Nucleosynthesis in stellar flares

V. Tatischeff\textsuperscript{1,2}, J.-P. Thibaud\textsuperscript{1}, I. Ribas\textsuperscript{2}

\textsuperscript{1}Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, CNRS/IN2P3 and Univ Paris-Sud, F-91405 Orsay, France
\textsuperscript{2}Institut de Ciències de l’Espai (CSIC-IEEC), Campus UAB, Fac. Ciències, 08193 Bellaterra, Barcelona, Spain

Abstract Nuclear interactions of ions accelerated at the surface of flaring stars can produce fresh isotopes in stellar atmospheres. Although this nucleosynthesis is not significant for the chemical evolution of the Galaxy, it can be important for a number of measurements of “anomalously” high $^6$Li and $^7$Li abundances. We discuss the possible role of stellar flares to explain the recent report of high $^6$Li abundances in metal-poor halo stars and the well-established correlation between Li abundance and stellar activity in young open clusters. We then study the possibility of observing directly Li production during flares of nearby and active dwarfs of spectral type M.

1 Introduction

Nuclear interactions of ions accelerated in solar flares produce a characteristic gamma-ray emission in the solar atmosphere. Repeated spectroscopic observations of this emission have furnished valuable information on the physical conditions prevailing within solar active regions, as well as on the composition, energy spectrum, and angular distribution of the flare-accelerated ions \cite{21}. The solar-flare gamma-ray line emission testifies that fresh nuclei are synthesized in abundance in energetic solar events. Thus, the gamma-ray lines at 478 and 429 keV emitted in the reactions $^4$He($\alpha$,p)$^7$Li and $^4$He($\alpha$,n)$^7$Be, respectively, allow to trace the production of $^7$Li ($^7$Be decays to $^7$Li with a half-life of 53 days). There is no observable gamma-ray emission associated with the synthesis of $^6$Li. But evidence for significant production of this isotope in large solar flares is provided by optical observations of sunspots \cite{31} and measurements of the solar wind Li isotopic ratio in lunar soil \cite{6}.

Solar-type activity is believed to be a phenomenon inherent to the vast majority if not all main-sequence stars. The Sun is not an active star in comparison with numerous stellar objects in the solar neighbourhood that show much higher luminosities in emissions associated with coronal and chromospheric activities. Although gamma-ray line emission from other flaring stars cannot be observed with the current sensitivity of the gamma-ray space instruments, it is more than likely that the Sun is not the only star producing surface nucleosynthesis in flares.

It is instructive to compare the energetics of stellar flares with that of the galactic cosmic rays, as the latter are a significant source of nucleosynthesis of the light elements Li, Be and B \cite{30}. There are typically 375 gamma-ray flares per solar cycle (duration 11 yr) each releasing on average about $10^{31}$ erg of kinetic energy in accelerated ions of
energy \geq 1 \text{ MeV per nucleon} \ [27]. The power in these particles averaged over a solar cycle is \( \sim 10^{25} \text{ erg s}^{-1} \). Assuming that there are about \( 10^{11} \) flaring stars with the solar activity in the Milky way, one gets a total power of \( \sim 10^{36} \text{ erg s}^{-1} \) available for stellar-flare nucleosynthesis, which is about \( 10^5 \) times less than the power contained in the galactic cosmic rays. This shows that nucleosynthesis in stellar flares is not important for the galactic chemical evolution. However, it can produce fresh nuclei \textit{in situ}, i.e. in stellar atmospheres where abundances are usually measured. The purpose of this paper is to study the possible role of stellar flares in a few selected abundance measurements.

In the next section, we first calculate the yields for synthesis of the light elements in stellar flares and show that the Li isotopes should generally be more efficiently produced than the other species. In Sect. 3 we discuss the recent report of relatively high \(^6\text{Li}\) abundances in metal-poor halo stars. In Sect. 4 we propose a new model based on stellar flare nucleosynthesis to explain the observed correlation between Li abundance and stellar activity in young open clusters. In Sect. 5 we study the possibility of observing directly the creation of Li during large flares of active M-type dwarfs. Conclusions are given in Sect. 6.

