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Lithium isotope ratios near the supernova remnant IC 443

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Abstract. The rapid rise in the ^{7}Li abundance for stars of near solar metallicity requires the existence of one or more stellar sources of ^{7}Li. Likely candidates include red giant and asymptotic giant branch stars, which produce ^{7}Li via the Cameron-Fowler mechanism, and Type II supernovae, in which ^{7}Li is synthesized by neutrino-induced spallation. Direct evidence of the neutrino-process remains elusive, yet could be provided by detailed studies of Li isotope ratios in interstellar gas surrounding supernova remnants. Here, we present the results of the first such investigation, based on high-resolution measurements of Li I along four lines of sight through the supernova remnant IC 443. While our observations probe material presumably contaminated by the ejecta of a core-collapse supernova, we find no evidence of ^{7}Li synthesis by neutrino-induced spallation. Rather, our results indicate that the abundance of ^{6}Li relative to ^{7}Li has been enhanced by interactions between shock-accelerated cosmic rays and the molecular cloud surrounding the remnant. Future observations will help to establish unequivocally the role that neutrino spallation plays in ^{7}Li production.

Key words. ISM: abundances — ISM: atoms — ISM: individual objects (IC 443) — ISM: supernova remnants

1. Introduction

The production of Li involves contributions from a number of different astrophysical sources, including the big bang, Galactic cosmic rays (GCRs), red giant branch (RGB) and asymptotic giant branch (AGB) stars, and Type II supernovae (SNe II). Nuclear reactions induced by GCRs in interstellar gas are the primary source of ^{6}Li (e.g., Meneguzzi et al. 1971; Ramaty et al. 1997). However, GCRs can account for no more than 20% of the present-day abundance of ^{7}Li (e.g., Prantzos 2012). Since the primordial ^{7}Li abundance arising from the big bang is approximately a factor of 10 less than the present-day abundance, the majority of ^{7}Li must be produced in stars. However, the precise nature of the stellar source remains unclear.

SNe II produce ^{7}Li by neutrino-induced spallation occurring in the He and C shells of the progenitor star during core collapse (the ν-process; Woosley et al. 1990). Since virtually no ^{6}Li is expected to be produced, interstellar material contaminated by SN II ejecta

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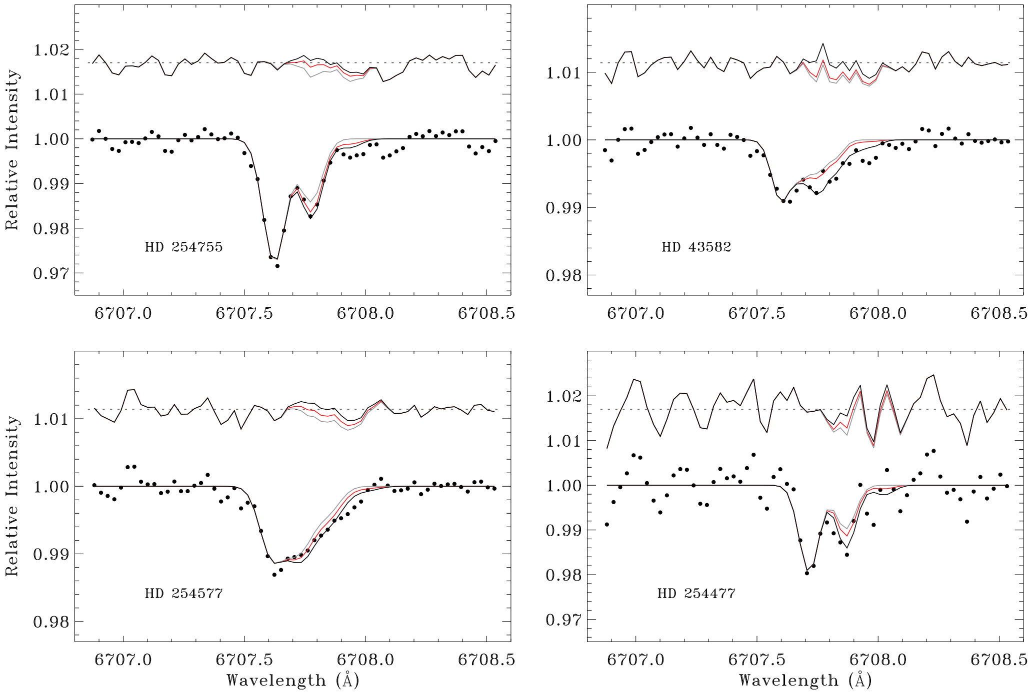

Fig. 1. Profile synthesis fits to the Li I features toward stars probing IC 443. The fine structure lines of ^{7}Li I and ^{6}Li I were fit simultaneously with the isotope ratio left as a free parameter. Along with the best-fit synthetic profile (black line), two alternative syntheses are shown in each case, one assuming a solar system ^{7}Li/^{6}Li ratio (red line) and one assuming no ^{6}Li is present (gray line). The parameters for ^{7}Li in these alternative syntheses are the same as in the best-fit cases. Residuals are given above each fit. Note that the alternative syntheses are less satisfactory in general, but particularly for HD 43582.

should exhibit a ^{7}Li/^{6}Li isotope ratio that is enhanced over the ambient value. However, a reduction in ^{7}Li/^{6}Li might also be anticipated near a supernova remnant (SNR) as a result of interactions between cosmic rays, accelerated by the supernova shock, and the surrounding interstellar gas. Such interactions will drive the ^{7}Li/^{6}Li ratio toward the GCR value of about 1.5.

