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# The Interstellar Lithium Isotope Ratio toward Per OB2

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**Abstract.** We are conducting a survey on the $^{7}$Li/$^{6}$Li ratio in interstellar space in order to seek limits on the variation in this ratio. The analysis is based on the technique we adopted in extracting the $^{11}$B/$^{10}$B ratio. This technique uses a line of comparable strength, from a species likely to occupy the same volume of the interstellar cloud, as a template for separating velocity components within the line profile. For our study of the $^{7}$Li/$^{6}$Li ratio, the K I line at 4044 Å serves as the velocity template. Our initial focus is on the variation in the $^{7}$Li/$^{6}$Li ratio around the star-forming region IC 348. Our high-resolution observations of the Li I lines toward o and $\zeta$ Per show remarkably different isotope ratios: $^{7}$Li/$^{6}$Li = 2–4 and 11, respectively, where the Solar System ratio is 12.3 and cosmic ray spallation yields a ratio of about 2. The significance of the very low ratio toward o Per is that it is essentially the value predicted for cosmic rays through spallation reactions. The direction to o Per passes closer to IC 348, a site of massive star formation, than does the line of sight to $\zeta$ Per. Furthermore, our analysis of OH column densities (Federman, Weber, & Lambert 1996) showed that the cosmic ray flux through o Per's diffuse clouds is higher than average, presumably reflecting the nearby presence of IC 348.

## 1. Introduction

The abundance of lithium is an important ingredient for studies of the chemical evolution of the Galaxy involving Big Bang Nucleosynthesis (BBN), Galactic cosmic ray (GCR) spallation reactions, and synthesis in Type II supernovae (SN II). Models of BBN show that no light element heavier than $^{7}$Li is produced in significant amounts. BBN was the main source of $^{7}$Li production in the early Galaxy. GCR spallation reactions involve high energy cosmic rays interacting with interstellar nuclei. These reactions account for the relative abundances of present day $^6$Li, $^9$Be, $^{10}$B but only about 10% of the $^7$Li and about half the $^{11}$B (Fields, Olive, & Schramm 1994; Meneguzzi, Audouze, & Reeves 1971; Meneguzzi & Reeves 1975; Pagel 1997; Ramaty et al. 1996, 1997; Reeves et al. 1973; Reeves 1974). These calculations yield an isotopic ratio $^7$Li/$^6$Li of 2.0 and $^{11}$B/$^{10}$B of 2.5, compared to the Solar System values of 12.3 and 4.05, respectively (Anders & Ebihara 1982).

This suggests the need for an additional source of $^7$Li and $^{11}$B production in the present day Galaxy. The search for an additional source of $^7$Li focused attention on the abundance of lithium in stars. Luminous intermediate-mass AGB stars are predicted and observed to synthesize $^7$Li (Smith & Lambert 1989). High lithium abundances are occasionally seen in red giants (Brown et al. 1989), suggesting lithium production during some phase of stellar evolution. Neutrino induced spallation reactions in core collapse SN II have been shown to produce both $^7$Li and $^{11}$B (Woosley et al. 1990). A higher flux of low energy cosmic rays have been invoked (e.g., Ramaty et al. 1996) to account for a higher $^{11}$B/$^{10}$B ratio, since $^{11}$B is preferentially produced over $^{10}$B at lower energies.

The interstellar medium (ISM) is another environment useful in studying light element synthesis. Neutral lithium has a low ionization potential. The dominant ion in the neutral ISM is Li II, which cannot be observed. This fact and the uncertainty in the amount of depletion onto interstellar grains make the total abundance difficult to determine with any precision. Interstellar lithium was detected toward $\zeta$ Per, $\epsilon$ Aur, and $\zeta$ Oph by Hobbs (1984) and vanden Bout et al. (1978) and toward $\sigma$ Sco, $\beta^1$ Sco and 55 Cyg by Snell & vanden Bout (1981). These early detections of interstellar Li I showed absorption with equivalent widths on the order of a few mÅ. Published determinations of the $^7$Li/$^6$Li ratio in the local ISM show a ratio that in some clouds may differ from that of the Solar System (12.3 ± 0.3, Anders & Ebihara 1982). Lemoine et al. (1993, 1995), and Meyer, Hawkins & Wright (1993) reported interstellar $^7$Li/$^6$Li ratios of $12.5^{+4.3}_{-3.4}$ toward $\rho$ Oph, $6.8^{+1.4}_{-1.7}$ toward $\zeta$ Oph, and $5.5^{+1.3}_{-1.1}$ toward $\zeta$ Per.