## 2 Yields of light element production in stellar flares

The light elements Li, Be and B are a priori the best candidates to trace nonthermal nucleosynthesis in stellar flares, because heavier species are presumably produced in too large amounts by thermal nucleosynthesis in stellar interiors and explosions. To calculate the efficiency for light element production in stellar flares, we assume the same thick target interaction model that is usually employed to describe nuclear processes in solar flares (see \[34\]). Fast particles with given energy spectra and composition are supposed to be accelerated in the stellar corona and to produce nuclear reactions as they slow down in the lower atmosphere. We use for the source energy distribution of the fast ions a power law of spectral index \( s \). Analyses of the gamma-ray line emission produced in solar flares have shown that the spectral index is usually in the range \( 3 < s < 5 \). We assume that \( s \approx 4 \) is also close to the mean of spectral index distribution in stellar flares.

The ambient and accelerated-ion abundances are also based on those employed in solar flare studies \[34\], but we rescale the abundances of both ambient and fast C and heavier elements to the metallicity of the star we are studying. We adopt an accelerated \( \alpha \)-to-proton abundance ratio of 0.1. Enormous enhancements of accelerated \(^3\text{He}\) are measured in impulsive solar flares: the \(^3\text{He}/\alpha\) ratios found in these events are frequently three to four orders of magnitude larger than the corresponding value in the solar corona and solar wind, where \(^3\text{He}/\alpha\sim 5 \times 10^{-4}\) \[29\]. Such an enrichment of accelerated \(^3\text{He}\) is caused by resonant wave-particle processes that are characteristic of the stochastic acceleration mechanism at work in impulsive solar flares. It is reasonable to assume that this acceleration process enhances the accelerated \(^3\text{He}\) in stellar flares as well, but the abundance of fast \(^3\text{He}\) is nonetheless uncertain.
Figure 1: Yields of light element production in stellar flares as a function of the power-law spectral index of the accelerated particle energy distribution. The calculations are normalized to a total kinetic energy of 1 erg in protons of energy $E \geq 10$ MeV. **Solid curves:** $[\text{Fe/H}]=0$ and accelerated $^3\text{He}/\alpha=0.5$  
**Dashed curves:** $[\text{Fe/H}]=-2$ and $^3\text{He}/\alpha=0.5$.  
**Dotted curve:** $^6\text{Li}$ production for $[\text{Fe/H}]=0$ and $^3\text{He}=0$.

The cross sections for the nuclear reactions producing the light elements are mostly from Ref. [26], but we took into account the more recent measurements of Ref. [19] for production of $^6\text{Li}$ and $^7\text{Li}$ in the $\alpha + \alpha$ reactions and the evaluation of Ref. [27] for the cross section of the reaction $^4\text{He}(^3\text{He},p)^6\text{Li}$.

Figure 1 shows calculated production yields as a function of $s$. The calculations are normalized to a total kinetic energy of 1 erg contained in flare-accelerated protons of energy greater than 10 MeV. We see that for $[\text{Fe/H}]=0$ ($[\text{Fe/H}]=\log([\text{Fe/H}]/[\text{Fe/H}])$ and $(\text{Fe/H})/(\text{Fe/H})_\odot$ is the Fe abundance relative to its solar value) the Li isotopes are the most efficiently synthesized and that for $s > 3$ and $^3\text{He}/\alpha = 0.5$, the largest production is that of $^6\text{Li}$. The importance of the reaction $^4\text{He}(^3\text{He},p)^6\text{Li}$ for the synthesis of this isotope can be seen by comparing the upper curve with the dotted one, for which we set the accelerated $^3\text{He}$ abundance to zero. We find that for $s = 4$ and $^3\text{He}/\alpha = 0.5$, the $^3\text{He}+^4\text{He}$ reaction accounts for 85% of the total $^6\text{Li}$ production.

The metallicity dependence of the production yields can be seen by comparing the curves obtained for $[\text{Fe/H}]=0$ with those for $[\text{Fe/H}]=-2$. The productions of Be and B are proportional to the abundance of metals, because these species result from spallation of fast (resp. ambient) C, N and O interacting with ambient (resp. fast) H and He. On the other hand, the productions of $^6\text{Li}$ and $^7\text{Li}$ are almost independent of metallicity for
s > 3, because the Li isotopes are then produced almost exclusively in accelerated $^3$He and $\alpha$-particle interactions with ambient He.

