A&A 469, 265–274 (2007)
DOI: 10.1051/0004-6361:20066635

Astronomy & Astrophysics

Is ^{6}Li in metal-poor halo stars produced in situ by solar-like flares?

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Received 25 October 2006 / Accepted 15 March 2007

ABSTRACT

The high ^{6}Li abundances recently measured in metal-poor halo stars are far above the value predicted by Big Bang nucleosynthesis. They cannot be explained by galactic cosmic-ray interactions in the interstellar medium either. Various pre-galactic sources of ^{6}Li have been proposed in the literature. We study the possibility that the observed ^{6}Li was produced by repeated solar-like flares on the main sequence of these low-metallicity stars. The time-dependent flaring activity of these objects is estimated from the observed evolution of rotation-induced activity in Pop I dwarf stars. As in solar flares, ^{6}Li could be mainly created in interactions of flare-accelerated ^{3}He with stellar atmospheric ^{4}He, via the reaction ^{4}He(^{3}He, p)^{6}Li. Stellar dilution and destruction of flare-produced ^{6}Li are evaluated from the evolutionary models of metal-poor stars developed by Richard and co-workers. Stellar depletion should be less important for ^{6}Li atoms synthesized in flares than for those of protostellar origin. Theoretical frequency distributions of ^{6}Li/^{7}Li ratios are calculated using a Monte-Carlo method and compared with the observations. Excellent agreement is found with the measured ^{6}Li/^{7}Li distribution, when taking into account the contribution of protostellar ^{6}Li originating from galactic cosmic-ray nucleosynthesis. We propose as an observational test of the model to seek for a positive correlation between ^{6}Li/^{7}Li and stellar rotation velocity. We also show that the amounts of ^{7}Li, Be and B produced in flares of metal-poor halo stars are negligible as compared with the measured abundances of these species. ^{6}Li in low-metallicity stars may be a unique evidence of the nuclear processes occuring in stellar flares.

Key words. stars: abundances – stars: flare – nuclear reactions, nucleosynthesis, abundances

1. Introduction

The origins of the light elements Li, Be, and B (hereafter LiBeB) differ from those of heavier nuclides. Whereas most elements are produced by stellar nucleosynthesis, LiBeB are mainly destroyed in stellar interiors by thermonuclear reactions with protons. Thus, ^{6}Li is rapidly consumed at stellar temperatures higher than 2×10^6 K. The major source of ^{6}Li has been thought for decades to be the interaction of galactic cosmic rays (GCRs) with the interstellar medium (for a review see Vangioni-Flam et al. 2000). Unlike ^{7}Li, ^{6}Li is predicted to be formed at a very low level in Big Bang nucleosynthesis, ^{6}Li/H $\simeq 10^{-14}$ (Thomas et al. 1993; Vangioni-Flam et al. 1999).

However, recent major observational advances have allowed new measurements of the ^{6}Li/^{7}Li isotopic ratio in stars, which challenge our understanding of the origin of ^{6}Li. Asplund et al. (2006) have recently reported the observation of ^{6}Li in several halo stars of low metallicity, [Fe/H] < -1 (where [Fe/H] = log[(Fe/H)/(Fe/H)$_\odot$] and (Fe/H)/(Fe/H)$_\odot$ is the Fe abundance relative to its solar value). These authors have detected ^{6}Li at $\geq 2\sigma$ confidence level in nine of 24 studied stars. The ^{6}Li/H values measured in these metal-poor halo stars (MPHSs) are $>10^{-12}$, i.e. more than 100 times higher than the predicted abundance from standard Big Bang nucleosynthesis. Reported ^{6}Li abundances at [Fe/H] $\lesssim -2.3$ are also larger than expected if GCR nucleosynthesis was the major source of ^{6}Li (Rollinde et al. 2005; Prantzos et al. 2006). This result was already pointed out by Ramaty et al. (2000a) after the first detection of ^{6}Li in two MPHSs of metallicity [Fe/H] ≈ -2.3 (Smith et al. 1993; Hobbs & Thorburn 1997; Smith et al. 1998; Cayrel et al. 1999).

Two alternative types of pre-galactic ^{6}Li sources have been proposed: (1) production in the early universe induced by the decay of supersymmetric dark matter particles during Big Bang nucleosynthesis (Jedamzik 2000; Jedamzik et al. 2006; Kawasaki et al. 2005; Ellis et al. 2005; Kusakabe et al. 2006) and (2) production by the interaction of cosmological cosmic rays that could be accelerated in shocks induced by large-scale structure formation (Suzuki & Inoue 2002) or by an early population of massive stars (Pop III stars; Rollinde et al. 2005, 2006).

Because a substantial stellar depletion of ^{6}Li seems to be unavoidable, any model of pre-galactic production should account for a higher ^{6}Li abundance in the early Galaxy than those measured in evolved MPHSs. The value of the so-called "Spite plateau" (Spite & Spite 1982), namely the nearly constant abundance of Li (mostly ^{7}Li) measured in most MPHSs (see Bonifacio et al. 2007), is a factor of two to four lower than the primordial ^{7}Li abundance calculated in the framework of standard Big Bang nucleosynthesis (^{7}Li/H $= 4.27^{+1.02}_{-0.83} \times 10^{-10}$, Cyburt 2004; ^{7}Li/H $= 4.15^{+0.49}_{-0.45} \times 10^{-10}$, Coc et al. 2004). According to recent stellar-evolution models that include diffusion and turbulent mixing (Richard et al. 2005; Korn et al. 2006), this discrepancy is probably due to the stellar depletion of ^{7}Li. In such a case, an even larger depletion of pre-galactic ^{6}Li is expected. Given that depletion during the pre-main sequence of the MPHSs is predicted to be negligeable for ^{7}Li, but ≥ 0.3 dex for ^{6}Li (Richard et al. 2002, 2005; Piau 2005), the stellar destruction of protostellar ^{6}Li is probably higher than 0.6 dex.

In this paper, we assess the possibility that the excess ^{6}Li discovered in MPHSs is not of pre-galactic origin, but was produced in situ by repeated solar-like flares on the main sequence of these stars. Predictions for significant synthesis of ^{6}Li in stellar flares have been made long ago (Canal et al. 1975; Walker et al. 1985; see also Ryter et al. 1970). ^{6}Li enhancement has been found during a long-duration flare of a chromospherically active binary (Montes & Ramsey 1998) and in the atmosphere of a single chromospherically active K dwarf (Christian et al. 2005). In both cases, a flare production was found to be consistent with the activity level of the object. A high Li abundance associated with a large flare has also been observed in a very active late-type dwarf star (Mathioudakis et al. 1995). In this case, however, the Li isotopic ratio was not measured.

Evidence for significant synthesis of ^{6}Li in large solar flares is provided by optical observations of sunspots (Ritzenhoff et al. 1997) and measurements of the solar wind lithium isotopic ratio in lunar soil (Chaussidon & Robert 1999). Calculations of ^{6}Li production by nuclear interaction of solar-flare-accelerated particles were performed by Ramaty et al. (2000b). They have shown that a major ^{6}Li production channel is due to accelerated ^{3}He interactions with solar atmospheric ^{4}He, via the reaction ^{4}He(^{3}He, p)^{6}Li.

Deliyannis & Malaney (1995) have already studied the in situ production of ^{6}Li from flares of MPHSs, following the first report of a ^{6}Li detection in the halo star HD 84937 (Smith et al. 1993). They found that large flares could account for the ^{6}Li abundance measured in that star. However, Lemoine et al. (1997) have questioned this result on the basis of the ^{6}Li production efficiency: assuming the flaring activity of the contemporary Sun for one billion years, they found the amount of flare-produced ^{6}Li to be negligible as compared with the abundance measured in HD 84937.

There are two main reasons that flare production of ^{6}Li in MPHSs can be more important than previously thought. First, the ^{6}Li production efficiency was underestimated in previous studies, because the reaction ^{4}He(^{3}He, p)^{6}Li was not taken into account. Second, it is very likely that most halo stars were much more active in their youth than the contemporary Sun. Indeed stellar rotation being the decisive factor of solar-like activity of dwarf stars, magnetic braking during the main sequence leads to a well-known decay with stellar age of chromospheric and coronal activities (e.g. Gershberg 2005).