Here, we present an analysis of ^{7}Li/^{6}Li isotope ratios along four sight lines through the intermediate-age core-collapse SNR IC 443, which is interacting with a dense molecular cloud in its vicinity.

2. HET observations

The target stars were observed with the 9.2 m Hobby-Eberly Telescope (HET) at McDonald Observatory using the High Resolution Spectrograph ($R \approx 100,000$). Two spectrographic settings (at 4931 Å and 5936 Å) provided data on K I λ7698, Li I λ6707, CH λ4300, and K I λ4044. Three stars were observed with both setups, resulting in total exposure times on Li I of 6.1 hr for HD 254577 and 4.7 hr for HD 43582 and HD 254755. These exposure times yielded final S/N ratios per resolution element near Li I of about 1100. An additional star, HD 254477, was observed only with the longer wavelength setting for a total of 2 hr, resulting in a S/N of 380.

To ensure the highest possible resolution, wavelength-calibrated spectra from different nights were aligned via atmospheric emission lines before coadding. Figure 1 presents the final reduced spectra for the four sight lines probing IC 443.

Table 1. Sight line information and profile synthesis results

Target	r (pc)	$N(^7$Li I) (10^9 cm^{-2})	$N(^6$Li I) (10^9 cm^{-2})	^{7}Li/^{6}Li	N(Li I) (10^9 cm^{-2})	N(K I) (10^{11} cm^{-2})	Li I/K I ($\times 10^{-3}$)
HD 254477	5.1	10.2 ± 1.8	$\lesssim$ 5.4	$\gtrsim$ 1.9	12.4 ± 2.5	18.3 ± 0.1	6.8 ± 1.4
HD 254577	7.0	10.0 ± 0.9	1.7 ± 0.9	6.1 ± 3.2	11.7 ± 1.2	19.7 ± 0.1	5.9 ± 0.6
HD 43582	5.4	6.2 ± 0.8	2.0 ± 0.8	3.1 ± 1.4	8.3 ± 1.2	12.9 ± 0.1	6.4 ± 0.9
HD 254755	8.6	16.6 ± 0.8	2.3 ± 0.8	7.1 ± 2.4	18.9 ± 1.1	69.4 ± 1.7	2.7 ± 0.2

3. Profile synthesis

Li isotope ratios were derived by means of profile synthesis (see Fig. 1) using the rms-minimizing code ISMOD (Y. Sheffer, unpublished). First, the line-of-sight component structure was obtained through profile fitting of the K I and CH lines. The dominant components in these species then served as templates for the Li I profile.

Both HD 254477 and HD 254755 exhibit only a single dominant component in K I and CH, while HD 254577 and HD 43582 show evidence for two closely blended components that dominate the absorption profiles. For the latter cases, the component structure was held fixed in the Li I syntheses, with component parameters determined separately from the two dominant components in K I and CH. Final results (see Table 1) were obtained from the average of the two fits. More details regarding the profile synthesis analysis can be found in Taylor et al. (2012).

4. Results and implications

The left panel of Figure 2 gives the positions of the target stars in relation to one of the subshells that compose IC 443 (dubbed shell A; see, e.g., Lee et al. 2008). On the right, we plot the Li isotope ratios as a function of the on-sky distance (r) of each sight line to the center of the shell (listed in Table 1), assuming the distance to IC 443 is 1.5 kpc.

The line of sight to HD 254755 passes beyond the outer edge of shell A in the northeast of IC 443. The ^{7}Li/^{6}Li ratio we find in this direction (7.1 ± 2.4) is very similar to the overall mean value of ^{7}Li/^{6}Li in the local ISM (7.3 ± 0.6; see Taylor et al. 2012). The gas toward HD 254755 may thus represent material relatively unaffected by the supernova shock, implying that a ^{7}Li/^{6}Li of ∼7 characterized the ambient cloud before the occurrence of the supernova.

In contrast, the ^{7}Li/^{6}Li ratio we find in the direction of HD 43582 (3.1 ± 1.4) is almost 60% lower than the ISM mean. The stars HD 254755 and HD 43582 are separated by only 7′.4 on the sky (3.2 pc at the distance of IC 443), but the line of sight to HD 43582 clearly penetrates the interior region of the SNR. If the molecular gas in this direction has been subjected to a more intense cosmic-ray irradiation than that toward HD 254755, then an enhancement in the abundance of ^{6}Li (relative to ^{7}Li) would be a natural consequence.

