ON NONPRIMORDIAL DEUTERIUM PRODUCTION BY ACCELERATED PARTICLES

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ABSTRACT

Deuterium plays a crucial role in cosmology because the primordial D/H abundance, in the context of big bang nucleosynthesis (BBN) theory, yields a precise measure of the cosmic baryon content. Observations of D/H can limit or measure the true primordial abundance because D is thought to be destroyed by stars and thus D/H monotonically decreases after BBN. Recently, however, Mullan & Linsky have pointed out that D arises as a secondary product of neutrons in stellar flares that then capture on protons via \( n + p \rightarrow d + \gamma \) and that this could dominate over direct D production in flares. Mullan & Linsky note that if this process is sufficiently vigorous in flaring dwarf stars, it could lead to significant non-BBN D production. We have considered the production of D in stellar flares, both directly and by \( n \) capture. We find that for reasonable flare spectra, \( n/d \lesssim 10 \) and \( (n + d)/6^{\text{Li}} \lesssim 400 \), both of which indicate that the \( n \)-capture channel does not allow for Galactic D production at a level that will reverse the monotonic decline of D. We also calculate the 2.22 MeV gamma-ray line production associated with \( n \) capture and find that existing COMPTEL limits also rule out significant D production in the Galaxy today. Thus, we find that flares in particular and neutron captures in general are not an important Galactic source of D. On the other hand, we cannot exclude that flare production might contribute to recent Far Ultraviolet Spectroscopic Explorer (FUSE) observations of large variations in the local interstellar D/H abundance; we do, however, offer important constraints on this possibility. Finally, since flare stars should inevitably produce some \( n \)-capture events, a search for diffuse 2.22 MeV gamma rays by \textit{INTEGRAL} can further constrain (or measure!) Galactic deuterium production via \( n \)-capture.

\textit{Subject headings:} cosmology: theory — gamma rays: theory — nuclear reactions, nucleosynthesis, abundances — stars: flare

\textit{On-line material:} color figure

1. INTRODUCTION

In the past two decades big bang nucleosynthesis (BBN) has become one of the most important cosmological probes (Olive, Steigman, & Walker 2000 and references therein). Its success lies in the good agreement of predictions for the abundances of four light elements D, \(^3\text{He}, \(^4\text{He}, \) and \(^7\text{Li}\) with their observations. A key element is deuterium, which is considered to be the best cosmic "baryometer" among the light elements (Schramm & Turner 1998) because of its strong dependence on the baryon density, or equivalently, the baryon-to-photon ratio \( \eta \). Furthermore, now that the cosmic microwave background anisotropy measurements of \textit{WMAP} have independently measured \( \eta \) to high precision (Spergel et al. 2003), D takes a new role as a probe of both early universe physics and astrophysics (Cyburt, Fields, & Olive 2002, 2003). Therefore, it is crucial that we fully understand the evolution of deuterium after BBN, in order to correctly infer the primordial abundance from observations in the \( z \ll 10^{10} \) universe.

Key to D is that there is no significant astrophysical production site except for the big bang and that stars destroy D in their fully convective, pre-main-sequence phase (Bodenheimer 1966). Together, these guarantee that any measurement of D is a solid lower bound on the primordial abundance and that in sufficiently primitive environments D should be essentially primordial. The lack of astrophysical D production was established in the classic paper by Epstein, Lattimer, & Schramm (1976, hereafter ELS), who considered all known sites in which \textit{any} nucleosynthesis occurs and demonstrated that none of these produce D in significant quantities.

Deuterium is observed in diverse astrophysical settings. In high-redshift (\( z \sim 3 \)) QSO absorption systems, neutral D is observed. The five best systems (Burles & Tytler 1998a, 1998b; O'Meara et al. 2001; Kirkman et al. 2003; Pettini & Bowen 2001) give \( (D/H)_{\text{QSOALS}} = (2.78 \pm 0.29) \times 10^{-5} \). The D abundance in solar nebula is inferred from solar wind observations of \(^3\text{He}\) (which measure presolar D.+\(^3\text{He}\)) minus meteoritic determinations of \(^3\text{He}\) alone. These give (Geiss & Gloeckler 1998) a value \( (D/H)_{\text{presolar}} = (2.1 \pm 0.5) \times 10^{-5} \), which probes protosolar material 4.6 Gyr ago, or at \( z \sim 0.4 \). D/H is also observed (Rogerson & York 1973; Linsky et al. 1993) in the local interstellar medium (ISM); recent \textit{Far Ultraviolet Spectroscopic Explorer (FUSE)} observations (Moos et al. 2002) give \( (D/H)_{\text{ISM}} = (1.52 \pm 0.08) \times 10^{-5} \) in the Local Bubble today, at \( z = 0 \).