We present in this paper a time-dependent model for flare production of LiBeB in MPHSs. The flaring activity of these Population II stars is estimated from the observed evolution of rotation-induced activity in their Pop I counterparts. Dilution and depletion of flare-produced ^{6}Li in the surface convection zone of MPHSs are evaluated from the evolutionary stellar models of Richard et al. (2002). In Sect. 2 we first calculate the efficiency for synthesis of ^{6}Li and the other LiBeB isotopes in stellar flares. The model for the time evolution of ^{6}Li abundance at the surface of MPHSs is described in Sect. 3.1. In Sect. 3.2 we use a Monte-Carlo simulation to calculate theoretical frequency distributions of ^{6}Li/^{7}Li values in MPHSs, which are then compared to the observations. In Sect. 4.1 we comment on the dispersion of the ^{6}Li/^{7}Li data in the light of our Monte-Carlo results. We discuss in Sect. 4.2 ^{6}Li production from flares of young stellar objects. We show in Sect. 4.3 that ^{6}Li is the only LiBeB isotope which can be produced in non-negligible amount in flares of MPHSs relative to other production modes. Observational tests of the flare model are discussed in Sect. 4.4. A summary is given in Sect. 5.

2. Yields of LiBeB production in stellar flares

We calculated the efficiency for LiBeB production in flares of MPHSs assuming the same thick target interaction model that is usually employed to describe nuclear processes in solar flares (see Tatischeff et al. 2006). Fast particles with given energy spectra and composition are assumed to be accelerated in the stellar corona and to produce nuclear reactions as they slow down in the lower stellar atmosphere.

For the source energy spectrum of the fast ions we used an unbroken power law of spectral index s, extending from the threshold energies of the various nuclear reactions up to $E_{\max}$ = 1 GeV nucleon^{-1}. For solar flares, Ramaty et al. (1996) found from analyses of gamma-ray line ratios a range of spectral indexes of about $s = 4 \pm 1$. We assumed that $s \simeq 4$ 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 (Tatischeff et al. 2006), but we rescaled the abundances of both ambient and fast C and heavier elements to the metallicity of the MPHSs. We performed calculations with an accelerated α/p ratio of 0.1, which is typical of the abundance ratio measured in impulsive solar energetic events (e.g. Reames 1999). Gamma-ray spectroscopic analyses have provided evidence that the accelerated α/p ratio could be as high as 0.5 in some solar flares (Share & Murphy 1997; Mandzhavidze et al. 1999). It is noteworthy that such a large α/p ratio would significantly enhance the efficiency for production of ^{6}Li, because this isotope is mainly synthesized in He+He interactions (see below). However, we adopted here the canonical $\alpha/p = 0.1$.

We took the accelerated ^{3}He/α ratio to be 0.5, which is also typical of the abundances found in impulsive solar energetic events (Reames 1999). Such an enrichment of fast ^{3}He is caused by resonant wave-particle processes that are characteristic of the stochastic acceleration mechanism at work in impulsive solar flares (e.g. Temerin & Roth 1992). We assume that this acceleration process enhances the accelerated ^{3}He in stellar flares as well.

The cross sections for the nuclear reactions are mostly from Ramaty et al. (1997), but we took into account the more recent measurements of Mercer et al. (2001) for production of ^{6}Li and ^{7}Li in the $\alpha + \alpha$ reaction. The cross section for the reaction ^{4}He(^{3}He, p)^{6}Li was evaluated by Ramaty et al. (2000b). We also included in our calculations the reaction ^{12}C(^{3}He,x)^{7}Be (^{7}Be decays to ^{7}Li with a half-life of 53 days), whose cross section was evaluated by Tatischeff et al. (2006).

Figure 1 shows calculated thick-target yields for LiBeB productions as a function of spectral index 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 $s > 2.8$, the largest production is that of ^{6}Li. The importance of the reaction ^{4}He(^{3}He, p)^{6}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}He abundance to zero. For $s = 4$, the ^{3}He+^{4}He reaction accounts for 87% of the total ^{6}Li production.

The metallicity dependence of the production yields can be seen by comparing the curves obtained for [Fe/H] = -1 with those for [Fe/H] = -3. 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}Li and ^{7}Li are almost independent of metallicity, because, for [Fe/H] < -1, the Li isotopes are produced almost exclusively in He+He reactions. Consequences of these different metallicity dependences are discussed in Sect. 4.3.

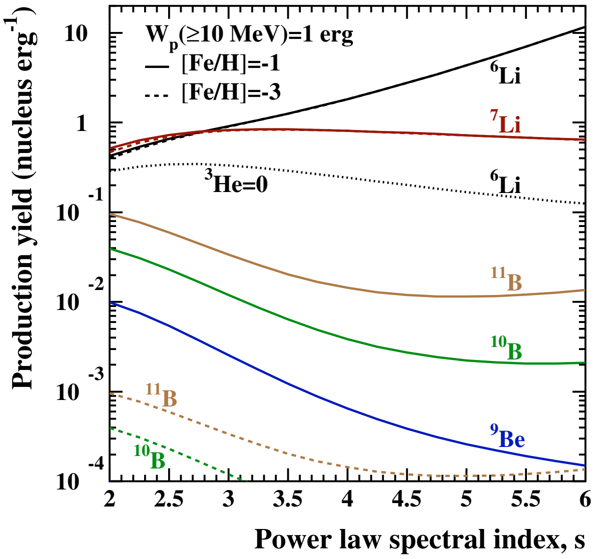

Fig. 1. LiBeB productions by stellar-flare accelerated particles with power law in kinetic energy per nucleon spectra with spectral index s. The calculations are normalized to a total kinetic energy of 1 erg in protons of energy $E \geq 10$ MeV. *Solid curves*: [Fe/H] = −1. *Dashed curves*: [Fe/H] = −3. Li production is almost independent of metallicity, because it is mostly due to accelerated ^{3}He and α-particle interactions with ambient He. *Dotted curve*: ^{6}Li production for ^{3}He = 0 and [Fe/H] = −1.

3. ^{6}Li production model

3.1. Time evolution of ^{6}Li abundance in MPHSs

We calculated the ^{6}Li abundance in the atmosphere of MPHSs by assuming that the ^{6}Li nuclei produced by interaction of flare-accelerated particles with stellar atmospheric matter are instantaneously mixed into the bulk of the surface convection zone (SCZ). This is justified because the characteristic timescales for variation of the depth of the SCZ are much larger than typical convective turnover times (Kim & Demarque 1996). If the mass contained in the SCZ, $M_{\rm cz}(t)$, is a decreasing function of time, which is the case during the main sequence evolution (e.g. Richard et al. 2002), the net rate of variation of ^{6}Li/H at the surface of a MPHS is independent of the variation of $M_{\rm cz}(t)$, and can be written as

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{^6\mathrm{Li}}{\mathrm{H}}\right) = \frac{Q(^6\mathrm{Li})L_{\rm p}^{\odot}(\geq 10\ \mathrm{MeV})f_{\rm a}(t)}{M_{\rm cz}(t)/(1.4m_{\rm p})} - \lambda_{\rm D}(t)\left(\frac{^6\mathrm{Li}}{\mathrm{H}}\right), \tag{1}$$

where $Q(^6\mathrm{Li})$ is the ^{6}Li production yield plotted in Fig. 1 ($Q(^6\mathrm{Li})$ ~ 2 nuclei per erg for s = 4), $L_{\rm p}^{\odot}(\geq 10$ MeV) ~ 10^{23} erg s^{-1} is the average power contained in solar-flare accelerated protons of energy $E \geq 10$ MeV (Ramaty & Simnett 1991; Ramaty et al. 2000b), $f_{\rm a}(t)$ is the time-dependent luminosity of the flare-accelerated protons which irradiate the MPHS with respect to that of the contemporary Sun, $m_{\rm p}$ is the proton mass, and $\lambda_{\rm D}(t)$ is the characteristic rate of ^{6}Li loss from the SCZ. This last term accounts for ^{6}Li stellar depletion by various processes including nuclear burning, gravitational settling, rotational mixing, and the possible ejection of an unknown fraction of flare-produced nuclei in stellar wind. The depletion of H due to the SCZ shrinking is taken as identical to that of ^{6}Li.