Generally there exists multiple interstellar clouds on any given line of sight. The velocity structure has to be well known before an accurate lithium isotope ratio can be obtained (Lemoine et al. 1993, 1995). Therefore, it is useful to find lines of sight with relatively simple velocity structure (i.e., one or two interstellar clouds on a line of sight). In addition, it is highly desirable to obtain data on another species, which has similar properties to lithium and resides in the same portion of the interstellar cloud, to use as a template of the velocity structure. Our method differs slightly from the technique of Lemoine et al. (1993, 1995). Lemoine et al. used the resonance line of K I ($\lambda$ 7699) as their velocity template. This line of K I is much too strong to use as an effective velocity template. For this reason we obtained data on K I $\lambda$ 4044 which is of comparable strength to the lithium lines and therefore a better template. Moreover, high signal to noise (SNR), high resolution spectra of the Li doublet lines at 6707 Å are required, since the fine structure splitting for $^7$Li I is comparable to the isotope shift of $^6$Li I ($\sim$ 0.160 Å), resulting in a blend of the $^7$Li and $^6$Li lines (see Figure 1). We have obtained high SNR, high resolution spectra of interstellar lithium toward $\zeta$ Per and o Per in the Perseus OB2 association as part of a study to improve our understanding of light element synthesis.

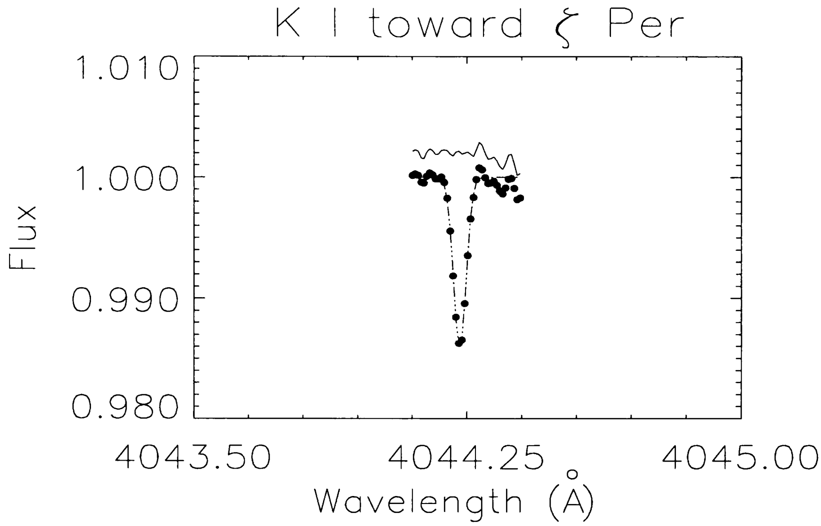


Figure 1. These graphs show interstellar K I and Li I toward $\zeta$ and o Per. The data points are the filled circles. The dot-dashed line is the fit to the line profiles using the K I line for the velocity structure. The solid line is the residuals of the fit. The vertical dashes in the o Per K I plot show the positions of the two velocity components. The vertical dashes in the $\zeta$ Per Li I plot show the relative positions of the $^7$Li and $^6$Li fine structure lines.