The central ELS argument—that the big bang is the sole source of D—has stood the test of time, borne out by the drop in D/H from its high-redshift to presolar to local ISM abundances. But given the crucial role of D in cosmology, it is important to carefully examine the assumptions made and to identify any possible loopholes. Moreover, such an effort becomes crucial in light of growing evidence that D/H has large variations over short distances in the local ISM. Recent \textit{FUSE} observations (Hoopes et al. 2003) add weight to earlier suggestions (Vidal-Madjar 2001 and references...
therein) that D/H can vary by as much as a factor of 2 over different lines of sight, pointing to inhomogeneities on scales $\gtrsim 100$ pc.$^1$

Such a reanalysis of ELS was recently carried out by Mullan & Linsky (1999, hereafter ML). Specifically, they discussed D production by suprathermal energetic particles in flare stars. Although ELS had considered flare production, ML note that ELS had neglected flare production of neutrons, which can then go on to produce D via radiative capture onto a proton,

$$n + p \rightarrow d + \gamma,$$  

with the emission of a photon with energy $E_\gamma = 2.233$ MeV. ML do not make a detailed calculation of $n$ yields from spallation reactions, but note that $n$ production can be large compared with direct $d$ production, depending on the energetic particle spectra. ML then suggest that D created in such a way can escape from the flare site into the stellar wind. Also, because of its low-mass D might be preferentially ejected relative to the heavier Li, Be, and B, which would otherwise contaminate the ISM. ML thus raise the possibility that flares could be a significant source of D in the Galaxy. From the point of view of Galactic chemical evolution, this mechanism might then explain some or all of the ISM variation in D. Moreover, from the point of view of cosmology, the chance of significant D production would call into question the ELS argument, which underlies the recent spectacular agreement between high-redshift D/H measurements and the predictions of BBN with the WMAP baryon density.

Thus, the ML scenario has important implications and deserves careful further examination. In this paper we expand the analysis of ELS to include the $n$ channel for D production suggested by ML. Our approach is to identify general nuclear physics constraints that follow from detailed calculations of $n$, $d$, and gamma-ray production by energetic particles. The result is to close this loophole; i.e., we show that flare D production is not sufficient to offset the monotonic decline of D with time. However, flare D production should occur at some level, and we find that gamma-ray observations by the recently launched INTEGRAL mission may be able to probe this process.

### 2. LIGHT-ELEMENT PRODUCTION BY FLARES

Flares are violent releases of magnetic energy during which matter reaches temperatures of tens or hundreds of million kelvin and particles get accelerated to very high energies. They are associated with active stellar regions (Haisch, Strong, & Rodono 1991). Nuclear reactions then occur between flare-accelerated particles and the ambient stellar atmosphere. In this section we discuss spallation reactions that result in production of neutrons, deuterium, and lithium. We show that as a result of spallation, $1 \leq n/d \leq 10$ for most spectral indexes, which means that ML channel is indeed more important than channels considered by ELS, confirming and quantifying the suggestion of ML. However, we see that even including this channel for $d$ production, the concomitant Li production remains large and thus severely constrains the possibility that flares are an important source of D.

#### 2.1. Formalism

Nuclide production in flares depends on the initial spectrum of the flare, its modification as it interacts with the stellar atmosphere, and the compositions of the flare and the atmosphere. In general, the nucleosynthesis yields in flares have a complicated time dependence. Fortunately, there are two limiting approximations for energetic particles in flares: the thin-target and thick-target models (Ramaty & Lingenfelter 1975). In the thin-target model, particle production is assumed to occur before the spectrum of accelerated particles is modified by ionization energy losses. On the other hand, in the thick-target model, energy losses are taken to be large and the particles slow because of ionization losses as they move downward form the flare region, prior to nuclear interactions.

But are both of these scenarios equally important for flare processes? A simple analysis of the mean free path of projectile particles sheds light on this question. The mean free path of projectiles against nuclear interactions is

$$\lambda = \frac{1}{n\sigma},$$

where $n$ is the target number density and $\sigma$ is the reaction cross section, while mean free path of a flare particle (charge $Z$, mass number $A$) that is losing energy because of its interaction with the surrounding medium is given by

$$\lambda_\epsilon = \frac{A}{Z^2} \frac{R_p(\epsilon)}{nm_p}.$$  

Here $\epsilon$ is the projectile energy per nucleon, $n$ stands for the number density of the medium, $\sigma$ is the cross section for a reaction of interest, $m_p$ is the proton mass, and $R_p(\epsilon)$ is the ionization energy loss range of protons in units of g cm$^{-2}$. In the thin-target limit $\lambda \ll \lambda_\epsilon$, which puts a lower limit on the projectile range,

$$R_p(\epsilon) \gtrsim 167 \frac{Z^2}{A} \left( \frac{\sigma}{10 \text{mbarn}} \right)^{-1} \text{g cm}^{-2},$$  

For low energies, $R_p(\epsilon) \approx 4 \times 10^{-4}$ g cm$^{-2} (\epsilon \text{ MeV}^{-1})^2$, so that equation (4) implies that the thin-target approximation holds for energies

$$\epsilon \gtrsim 600 \sqrt{\frac{Z^2}{A}} \text{ MeV nucleon}^{-1}.$$  

This energy is much larger than those of typical flare particles. Thus, we conclude that the thick-target approximation is well satisfied and is the appropriate one for flare processes. This result, based on the physics of particle propagation, is in agreement with the empirical result of Ramaty, Lingenfelter, & Kozlovsky (1982), who found that flare data are best described by thick-target rather than thin-target models.