Although young stellar objects are known to present high levels of flaring activity in all evolutionary stages from Class I protostars to zero-age main sequence (Feigelson & Montmerle 1999), we show in Sect. 4.2 that ^{6}Li production on the pre-main sequence can be neglected. This is because (1) the duration of the pre-main sequence is much shorter than that of the main sequence and (2) the convection zones are deepest during the early stages of stellar evolution, such that dilution of spallogenic ^{6}Li is more important. We thus consider here only the production of ^{6}Li by stellar flares during the main sequence.

It has been known for many years that the chromospheric and coronal activities of dwarf stars are closely related to their rotation (Kraft 1967). This relationship results from the generation and amplification of surface magnetic fields by a complex dynamo mechanism, whose efficiency depends on the interaction between differential rotation and subphotospheric convection (Charbonneau & MacGregor 2001). There exists ample evidence that stellar activity depends primarily on two quantities, namely the stellar rotation period, $P_{\rm rot}$, and the effective temperature, $T_{\rm eff}$. The first controls how much vorticity is injected into turbulent motions in the convective envelope. The second quantity is the best indicator of how deep is the SCZ where magnetic fields are generated (Richard et al. 2002). In particular, the SCZ characteristics in main-sequence stars of Pop II are extremely close to those in Pop I stars with the same $T_{\rm eff}$ (e.g. Talon & Charbonnel 2004, Fig. 1). We thus assume that for given $T_{\rm eff}$ and $P_{\rm rot}$, both main-sequence star populations generate the same surface magnetic fields.

We also assume that the rate of proton acceleration in stellar flares does not depend on metallicity, but only on surface magnetic flux. In solar flares, the particle acceleration processes at work in impulsive events are related to excitation of plasma waves that are essentially independent of the heavy element content of the coronal plasma. Thus, in our model, the scaling of the stellar-flare accelerated protons ($f_{\rm a}(t)$ in Eq. (1)) only depends on $T_{\rm eff}$ and $P_{\rm rot}$, such that it can be estimated using the wealth of available data for the stellar activity of Pop I stars.

Numerous studies have searched for correlations between observable manifestations of stellar magnetic activity and rotation. X-ray emission may be the most widely available tracer of surface magnetic activity. Although the exact mechanism(s) of stellar coronal heating remains poorly understood, it leaves no doubt that magnetic fields play the crucial role, such that coronal X-ray measurements provide a good proxy for the stellar magnetic flux (Pevtsov et al. 2003) and in turn for the flaring activity. We used the extensive study of Pizzolato et al. (2003) on the relationship between stellar rotation and coronal X-ray emission in Pop I stars. These authors have selected a sample of 259 late-type main-sequence stars that were observed with *ROSAT*, consisting of 110 field stars and 149 stars belonging to young open clusters. The stellar rotation periods, which were generally derived from photometric measurements, cover the range $0.2 < P_{\rm rot} < 50$ days. Strong correlations between the X-ray luminosity, $L_{\rm X}$, and $P_{\rm rot}$ were found. These correlations depend on the $B-V$ color of the stars, which reflects the dependence of the surface magnetic fields on the depth of the convection zone. To take into account this dependency, stellar magnetic activity is usually studied as a function of the so-called Rossby number, $R_0 = P_{\rm rot}/\tau_{\rm conv}$, where $\tau_{\rm conv}$ is the convective turnover time, which, for main sequence stars, is essentially a function of the $B-V$ color only. The 24 stars observed by Asplund et al. (2006) are situated in the turnoff region of the Hertzsprung-Russel diagram and cover the $B-V$ color range $0.37 < B-V < 0.49$. Using the database computed with the Yale Stellar Evolution Code (Demarque et al. 2004, and references therein), we find that earlier in the main sequence life, the stars selected by Asplund et al. (2006) were in the color range ~$0.45 < B-V < 0.60$. Pizzolato et al. (2003) obtained the following relationship for the close color range $0.50 < B - V < 0.60$:

$$L_X = 10^{30.1} \text{ erg s}^{-1} \quad \text{for } P_{\rm rot} \leq 1.8 \text{ days},$$
$$= 10^{30.1} \left(\frac{P_{\rm rot}}{1.8 \text{ days}} \right)^{-2} \text{ erg s}^{-1} \quad \text{for } P_{\rm rot} > 1.8 \text{ days}. \quad (2)$$

Given the relatively narrow color range of interest, we used for simplicity this relation to derive the time-dependent activity level of Pop I stars, instead of a possible more general scaling from the Rossby number[1].

The time evolution of stellar rotation period during the main sequence depends on the adopted law for the angular momentum loss of the star. Pioneering observations have established that measured rotational velocities on the main sequence roughly decrease as the inverse square root of the age (Skumanich 1972). This is usually attributed to the loss of angular momentum through magnetic stellar winds and corresponds to a loss law of the form $\mathrm{d}J/\mathrm{d}t \propto \omega^3$, where ω is the angular velocity (Kawaler 1988). Further observations have revealed the existence of more rapid rotators on the early main sequence than predicted by the above angular momentum loss law (see Krishnamurthi et al. 1997, and references therein). However, we adopted for simplicity the time dependence

$$P_{\rm rot}(t) = P_{\rm ZAMS} \sqrt{\frac{t}{t_{\rm ZAMS}}}, \quad (3)$$

where $P_{\rm ZAMS}$ is the rotation period at the zero-age main sequence (ZAMS), which we estimated from the recent study of Herbst & Mundt (2005) (see below).

It is possible, however, that the rotational evolution of Pop II stars has been different from their Pop I counterparts. The existing data on the surface rotation velocity of MPHSs are scarce and not very constraining (see Lucatello & Gratton 2003, and references therein). But it is well known that radiation-driven mass loss, which carries away angular momentum, is metallicity dependent. This is because the main source of radiation opacity is provided by metal lines. This effect could lead to higher rotation rate and hence higher surface magnetic field and ^{6}Li production by flares in MPHSs than in Pop I stars of the same stellar age and initial rotation period $P_{\rm ZAMS}$.

Finally to obtain an estimate of $f_{\rm a}(t)$ (Eq. (1)), we need to relate the coronal X-ray luminosity to the flare-accelerated proton luminosity, $L_{\rm p}(\geq 10 \text{ MeV})$. We use the following relation:

$$f_{\rm a}(t) = \frac{L_{\rm p}(\geq 10 \text{ MeV})}{L_{\rm p}^{\odot}(\geq 10 \text{ MeV})} = \left(\frac{L_X}{L_X^{\odot}} \right)^{\alpha}, \quad (4)$$

where the index α accounts for the fact that proton luminosity may not scale linearly with X-ray luminosity, in the sense that most of the energetic protons can be produced by the most powerful flares, whereas heating of stellar coronae can essentially be related to less powerful but more frequent flares. The relationship between X-ray luminosity and accelerated proton fluence has been discussed several times for the young Sun to address the role of energetic processes in the early solar system (e.g. Lee et al. 1998; Feigelson et al. 2002; Gounelle et al. 2006). In these studies, the proton luminosity in the young solar nebula is inferred from X-ray observations of stellar analogs of the pre-main sequence Sun. The mean characteristic X-ray luminosity of these objects is measured to be $L_X \sim 2 \times 10^4 \, L_X^{\odot}$ and the proton luminosity is estimated to be $L_{\rm p}(\geq 10 \text{ MeV}) \sim 3 \times 10^6 \, L_{\rm p}^{\odot}(\geq 10 \text{ MeV})$. This corresponds to $\alpha \sim 1.5$. Feigelson et al. (2002) have argued that such a nonlinearity is reasonable because the frequency distribution of solar proton events as a function of energy, $\mathrm{d}N/\mathrm{d}E \propto E^{-1.15}$, is significantly flatter than that of X-ray events, $\mathrm{d}N/\mathrm{d}E \propto E^{-1.6} - E^{-1.8}$.