## 2. Observations

The observations were acquired with the 2.7 meter telescope and the "2dcoudé" spectrograph at McDonald Observatory (Tull et al. 1995). We observed $\zeta$ Per (B1 Ib; $V = 2.85$; $v\ sini = 59$ km s$^{-1}$) in 1996 November and 1997 January and o Per (B1 III; $V = 3.83$; $v\ sini = 85$ km s$^{-1}$) in 1998 January. High resolution spectra (R $\sim$ 170,000) in two spectral regions were obtained, at 4044 Å for K I and 6707 Å for Li I. The spectra were reduced in a standard manner with NOAO SUN/IRAF (Revision 2.10.4). The stellar images were corrected for the bias and were flat fielded to remove any instrumental effects. The scattered light, which was negligible, was removed before aperture extraction. The extracted spectra were then placed on a wavelength scale with spectra from a Th-Ar hollow cathode which were taken periodically through the night. The final spectra were Doppler corrected and coadded yielding a final SNR of approximately 2500:1 for each stellar spectrum. Figure 1 displays the observations and profile fits for K I and Li I toward $\zeta$ and o Per. The data exhibit one interstellar velocity component toward $\zeta$ Per and two components toward o Per. The Li spectrum for gas toward o Per clearly reveals a non-solar isotope ratio: substantial absorption from $^6$Li is evident after taking note of the 2:1 fine structure ratio for the $^7$Li doublet and the two velocity components seen in $\lambda$ 4044

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## 3. Analysis

Comparison of observed and synthetic profiles was accomplished with a code (J. Zsargó, unpublished) in which the adjustable parameters of the synthetic profiles were changed until a minimum $\chi^2$ was obtained. In determining the synthetic profile of the interstellar lines, we included the hyperfine structure splitting for both $^6$Li and $^7$Li (Sansonetti et al. 1995). The hyperfine structure splitting of K I $\lambda$ 4044 was found to be negligible ($\sim$ 0.002 mÅ) and was not included in the analysis. The profiles of the unblended $^7$Li I line and K I line were fitted first to obtain the *b*-value, column density ($N$) and lsr velocity of the line. The *b*-value and velocity were then fixed and used in the fit of the Li I profile, allowing for a relatively straightforward determination of the isotope ratio. This method was successfully used in our determination of interstellar $^{11}$B/$^{10}$B (Federman et al. 1995; Lambert et al. 1998).

Table 1. **$^7$Li and $^6$Li Results**

| Star | Isotope | *b*-value km s$^{-1}$ | $v_{lsr}$ km s$^{-1}$ | $N$ cm$^{-2}$ | Ratio |
|---|---|---|---|---|---|
| $\zeta$ Per | $^7$Li | 1.7 | 6.5 | $(3.5 \pm 0.1) \times 10^9$ | |
| | $^6$Li | 1.7 | 6.5 | $(3.3 \pm 0.9) \times 10^8$ | $10.3 \pm 3.1$ |
| o Per | $^7$Li | 2.1 | 6.5 | $(2.6 \pm 0.1) \times 10^9$ | |
| | $^6$Li | 2.1 | 6.5 | $(7.2 \pm 1.1) \times 10^8$ | $3.6 \pm 0.3$ |
| o Per | $^7$Li | 0.7 | 3.5 | $(5.5 \pm 0.5) \times 10^8$ | |
| | $^6$Li | 0.7 | 3.5 | $(3.2 \pm 0.5) \times 10^8$ | $1.8 \pm 0.3$ |

The fitting routine was performed twice, once using the relatively unblended $^7$Li I line for the profile parameters and the second time using the K I line. The results of the two fits yielded agreement in column densities at the 1 $\sigma$ level, leading to a heightened confidence in our method. The final results toward each star are the weighted average of the isotope ratio determined by the two methods. The isotope ratio and profile parameters are displayed in Table 1.

Another useful measure of lithium is the total abundance ($N$(Li)/$N$(H)). Derivation of the total interstellar abundance is no trivial task because knowledge of the Li II abundance and depletion mechanisms is necessary. Since the ionization potential of Li II is 75.6 eV, we need only consider Li I and Li II. An estimate for Li II abundance requires the electron density. Information on $N$(C II) and $N$(H) exists, and it is straightforward to calculate the electron density ($n_e = n$ ($N$(C II)/$N$(H)). $N$(H) is the total proton column density, represented by ($N$(H) = $N$(H I) + 2$N$($H_2$)).

