BERYLLIUM IN METAL POOR STARS

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INTRODUCTION

The relationship between the abundance of beryllium and that of heavier elements, especially CNO and Fe, is a direct probe of the history of cosmic rays, magnetic fields, supernovae and the mixing of the interstellar medium in the Galaxy. For the most metal poor stars in the Galaxy, this relationship is not only uniquely powerful as a probe of the physical conditions in the proto Galaxy, but also provides a test of the predictions of Big Bang nucleosynthesis models when extrapolated back to zero heavy element abundance. Recent echelle spectrograph observations have extended the range of stars for which beryllium abundances are available to metallicities approaching [Fe/H]= -2.8 (Gilmore etal 1991,1992; Ryan etal, 1992), a factor of thirty lower than was available a year ago. In this paper we consider the reliability of the present data, and the general conclusions concerning the evolution of the Galaxy and the primordial abundances of the light elements which these results require.

THE PRECISION OF AVAILABLE BERYLLIUM ABUNDANCES

The precision with which the abundances of beryllium and heavier elements have been determined is difficult to define. Factors entering the calculation include not only the obvious observational parameters of spectral resolution and signal-to-noise ratio, but also the stellar modelling and the atomic and molecular physics uncertainties. For present purposes, it is important to distinguish carefully between *random* and *systematic* errors.

Beryllium is visible as a weak doublet with much stronger lines of VII, TiII, and OH within $\sim$ 0.2Å. Hence, there is a threshold in resolution below which the beryllium lines are visible only as wings on strong and complex features. The consequence of this is most clearly seen by comparing figure 3 of Rebolo etal (1988) with figure 1 of Gilmore etal (1991). The observations of Rebolo etal were obtained at a resolution of $\sim$ 0.28Å, so that neither of the beryllium lines is resolved from other stronger features. The derived beryllium abundances are necessarily of lower precision than the more recent observations, which have a resolution $\lesssim$ 0.1Å. Since the Rebolo

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etal data were the only abundance measurements of beryllium for stars more metal poor than [Fe/H]$\lesssim -0.6$ prior to the recent work, the most conservative attitude to available data is to use only the most recent abundance data for stars more metal poor than the old disk, or [Fe/H]$\lesssim -0.6$. Conversely, it will also clearly be of interest to study the abundance of beryllium in the more metal rich stars of the thin disk with high spectral resolution.

When the data for metal poor stars are restricted in this way, we have available data for a total of 8 stars with [Fe/H] $\lesssim -0.6$ from Gilmore etal (1992), and for 3 stars from Ryan etal (1992). There is one star in common to these studies, HD140283, in addition to consistent upper limits for an additional star, HD84937. For HD140283 Gilmore etal derive [Be/H]$= -12.97$, while Ryan etal derive [Be/H]$= -13.25$. Of this difference of 0.28dex, $\sim$ 0.2dex is caused by a systematic difference in the adopted stellar gravity. The stars observed twice by Gilmore etal have derived beryllium abundances which agree to $\sim$ 0.18dex between observations. The *random* errors in the beryllium abundances of very metal poor stars are clearly surprisingly small, based on this simple comparison, with internal random errors in the beryllium abundance being $\lesssim$ 0.15dex.

Iron abundances for the same stars observed by Gilmore etal were derived from equivalent widths measured in visual spectra. We included only spectral lines for which the oscillator strength is known to an accuracy better than ± 0.10 dex, and which are weaker than about 80 mÅ in the spectra of the metal poor stars studied here, and assumed the LTE approximation.

The iron abundance for the 8 halo stars derived from FeII lines is larger than the abundance derived from FeI lines, the average value of [FeII/FeI] being 0.15 dex. This may suggest that we have systematically overestimated the $\log g$ values by about 0.4 dex, or it could be a non-LTE effect. It is, however, interesting that the rms deviation of [FeII/FeI] is 0.08 dex only, suggesting that the *differential* $\log g$ values have been determined to an accuracy better than $\pm$ 0.20 dex. Similarly, the absolute [Fe/H] values may be underestimated by about 0.15 dex, but the differential [Fe/H] values have errors less than 0.08 dex. This is important, because only the *differential* values of $\log g$ and [Fe/H] are relevant for the value of the slope of the $\log(N_{\rm Be}/N_{\rm H})$ – [Fe/H] relation for halo stars.