The total luminosity of the Sun's corona in the *ROSAT*/PSPC band (0.1−3 keV) ranges from $\approx 2.7 \times 10^{26}$ erg s^{-1} during the quiet phase to $\approx 4.7 \times 10^{27}$ erg s^{-1} during maximum phase (Peres et al. 2000). We use the average solar luminosity $L_X^{\odot} \simeq 10^{27}$ erg s^{-1}.

Equations (2)−(4) allow to estimate the time-dependent luminosity of flare-accelerated protons for any Pop I, main-sequence star in the color range $0.5 < B-V < 0.6$ given its initial rotation period $P_{\rm ZAMS}$. As discussed above, this estimate is expected to be valid to first order to Pop II stars in the same color range as well. Clearly, the relation between the flare-accelerated proton luminosity and the coronal X-ray luminosity (Eq. (4)) is the most uncertain step of the model, due to our lack of knowledge of the heating and particle acceleration processes at work in stellar flares.

Figures 2a and b show the evolution of ^{6}Li/H abundance ratios as the function of stellar age calculated from Eq. (1). For these figures, the calculations assume no ^{6}Li depletion ($\lambda_{\rm D} = 0$) and no presence of protostellar ^{6}Li (for example of cosmic-ray origin) in the stellar atmospheres (see below). We took $M_{\rm cz}$ from the evolutionary models of MPHSs calculated by Richard et al. (2002, Fig. 1). The age for the beginning of the main sequence, $t_{\rm ZAMS}$ in Eq. (3), is also from Richard et al. (2002). The dependence of $M_{\rm cz}$ on stellar mass and metallicity can be seen in Fig. 2a, where the ^{6}Li production is calculated for $P_{\rm ZAMS} = 1$ day and $\alpha = 1.5$. We see that the ^{6}Li/H ratio increases with increasing stellar mass, because the SCZ becomes shallower. For example, in going from $M_* = 0.7$ to 0.8 $M_{\odot}$ for [Fe/H] = −2.31, $M_{\rm cz}$ near turnoff is reduced by a factor of ∼50. The ^{6}Li/H ratio also increases with decreasing [Fe/H], because the SCZ also becomes shallower as the metallicity is reduced (Richard et al. 2002; see also Deliyannis & Malaney 1995).

Figure 2b shows the dependence of ^{6}Li production on α and $P_{\rm ZAMS}$. The ^{6}Li synthesis by flares is less important for $\alpha = 1$ than for $\alpha = 1.5$, because the average proton luminosity is lower in the former case. The time evolution of the ^{6}Li/H ratio is also very different for the two values of α. For $\alpha = 1$, ^{6}Li/H is strongly increasing near turnoff as $M_{\rm cz}$ becomes shallower. The production of ^{6}Li during the early main sequence is more important for $\alpha = 1.5$, because the luminosity of flare-accelerated protons is high enough to compensate the deeper SCZ. We also see that ^{6}Li production strongly depends on $P_{\rm ZAMS}$. For $P_{\rm ZAMS} = 1$ day, the ^{6}Li/H ratio reaches 5.3×10^{-12} and 2.8×10^{-11} at turnoff, for $\alpha = 1$ and 1.5, respectively. But for $P_{\rm ZAMS} = 5$ days, we have only $^6\mathrm{Li/H} \lesssim 3 \times 10^{-13}$. The latter value is below the sensitivity of the present ^{6}Li measurements, which are shown in Fig. 2c as a function of metallicity.

The data shown in this figure are from Asplund et al. (2006), Smith et al. (1998) and Cayrel et al. (1999). The data of Asplund et al. (2006) are often restricted in the recent literature on this subject (see e.g. Prantzos 2006) to the nine detections of ^{6}Li at $\geq 2\sigma$ confidence level. This procedure is valuable when the main concern is to discuss the existence of high ^{6}Li abundances even at low metallicity. But it would have introduced a strong bias in our subsequent statistical analysis, especially when analysing the dispersion of the data. In the definition of

[1] MPHSs probably have much lower X-ray luminosities than those given by Eq. (2) (see Ottmann et al. 1997), due to the fact that coronal X-ray emission is strongly dependent on metallicity, because, for coronal temperatures below $\sim 2 \times 10^7$ K, the bulk of X-ray radiation is emitted in lines from heavy elements. For MPHSs, this possibly lower X-ray luminosity is not an indication of lower surface magnetic fields.

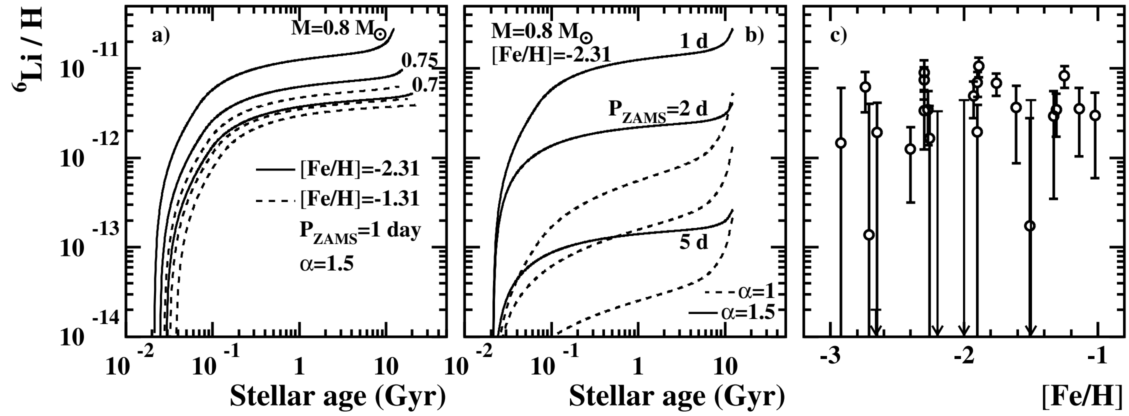

Fig. 2. a), b) Calculated evolution of ^{6}Li/H on the main sequence of MPHSs. The calculations assume that there is no ^{6}Li in the stellar atmospheres at the zero-age main sequence and do not take into account ^{6}Li depletion. Panel **a)** shows the dependence of predicted ^{6}Li/H on the star mass and metallicity, whereas panel **b)** shows the effects of changing $P_{\rm ZAMS}$ (Eq. (3)) and α (Eq. (4)). **c)** Observed ^{6}Li/H ratios as a function of metallicity. The data are from Asplund et al. (2006), Smith et al. (1998) and Cayrel et al. (1999). The downward-directed arrows correspond to 1σ upper limits, except for the star BD +09°2190 at [Fe/H] = −2.66, whose measured isotopic ratio is ^{6}Li/^{7}Li = −0.033 ± 0.027 (Asplund et al. 2006).

our sample, we thus kept all the measured ^{6}Li/^{7}Li ratios whatever their values. However, following Asplund et al. (2006), we excluded from their data the Li-rich star HD 106038, which has strong overabundances in Be, Si, Ni, Y and Ba, suggesting an enrichment by mass transfer from a companion star. We also did not take into account the relatively cool ($T_{\rm eff}$ = 5980 K) star HD 19445, whose mass ($M_* < 0.7\ M_\odot$) is significantly lower than that of the other stars observed by Asplund et al. (2006). As discussed by the authors, this metal-poor dwarf was only included in the observational program to provide a consistency check of the measurements, given that no significant ^{6}Li was expected to be detected. Smith et al. (1998) reported measurements of ^{6}Li/^{7}Li isotopic ratios with 1σ errors in nine single MPHSs. Among them, the four stars not observed by Asplund et al. (2006) were included in the data sample: HD 74000, HD 84937, BD +42°2667, and BD +20°3603. For HD 84937, however, we used the more accurate isotopic ratio measured by Cayrel et al. (1999): ^{6}Li/^{7}Li = 0.052 ± 0.019. In total, the sample contains 26 stars. The ^{6}Li/H ratios plotted in Fig. 2c were obtained by multiplying ^{6}Li/^{7}Li with the measured non-LTE Li abundances.

