From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution
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^{6}Li in very metal-poor halo stars observed by Subaru/HDS and implications

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Abstract. We discuss the results obtained so far in our ongoing search for the ^{6}Li isotope in very metal-poor halo stars through very high resolution and S/N spectroscopy with the Subaru High Dispersion Spectrograph, and the consequent implications. Besides definitively confirming the existence of ^{6}Li in the star HD 84937, we achieve a tentative detection in the extremely metal-poor star G 64-12 ([Fe/H] $\simeq -3.2$). For two other stars with [Fe/H] ~ -3, only upper limits were derived. Together with the VLT/UVES results of Asplund *et al.*, this indicates unexpectedly high ^{6}Li abundances in at least some stars at very low [Fe/H]. The findings are discussed in light of different production scenarios, including the structure formation cosmic ray model and other possibilities.

Keywords. Stars: abundances; stars: Population II; cosmic rays; nuclear reactions, nucleosynthesis, abundances; Galaxy: formation; supernovae: general

1. Introduction: structure formation cosmic rays and ^{6}Li

Apart from ^{7}Li, the bulk of the light elements Li, Be and B in the universe are believed to have originated through nonthermal nuclear reactions induced by cosmic rays (CRs; see Vangioni-Flam, Cassé & Audouze 2000; Prantzos 2004 for reviews). Most models of light element evolution in the Galaxy have focused on shocks driven by supernovae (SNe) as the principal CR sources. Observations of metal-poor halo stars (MPHS) in our Galaxy show a linear relation between [Fe/H] and Be/H or B/H, which can be reasonably understood as resulting from spallation of CRs enriched with CNO from fresh SN ejecta while impinging on interstellar H or He.

During the early formation era of the Galaxy, another source of CRs should also have been active: structure formation (SF) shocks, i.e. shocks induced by the gravitational infall and merging of sub-Galactic clumps during the hierarchical build-up of Galactic structure (Suzuki & Inoue 2002, hereafter SI02; 2004; Inoue *et al.* 2004). Such shocks are inevitable consequences in the currently standard theory of hierarchical structure formation driven by cold dark matter. Through the standard shock acceleration mechanism, CRs can be naturally accelerated to the transrelavistic energies of interest for LiBeB production, as long as magnetic fields with strengths $B \gtrsim 10^{-14}$G are present. Based on the latest measurements of the total mass of the Galaxy (Sakamoto, Chiba & Beers 2003), SI02 showed that the gas kinetic energy dissipated at the main SF shock, determined by the available gravitational potential at the final major merger stage, should have been greater than the total kinetic energy of SNe in the early Galactic halo. A similar relation should then hold between the energy in SF CRs and SN CRs at this epoch. It is unlikely to have been otherwise; had the SN energy dominated over the gravitational potential, a major fraction of the gas would have been blown out of the forming halo, a situation that could have occurred in elliptical or dwarf galaxies but is very unlikely to end up in large disk galaxies like our own. Thus, at some point in the early Galaxy, SF CRs should have played an important role for light element production.