A similar analysis of Mg, Ca, Ti and Cr for our programme stars shows that the rms deviation in [X/Fe] for X = Mg, Ca, Ti, Cr, is as small as 0.06 dex, confirming that very accurate differential metal abundances have indeed been obtained. Similarly, those stars observed twice have derived oxygen abundances which are consistent to

$\lesssim 0.05$dex from the two spectra. Conservatively, we adopt an internal error of 0.1dex in the oxygen abundances.

Note that although there is no reason to suspect their existence, the possibility of *systematic* zero point offsets in the beryllium abundance scale cannot yet be ruled out. This makes it difficult as yet to determine the reliability of an extrapolation of the relationship observed between the abundances of beryllium and heavier elements, especially oxygen, back to zero abundance, and hence to deduce the primordial beryllium abundance. This extrapolation is of course further uncertain due to our poor understanding of the physics of cosmic ray generation in the very early Galaxy. For present purposes we restrict discussion to the implications of present data for Galactic cosmic ray production models of beryllium and lithium.

The level of internal consistency apparent in the data allows a quite precise determination of the relationship between the abundances of beryllium and oxygen in halo stars. Additionally, the statistical fits to this relationship provide strong confirmation of the internal consistency of the data derived above. The beryllium abundances for the ten different metal poor stars with good abundances published by Gilmore etal (1992) and by Ryan etal (1992) are shown in Figure 1. Also shown is a linear least squares fit to the halo stars. Within a formal uncertainty of $\sim 25\%$, the relationship between the logarithmic beryllium abundance and the logarithmic oxygen abundance has slope unity, so that $N_{Be} \propto N_O^{1\pm0.25}$. This result is derived by both non-linear weighted least squares and by maximum likelihood techniques, and in both cases the statistical significance of the fit supports the adopted internal error estimates.

IMPLICATIONS OF THE OBSERVED BERYLLIUM *VS* OXYGEN RELATIONSHIP

The evolution in the early Galaxy of the light elements created by spallation has been well reviewed recently by Reeves (1991). The essential physics is described by

$$\frac{d(N_{\rm X}/N_{\rm H})}{dt} \propto \zeta(t) \times \int \sigma(E) \times \Phi(E,t)\, dE - \text{loss terms}, \qquad (1)$$

where $N_{\rm X}$ is the abundance of the element being created through spallation of CNO nuclei and $N_{\rm H}$ the hydrogen abundance, $\zeta(t)$ is the relative abundance of the target heavy-elements which are spalled, $\sigma(E)$ is the reaction cross section which is dependent on the energy E of the cosmic rays, and $\Phi(E,t)$ is the time-dependent cosmic ray flux spectrum. $\sigma(E)$ is measured in a laboratory and for present purposes can be assumed known. For the spallogenic production of lithium the low energy production is dominated by ^{4}He + ^{4}He reactions. Since ^{4}He is an abundant primordial element, $\zeta(t)$ for Li production is effectively constant, and the Li production rate depends only

on $\Phi(E,t)$.

The heavy elements of interest as targets, particularly oxygen, are created in supernovae from high-mass stars. Thus $\zeta(t)$ is a measure of the integrated number of supernovae in the relevant part of the proto-Galaxy. Cosmic rays require kinetic energy for their acceleration, and this energy input is also probably dominated by winds and supernovae from high-mass stars. Thus, the cosmic-ray flux prior to any losses is also dependant on the total number of supernovae in the relevant part of the proto-Galaxy, and may also be parameterised by the heavy element abundance, $\zeta(t)$. Thus one expects, in the simplest case, a ***quadratic*** dependence of the beryllium abundance on the oxygen abundance, in contradiction with the results of figure 1.

The two limiting cases of spallation production are easily seen from equation 1 – the production may be limited by either the target abundance or the cosmic ray abundance, or by both. Observations require one of these limiting cases to be appropriate for the halo phase of galactic formation. Preliminary models of cosmic ray limited production have been presented by Feltzing & Gustafsson (1992), though no detailed models of target limited spallation which reproduce the data are yet available.