From a qualitative comparison between Figs. 2b and 2c, it can be anticipated that results of the model would not be excluded by the current data, provided the distribution of $P_{\rm ZAMS}$ for MPHSs includes both slowly ($P_{\rm ZAMS} \gtrsim 2$ days) and rapidly rotating stars during the early main sequence. To check further the validity of the model, one needs, however, to compare the data to predicted frequency distributions of ^{6}Li abundances in MPHSs.

3.2. Frequency distribution of ^{6}Li/^{7}Li ratios in MPHSs

Theoretical frequency distributions of ^{6}Li/H values were calculated using a Monte-Carlo method. We first generated cubes of ^{6}Li abundance values near turnoff using $P_{\rm ZAMS}$, M_* and [Fe/H] as axes of each cube. We assumed the age of the MPHSs to be ~13.5 Gyr (e.g. Richard et al. 2002). For the stars that are already on the subgiant branch at 13.5 Gyr, we used their turnoff age (Richard et al. 2002), which depends on M_* and [Fe/H]. Star samples with given distributions of rotation rate, mass and metallicity were then built by generation of the appropriate random numbers. The ^{6}Li surface abundance of each generated star was obtained from polynomial interpolation in the cubes. The calculated ^{6}Li/H values were finally binned to give the corresponding relative frequencies.

We estimated the statistical distribution of $P_{\rm ZAMS}$ from the study of Herbst & Mundt (2005). These authors have analyzed available data for the rotation period of ~500 pre-main sequence and early main sequence stars belonging to five nearby young clusters: the Orion nebula cluster, NGC 2264, α Per, IC 2602, and the Pleiades. They found that 50−60% of young main sequence stars of solar-like mass (0.4−1.2 $M_\odot$) are rapidly rotating ($P_{\rm ZAMS} \lesssim 2$ days). As discussed by Herbst & Mundt, these stars were probably released from any accretion disk locking mechanism very early on and thus conserved angular momentum throughout most of their pre-main sequence evolution. On the other hand, the remaining 40−50% stars that are more slowly rotating lost substantial amounts of angular momentum during their first million years, probably through interactions with their accretion disk. We approximated the observed bimodal distribution of stellar rotation period by two Gaussian distributions of equal weight, with means and standard deviations ($\mu_{\rm F}$ = 0.8 day; $\sigma_{\rm F}$ = 0.3 day) and ($\mu_{\rm S}$ = 4.3 days; $\sigma_{\rm S}$ = 2 days) for the fast and slow rotators, respectively. For the fast rotators, a cutoff was introduced at $P_{\rm ZAMS}$ = 0.2 day (Herbst & Mundt 2005).

It is likely, however, that the distribution of $P_{\rm ZAMS}$ in metal-poor Pop II stars has been different from that observed in Pop I stars, due to some metallicity effects in the process of star formation, e.g. a possible weakening of the magnetic coupling between the forming star and its surrounding with decreasing [Fe/H]. Such effects could lead to an enhancement of the fraction of rapidly rotating MPHSs in comparison with the proportions measured for their Pop I counterparts (see Maeder et al. 1999).

We assumed the mass distribution of the 26 single stars of the sample to be uniform between 0.7 and 0.8 $M_\odot$. This is the approximate mass range estimated by Asplund et al. (2006, see Fig. 6) for their star sample, using the evolutionary tracks calculated by VandenBerg et al. (2000).

Figure 3a shows calculated frequency distributions of flare-produced ^{6}Li abundances for 3 stellar metallicities: [Fe/H] = −2.92, −1.02 and −2.02. The first two values are the minimum and maximum measured metallicities of the data sample. The ^{6}Li/H distributions were obtained from the distributions of $P_{\rm ZAMS}$ and M_* discussed above, assuming α = 1.5 (Eq. (4))

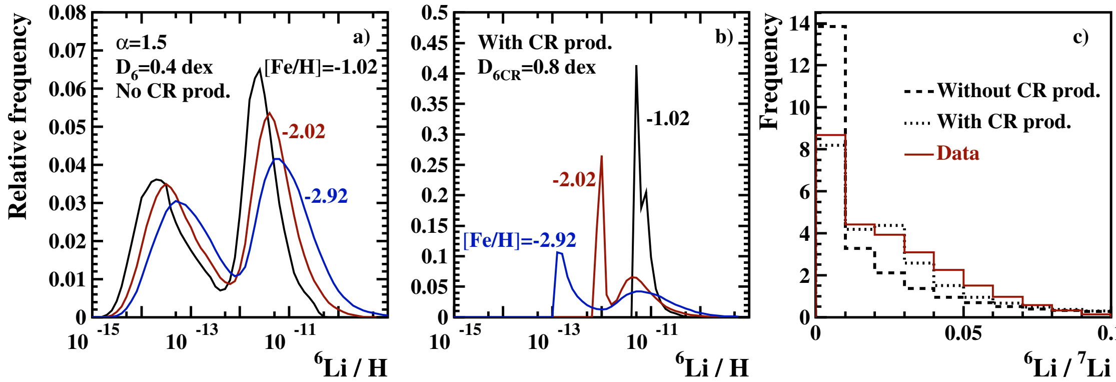

Fig. 3. Normalized frequency distributions of **a)** calculated ^{6}Li/H ratios for 3 values of [Fe/H] without cosmic-ray ^{6}Li production, **b)** the same but with a cosmic-ray ^{6}Li contribution, and *c)* calculated and observed ^{6}Li/^{7}Li ratios averaged over metallicity. The calculations assume α = 1.5 (Eq. (4)) and depletion factors for flare-produced and cosmic-ray produced ^{6}Li of 0.4 and 0.8 dex, respectively (see text).

and a constant ^{6}Li depletion factor for all stars, D_6 = 0.4 dex. This value is the approximate average of the main sequence depletion of ^{6}Li predicted from the so-called T6.09 turbulent diffusion model of Richard et al. (2002, 2005; see also Table 6 of Asplund et al. 2006). The bimodal character of the ^{6}Li/H distributions shown in Fig. 3a results from that of the $P_{\rm ZAMS}$ distribution. Thus, rapidly (slowly) rotating MPHSs produce ^{6}Li/H abundance ratios greater (lower) than $\sim 10^{-12}$. We also see in Fig. 3a that the predicted ^{6}Li distributions are shifted to higher values as the metallicity decreases. This is because the SCZ becomes shallower with decreasing [Fe/H] (see also Fig. 2a).

We have neglected up to now ^{6}Li production by galactic cosmic-ray (GCR) nucleosynthesis. However, the production of that light isotope by interaction of energetic nuclei in GCRs with the interstellar medium is well established (e.g. Reeves et al. 1970; Vangioni-Flam et al. 2000). In fact, galactic chemical evolution models show that ^{6}Li production by GCR interactions can exceed the observed ^{6}Li stellar abundances for metallicities [Fe/H] $\gtrsim -2$ (Rollinde et al. 2005; Prantzos 2006). This can be accounted for by significant ^{6}Li depletion at relatively high metallicities. In particular, the relatively low abundances measured by Nissen et al. (1999) in two galactic disk stars with [Fe/H] $\simeq -0.6$ (HD 68284 and HD 130551; ^{6}Li/H $\simeq 10^{-11}$) require a depletion of GCR-produced ^{6}Li by ~0.8 dex (Prantzos 2006). This depletion factor can result from a significant ^{6}Li depletion during the pre-main sequence (see Asplund et al. 2006, Table 6; Piau 2005), in addition to that occuring on the main sequence. We took into account the GCR-produced ^{6}Li from the galactic evolution curve shown in Fig. 3 of Prantzos (2006), assuming, for simplicity, a metallicity-independent depletion factor $D_{\rm 6CR}$ = 0.8 dex for all stars[2]. $D_{\rm 6CR}$ is higher than D_6, because of the additional depletion of GCR-produced ^{6}Li on the pre-main sequence. Calculated ^{6}Li distributions with the GCR contribution are shown in Fig. 3b. The three distributions now appear to be significantly different, as a result of the metallicity dependence of the GCR-produced ^{6}Li component. But we can see from a comparison between Figs. 3a and 3b that for [Fe/H] < -2, the GCR contribution does not significantly modify the flare-produced ^{6}Li/H distributions for the population of fast stellar rotators.