3 $^6$Li production in flares of metal-poor halo stars

Asplund et al. [2] have recently reported the detection of $^6$Li at $\geq 2\sigma$ confidence level in nine halo stars of low metallicity, [Fe/H]$<-1$, situated in the turnoff region of the Hertzsprung-Russel diagram. The $^6$Li abundances measured in these objects are far above the value predicted by Big Bang nucleosynthesis and cannot be explained by galactic cosmic-ray interactions in the interstellar medium either. Proposals to explain these observations include: $^6$Li production in the early universe induced by the decay of supersymmetric dark matter particles during Big Bang nucleosynthesis, (2) production by the interaction of cosmological cosmic rays that could be accelerated in shocks induced by large-scale structure formation or by an early population of massive stars (Pop III stars), and (3) variations of the fundamental physical constants. However, the $^6$Li abundances reported in Ref. [2] and previous works are now questioned, as Cayrel et al. [4] have just shown that convective Doppler shifts in stellar atmospheres can generate an asymmetry of the Li I line at 6707.8 Å similar to the slight blending produced by the contribution of $^6$Li.

Tatischeff & Thibaud [35] have shown that a significant amount of $^6$Li can be produced in the atmospheres of metal-poor halo stars from repeated solar-like flares during their main-sequence evolution. These authors have developed a model of light element production by stellar flares, which is based on our current knowledge of the flaring activity of main-sequence dwarf stars. It is now well established that stellar activity depends primarily on two quantities: the effective temperature, which is the best indicator of how deep is the surface convection zone of the star, and the rotation rate, which controls the generation and amplification of magnetic fields by a complex $\alpha - \Omega$ process in the convective envelope. In the model of Ref. [35], the decisive factor for a significant flare production of $^6$Li is the star rotation period at the zero-age main sequence, $P_{\text{ZAMS}}$. The flare productions of the other light species $^7$Li, Be and B were found to be always negligible as compared with the observed abundances of these elements in metal-poor halo stars.

We show in Fig. 2 a comparison of the $^6$Li data of Ref. [2] and references therein with a Monte-Carlo simulation [35] in which stars were generated at random with constraints on their mass, metallicity and $P_{\text{ZAMS}}$. The statistical distribution of $P_{\text{ZAMS}}$ has been obtained from the study of Herbst & Mundt [11], who found that 50–60% of young main-sequence dwarf stars are rapidly rotating ($P_{\text{ZAMS}} < 2$ days), probably because they were released from any accretion disk locking mechanism very early on and thus conserved angular momentum throughout most of their pre-main sequence evolution, whereas the remaining 40–50% stars that are more slowly rotating lost substantial amounts of angular momentum during their first million years. The effect of this bimodal distribution on the calculated $^6$Li production can be seen in the left panel of Fig. 2. For [Fe/H]$<-1.7$, about half of the simulated stars have $^6$Li/H $> 2 \times 10^{-12}$, as a result of a significant $^6$Li production by
flares in these stars that have $P_{ZAMS} \lesssim 2$ days. The lower $^6$Li abundances of the other stars that are slow rotators mainly come from the simulated galactic cosmic-ray (GCR) nucleosynthesis, as the flare production was found to be very small in these objects. For [Fe/H]$>-1.7$, the flare and GCR contributions are of similar magnitude.

The $^6$Li/$^7$Li frequency distribution measured in metal-poor halo stars can result from a combination of flare-produced $^6$Li with a protostellar $^6$Li component from GCR nucleosynthesis (see Fig. 2 right panel). This scenario implies a relatively large dispersion of the $^6$Li abundances at low metallicities, which is compatible with the current data (see [35]). It predicts that the metal-poor stars with the highest $^6$Li abundances should have higher rotation velocities.