Unlike SNe, SF shocks do not synthesize fresh CNO, Fe nor any other metals, leading to crucial differences in the CR nucleosynthesis. First, the composition of SF CRs is entirely ascertained by the pre-existing ISM. In metal-poor conditions, they produce very little Be or B through spallation, and the only effective channel is Li production by $\alpha - \alpha$ fusion. Although this process generates both ^{7}Li and ^{6}Li in comparable amounts, the CR-produced ^{7}Li should generally be overwhelmed by the "Spite plateau" from big bang nucleosynthesis (BBN; Spite & Spite 1982, Ryan, Norris & Beers 1999) at sufficiently low [Fe/H]. The main visible imprint of SF CRs is therefore expected to be the ^{6}Li isotope, whose standard BBN abundance is much smaller (Vangioni-Flam *et al.* 1999). Second, the SF CR flux need not be directly related to metallicity. Depending on how star formation proceeds with respect to SF, distinctive evolutionary trends may arise, such as a plateau or a very slow decrease in ^{6}Li/H with decreasing [Fe/H] followed by a downturn reflecting the main SF epoch, and a ^{6}Li/Be ratio that can increase to very high values at low [Fe/H]. This is in marked contrast to SN CR models, for which ^{6}Li/H and [Fe/H] must be closely correlated with logarithmic slope $\simeq$1 or greater, and the ^{6}Li/Be ratio at low [Fe/H] is constant. Together with the superior energetics, these unique properties of SF CRs can allow the associated ^{6}Li production to completely dominate over SN CRs at low metallicity. In fact, despite giving a good account of the Be and B observed in MPHS, SN CR models already faced a challenge in explaining the high ^{6}Li abundance measured in the star HD 84937 at [Fe/H]=-2.2 (Ramaty *et al.* 2000; Suzuki & Yoshii 2001), and SI02 pointed out that SF CRs should provide a more natural solution. Furthermore, through potential correlations between the ^{6}Li abundance and stellar kinematical properties, they may offer an important probe of how the Galaxy and its halo formed, as well as interesting clues to some currently unresolved cosmological issues (Suzuki & Inoue 2004; Inoue *et al.* 2004).

Observationally, determination of ^{6}Li abundances in MPHS is an extremely challenging task, requiring very high resolution and high S/N spectroscopy to discern the subtle isotopic shift feature in the red wing of the much stronger ^{7}Li line. (For the interest of ^{6}Li, the "Spite plateau" is simply a nuisance!) Until a few years ago, HD 84937 was the sole MPHS in which ^{6}Li had been reliably detected, along with a handful of other stars with marginal detections or upper limits (Smith, Lambert & Nissen 1998; Cayrel *et al.* 1999; Hobbs, Thorburn & Rebull 1999). With the advent of high resolution spectrographs on 8-m class telescopes, the quest for ^{6}Li in MPHS has become a more feasible (albeit still difficult) endeavor. Using VLT/UVES, Asplund *et al.* (2001; 2005, in preparation; these proceedings; Lambert 2004) have recently conducted a dedicated survey for ^{6}Li in 24 MPHS with a wide range of metallicities and effective temperatures. We are employing the Subaru High Dispersion Spectrograph (HDS; Noguchi *et al.* 2002) to search for ^{6}Li specifically in selected, very metal-poor stars with high effective temperatures, with the goal of clarifying the origin of ^{6}Li at low [Fe/H], and in particular seeking the predicted signatures of the SF CR model. Below we briefly discuss the results obtained to date and their implications. More details will be described in forthcoming papers.

Table 1. Properties of target stars and observation results

object	V	T_{eff}[K]	[Fe/H]	S/N	^{6}Li/^{7}Li (2σ)
HD 84937	8.31	6220	-2.2	800	0.057±0.028
BD +03°740	9.81	6230	-2.8	550	<0.035
BD -13°3442	10.26	6270	-2.9	500	<0.035
G 64-12	11.45	6220	-3.2	450	0.057±0.047

2. Observations with Subaru/HDS

In the initial phase of our program carried out in Feb. 2003, we concentrated on four stars: HD 84937, to confirm and improve on earlier, lower S/N observations; BD +03°740, BD -13°3442 and G64-12, to search for ^{6}Li for the first time in very MPHS ([Fe/H] ~ -3) where the consequences of SF CRs should be most evident. All have effective temperatures $T_{eff} > 6200$ K, so that standard depletion effects are expected to be minimal (Lambert 2004). The resolving power was R=100,000, except for G 64-12, our faintest object, for which we chose R=90,000. Additional data was taken for G 64-12 in May 2004. Table 1 summarizes some properties of the target stars and the approximate S/N per pixel achieved at the 6708 Å Li I line.