[2] The stellar evolution calculations of Richard et al. (2002, 2005) and Piau (2005) predict an increase of the ^{6}Li pre-main sequence depletion with increasing [Fe/H]. However, the pre-main sequence depletion factors are considered to be very uncertain (e.g. Proffitt & Michaud 1989) and it is sufficient for the scope of this paper to neglect the possible metallicity dependence of $D_{\rm 6CR}$.

In the comparison to the data, both experimental and theoretical ^{6}Li/^{7}Li ratios were averaged over the metallicity distribution. Although it necessarily limits the sensitivity of the test of the model, averaging over metallicity appears to be unavoidable for the test to be statistically significant, given the scarcity of the current data and the relatively large experimental uncertainties.

We show in Fig. 3c a comparison of observed and calculated frequency distributions. The data distribution takes into account the experimental errors. It was obtained by creating Gaussian distributions whose means were the measured isotopic ratios and whose standard deviations were the measured 1σ errors, and then summing them. The resulting distribution was then binned into a histogram using a bin width of 0.01, which is comparable to the experimental errors. For the data compatible with ^{6}Li/H = 0, the probabilities associated with potential negative values of ^{6}Li/H were taken into account when calculating the content of the first bin. The theoretical distributions were obtained by dividing the ^{6}Li abundances calculated for each generated MPHS (i.e. as a function of $P_{\rm ZAMS}$, M_* and [Fe/H]), by the estimated metallicity-dependent ^{7}Li content of that star. We used the univariate linear fit given by Asplund et al. (2006):

$$\log \epsilon_{^7{\rm Li}} = (2.409 \pm 0.020) + (0.103 \pm 0.010) \cdot [{\rm Fe/H}]\,, \quad (5)$$

where $\log \epsilon_{^7{\rm Li}} = \log(^7{\rm Li/H}) + 12$.

To test the null hypothesis that the ^{6}Li/^{7}Li data sample comes from a specific distribution calculated in the framework of the model, we used a generalization of the standard chi-square goodness-of-fit test. We chose for the test statistic the general χ^2 statistic given by Baker & Cousins (1984) for Poisson-distributed data:

$$\chi^2_\lambda = 2 \sum_i [(y_i - n_i) + n_i \ln(n_i/y_i)]\,, \quad (6)$$

where i is the ^{6}Li/^{7}Li bin number, y_i is the average number of stars predicted by the model with a given set of parameters to be in the ith bin, and n_i is the number of events in the ith bin from a given draw of 26 stars. The probability density function of χ^2_λ was constructed by generating random ^{6}Li/^{7}Li frequency distributions from a large number of samples of size $N_{\rm star}$ = 26, drawn from the population described by the model with the given set of parameters. The distributions were limited to the seven most significant bins for the test, i.e. ^{6}Li/^{7}Li $<$ 0.07. The experimental value, $\chi^2_{\lambda,\rm exp}$, was calculated from the data distribution using the same values of y_i (i.e. the same model parameters) as above. The result of the test was then obtain by deriving from the calculated probability density function the probability of observing a value $\chi^2_\lambda > \chi^2_{\lambda,\mathrm{exp}}$ (see Brandt 1976).

The corresponding probabilities without and with the cosmic-ray ^{6}Li production were found to be 34.7% and 99.8%, respectively. Thus, given the usual significance level of 5%, the null hypothesis "the considered ^{6}Li/^{7}Li data distribution is correctly described by the model with the given parameter values" must not be rejected when cosmic-ray ^{6}Li production is taken into account. When the contribution of GCR-produced ^{6}Li is not taken into account, the fraction of slowly rotating stars that produce ^{6}Li/^{7}Li ratios lower than 0.01 is too high to get a quantitatively good agreement with the data (Fig. 3c), even if the overall trend of the observed frequency distribution is reproduced. It is noteworthy that a strong discrepancy is observed between the data and the model when ^{6}Li is supposed to be only produced by GCR with a depletion of 0.8 dex. In that case, the probability for ^{6}Li/^{7}Li to be higher than 0.03 vanishes.

The statistical test described above can also be used to estimate confidence intervals for the model parameters. We studied in particular confidence limits for α (Eq. (4)). We found this parameter to be strongly correlated with the ^{6}Li depletion factor. For the extreme case $D_6 = 0$ (i.e. no depletion of flare-produced ^{6}Li) we obtained $\alpha > 1.2$ with a confidence level of 68% (i.e. 1σ). Thus, a necessary condition for the model to be valid is that the stellar-flare-accelerated proton luminosity does not scale linearly with the coronal X-ray luminosity.

4. Discussion

4.1. There is no ^{6}Li plateau

We have presented a model of ^{6}Li production by stellar flares that can explain the recent measurements of ^{6}Li in several MPHSs. We have shown that the measured ^{6}Li/^{7}Li frequency distribution can result from a combination of flare-produced ^{6}Li with a protostellar ^{6}Li component from GCR nucleosynthesis. This scenario implies a relatively large dispersion of the ^{6}Li/^{7}Li ratios, which is mainly due to variations in the ^{6}Li production of each star, rather than variations in the ^{6}Li depletion.

The good agreement observed between data and model predictions suggests a large scatter of observational ^{6}Li/^{7}Li ratios around mean value. In view of this, the existence of a "^{6}Li plateau" from the data of Asplund et al. (2006), as is almost always reported in the recent literature on this subject, appears highly questionable. We note that Asplund et al. themselves carefully caution that their ^{6}Li data do not necessarily imply the existence of a plateau given the observational scatter and the current sensitivity of the ^{6}Li abundance measurements. This wording is reminiscent of the well-known "Spite plateau" for ^{7}Li (Spite & Spite 1982), and thus suggests the same pregalactic origin for the two isotopes.

But we think that it is misleading and to further demonstrate this point, we performed a statistical test of the existence of the "^{6}Li plateau". The null hypothesis "there is a plateau" (i.e. a moderately tilted averaged linear dependence of ^{6}Li/H on metallicity with a small data dispersion around the mean value) was tested by performing a least squares linear regression to the data of Fig. 2c. From the obtained minimum χ^2, $\chi^2_{\mathrm{min}} = 37.4$ for 24 degrees of freedom, it can be concluded that the hypothesis "there is a plateau" can be rejected at the usual significance level of 5%. This high value of χ^2_{min} reflects a significant intrinsic scatter of the data ($\sigma_{\mathrm{obs}} = 3.44 \times 10^{-12}$ for a ^{6}Li/H mean value of 3.34×10^{-12}), when compared to the measurement errors. In comparison, the equivalent linear regression performed by Asplund et al. (2006) on ^{7}Li/H values indicates a very small scatter of 0.033 dex around the fit. We checked that similar results were obtained with our somewhat enlarged sample, with $\sigma_{\mathrm{obs}} = 1.51 \times 10^{-11}$ for a ^{7}Li/H mean value of 1.63×10^{-10}.

4.2. ^{6}Li production in young stellar objects

Young stellar objects (YSOs) are sites of very intense flares that are observed in X-rays. Recent observations of the Orion Nebula Cluster (ONC) with the *Chandra* satellite have shown that the X-ray activity of nonaccreting T Tauri stars (TTSs) is consistent with that of rapidly rotating main-sequence stars, while accreting TTSs are on average less X-ray active (Preibisch et al. 2005). These measurements suggest that a similar magnetic dynamo mechanism produces the X-ray activity in TTSs and main-sequence stars, although the correlation between X-ray activity and stellar rotation is not observed in pre-main sequence stars (Preibisch & Feigelson 2005; Preibisch et al. 2005). Magnetic field generation in YSOs may involve a turbulent convective dynamo that does not depend on rotation (Barnes 2003).