Since no precise $N$(C II) measurements exist for the direction toward o Per, the weighted mean interstellar ratio of $N$(C II)/$N$(H) = $(1.42 \pm 0.13) \times 10^{-4}$ (Sofia et al. 1997) was utilized, yielding a value of $N$ (C II) = $(2.3 \pm 0.8) \times 10^{17}$ cm$^{-2}$. The value of $N$(C II) is $(1.84 \pm 0.32) \times 10^{17}$ cm$^{-2}$ toward $\zeta$ Per (Cardelli et al. 1996). The values of $N$(H), $(16.1 \pm 5.6) \times 10^{20}$ cm$^{-2}$ toward o Per and $(15.8 \pm 4.7) \times 10^{20}$ cm$^{-2}$ toward $\zeta$ Per, were obtained from Bohlin et al. (1978) and an $n$ of 800 and 700 cm$^{-3}$ toward o and $\zeta$ Per, respectively, were used

(Federman et al. 1994). We then computed $N(\text{Li}) = N(\text{Li I})[G/(\alpha n_e)]$. A value of 41 was used for the photoionization rate to recombination rate coefficient, $G/\alpha$ (White 1986). The resulting total Li abundances are $(7.1 \pm 2.7) \times 10^{-10}$ toward o Per and $(11.1 \pm 2.0) \times 10^{-10}$ toward $\zeta$ Per. Since a Li isotope ratio of $\sim$ 2 toward o Per suggests newly processed Li in this direction, the comparable Li abundances are unexpected. The two abundances, however, are very similar to previous results for the ISM. Vanden Bout et al. (1978) derived an abundance $(8.8 \pm 3.4) \times 10^{-10}$ toward $\zeta$ Per and $(1.8 \pm 0.3) \times 10^{-9}$ toward $\epsilon$ Aur. Traub & Carleton (1973) derived an abundance of $(2.9 \pm 0.7) \times 10^{-10}$ toward $\zeta$ Oph. There remains the uncertain correction for depletion onto grains.

## 4. Discussion and Conclusions

The interstellar Li isotope ratio does vary from line of sight to line of sight and ranges from the GCR spallation reaction value of 2 to the Solar System value. The results for the two components toward o Per, $1.8 \pm 0.3$ and $3.6 \pm 0.3$, show that there exists a higher flux of high energy cosmic rays (CR) toward o Per than toward $\zeta$ Per, where the ratio is $10.3 \pm 3.1$. The isotope ratio toward $\zeta$ Per was previously determined to be $5.5^{+1.3}_{-1.1}$ (Meyer et al. 1993), and to within the errors, the two results agree. The total lithium abundances derived in this work compare well with other determinations for the ISM. Since a weighted interstellar average of C II was utilized in determining $n_e$ toward o Per, there is additional uncertainty in the derived lithium abundance. This may contribute to the contradictory results involving newly synthesized Li and the Li elemental abundance.

The line of sight toward o Per lies closer than that of $\zeta$ Per to a site of star formation, IC 348, where CR's might arise. From OH and HD chemistry, Federman et al. (1996) found approximately an order of magnitude higher CR flux toward o Per. Their analysis was performed with O and D abundances precisely determined with HST. In essence, $\zeta_H \ \alpha \ N(\text{OH})/N(\text{O})$, $N(\text{HD})/[\xi_D N(\text{H}_2)]$, was used to determine the CR ionization rate. This provides independent confirmation for a larger CR flux toward o Per.

Our initial results for o and $\zeta$ Per suggest other directions now being pursued. Further measurements of $^7\text{Li}/^6\text{Li}$, at ultra high resolution, are needed to fully resolve the velocity structure ($\approx 1$ km s$^{-1}$) on lines of sight to other stars. Measurements of $^{11}\text{B}/^{10}\text{B}$ toward the stars are useful in helping to disentangle the various synthesis routes and in this way further constrain models of light element nucleosynthesis.

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