4 The correlation between Li abundance and stellar activity in young open clusters

A significant star-to-star scatter of the Li abundance for the same $B - V$ color is observed in all young open clusters for stars with masses lower than $\sim 0.9 \, M_\odot$ (e.g. IC 2602 at age 30 Myr, IC 4665 at 35 Myr, $\alpha$ Persei at 50 Myr, the Pleiades at 70–100 Myr; e.g. [28]). The Li/H ratios measured in these clusters were found to depend on stellar rotation and activity: the most rapid rotators, which are also the most active stars in
Figure 3: Li abundances as a function of effective temperature for stars of the Pleiades. (a) *Filled circles:* $P_{\text{rot}} \leq 2$ days; *open circles:* $P_{\text{rot}} > 2$ days. (b): *Filled circles:* $\log(L_X/L_{\text{bol}}) \geq -3.3$; *open circles:* $\log(L_X/L_{\text{bol}}) < -3.3$. *Dashed curve:* calculated Li/H without flare production; *solid curves:* total Li abundances where the flare Li production is obtained from eq.(4) with $\alpha = 1.5$ and $\mu = 0.5$, and for three values of $\log(L_X/L_{\text{bol}})$: -2.8 (top), -3.3 (middle) and -4 (bottom curve). The Li/H and $T_{\text{eff}}$ data are from \[33\], and the $P_{\text{rot}}$ and $L_X/L_{\text{bol}}$ data are from \[25\] and references therein. The $L_X$ values were measured in the ROSAT/PSPC 0.1–2.4 keV energy band.

chromospheric and coronal emissions, appear to be the most Li rich. This is illustrated in Fig. 3 for a selection of Pleiades stars. We see that for a given effective temperature, stars of rotation period $P_{\text{rot}} \leq 2$ days and X-ray-to-bolometric luminosity ratio $L_X/L_{\text{bol}} \geq 5 \times 10^{-4}$ have generally higher Li abundances. A noticeable exception is the moderately active ($L_X/L_{\text{bol}} = 3.7 \times 10^{-4}$) star HII 263, which has Li/H = 1.3 × 10$^{-9}$. We also note the strong decrease of Li/H for $T_{\text{eff}} < 5000$ K, which is due to the rapid destruction of Li in K-type stars. In slightly older open clusters like the Hyades and Praesepe, both of age ≈700 Myr, the observed Li/H dispersion is significantly less pronounced, although it is nonetheless inconsistent with the observational errors \[36\].

The Li–activity correlation is not well understood. It has been suggested that the observed dispersion is not due to an intrinsic scatter in Li abundances, but caused by observational effects associated with chromospheric activity, like the presence of starspots and faculae (e.g. \[32, 39\]). However, Barrado y Navascués et al. \[3\] have found that only a small part of the Li dispersion observed in Pleiades stars can be explained by such systematic effects. Recently, Leone \[16\] has proposed that the magnetic intensification of Li lines can result in an overestimation of Li abundances in active stars, thus contributing to the observed spread.

García López et al. \[10\] and Randich et al. \[28\] have suggested that the connection
between Li abundance and rotation could be caused by the inhibition of Li depletion in the most rapid rotators during their pre-main sequence evolution. In this scenario, fast rotators that have dissipated their circumstellar disk at early stages of their evolution, would have depleted less Li because they have undergone little angular momentum loss and transport, and hence little rotationally-driven mixing, until they have reached the zero-age main sequence. However, recent observations of weak lined T Tauri stars show that rapid rotation does not inhibit Li depletion among low-mass pre-main sequence stars \[40\]. This scenario is also not supported by stellar models of rotation-induced Li depletion, which predict on the contrary that fast rotation enhances the mixing processes that lead to Li destruction \[5, 24\].

In this paper, we assess the possibility that the observed Li-rotation correlation is due to a significant in situ production of Li by stellar flares in the most active main sequence stars. We assume that the Li atoms produced by nonthermal reactions in the atmosphere of a given star are mainly evacuated by the stellar wind on a relatively short timescale, rather than being mixed into the bulk of the star convection zone. Comparison of the solar wind $^6$Li abundance with calculations of the production of this isotope in solar flares has shown that this assumption is reasonable for the contemporary Sun \[27\]. At steady state between Li production by flares and loss in the wind, the surface Li abundance of a given star can be expressed as

$$
\frac{\text{Li}}{\text{H}} = \left(\frac{\text{Li}}{\text{H}}\right)_0 + \frac{1.4m_p\dot{N}_f(\text{Li})}{\dot{M}},
$$