The production of lithium is potentially of interest. The targets for production of lithium are ^{4}He nuclei, α particles, which are always abundant, since the primordial helium abundance is so high. Allowing for this dependence, Steigman & Walker (1992) show that the lithium production will follow $\log(N_{\rm Li}/N_{\rm Be}) = -[{\rm Fe/H}]$, if the cosmic ray energy spectrum at early times was like that observed now. With that energy spectrum, spallation provides a production ratio $(N_{\rm Li}/N_{\rm Be}) \approx 200$ at [Fe/H]=–2.3. The normalisation of this ratio is sensitive to the cosmic ray energy spectrum, and will be lower by a multiplicative factor of a few for an energy spectrum which also reproduces current measurements of the Be/B ratio.

An intriguing feature of the linear dependance of the spallation production of lithium on (logarithmic) heavy element abundance, is that the beryllium abundance itself has just the same linear dependance, but with opposite slope. These compensating dependencies on the metallicity of the ISM cancel out. Thus the predicted spallation production of lithium consequent upon the spallation production of beryllium is independent of [Fe/H], at an (uncertain) level of approximately $\log(N_{\rm Li}) = -10.4$. This spallation production, being independent of [Fe/H], would not be visible in the 'Population II plateau', but acts as a zero point offset to the primordial lithium abundance. The resulting primordial abundance, in the absence of later depletion, is consequently uncertain, but is near $\log(N_{\rm Li}) = -10.1$.

Nearly one-half of the lithium produced by early spallation is however ^{6}Li. This element is extremely fragile, and could have been completely destroyed even if initially very abundant in the stars of interest here, if rotational mixing is the predominant depletion mechanism. If however diffusive settling is the dominant destruction mechanism, then the ^{6}Li will be depleted in roughly the same proportion as is the ^{7}Li, and one might still see some cosmic ray production. Particularly interesting in this regard is the measurement of a ratio of ^{6}Li/^{7}Li of ~ 0.05 in the halo star HD84937, one of the stars for which Gilmore etal have measured beryllium. Since standard Big Bang models predict insignificant ^{6}Li production, while spallation with the present day energy spectrum predicts roughly equal amounts of ^{6}Li and ^{7}Li, this observation both precludes efficient deep mixing, and requires at least 10% of the Li in this Pop II star to be made by spallation production. The simplest prediction from the observed beryllium abundance is then that some $\sim 30\%$ of the Population II lithium 'plateau' abundance is created by cosmic ray spallation. This is illustrated in Figure 2.

CONCLUSIONS

Recent high resolution observations of very metal poor stars allow the derivation of abundances of beryllium, iron and oxygen with internal random errors of $\lesssim 0.15$dex, $\lesssim 0.10$dex and $\lesssim 0.10$dex respectively. The resulting relationship between the beryllium and oxygen abundances in stars with [Fe/H]$\lesssim -1.5$ is $N_{Be} \propto N_O^{1.\pm 0.25}$. This result is inconsistent with published models of cosmic ray spallation production, and requires that the cosmic ray production be either target limited or cosmic ray limited. Spallative lithium production with this beryllium production is predicted to be independent of [Fe/H]. This lithium can provide a significant contribution to the Pop II Li plateau abundance, though in an abundance which is sensitively dependant on the cosmic ray energy spectrum in the early Galaxy.

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Figure 1: Beryllium abundance *vs* logarithmic oxygen abundance relative to the solar value for the metal poor stars observed by Gilmore etal and by Ryan etal. The line is a least squares fit to the data for the stars with [O/H] < −1.