For each star, the reduced data were compared with synthetic spectra based on 1D, hydrostatic atmosphere models to determine the best fit ^{6}Li/^{7}Li isotope ratio, following Aoki *et al.* (2004). Note that although 3D, hydrodynamic atmosphere models are more desirable, Asplund *et al.* (these proceedings; Nissen *et al.* 2000) demonstrate that for determination of ^{6}Li/^{7}Li, analysis with 1D models give results consistent with detailed 3D models. The final column of Table 1 shows our deduced ^{6}Li/^{7}Li ratios with 2σ errors.

From the very high S/N spectrum of HD 84937, we get ^{6}Li/^{7}Li=0.057 ± 0.028, in very good agreement with previous measurements as well as the recent VLT/UVES results of Asplund *et al.* The possibility that line asymmetries due to convective motions in the stellar atmosphere are causing a spurious detection of ^{6}Li has been ruled out by Smith *et al.* (2001), since no asymmetries are detected in the K I line, which should arise from the same region as the Li I line in this star. Thus the existence of ^{6}Li in this star is certified with a high degree of confidence.

Our first attempt at measuring ^{6}Li in very MPHS with [Fe/H] ~ -3 give mixed results. For BD +03°740 and BD -13°3442, only upper limits could be derived at ^{6}Li/^{7}Li<0.035, despite the high S/N of $\gtrsim$ 500. However, most intriguingly, we arrive at a positive detection for G 64-12, our most metal-poor object, with ^{6}Li/^{7}Li=0.057 ± 0.047 (Fig.1, left). To check whether this might be affected by convective line asymmetries, we have analyzed the Na I D line, which should have a similar strength and ionization state to the Li I line for this star. In the right of Fig.1, the data are compared with synthetic spectra in which artificial asymmetric components that mimic different amounts of ^{6}Li in the Li I line are included. The result is that although a symmetric profile may be consistent, the present data cannot exclude such asymmetries at the level of a few percent. Given the relatively large errors in the measured ^{6}Li/^{7}Li, the case for ^{6}Li in G 64-12 is not as strong as in HD 84937, and at this moment we can only claim a tentative detection.

Further progress is possible if spectra with sufficiently high S/N can be attained such that any effects of convective motions can be reliably distinguished from ^{6}Li. In fact, in a second observing run in May 2005, we were able to acquire more data for G 64-12 and bring the total S/N up to ∼540, along with good quality data for several other MPHS. Clearer conclusions can be expected from a detailed analysis of the whole data set, which is currently being undertaken. Below, we discuss the theoretical implications

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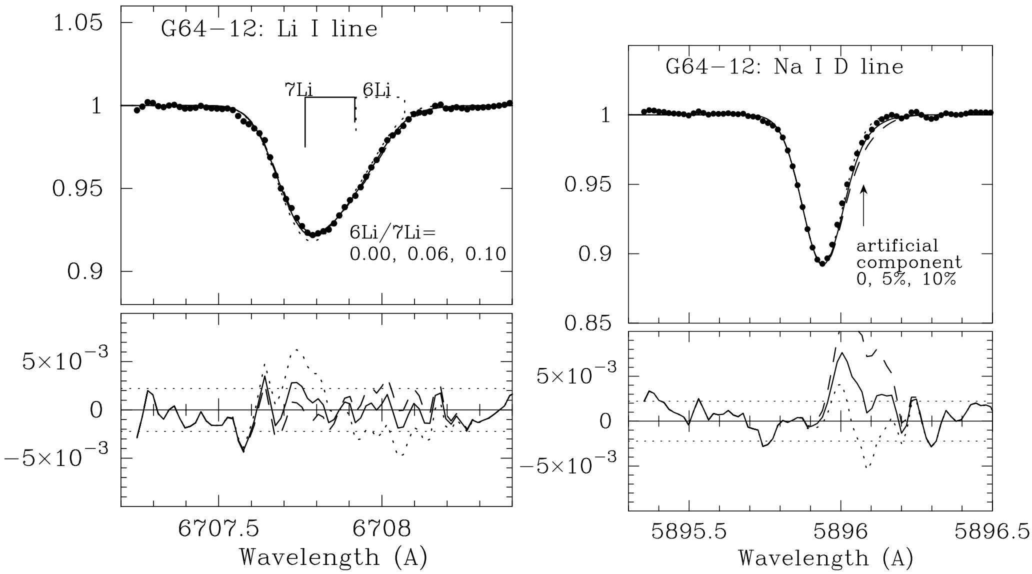