where $(\text{Li}/\text{H})_0$ is the surface abundance of Li of protostellar origin, $m_p$ is the proton mass, $\dot{N}_f(\text{Li})$ is the Li flare-production rate and $\dot{M}$ is the stellar mass-loss rate. Following \[35\], the Li production rate can be estimated to be

$$
\dot{N}_f(\text{Li}) = Q(\text{Li})L_p^\odot(\geq 10 \text{ MeV}) \left(\frac{L_X^\odot}{L_X}\right)^\alpha,
$$

where $Q(\text{Li})$ is the Li production yield plotted in Fig. 1 ($Q(\text{Li}) = 2 \pm 1$ atoms per erg for $s = 4$, depending on the accelerated $^3$He abundance), $L_p^\odot(\geq 10 \text{ MeV}) \sim 10^{23} \text{ erg s}^{-1}$ is the average power contained in solar-flare accelerated protons of kinetic energy $E \geq 10 \text{ MeV}$ \[27\], $L_X$ is the star X-ray luminosity in the ROSAT/PSPC band, $L_X^\odot \sim 10^{27} \text{ erg s}^{-1}$ is the average solar luminosity in the same X-ray band, and the index $\alpha$ accounts for the fact that accelerated proton luminosity may not scale linearly with X-ray luminosity, because most of the energetic protons could be produced by the most powerful flares, whereas heating of stellar coronae could essentially be related to less powerful but more frequent flares. In \[35\], based on the work of \[9\], we adopted $\alpha = 1.5$.

\[3\]In § 3 we have assumed on the contrary that flare-produced $^6$Li atoms mainly accumulated in the convection zone of the studied metal-poor halo stars. This assumption was justified by the fact that the mass-loss rates of these low-metallicity objects are expected to be very low. Indeed, stellar winds are driven by radiation pressure and it is well known that the main source of radiation opacity is provided by metal lines.
The mass-loss rates of cool main-sequence stars are poorly known, because the tenuous and highly ionized winds of these stars cannot be directly detected. However, theory predicts that mass loss is associated with coronal heating, such that the mass-loss rate should scale with the X-ray luminosity (e.g. [8]). The former quantity can then be written as:

$$\dot{M} = \dot{M}_\odot \left( \frac{L_X}{L_{bol}} \right)^{\alpha - \mu} \left( \frac{L_X}{L_{bol}} \right)^{\mu},$$

where $$\dot{M}_\odot = 2.07 \times 10^{-14} \ M_\odot \ yr^{-1}$$ is the solar mass loss rate [12], $$L_{bol} = 3.85 \times 10^{33} \ erg \ s^{-1}$$ is the solar bolometric luminosity and the index $$\mu$$ is related to the fact that coronal X-ray emission mainly comes from closed magnetic loops, whereas mass loss proceeds along open magnetic flux tubes. Holzwarth & Jardine [12] recently estimated that $$\mu \approx 0.5$$, whereas Wood et al. ([38] and references therein) previously found $$\mu$$ ranging from $$\approx 1$$ to 1.3.

Inserting eqs. (2) and (3) into eq. (1) we obtain:

$$\frac{Li}{H} = \left( \frac{Li}{H} \right)_0 + \frac{2.7 \times 10^{-3}}{(3.8 \times 10^6)\mu} \left( \frac{L_X}{L_{bol}} \right)^{\alpha - \mu} \left( \frac{L_{bol}}{L_{bol}} \right)^{\mu}. $$

Calculated Li abundances are shown in Fig. 3b for $$\alpha = 1.5$$ and $$\mu = 0.5$$. We modeled $$(Li/H)_0$$ as a function of $$T_{eff}$$ with a simple empirical expression of exponential decay form. We see that the flare contribution to the total Li abundance can be significant for active stars with saturated X-ray emission, $$L_X/L_{bol} \sim 10^{-3}$$. In particular, in situ production by flares can explain the non-negligible amounts of Li detected in Pleiades stars with $$T_{eff}$$ lower than $$\sim 4500$$. For which depletion of protostellar Li is expected to be $$\gtrsim 3$$ dex. We also see that the Li abundances in very active stars with $$T_{eff}$$ greater than $$\sim 5600$$ can exceed the presently cosmic, i.e. meteoritic value $$Li/H = 2 \times 10^{-9}$$ [17]. However, this prediction crucially depends on the uncertain parameters $$\alpha$$ and $$\mu$$. In particular, the model is not valid if $$\mu$$ is significantly larger than 0.5. We also did not take into account in these calculations the possible dependence of Li depletion with stellar rotation. According to recent stellar evolution models with internal gravity waves [5], protostellar Li could be slightly more depleted in rapidly rotating stars.