In the thick-target model, the production of secondary particles of species $l$ from reaction $i + j \rightarrow l + \ldots$ is given by

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$^1$ More observations are needed to firmly establish the nature and degree of D variations and their (anti)correlations with metallicity (Steigman 2003). Nevertheless, it is already clear that FUSE is opening new windows on the Galactic and local evolution of deuterium; this in turn motivates a careful reexamination of the basic ELS assumptions that have guided our thinking on these issues.
\[ Q_l = y_i y_j \int_{v_{th}}^{\infty} \frac{\sigma_p(v)}{m} \frac{dR_i}{dv} dv \int_{v}^{\infty} \sigma_p(e') \frac{dN_p(e')}{dv} dv, \]  

(6)

where \( Q_l \) is the total number of secondary particles produced per incident flare particle and \( \epsilon_{th} \) is the threshold energy for a particular reaction. The ambient number density of target species \( j \) is \( n_j \), and \( \sigma_{ij} \) is the cross section for the reaction of interest. Projectile and target abundances are given as numbers relative to hydrogen: \( y_i = n_i/n_p \); these are used to compute the mean target mass

\[ \langle m \rangle \approx m_p \sum_i A_i y_i / \sum_j y_j = 1.4 m_p. \]

The projectile and target compositions are poorly known for flare stars, but one can imagine several possibilities. Since solar flares show enhanced metals and helium relative to hydrogen (Mandzhavidze, Ramaty, & Kozlovsky 1999), one might expect similar enrichment for flare stars. On the other hand, one expects M dwarfs in general to have metallicities similar to those of G or K dwarfs (Wyse & Gilmore 1995; Kotoneva et al. 2002) and thus on average to be subsolar in metallicity. Thus we examine several possible compositions and find the impact of composition on spallation production. For a fiducial case, we assume solar abundances (Anders & Grevesse 1989) for both projectiles and targets. We then examine the effect of more extreme variations: a fivefold increase in metals and helium, as in solar flares, and a metal-free primordial case.

The spectrum \( N_i(e) \, de \) measures the total number of projectile particles with energy in \((e, e + de)\). Following Ramaty & Lingenfelter (1975), we adopt the power-law form

\[ N_p(e) = k_p e^{-s}, \]

\[ N_i(e) = y_i N_p(e), \]

(7)

(8)

where \( k_p \) is the constant determined by normalizing \( N_p \) to 1 proton of energy greater than \( \epsilon_0 = 30 \text{ MeV} \) and \( s \) is the spectral index, which is assumed to be the same for all accelerated particles. The choice of this particular spectrum normalization is purely conventional (see, e.g., Ramaty & Lingenfelter 1975), but in any case it will not matter in our analysis since we are interested only in ratios of productions of different particle species and the normalization will drop out.

In addition to the particle compositions, the spectral index \( s \) is the other key parameter for the results we present. We present results for a range of \( s \), but some observations exist that constrain its value. For solar flares, Ramaty, Mandzhavidze, & Kozlovsky (1996) find that gamma-ray line ratios in an ensemble of flares point to a range of spectral indexes of about \( s = 4 \pm 1 \). For flare stars themselves, information on the spectra of the ions is not available, but radio data from electron synchrotron emission points to electron spectra with \( s_e \approx 2-3 \). Whether the ions should have the same indexes is, however, unclear. In the case of the Sun, Lin, Mewaldt, & van Hollebeke (1982) find that electron spectral indexes (for \( E_e < 100 \text{ keV} \)) are correlated with proton indexes, but with \( s_e = 2 \) corresponding to \( s \approx 4 \); they find no significant correlation for \( E_e > 200 \text{ keV} \). These results hint that the ion spectral indexes in flare stars may also prefer \( s \approx 4 \), but this parameter remains uncertain.

The particle ionization energy loss is measured by

\[ \frac{d\epsilon}{dR} = \frac{|d\epsilon/dt|}{\rho v}, \]

(9)

with units of \([\text{MeV/(g cm}^{-2}])\), where \( v \) is the velocity of the incident particle. We adopt the usual Bethe-Bloch energy formula (Bethe 1930)

\[ \frac{d\epsilon}{dR} = \frac{4\pi z^2 e^4}{A(m_\text{v})_v^5} \left[ \ln \left( \frac{2\gamma^2 m_\text{v}^2}{I} \right) - \frac{\epsilon^2}{\gamma^2} \right]. \]

(10)

In this equation \( Z \) is the charge of the projectile, \( z \) is number of electrons per atom (approximately equal to 1 in the solar atmosphere), \( A \) is the number of nucleons of projectile, \( m_\text{v} \) is electron mass, and the mean excitiation potential is the value for hydrogen, \( I = 13.6 \text{ eV} \).