The flaring activity of YSOs is thought to be responsible for various high energy processes that are important for the formation of asteroids and planets (e.g. Feigelson & Montmerle 1999). In particular, irradiation of the inner accretion disk (the so-called "reconnection ring") by flare-accelerated ions can produce the relatively short-lived radionuclei ($T_{1/2} < 5$ Myr) that were present in the solar system when the calcium-aluminium-rich inclusions were formed (Lee et al. 1998; Gounelle et al. 2006, and references therein). In this scenario, the flare-accelerated particles are confined by magnetic fields that connect the star with the inner part of the accretion disk.

To obtain an upper limit on ^{6}Li production in YSOs, we assumed that all flare-accelerated particles are impinging on the stellar atmosphere, where they produce nuclear reactions in thick target interactions. The level of proton irradiation was estimated from Eq. (4), with $\alpha = 1.5$. We used for the mean characteristic X-ray luminosity of YSOs the fit as a function of stellar age obtained by Preibisch & Feigelson (2005) for ONC stars in the mass range 0.4–1 $M_\odot$:

$$\log L_{\mathrm{X}} = 30.25 - 0.32 \log\left(\frac{t}{10^6\ \mathrm{yr}}\right) \mathrm{erg\ s^{-1}}. \quad (7)$$

These X-ray observations were made with *Chandra* in the 0.5–8 keV energy band. The average solar luminosity in the same energy range is $\log L_{\mathrm{X}}^{\odot} \sim 26.1$ erg s^{-1} (see Peres et al. 2000).

The surface ^{6}Li abundance should be strongly diluted during the pre-main sequence, when the convection zones are deepest. We took the time evolution of M_{cz} in metal-poor YSOs from Deliyannis & Malaney (1995, Fig. 2). Using their results for [Fe/H] $= -2.3$ and $M_* = 0.8\ M_\odot$, which give the shallowest SCZ for $t \gtrsim 1$ Myr, we get from Eq. (1) with $\lambda_{\mathrm{D}} = 0$: ^{6}Li/H $= 4.2 \times 10^{-13}$ at $t = 10^7$ yr. The ^{6}Li abundance will be further depleted before the star reachs the turnoff region. Thus, production of spallogenic ^{6}Li during the pre-main sequence should not significantly contribute to the observed ^{6}Li abundances (see Fig. 2c).

4.3. ^{7}Li, Be and B production by stellar flares

Deliyannis & Malaney (1995) have proposed to use the ^{6}Li/Be and B/Be ratios in the MPHS HD 84937 to discriminate flare-produced ^{6}Li from ^{6}Li of protostellar origin. However, Lemoine et al. (1997) have pointed out that the amount of flare-produced Be and B should anyhow be negligible with respect to the amount of Be and B observed in this star.

Be and B are produced by spallation from C, N and O, whereas ^{6}Li is mainly produced by the interactions of accelerated ^{3}He and α-particles with atmospheric He (Sect. 2). The flare-produced Be/^{6}Li and B/^{6}Li ratios are thus proportional to the star metallicity. For the accelerated particle spectral index $s = 4$, we find the following yield ratios (see Fig. 1):

$$\frac{Q(\mathrm{Be})}{Q(^6\mathrm{Li})} = 3.5\times10^{-3}\frac{Z}{Z_\odot} \text{ and}$$
$$\frac{Q(\mathrm{B})}{Q(^6\mathrm{Li})} = 0.10\frac{Z}{Z_\odot}, \quad (8)$$

where $Z/Z_\odot = 10^{[\mathrm{Fe/H}]}$. The observed limit $^6\mathrm{Li/H} < 2\times10^{-11}$ (see Fig. 2c) implies for the flare-produced Be and B abundances:

$$\left(\frac{\mathrm{Be}}{\mathrm{H}}\right)_{\mathrm{Flare}} < 7\times10^{-14}\frac{Z}{Z_\odot} \text{ and}$$
$$\left(\frac{\mathrm{B}}{\mathrm{H}}\right)_{\mathrm{Flare}} < 2\times10^{-12}\frac{Z}{Z_\odot}. \quad (9)$$

These limits should be compared with the Be and B abundances measured in MPHSs. It is well-known that these abundances are both approximately proportional to $Z/Z_\odot$. The following fits to the data have been obtained (see Boesgaard et al. 1999 for Be, Duncan et al. 1997 for B):

$$\frac{\mathrm{Be}}{\mathrm{H}} \simeq 4\times10^{-11}\frac{Z}{Z_\odot} \text{ and}$$
$$\frac{\mathrm{B}}{\mathrm{H}} \simeq 6\times10^{-10}\frac{Z}{Z_\odot}. \quad (10)$$

Thus, the amounts of Be and B produced in flares should always be negligible as compared with the observed abundances, as Lemoine et al. (1997) already showed for HD 84937.

This conclusion holds true for ^{7}Li as well. For $s = 4$, we calculate that independently of metallicity $Q(^7\mathrm{Li}) = 0.45Q(^6\mathrm{Li})$ (Fig. 1). The measured isotopic ratios ^{6}Li/^{7}Li are <0.1 (Fig. 3c). Thus, if ^{6}Li and ^{7}Li are similarly depleted during the main sequence (Richard et al. 2005), flares should contribute less than a few percent to the ^{7}Li content of MPHSs.

4.4. Observational tests of the model

Flare-produced ^{6}Li is most likely to be observed in active MPHSs having a relatively thin SCZ on the main sequence. The mass M_{cz} of the SCZ during the main sequence and at turnoff is a decreasing function of the stellar effective temperature T_{eff} (e.g. Richard et al. 2002). Thus, as discussed by Deliyannis & Malaney (1995), we expect to observe an increase of ^{6}Li/^{7}Li as a function of T_{eff}. Such a relationship, however, is also expected from stellar depletion of protostellar Li (Richard et al. 2005; Deliyannis & Malaney 1995). Thus, even if a large database of Li measurements in MPHSs could allow one to identify a dependence of ^{6}Li/^{7}Li on T_{eff}, which is not the case with the current data, this would not allow one to unambiguously discriminate between flare-produced and protostellar ^{6}Li.

Deliyannis & Malaney (1995) have proposed more specifically to use ^{6}Li/^{7}Li as a function of T_{eff} on the subgiant branch, in the temperature range 6000−6600 K. They argued that if ^{6}Li is produced by flares, ^{6}Li/^{7}Li should decrease with decreasing T_{eff} because of the increasing M_{cz} past the turnoff, whereas the same ratio should be constant if ^{6}Li is of protostellar origin, because the preservation region of protostellar ^{6}Li in subgiant MPHSs is expected to be larger than the SCZ. However, Lemoine et al. (1997) have questioned the reliability of this observational test, which strongly depends on the adopted stellar physics. In particular, stellar-evolution models including diffusion and turbulent mixing (Richard et al. 2005; Korn et al. 2006) may not predict the same ^{6}Li/^{7}Li vs. T_{eff} relationships.

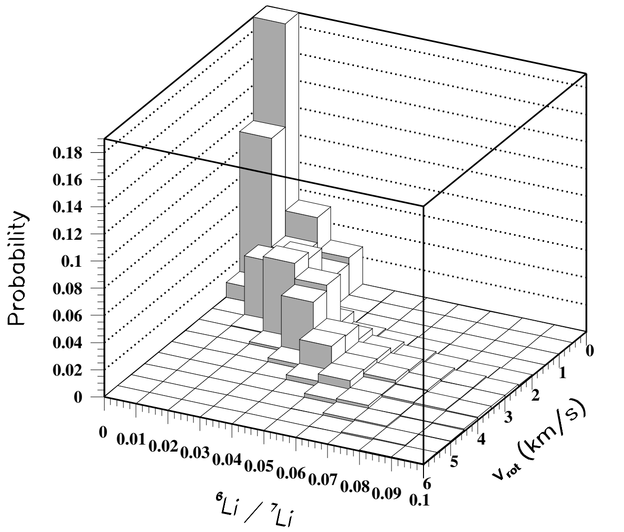

Fig. 4. Double differential probability distribution showing the correlation expected between ^{6}Li/^{7}Li and the stellar rotation velocity. The calculations were performed with $\alpha = 1.5$, $D_6 = 0.4$ dex and $D_{6\mathrm{CR}} = 0.8$ dex.