We find that creation of Li by flares can explain the dispersion in Li abundances observed in young open clusters like the Pleiades and $$\alpha$$ Persei. Future measurements of the isotopic ratio $$^6Li/^7Li$$ could allow to test this possibility. $$^6Li$$ of protostellar origin should be strongly depleted and therefore undetectable in stars with $$Li/H \lesssim 2 \times 10^{-10}$$, because $$^6Li$$ is more rapidly consumed than $$^7Li$$ in stellar interiors. On the other hand, significant $$^6Li$$ can be produced by flare-accelerated $$^3He$$ and $$\alpha$$-particle interactions with ambient $$^4He$$. The Li isotopic ratio from flare production is predicted to be in the range $$0.3 < ^6Li/^7Li < 2.2$$ for $$s = 4$$ and $$0 < ^3He/\alpha < 0.5$$ (Fig. 1).

It is remarkable that this simple model of Li production by stellar flares is also consistent with the lower dispersion in Li/H observed in intermediate-age and old open clusters. The X-ray luminosities of dwarf stars in open clusters and the solar neighbourhood are found to rapidly decline with the stellar age $$t$$ for $$t \gtrsim 0.1$$ Gyr. Cranmer [8] uses the following relationship to describe a large selection of X-ray luminosities in the ROSAT/PSPC
band:
\[ \frac{L_X}{L_{\text{bol}}} = \frac{4.48 \times 10^{-4}}{1 + (12.76t_{\text{Gyr}})^{1.79}} , \]

where \( t_{\text{Gyr}} \) is the stellar age in units of Gyr. This gives for the age of the Hyades \((t \approx 0.7 \text{ Gyr})\) a reduction of \( L_X/L_{\text{bol}} \) by a factor of \( \sim 25 \) as compared with the average ratio for the Pleiades. Equation (4) shows that a similar reduction can be expected for the Li dispersion, in good agreement with the Hyades observations [36].

5 Can Li production be observed live during stellar flares?

There are a number of observations reported in the literature that suggest that a significant amount of Li can be synthesized in large stellar flares. For example, a relatively high Li abundance has been reported in the K7 flaring star HD 358623 [18]. This rapidly rotating and very active dwarf has later been identified as a member of the \( \sim 12 \text{ Myr-old} \) \( \beta \) Pictoris Moving Group [14]. Anomalously high Li abundances have been measured in other K-type stars showing strong chromospheric activity. The possibility that the excess Li was produced in situ by flares has already been discussed by Pallavicini et al. [22]. \(^6\)Li enhancement has been found during a long-duration flare of a chromospherically active binary [20] and in the atmosphere of a single chromospherically active K-type dwarf [7]. In both cases, a flare production has been found to be consistent with the activity level of the object.

We study here the possibility of observing directly Li synthesis during flares of active M-type dwarfs. Li observations in clusters and associations indicate that these cool stars \((T_{\text{eff}} < 4000 \text{ K})\) fully deplete their initial Li very rapidly, mainly during their pre-main sequence evolution. M-type main-sequence stars are almost free of Li of protostellar origin. There are several very active M-type dwarfs with high X-ray luminosities in the solar neighbourhood, e.g. AD Leo \((L_X = 10^{28.95} \text{ erg s}^{-1})\) and EV Lac \((L_X = 10^{28.74} \text{ erg s}^{-1})\) [1]. Large flares releasing more than \( 5 \times 10^{32} \text{ erg} \) in X-rays are observed in these objects at a rate of about one event per day [1].