Table 1 lists the reactions we have included, their lab-frame threshold energies, and references for the cross sections. We note here that cross sections for deuterium production via \( \alpha + \alpha \rightarrow D + \ldots \) are unavailable. To make an estimate of deuterium production via \( \alpha \alpha \alpha \) reactions, we use exponential fit of Mercer et al. (2001) to the cross sections for \( \alpha + \alpha \rightarrow D + ^6\text{Li} \), the channel with the lowest threshold, and ignore other possible final states (4d, 6d4He). Also, the only existing cross sections for \( \alpha + C \) and \( \alpha + O \) production of deuterium are given for the single energy \( E_0 = 58 \text{ MeV} \), or \( \epsilon_0 = 14.5 \text{ MeV nucleon}^{-1} \) (Bertrand, Peelle, & Kalbach-Cline 1974). In this case we approximated the cross sections with

\[ \sigma(\epsilon) = \begin{cases} \sigma_0 e^{-2\eta \epsilon} & \epsilon > \epsilon_{th}, \\ 0 & \epsilon \leq \epsilon_{th}, \end{cases} \]

(11)

where \( \sigma_0 \) is normalized to experimental values (Bertrand et al. 1974) and the Gamow factor \( \eta = z_\text{C} \epsilon^2/\hbar c \beta \) accounts for the Coulomb barrier.
2.2. Results

Before we present our final results let us first make analytic estimates for couple of reactions for this model. In order to perform analytic estimates some approximations will be needed. To analytically solve thick-target case, we approximate energy losses via

\[ \frac{dR}{d\epsilon} = 0.14 \frac{Am}{2\pi Z^2 \epsilon} \frac{m_e}{\epsilon^2}. \]  

(12)

Let us also assume that a cross section for a particular reaction is flat and that we can neglect relativistic corrections, which is a valid assumption for low projectile energies. Therefore, equation (6) now has the following form:

\[ Q_l = 5.7 \times 10^{-4} \frac{\sigma}{(s-3) \epsilon^2} \left( \frac{\epsilon_{th}}{10 \text{ MeV}} \right)^2 \left( \frac{\epsilon_{th}}{\epsilon_0} \right)^{1-s} \]  

(13)

In Figure 1 we present our analytic estimates along with numerical results for deuterium production by \( p\alpha \), \(^6\text{Li} \) production by \( \alpha\alpha \), and neutron production by \( p\alpha \) reactions. The analytic result is calculated for the case of \( s = 4 \), which is the best choice given the assumptions that were made, while numerical results are functions of spectral index \( s \). Note that our results also include reactions where target and projectile species are interchanged (initial-state particle species can also serve as targets, since we assume that flares have the same composition as the ambient medium).

Although we made some rough estimates we see that they are in good agreement with our numerical predictions, which gives us confidence in our code.

Our numerical results for production of neutrons, deuterium, and \(^6\text{Li} \) are shown in Figure 2. Results are represented in the form of ratios of total numbers of particles produced in spallation as a function of the spectral index \( s \). The purpose of this was to see how neutron production compares with production of deuterium, since the key idea of ML paper was that a significant amount of neutrons can be produced via spallation, which can then undergo radiative capture to make a nonnegligible amount of deuterium. We see that indeed, \( n \approx d \approx 1 \), so that neutron production does in fact dominate direct \( d \) production for all spectral indexes \( s \). More specifically, \( n/d = 1 \) around \( s = 4 \), the best-fit value for solar flares, and can be as high as \( n/p = 200 \) for an extreme value of \( s = 7 \). These calculations thus confirm the suggestion of ML that in fact \( n \) production is significant compared with deuterium production, and thus radiative capture of the neutrons offers an important channel for deuterium synthesis, which had been neglected by ELS.

With the neutron production in hand, we can now update the ELS argument to address the ML loophole. The key
point here is that spallation production of $d$ and $n$ is also inevitably accompanied by production of other light elements, notably lithium. In particular, since $^6$Li is uniquely produced by spallative processes (Fields & Olive 1999; Vangioni-Flam et al. 1999), it offers the strongest constraint, as follows. Assume that all neutrons made in flares undergo radiative capture onto protons rather than suffering decay or nonradiative capture on $^3$He. We also assume that all $^6$Li in the ISM comes from flares, which maximizes the flare contribution. Then by using our $(n + d)/^6$Li ratio for the entire range of spectral indexes, $20 \lesssim (n + d)/^6$Li $\lesssim 1000$, combined with the solar $^6$Li/H $= 1.5 \times 10^{-10}$, we infer a flare-produced deuterium abundance in the range $3 \times 10^{-9} \lesssim D/H \lesssim 1.5 \times 10^{-7}$, much smaller than observed deuterium abundance. This limit would be further strengthened if we also note that a large fraction ($\gtrsim 50\%$) of neutrons escape the Sun or are captured onto $^3$He rather than on protons (Ramaty 1986). If $f_{np} \lesssim 0.5$ is the fraction of $n$ that do capture on protons, the correct ratio for $D/^6$Li is $(f_{np}n + d)/^6$Li $= (f_{np}n/d + 1)d/^6$Li, which lowers the total deuterium production by an additional $\sim 25\%$ for $n/d \sim 1$ and $f_{np} = 0.5$.