A more powerful observational test might be provided by the correlation expected between the abundance of flare-produced ^{6}Li and the stellar rotation velocity, which is probably one of the best indicators of the level of flaring activity that the stars experienced during their main sequence evolution. To study this relationship, we introduced the equatorial rotation velocity of each generated star into our Monte-Carlo simulation,

$$v_{\mathrm{rot}} = \frac{2\pi R_*}{P_{\mathrm{rot}}}, \quad (11)$$

where the stellar radius R_* at $t \sim 13.5$ Gyr was obtained from the Dartmouth stellar evolution code developed by Chaboyer et al. (2001) and Guenther et al. (1992)[3], and the rotation period P_{rot} was estimated from Eq. (3). We remind the reader that Eq. (3) only provides a first-order description of the rotation period evolution during the main sequence (see Krishnamurthi et al. 1997; Piau 2005). Figure 4 shows a calculated distribution of stars as a function of ^{6}Li/^{7}Li and v_{rot}. We used the same parameters as before: $\alpha = 1.5$, $D_6 = 0.4$ dex and $D_{6\mathrm{CR}} = 0.8$ dex (see Fig. 3c). We see that, on average, ^{6}Li/^{7}Li increases with increasing v_{rot}. Thus, the calculated mean isotopic ratio is $^6\mathrm{Li}/^7\mathrm{Li} = 0.012$ for $0 < v_{\mathrm{rot}} \le 2$ km s^{-1} and $^6\mathrm{Li}/^7\mathrm{Li} = 0.045$ for $2 < v_{\mathrm{rot}} \le 4$ km s^{-1}.

We did not take into account in these calculations the possible dependence of Li depletion with stellar rotation. Stellar-evolution models with rotationally-induced mixing predict that ^{6}Li depletion increases faster than ^{7}Li depletion with increasing rotation rate (Pinsonneault et al. 1999). This effect could lead to a reduction of the ^{6}Li/^{7}Li ratio with increasing v_{rot}.

Asplund et al. (2006) have derived the projected rotation velocity $v_{\mathrm{rot}} \sin i$ of 18 MPHSs from an analysis of several spectral

[3] See also URL `http://stellar.dartmouth.edu/~evolve/`

lines using 3D LTE model atmospheres. The derived $v_{\rm rot} \sin i$ values range from 0.4 to 3.8 km s^{-1}. These high estimated $v_{\rm rot} \sin i$ values would help the flare model for the origin of ^{6}Li. However, as discussed by Asplund et al., it is possible that part or all of the estimated rotational velocities are spoilt by systematic uncertainties due to the adopted stellar parameters for the 3D models. We note also that the expected correlation should be more difficult to identify with the *projected* rotation velocity $v_{\rm rot} \sin i$, which of course is lower than the true $v_{\rm rot}$ used in Fig. 4.

The relationship between Li abundance and stellar rotation can be more easily investigated in young Pop I stars, which have larger rotational velocities. Observations of dwarf stars in young open clusters (Soderblom et al. 1993; García-López et al. 1994; Randich et al. 1998) and in the solar neighbourhood (Cutispoto et al. 2003) have shown than the largest Li abundances are found in rapidly rotating stars with the strongest chromospheric emission. These observations are not explained 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 (e.g. Charbonnel et al. 1992; Pinsonneault 1997; Piau & Turck-Chièze 2002). As discussed in Randich et al. (1998), it is possible that rapidly rotating, young stars deplete less Li because they undergo little angular momentum loss and transport, and hence little rotationally-driven mixing, until they reach the ZAMS. The observed correlation between $\log \epsilon_{\rm Li}$ and $v_{\rm rot} \sin i$ could also be partly due to stellar activity phenomena that may not be properly taken into account in Li abundance measurement (Cutispoto 2002; Xiong & Deng 2005). However, Li production by flares could also play a role, although the SCZs of these young stars are relatively deep. Our calculations show that the high Li abundances found in the fast rotating stars (Li/H $\sim 10^{-9}$) could be produced in flares, only if the spallogenic Li is not too rapidly diluted into the bulk of the SCZs. A large fraction of these Li atoms would then be ^{6}Li.

5. Summary

We have developed a model of light element production by stellar flares that can explain the recent observations of ^{6}Li in several MPHSs near turnoff, thus avoiding the need for a significant pregalactic source of this isotope. We have shown that ^{6}Li could be mostly produced by the reaction ^{4}He(^{3}He, p)^{6}Li, if, as in solar flares, energetic ^{3}He nuclei are strongly enriched by a stochastic acceleration process.

The model is based on our current knowledge of the flaring activity of Pop I dwarf stars. Assuming for these high-metallicity objects a power-law relationship between the luminosity of flare-accelerated protons and the coronal X-ray luminosity, and using a well-established dependence of the X-ray luminosity on stellar rotation and in consequence on age, we have constructed a simple time-dependent model for the average power contained in stellar-flare accelerated particles. We then have used this flaring-activity parameter to model the production of ^{6}Li in the atmospheres of MPHSs.

Theoretical frequency distributions of ^{6}Li/^{7}Li in MPHSs near turnoff were calculated using a Monte-Carlo method and compared with the data of Smith et al. (1998), Cayrel et al. (1999) and Asplund et al. (2006). We took into account protostellar ^{6}Li produced by GCR nucleosynthesis as an additional contribution, which is only significant in stars of [Fe/H] > -2. Excellent agreement was found with the measured ^{6}Li/^{7}Li distribution.

Both stellar depletion factors for flare-produced and cosmic-ray produced ^{6}Li were treated in a first approximation as metallicity-independent parameters. The average values of these parameters were estimated from the stellar-evolution calculations of Richard et al. (2002, 2005). Prantzos (2006) has argued that if a pre-galactic source of protostellar ^{6}Li is to explain the abundances measured in the lowest metallicity stars, the unavoidable contribution of GCR-produced ^{6}Li at [Fe/H] > -2 implies the existence of a "fine-tuned and metallicity-dependent depletion mechanism". This "fine-tuning" is relaxed in the flare model, because the flare-produced ^{6}Li component is less dependent on metallicity and less depleted than the protostellar ^{6}Li contribution from the GCR.

An observational signature of the flare model will be difficult to obtain. We propose to seek for a positive correlation between ^{6}Li/^{7}Li and stellar rotation velocity. We hope that the current development of 3D model atmospheres will allow accurate measurements of the projected rotation velocities of many MPHSs. The predicted increase of ^{6}Li/^{7}Li as a function of $v_{\rm rot}$ is not expected in models of MPHSs that include rotational mixing and Li depletion (Pinsonneault et al. 1999).

Further improvements in the model would be necessary to make more detailed predictions realistic. Such improvements rely on advances in our understanding of physical processes underlying stellar rotation and flaring activity, as well as more high-quality measurements of Li isotopic abundances in both Pop I and II stars.

We have shown that the amounts of ^{7}Li, Be and B produced in flares should always be negligible as compared with the observed abundances of these species in MPHSs. ^{6}Li may provide a unique tool to study the nuclear processes occuring in stellar flares.

Acknowledgements. We would like to thank Mike Harris for fruitful discussions and his constructive comments on the manuscript. We are also indebted to Elisabeth Vangioni, Alain Coc, Jürgen Kiener, Matthieu Gounelle, and Nikos Prantzos for extremely helpful conversations. We finally acknowledge a very valuable discussion with Martin Asplund on the ^{6}Li data.

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