The sight lines to HD 254577 and HD 254477 presumably also pass through the interior of the SNR. However, given the uncertainties, the ^{7}Li/^{6}Li ratios we find in these directions are consistent with both the mean ISM value (as observed toward HD 254755) and the lower value we find toward HD 43582.

The discovery of a low ^{7}Li/^{6}Li ratio in IC 443 corroborates the conclusions drawn from γ-ray emission studies of the region (e.g., Acciari et al. 2009; Tavani et al. 2010; Abdo et al. 2010), which strongly suggest that the γ radiation results from the decay of neutral pions produced through cosmic-ray interactions with molecular gas.

A decrease in the ^{7}Li/^{6}Li ratio due to Li production by cosmic rays should be accompanied by an increase in the elemental Li abundance. If the clouds toward HD 43582 initially possessed a ^{7}Li/^{6}Li ratio of ∼7, then the presently observed ratio of 3.1 would imply

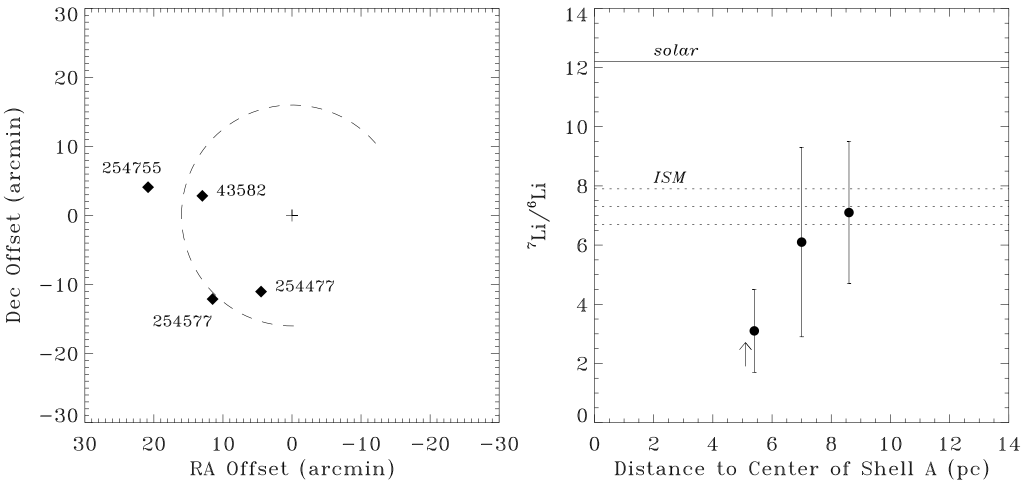

Fig. 2. Left panel: Schematic diagram showing the positions of the target stars relative to shell A, which forms the northeastern boundary of IC 443. The center of the shell (at $\alpha = 06^{\rm h}17^{\rm m}08^{\rm s}.4$, $\delta = +22^{\circ}36'39''.4$ J2000.0) is marked by a cross. The radius of the shell is $\sim 16'$ ($\sim$7 pc at d = 1.5 kpc). Right panel: Li isotope ratios toward the stars in our sample plotted against the on-sky distance from the center of shell A. The solid line represents the solar system ratio of 12.2 (Lodders 2003), while the dotted lines mark the weighted mean ISM ratio and 1σ errors (see Taylor et al. 2012).

a factor-of-two increase in the Li abundance. Some evidence for this effect can be seen in the N(Li I)/N(K I) ratios toward the stars in our sample (last column of Table 1). The three sight lines that pass through the interior of the remnant have N(Li I)/N(K I) $\approx 6 \times 10^{-3}$, while the ratio is $\approx 3 \times 10^{-3}$ toward HD 254755. (The K I column densities in Table 1 refer only to those components also seen in Li I.)

While our observations suggest an enhancement in the relative abundance of ^{6}Li due to cosmic ray interactions, we find no evidence of ^{7}Li synthesis by neutrino-induced spallation in material presumably contaminated by the ejecta of a core-collapse supernova. Given the age of the remnant (10–30 kyr), the hot ejecta should have had ample time to cool as it interacts with its dense surroundings. For comparison, Wallerstein et al. (1995) estimated a cooling time of 800 yr for the Vela remnant, which is about the same age as IC 443 but where the ambient ISM is of much lower density.

The lack of a neutrino signature in the Li isotope ratios near IC 443 is consistent with recent models of Galactic chemical evolution (e.g., Prantzos 2012), which suggest a very minor role for the ν-process in producing Li. Indeed, the Prantzos (2012) models indicate that as little as $\sim$3% of solar Li may be produced by neutrino spallation. It remains to be seen whether low-mass stellar sources of Li (e.g., RGB and AGB stars) can compensate for a weak ν-process contribution. In the meantime, measurements of ^{7}Li/^{6}Li in gas surrounding other SNRs will help to establish unequivocally the role that neutrino spallation plays in Li production.

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