We can also go the other way. Assume that just 10% of observed ISM deuterium abundance comes from flares. Then from our $(n + d)/^6$Li ratio for all spectral indexes we get that $^6$Li/H abundance is in the range $1.5 \times 10^{-9} \lesssim ^6$Li/H $\lesssim 7.5 \times 10^{-8}$, which is between 1 and 2.5 orders of magnitude larger than the observed solar abundance of $^6$Li (where overproduction of about 300 corresponds to the spectral index most favored for solar flares). Thus we conclude that then we can rule out the ML loophole if flare spallation products escape with equal probability. This result updates and reaffirms the same conclusion by ELS.

However, many flare stars will have fewer metals and thus a different composition. For example, disk G and K dwarfs are known (Wyse & Gilmore 1995; Kotoneva, Flynn, Chiappini, & Matteucci 2002) to have a mean metallicity that is subsolar by about a factor of 2. What effect will this have on the production ratios and ultimately the revised ELS constraints? To get a sense for this, we follow ELS and repeat our calculation for the extreme limit of a primordial composition, i.e., where the flare and the ambient medium contain only $^4$He (with mass fraction 24.8%) and the balance is H. The difference here is that we exclude reactions involving CNO, but since Li can be made by $\alpha\alpha$ fusion, the $^6$Li constraint remains. In this case the $(n + d)/^6$Li ratio is in the range of $10 \lesssim (n + d)/^6$Li $\lesssim 30,000$, as shown in Figure 3a, thus placing the upper limit (for very low spectral indexes) on the expected deuterium abundance due to flares about an order of magnitude higher. Therefore we see that even in primordial environment the ELS constraint holds, especially since thick-target production ratios that we are discussing change only slightly around most favorable spectral index of $s \approx 4$.

Now, although our fiducial calculation is based on the solar abundances, the Sun itself shows a different and more enriched composition in flare projectiles and possibly targets. In solar flares, $^4$He/H can be as much as 5 times higher than in mean solar matter, in which case protons and $\alpha$ particles can be within a factor of 2 of each other by number; abundances of other heavy elements can also be similarly enhanced in flares (Mandzhavidze et al. 1999).
Therefore, one might wonder, how will our results change in that case? Figure 3b plots our results obtained as before, but this time for abundances that are 5 times greater than solar. However, even in this case our main conclusions stay the same: (1) the neutron channel for D production can dominate over spallation production of D, but not enough to be a significant source of nonprimordial D, and (2) the ELS constraint on $^6\text{Li}/\text{D}$ holds and indeed is the strongest in this case, since overproduction of $^6\text{Li}$ goes between 1 and 3 orders of magnitude. Therefore we see that by using a solar composition to describe flare processes, our constraints were in fact generous compared with this case.

Of course, ML note that it is possible that D escapes more readily than does Li because of its small mass. Clearly, the question of transport is complex, involving competing effects such as convection and mass loss. These difficult issues in magnetohydrodynamics are beyond the scope of this paper, but we can at least quantify the bias needed to avoid our updated ELS constraint. We saw that if interstellar D is due to flares, then $^6\text{Li}$ is overproduced by a factor that is about between 10 and 250. Thus, $^6\text{Li}$ mass loss must be suppressed relative to D by at least this factor in order for the ML loophole to remain open. While it is difficult to rule this possibility out (or in!), clearly this offers a strong quantitative constraint on the particle loss mechanism.

Thus, we strongly constrain the ML loophole, which now requires a strong bias against Li escape. But if such a bias could be created, is the ML loophole viable? To further explore that scenario, we turn to the 2.22 MeV gamma-ray line as an additional constraint on neutron captures in the Galaxy.

3. GAMMA-RAY LINE CONSTRAINTS ON FLARE PRODUCTION OF DEUTERIUM

In the previous section we have seen that analysis of particle production through spallation reactions does not completely answer the question of the amount of deuterium produced in stellar flares. For that reason we now approach this problem from a different angle. The reaction of radiative capture $n + p \rightarrow d + \gamma$, which was proposed to be potentially significant source of deuterium in ML paper, has as a result, besides deuterium, a 2.22 MeV gamma-ray line. Our idea is to predict the Galactic gamma-ray intensity of that line under the assumption that flares produce significant amounts of deuterium. That way, without going into details about mechanisms that can transport produced deuterium into the ISM, we can place an upper limit on nonprimordial deuterium production via radiative capture.

If we denote number of 2.22 MeV gamma-ray lines produced by a single flare with $N_\gamma$ and use $N_{\gamma}^{\text{tot}}$ to denote number of deuterium produced by the same flare in both radiative capture and spallation processes, then we can write

$$\frac{N_{\gamma}^{\text{tot}}}{N_n} = \frac{1}{f_{2.2}} \frac{N_n^{\text{tot}}}{N_n} ,$$

where $N_n$ is the number of neutrons produced by the same star via spallation. The factor $f_{2.2}$ is the efficiency for neutron-to-2.22 MeV photon conversion, averaged over the neutron energy spectrum (Ramaty 1986); this includes stopping of the gamma rays, as well as neutron escape and neutron “poisoning” by capture onto $^3\text{He}$. Since deuterium is made via radiative capture as well as in spallation, we have $N_n^{\text{tot}} = N_n^{\text{spall}} + N_n^{\gamma}$. Let us further assume that all neutrons made in spallation reactions, $N_n$, go into making of deuterium by radiative capture, that is, $N_n^{\text{spall}} = N_n$. Thus the 2.22 MeV gamma-ray intensity estimated with this assumption corresponds to the upper limit of Galactic flare production of deuterium. We can now rewrite equation (14) and obtain $\Gamma_n^{\text{tot}}$, the rate of total deuterium production by a single star, as a function of deuterium-to-neutron spallation production ratio:

$$\Gamma_n^{\text{tot}} = \frac{\Gamma_n}{f_{2.2}} \left[ 1 + \left( \frac{d}{n} \right)_{\text{spall}} \right] .$$