Figure 1. Left: Observed spectra (filled circles) of the Li I line in G 64-12 compared with synthetic spectra (curves) assuming ^{6}Li/^{7}Li=0 (dotted), 0.06 (solid) and 0.1 (dashed). The bottom panel shows the difference between synthetic and observed spectra, with the horizontal dotted lines marking $\pm 1\sigma$ in the observed flux. Right: Same as left, except for the Na I D line. The synthetic spectra include artificial line asymmetries that mimic ^{6}Li in the Li I line at levels of 0 (dotted), 5 (solid) and 10 (dashed) %.

of our Subaru/HDS results on the premise that ^{6}Li indeed exists in G 64-12 at the level described above, together with the VLT/UVES results.

3. Implications and Outlook

In the top of Fig.2, we plot ^{6}Li/H vs. [Fe/H] for our sample, along with the large VLT/UVES data set of Asplund *et al.* To convert our ^{6}Li/^{7}Li ratios to ^{6}Li/H, here we have simply adopted the total Li abundance values A(Li) of Ryan *et al.* (1999). The upper limit for HD 140283 obtained from HDS commissioning observations (Aoki *et al.* 2004) is also included; note that its relatively low $T_{eff} \sim 5750$ K suggests that depletion may have been more effective compared to the other four stars.

Although our sample by itself is too small to delineate a clear trend, it augments and extends the striking results revealed by Asplund *et al.*: a number of stars at various metallicities exhibit high ^{6}Li abundances such that a plateau-like behavior in ^{6}Li/H vs. [Fe/H] is indicated. The most metal-poor, ^{6}Li-detected object for UVES is LP 815-43 at [Fe/H] $= -2.8$, and our (tentative) detection in G 64-12 appears to continue the trend down to [Fe/H] $= -3.2$. These observations all but rule out previous SN CR models for ^{6}Li production at low [Fe/H], in which log^{6}Li/H vs. [Fe/H] can never be much flatter than linear (see dashed curve in Fig.2). Also important is the presence of many stars in the entire range of [Fe/H] where only upper limits have been derived. Even in stars with similar [Fe/H] (and T_{eff}, as in our sample), appreciable differences in ^{6}Li/H may exist. This may imply that the ^{6}Li production mechanism causes abundance variations in different sites with similar [Fe/H], although it is also possible that some non-standard depletion processes are at work (Lambert 2004).

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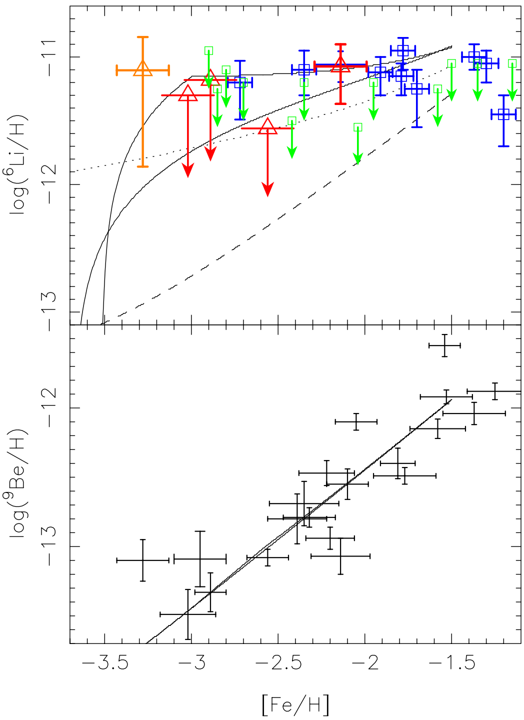

