Cosmic-Ray Lithium Production at a Type Ia Supernova Following a Nova Eruption

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Galactic Cosmic-rays (p, He, Li-Be-B, C, …)

(probably) produced via shock acceleration at SNRs

proton, He, C, etc.: primarily produced at SNRs, power-law spectrum

Li-Be-B: secondarily produced via spallation of heavier elements, steeper spectrum than primary CRs

However …
Spectral hardening of p, He, and Li

Direct measurements of CRs by PAMELA / CREAM / ATIC / AMS-02 etc.

(1) The spectra of $p$ and He are hardened above ~300 GeV

(2) The spectrum of Li (considered as secondary particles) is also hardened above ~300 GeV

(3) The hard components have similar indices

Is it implying the existence of primary sources that accelerate $p$, He and Li?
Galactic Lithium sources: novae

$^7$Be absorption lines in the early phase spectra of Classical nova V339 Del, $X (^7\text{Be}) \sim 10^{-4}$ (Tajitsu et al. 2015) … synthesized via $^3\text{He} (\alpha,\gamma)^7\text{Be}$ → decay into $^7\text{Li}$ by $e^-$ capture ($\tau_{1/2} \sim 53.22$ days)

Other examples:
$^7$Be absorption lines (V5668 Sgr, V2944 Oph; Tajitsu+ 2016)
$^7$Li absorption lines (V1369; Izzo+ 2015)
Type Ia supernova after a nova eruption?

**Classical nova**: gas accretion onto a white dwarf from its companion star $\rightarrow$ thermonuclear runaway

**Type Ia SN**: gas accretion onto a white dwarf from its companion star at higher rate $\rightarrow$ thermonuclear disruption (single degenerate scenario)

Nova eruptions may be followed by a Type Ia supernova (e.g.: PTF 11kx; Dilday+ 2012)

**Hypothesis**: CR Li nuclei are accelerated when a nova ejecta is swept up by a blast wave of a subsequent Type Ia SN.
Model

Distribution function of CRs emitted at the distance $r$ and time $t$

$$f_i(r, R, t) = \frac{Q_{i,0}(R)}{(4\pi D t)^{3/2}} \exp \left( -\frac{r^2}{4Dt} \right)$$

$R$ : rigidity
$D$ : diffusion coefficient
$Q_{i,0}$ : source spectrum

Assuming $Q_i \propto \varepsilon^{2.2}$, $D = D_0 \left( R / 1 \text{ GV} \right)^\delta$, the peak rigidity is

$$R_p = \left[ \frac{\delta}{\alpha + \frac{3}{2} \delta} \frac{r^2}{r_0^2} \right]^{1/\delta}$$

$r_0 = (4D_0 t)^{1/2}$: diffusion length for 1GV particles

Necessary conditions:
(1) $R_p < \sim 300 \text{ GeV}$ : the hard component does not have a break
(2) $E_{\text{CR,tot}} < \sim 10^{50} \text{ erg}$: typical CR energy injected into CRs per SN

fitting with the AMS-02 results (p, He, and Li)
Results

Note: From the conditions (1) and (2), the source should be located within $\sim 350$ pc, being independent of $D$.

\[
\begin{align*}
  r &= 150 \text{ pc}, \quad t = 6 \times 10^3 \text{ yr}, \\
  D &= 1 \times 10^{28} (\epsilon/1 \text{ GeV})^{1/3} \text{ cm}^2 \text{ s}^{-1}
\end{align*}
\]

\[
\begin{align*}
  M_{\text{CR, p}} &\sim 2 \times 10^{-6} M_{\text{sun}} \\
  M_{\text{CR, Li}} &\sim 1 \times 10^{-8} M_{\text{sun}}
\end{align*}
\]
Is it natural?

(1) total amount of accelerated particles

typical nova ejecta $\sim 10^{-4} M_{\text{sun}}$
$\rightarrow$ implying the efficiency $\sim 10^{-2}$

typical temperature of nova ejecta $\sim 10^4 K \rightarrow O.K.$

(2) composition

$[\text{CR Li}] / [\text{CR } p] \sim 3 \times 10^{-3}$
in a nova ejecta $\text{Li} / p \sim 10^{-4}$

However, the first ionization potential of Li ($\sim 5 \text{ eV}$) is much lower than that of $p$ ($\sim 13 \text{ eV}$) $\rightarrow$ more efficiently accelerated by a factor of $\sim 30$
Predictions from our model

• No hard component in Beryllium or Boron spectra (they are not synthesized in novae)
• Hard component in Carbon spectrum and steepening in B/C (Carbon is efficiently synthesized in novae)
• Anisotropy (existence of a nearby source)
• The isotopic ratio \( ^7\text{Li}/^6\text{Li} \) increases with energy above \( \sim 300 \text{ GeV} \) (\(^6\text{Li} \) is not produced in novae)
• candidate SNR?
  … Cygnus loop (\( \sim 500 \text{ pc}, \sim 10^4 \text{ yr} \), but generally regarded as a core-collapse SN)
  … SN Ia might have occurred in the low-density, high-latitude region, they are not always so bright in radio or X-ray.
Summary (see arXiv:1707.00212 for the detail)

• We propose the nearby Type Ia supernova occurring after a nova eruption, where a large amount of Li is synthesized, as the birth place of the hard CR Li component appearing $\gtrsim 300$ GV.
• The energy spectra of p/He/Li, total mass, abundance ratios, and efficiencies implied from observations are consistent with our scenario.
• Our scenario can be tested in various ways (Be and B spectrum, B/C, anisotropy, Li isotopic ratio) $\rightarrow$ AMS-02, CALET, DAMPE, ISS-CREAM, etc.