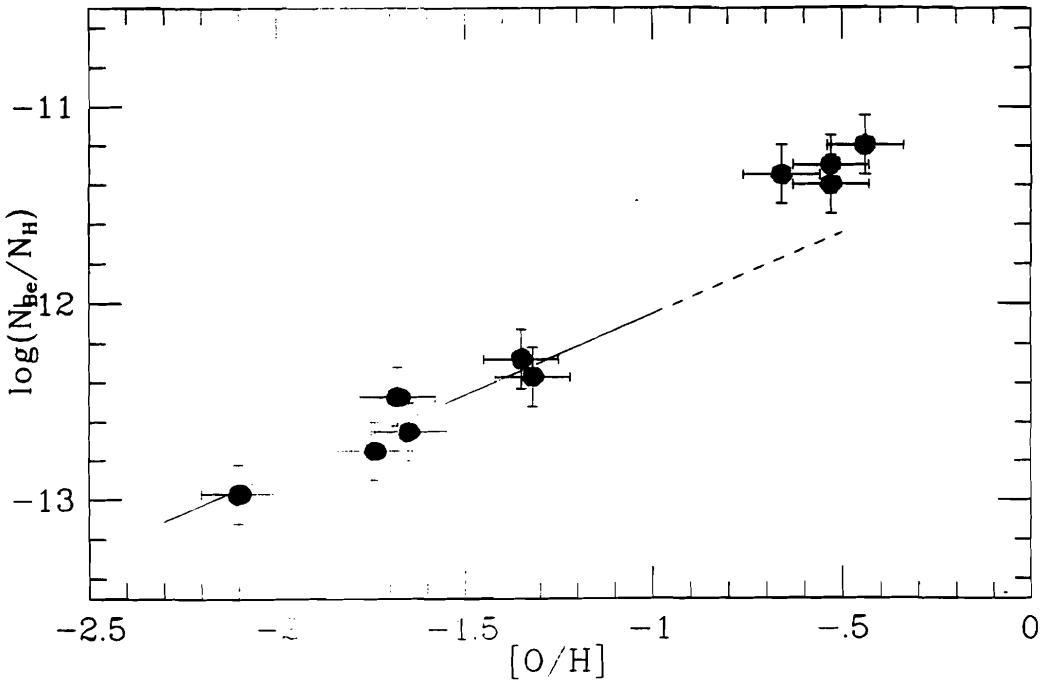
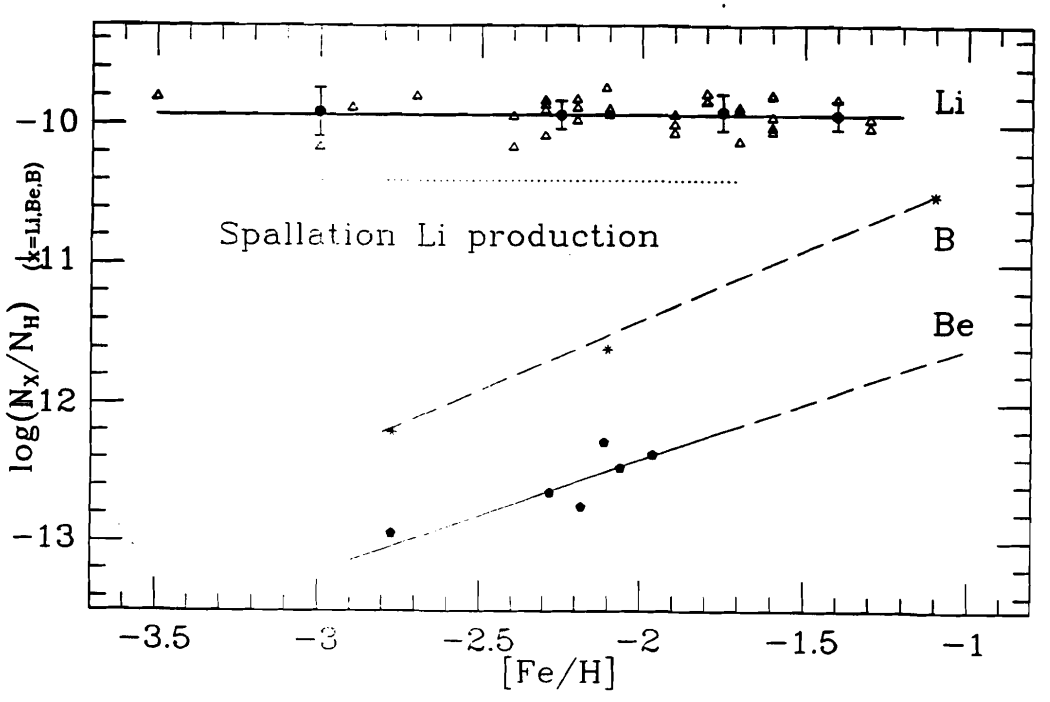
Figure 2: Observed abundances of Li, Be and B in metal poor stars. The solid dots are lithium mean values for all stars in the metallicity intervals [Fe/H] ≤ -2.5, -2.5 < [Fe/H] ≤ -2.0, -2.0 < [Fe/H] ≤ -1.5 and -1.5 < [Fe/H] ≤ -1.3, with mean errors indicated. The dashed line is the spallative production of lithium predicted to occur with the spallative production of Be and B if the early Galactic cosmic ray energy spectrum were like that now.