What we actually want is the Galactic deuterium production rate by mass, $M_d^{\text{Gal}}$, which is a function of total deuterium production rate $\Gamma_n^{\text{tot}}$ and total number of flare stars in the galaxy $N_\star$:

$$M_d^{\text{Gal}} = m_d \frac{\Gamma_n^{\text{tot}}}{N_\star}$$

$$= \frac{\Gamma_n}{f_{2.2}} \left[ 1 + \left( \frac{d}{n} \right)_{\text{spall}} \right] m_d \frac{N_\star^{\text{Gal}}}{N_\star} ,$$

where $N_\star$ is the number of flare stars in the Galaxy and $m_d$ is the deuteron mass.

We wish to find the observable Galactic 2.22 MeV gamma-ray intensity $I$, in terms of the 2.22 MeV emissivity $d_\gamma^{\text{Gal}}$, the total Galactic production rate of 2.22 MeV gamma rays per volume per steradian:

$$d_\gamma^{\text{Gal}} = \frac{\Gamma_n n_\star}{4\pi} ,$$

where $n_\star(r)$ is the number density of flare stars. The intensity is simply a line-of-sight integral:

$$I_\gamma = \int d_\gamma^{\text{Gal}} dl = \frac{\Gamma_n N_\text{los}}{4\pi} ,$$

where $N_\text{los} = \int_{l_0}^l n_\star(r) dl$, is the column density of flare stars along the line of sight $l$.

Therefore, we can link Galactic deuterium production rate by mass as a function of Galactic 2.22 MeV gamma-ray intensity by combining equations (17) and (18):

$$M_d^{\text{Gal}} = \frac{4\pi}{f_{2.2}} \left[ 1 + \left( \frac{d}{n} \right)_{\text{spall}} \right] m_d \frac{N_\star^{\text{Gal}}}{N_\text{los}} I_\gamma ,$$

or

$$I_\gamma = \left[ 1 + \left( \frac{d}{n} \right)_{\text{spall}} \right]^{-1} f_{2.2} \frac{N_\text{los}}{4\pi m_d N_\star} M_d^{\text{Gal}} .$$

Equation (20) allows us to estimate the most modest Galactic 2.22 MeV gamma-ray intensity that we expect if the flare stars are producing significant amounts of deuterium. In order to predict the lower intensity limit, let us take $d/n = 1$ (although from Fig. 2 we see that this ratio is always smaller than 1). We also adopt the $f_{2.2} = 0.1$ neutron-to-gamma ray conversion efficiency calculated by Ramaty (1986); this value is dominated by escape (followed by decay) and then the neutron poisoning due to the large $n$-capture cross section for $^3\text{He}$.

The Galactic distribution $n(r)$ of flare stars (i.e., M dwarfs) controls both the column density and flare star
number that appear in equations (21) and (20). We have verified that disk M dwarfs dominate the calculation, while spheroid ("stellar halo") M dwarfs (Gould, Flynn, & Bahcall 1998) do not contribute significant numbers or column of stars. For the disk M dwarfs, we adopt the (Zheng et al. 2001) distribution,

\[ n(r, z) = n_0 \exp \left( \frac{-r - R_0}{H} \right) \times \left[ (1 - \beta) \exp(-|z|/h_1) + \beta \exp(-|z|/h_2) \right]. \quad (22) \]

Zheng et al. (2001) use Hubble Space Telescope star counts to determine the initial mass function in the M dwarf range and find the parameters in eq. (22) to be as follows: local M dwarf density \( n_0 = \rho_0/(m_{\text{M dwarf}}) = 5.2 \times 10^{-2} \text{ pc}^{-3} \), radial scale length \( H = 2.75 \text{ kpc} \), solar Galactocentric distance \( R_0 = 8 \text{ kpc} \), and vertical scale parameters \( h_1 = 156 \text{ pc} \) and \( h_2 = 439 \text{ pc} \), and \( \beta = 0.381 \). With these we find the number of Galactic M dwarfs to be \( N = 2.4 \times 10^{10} \) and a column density toward the Galactic center of \( N_{\text{los}} = 5.1 \times 10^{19} \text{ cm}^{-2} \).