Figure 2. Top: Observational data for ^{6}Li/H vs. [Fe/H] from Subaru/HDS (triangles) and VLT/UVES (squares). Overlayed are ^{6}Li production model curves for: SN CRs (dashed); SF CRs with τ_{SF} = 0.1Gyr, t_{SF} = 0.12Gyr (upper solid) and τ_{SF} = 0.5Gyr, t_{SF} = 0.1Gyr (lower solid); SF CRs with SF history guided by simulations (dotted). Bottom: Observational data for Be/H, compared with model curves for SN CRs only (lower) and SN+SF CRs (upper) with parameters for the upper solid curve in the top panel.

Are these new observations consistent with a SF CR origin of ^{6}Li? Fig.2 compares the data with different model curves. The two solid curves follow the simple, toy model discussion of SI02, where the evolution of SF CRs is parameterized in terms of t_{SF}, the main epoch of Galactic SF relative to halo chemical evolution, and τ_{SF}, the main duration of SF. The dashed curve is based on a more realistic form for the SF history, guided by the numerical simulations of Abadi *et al.* (2003), as described in Inoue *et al.* (2004). Since the details of how star formation and chemical evolution had proceeded in relation to SF for our Galaxy is unknown, it is difficult to make straightforward conclusions at the moment. One general inference is that to account for the ^{6}Li observed at the lowest [Fe/H] with SF CRs, a relatively large time delay between the main epoch of SF and that of star formation may be required. Qualitatively speaking, such a SF history is indeed what is expected for large disk galaxies; most of the dark halo mass must have been assembled and virialized before the thin, fragile disk can be formed slowly and gently. However, more detailed studies are warranted to address this issue quantitatively (c.f. Prantzos 2004).

Observations of Be provide an interesting twist. Most MPHS with [Fe/H] $\gtrsim -3$ follow a linear correlation in Be/H vs. Fe/H (Boesgaard *et al.* 1999), but Primas *et al.* (2000a, b) have found Be abundances that are significantly higher than this trend in two stars with [Fe/H] ~ -3: LP 815-43 and G 64-12 (see bottom of Fig.2)! The fact that the two stars with high ^{6}Li/H also appear to have higher than average Be/H hint at some connection. Since SF CRs cannot give rise to any Be at low [Fe/H], this may be pointing us back

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to SNe, albeit of a different kind than normally considered. Some possibilities worth investigation are CRs accelerated in energetic hypernovae (Umeda & Nomoto 2005) or Pop III SNe (Rollinde, Vangioni & Olive 2005), and the fast ejecta of energetic SNIbc (Fields *et al.* 2002, Nakamura & Shigeyama 2004). (Note that although some "normal" SN CR models may account for the high Be/H at low [Fe/H] to some extent, they do not explain the high ^{6}Li/H; Fields, Olive & Vangioni-Flam 2005.)

Other important implications of ^{6}Li in MPHS not discussed here include non-standard stellar depletion processes involving diffusion, rotation, etc. (Lambert 2004), relation to the ^{7}Li discrepancy between observed and *WMAP* predicted values (Coc, these proceedings), and production from non-standard particle physics processes in the early universe (Jedamzik 2004, Kawasaki, Kohri & Moroi 2005). Although the true origin of ^{6}Li in MPHS is still an open question, further efforts from both observational and theoretical sides promise to bring us new and valuable information from many perspectives. The excitement initiated by the Spite's discovery of ^{7}Li in old stars has now been carried over to its lighter isotope, and should keep us fully engaged in the coming years!

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