In impulsive solar flares, the ratio of the power contained in accelerated protons of kinetic energy above 10 MeV to the hard X-ray (1.6–12 keV) flare luminosity is estimated to be \( L_p^\odot (\geq 10 \text{ MeV})/L_{\text{hard}} = 0.09 \) [15]. With this value and the calculated Li production yield \( Q(\text{Li}) = 2 \pm 1 \text{ atoms per erg for } s = 4 \) (see Fig. 1), a flare that radiates more than \( 5 \times 10^{32} \text{ erg} \) in X-rays can produce more than \( 9 \times 10^{31} \) Li atoms in the star atmosphere. Detailed calculations for solar flares have shown that the bulk of the nuclear interactions of the flare-accelerated particles occur at atmospheric depths corresponding to column densities in the range \( 10^{-3} - 10^{-1} \text{ g cm}^{-2} \) [13]. The models of Pavlenko et al. [23] for the formation of Li lines in M-type dwarfs show that the Li I line at 6707.81 Å is also produced at depths \( d \lesssim 10^{-1} \text{ g cm}^{-2} \). Thus, Li atoms can be synthesized in stellar flares right in the region where the strong Li I resonance line is formed. Taking the typical radius of mid-M
type main-sequence dwarfs to be $R = 0.4 \ R_\odot$, the total number of H atoms in this region is $N_H \approx 4\pi R^2 d/(1.4 m_p) \lesssim 4 \times 10^{14}$. The nucleosynthesis of more than $9 \times 10^{31}$ Li atoms in a large flare would thus give Li/H > $2.2 \times 10^{-13}$. From the models of Ref. [23] for a star with $T_{\text{eff}} = 3000$ K, surface gravity $\log g = 5$ and a solar-like quiescent chromosphere, the corresponding equivalent width of the Li I $\lambda 6708$ line would be $EW(\text{Li}) > 80$ mA. But the Li production region can be significantly heated by the flare energy deposition, which could decrease the line strength (see [23]).

Although challenging, the observation of Li enhancement during a strong flare of an active M-type dwarf appears to be possible. We have shown that energetic events occurring at a rate of about one per day could temporarily produce a Li absorption line of equivalent width $EW(\text{Li}) \gtrsim 80$ mA. This could be measured in high signal-to-noise spectra taken from nearby and relatively luminous objects, like AD Leo ($d = 4.9$ pc; $V = 9.43$ mag). Convective motions in the star upper atmosphere could rapidly reduce the line intensity. The detection of a variable Li absorption line from a flaring star would obviously shed new light on these dynamical processes.

6 Conclusions

The Li isotopes are likely to be the best tracers of the nucleosynthesis probably occurring in flares of active stars, because (i) background Li of protostellar origin can be rapidly depleted in cool dwarfs and (ii) $^6$Li and $^7$Li can be efficiently produced in stellar atmospheres by He+He reactions. If, as in solar flares, energetic $^3$He nuclei are strongly enriched by the particle acceleration process, $^6$Li can be mostly synthesized by the reaction $^4$He($^3$He,$p$)$^6$Li. The relatively high $^6$Li abundances recently measured in several metal-poor halo stars near turnoff have to be confirmed after the work of Ref. [4]. In any case, we have shown that stellar flares could account for significant $^6$Li production in these objects, thus avoiding the need for a new pre-galactic source of this isotope, such as non-standard Big Bang nucleosynthesis and cosmological cosmic rays.

We have proposed a model of Li production in flares that can explain the spread in Li abundances and the Li-activity correlation observed in young open clusters. Understanding the origin of the Li dispersion is critical, because the Li abundance is considered to be one of the best age indicator of young cool stars. Measurements of the isotopic ratio $^6$Li/$^7$Li in active stars of young open clusters could allow to test the flare production scenario.

But the most direct evidence for flare nucleosynthesis would be the detection of Li enhancement during a strong stellar flare. We suggest that the best target for such an observation would be an active M-type dwarf in the solar neighbourhood, because (i) main-sequence M-type stars are almost free of background Li of protostellar origin and (ii) models for the formation of Li lines in very cool dwarfs show that Li abundance as little as a few times $10^{-13}$ can be detected in these objects. We have estimated that large flares that could produce such a Li abundance may occur at a rate of about one per day in the most active M-type dwarfs. If the proposed observation is successful, it will certainly
provide unique information on the nuclear processes occurring in stellar flares.

V.T. acknowledges financial support from the AGAUR (grant 2006-PIV-10044).

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