The deuterium production rate that we would consider to be significant is one that is comparable to the Galactic destruction rate of deuterium due to its cycling through stars ("astration"), which burn D during the pre-main-sequence phase. The present rate at which deuterium is lost is

\[ M_d = -X_d \rho = -2.5 \times 10^{-5} M_{\odot} \text{ yr}^{-1}, \quad (23) \]

where \( X_d = 2.1 \times 10^{-5} \) is the present ISM mass fraction of deuterium and \( \rho \) is the current rate at which mass is ejected from dying stars. This is roughly given by \( \rho = R \psi \), where \( R \approx 0.3 \) is a conservative estimate of the "return fraction" of mass from stars (e.g., Pagel 1997), and we adopt a current Galactic star formation rate \( \psi \approx 4 M_{\odot} \text{ yr}^{-1} \) following, e.g., Fields et al. (2001).

We then can place a lower limit on the 2.22 MeV Galactic gamma-ray intensity that corresponds to flare production of deuterium equal to the amount of deuterium that is destroyed per year in the Galaxy:

\[ I_{\gamma} = 4 \times 10^{-2} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}. \quad (24) \]

We can compare this prediction with 2.22 MeV all-sky map done by COMPTEL (McConnell et al. 1997). This map contains a single possible point source, but no diffuse emission is found, down to a level estimated (M. McConnell 2003, private communication) to be

\[ I_{\gamma}^{\text{obs}} < 5 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}. \quad (25) \]

This limit is about 1% of what we would expect if a significant amount of deuterium originates in flares (eq. [24]). Or to go other way around, we can use eq. (21) to translate the COMPTEL upper limit into an upper limit for deuterium production by flares:

\[ M_d^{\text{Gal}} < 3.0 \times 10^{-7} M_{\odot} \text{ yr}^{-1} \approx 1 \times 10^{-2} M_d \text{ astrate}. \quad (26) \]

Thus we see that the maximum possible D production rate is at most 1% of the destruction rate, so that the net effect is that D is indeed destroyed and thus decreases with time. If we were to look only at the \( n \) channel of deuterium production, as was proposed by ML, we would get even lower production rate (by a factor of 2). Therefore, on the basis of COMPTEL observations and our numerical analysis of production rates we can conclude that stellar flares are not significant sources of nonprimordial deuterium on the Galactic scale and thus do not spoil the monotonic decline of D with time.

Although we have estimated the diffuse 2.22 MeV radiation from flare stars, our calculation in fact is generally applicable to any Galactic sources of deuterium via neutron radiative capture. The gamma-ray constraints are thus stronger than the abundance-based constraints of the previous section. Furthermore, further limits (or observations) at 2.22 MeV will constrain any source of D production from neutrons. We encourage INTEGRAL observations to be made to tighten the constraints we present here.

While gamma-ray observations rule out flare D production at a level that would overwhelm destruction, the fact remains that neutron production is a significant and inevitable result of flare activity, as emphasized by ML. Thus, a gamma-ray signature of this process must exist at some level. We can make a crude prediction of diffuse 2.22 MeV gamma-ray intensity that INTEGRAL might observe. The rate at which 2.22 MeV gamma-ray are produced in a single star is given by

\[ \Gamma_{\gamma} = f_{\gamma} \frac{Q_n}{\langle \epsilon \rangle} L_{\text{flare}}, \quad (27) \]

where \( L_{\text{flare}} \) is the time-averaged luminosity in the flare state, and

\[ \langle \epsilon \rangle = \int e N_i(\epsilon) d\epsilon = \int e k \epsilon^{-3/2} d\epsilon \sum_i y_i A_i. \quad (28) \]

measures the flare energy going into accelerated particles. Using the spectral index \( s = 4 \) favored by solar flares and integrating from the lowest threshold energy among reactions involved in neutron production (note that because of assumed power-law spectrum of flare particles it is not possible to extrapolate to zero energy), we find that the number of neutrons produced per flare unit energy is \( Q_n/\langle \epsilon \rangle = 0.015 \text{ atoms s}^{-1} \).

For the total number of neutrons produced per proton (above 30 MeV), we used our thick-target \( s = 4 \) numerical result \( Q_n = 5.53 \times 10^{-3} \). Then by taking a bolometric flare luminosity of a dM5e star to be \( L_{\text{flare}} = 1.9 \times 10^{29} \text{ ergs s}^{-1} \) (Colesman & Wood 1976) and the neutron-to-photon efficiency factor to be \( f_{2.2} = 0.1 \), it follows from equations (19) and (20) that

\[ I_{\gamma} \approx 1.2 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}. \quad (29) \]

In this calculation we took \( V_a = 10^{12} \text{ pc}^3 \) and \( n_a = 0.86 \text{ pc}^{-3} \) (Weistrop 1972), and we took the a line-of-sight length \( l = 20 \text{ kpc} \) toward the Galactic center. Finally, we note that using the same estimate of flare activity (i.e., scaling to the flare star luminosity), we can also arrive at an estimate of the flare D production rate, namely, \( M_d^{\text{flare}} \sim 2.5 \times 10^{-10} M_{\odot} \text{ yr}^{-1} \), which is completely negligible compared with the D astration rate.

The emission in equation (29) is low and, in particular, too dim to be observed by INTEGRAL. On the other hand, our estimate is crude, and while detection of flare stars would be a surprise, it would also provide unique new information about the particle content and energetics in stellar flares. Also, as we have noted, simply tightening the limits on diffuse 2.22 MeV radiation will strengthen the case that
D production is negligible and can go further to constrain (or probe) flares as a contributor to the D variation in the ISM (Hoopes et al. 2003). For these reasons, we encourage INTEGRAL observations at 2.22 MeV, particularly toward the Galactic center where the emission should be the strongest.  

