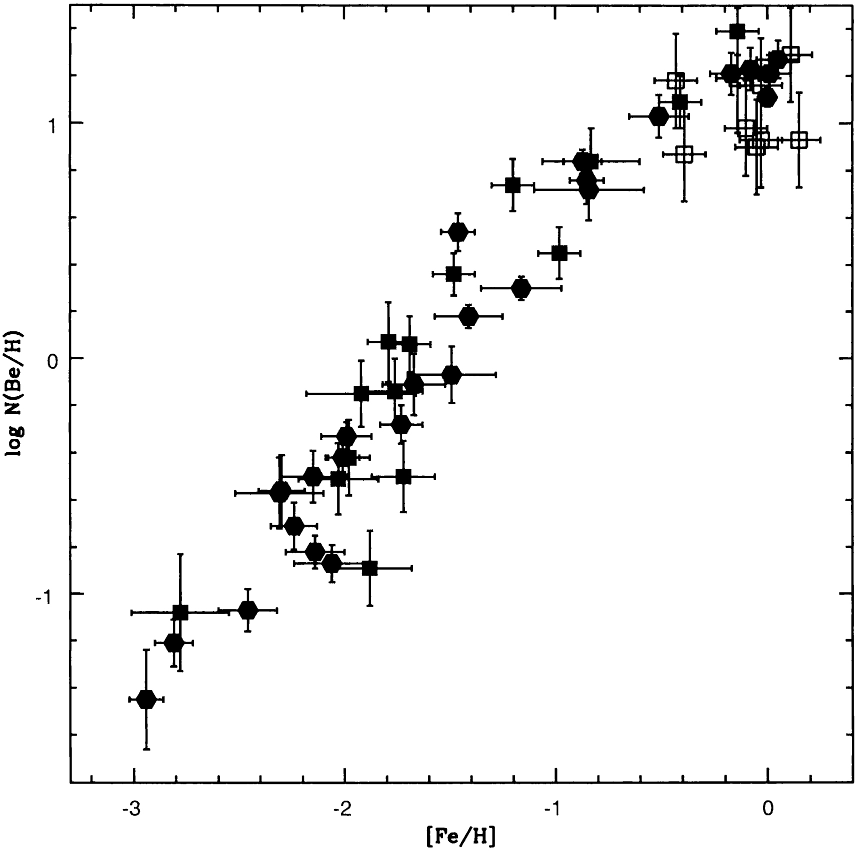

Figure 4. Beryllium abundances as log N(Be/H) vs [Fe/H] for the Keck observations are solid hexagons, for the CTIO and CFHT are solid squares, for the solar-type stars are open squares.

resolution of the Keck spectra. The signal-to-noise ratios in these spectra was 40-80. If we include this sample of stars with the Keck stars we add 22 more stars. In addition, we can add a few more solar type stars from our paper about correlated depletions of Li and Be (Deliyannis et al. 1998). The results from all these data are shown in Figure 4.

If Be is produced by cosmic ray protons breaking up CNO nuclei in the ambient interstellar medium, then, in the extreme case, the slope of the relationship between Be and O would be 2. This quadratic relationship results from the fact that the number of O atoms is proportional to the cumulative number of SNIIs (N) while the number of energetic proton cosmic rays is proportional to the instantaneous rate of SNIIs (dN). The abundance of the spallation products is therefore the integral of the product N dN $= kN^2$. Thus the spallation product (Be) vs O has a slope of two. However, chemical evolution effects, such as an outflow of mass from the halo, indicate that there would be a quadratic relation only at the very lowest metallicities (lower than the present sample), followed by a progressive shallowing of the slope to disk metallicities. From [Fe/H] between −1 and −2, the slope is close to 1.5. However, the slope would be 1 if Be is produced in the immediate vicinity of the SN IIs (the source of both the parent CNO atoms and the cosmic rays). The reaction CNO_{CR} + $\mathrm{H\&He}_{ISM}$ also produces a linear slope, the cosmic ray CNO being primary (Yoshii et al. 1997). Our slope for Be vs O is 1.5. This is consistent with the traditional mass outflow model where energetic protons and alpha particles impinge upon ambient CNO in the ISM, but less consistent with either of the linear slope scenarios just described.

We found no evidence of a Be plateau at abundances down to log N(Be/H) = −13.5. Therefore any primordial Be predicted by non-standard BBN must be below that value.

6. Summary

We obtained high-resolution and high S/N ratio spectra of 27 stars over a range of [Fe/H] of −3.0 to +0.1 with the Keck I telescope and HIRES in the blue and ultraviolet spectral region. We derived Be abundances in these stars from the Be II resonance lines by two methods which are in excellent agreement.

The special features of this work include 1) high spectral resolution, 2) high signal-to-noise ratios, 3) a self-consistent parameter set, 4) enhanced O/H in the spectrum synthesis. The results of the analysis show that Be and Fe increase together. The slope in log N(Be/H) vs [Fe/H] is 0.96 ±0.04, so Be and Fe increase at the same rate. We find that Be increase faster than O. The slope between log N(Be/H) and [O/H] is 1.45 ±0.04. As the abundant element, O, increases by 100 times, the trace element Be increases by 800 times.

Energetic cosmic rays interact ($\mathrm{H\&He}_{CR}$) with CNO nuclei to produce Be. Models with chemical evolution effects (e.g. mass outflow from the halo) predict a slope between log N(Be/H) and [O/H] of 1.5.

There is some evidence of an intrinsic spread in Be at a given [Fe/H] or [O/H]. This could result from different levels of production of Be in the interstellar medium in different sites. The stars formed in these different locales would have different Be contents, yet examples of each would be in the solar neighborhood now.

We found no evidence of even the beginning of a Be plateau at low values of [Fe/H]. This does not rule out an inhomogeneous early universe, however. The new large telescopes with sensitive UV spectrometers and detectors, should expand the search for this possible plateau. How much Be will we find at [Fe/H] = −4.0?

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