4. CONSTRAINTS ON LOCALIZED DEUTERIUM PRODUCTION

It is important to note, however, that this conclusion applies to the Galaxy as a whole. While the global D production rate due to flares is small, it is a separate question whether D production could be sufficient to create D variations on smaller scales.

To constrain local enrichment, we rely on the Galactic average deuterium production rate $\dot{M}_D$, which we have constrained in the previous subsection on the basis of gamma-ray observations and estimated using flare energetics. With the global production rate in hand, we can find the average D production rate for one star. The limit from equation (26) gives $\dot{m}_D = \dot{M}_D / V_u \sim 10^{-17} M_\odot$ yr$^{-1}$. Using this, let us find the needed D production to pollute a parcel of gas at a level of $\delta D/D \sim \delta M_D / M_D \sim 1$, i.e., to produce a factor of 2 variation in D/H over the current ISM level. To pollute a gaseous region of total mass $M_u$ given the entire age of the universe requires that $M_{\text{D,dwarf}} \sim 70 M_\odot$, and thus a gas fraction of no more than 1/70; that is, the M dwarfs must outweigh the ambient gas by a large factor. On the other hand, a clump of M dwarfs in the hot and diffuse ISM could achieve this level. If we instead adopt the deuterium production rate $\dot{M}_D \sim 10^{-10} M_\odot$ yr$^{-1}$, based on energetics, we find a needed gas fraction less than $10^{-5}$. This becomes harder to achieve, but is difficult to completely exclude.

5. DISCUSSION AND CONCLUSIONS

For more than a quarter-century, the ELS argument that all deuterium is primordial has played a central role in cosmology. The importance of this argument demands that its assumptions be carefully checked. In this context, Mullan & Linsky’s discovery that D production by neutron capture in flares can evade the ELS constraints is thus very important and demands further investigation.

In this paper we have examined and constrained the ML scenario in two ways. First, we have made a detailed calculations of spallation yields in flares. These calculations show that flares have $1 \leq n/d \leq 200$, confirming the ML suggestion that neutron production is at least as significant as direct deuterium production and considerably more so for some spectral indexes (albeit ones atypical of solar flares). We have thus updated the ELS constraints on flares, now taking into account neutron production (all which we assume leads to deuterium formation by radiative capture). Specifically, we consider $^6$Li production, which accompanies $n$ and $d$ synthesis. The ELS argument is quantitatively changed, because the $^6$Li/$(n+d)$ ratio is lower than the former $^6$Li/$d$ ratio, but the qualitative conclusion remains, i.e., that the solar $^6$Li abundance forbids a significant $d$ component from flares. The only way that flare nucleosynthesis could avoid this bound is for $d$ to escape the star preferentially with respect to $^6$Li, the needed bias being a factor of around 1000 in escape efficiency.

Second, we considered the implications of the 2.22 MeV gamma-ray line produced in the radiative capture. If D is currently produced in the Galaxy via this mechanism (either in flare stars or elsewhere), then there inevitably is an observable 2.22 MeV line signature. In the case of flare stars, the emission would be unresolved and would lead to a diffuse intensity tracing the Galactic plane. The observed limits on 2.22 MeV emission from COMPTEL immediately translate into a constraint on D production by radiative capture, and rule out this mechanism as a significant source of D at the global Galactic scale.

It is more difficult to constrain flare production of D as the source of the possible scatter in local D abundances as reported recently by FUSE (Hoopes et al. 2003). However, arguments based on energetics and on gamma-ray fluxes do demand that the mean D production rate per star is small. This means either that (1) to produce significant fluctuations requires a high local concentration of M dwarfs relative to the gas they pollute or that (2) flare D production is dominated by a very small fraction of M dwarfs, which dominate the global mean production and can thus create local anomalies. In either case, the nearest local sources may be detectable through their gamma-ray lines.

Another constraint on the ML scenario comes from observations of deuterated molecules toward the Galactic center. Lubowich et al. (2000) detect DCN in a molecular cloud 10 pc away from the Galactic center and on the basis of a molecular chemistry model estimate that $D/H = (1.7 \pm 0.3) \times 10^{-9}$ in this cloud. Unfortunately, the fractionation corrections here are large and thus the results are somewhat model dependent. With this caveat, the important point here is that D/H is found to be lower toward the Galactic center, suggesting that D indeed has a positive Galactocentric gradient, which argues against any significant stellar source of D, including flares.

Finally, we note that while flare star radiative capture synthesis of D is insufficient to alter the conclusions of ELS, it is certain that the process does occur at some level—the flares exist and must produce neutrons. Thus, the 2.22 MeV signature of this process must exist at some level. We have made a simple estimate of the surface brightness toward the Galactic center. We find this to be below the sensitivity of INTEGRAL, but given the crudeness of our estimate, it is worth investigation, since limits (or detection!) on this line have immediate implications for stellar flares, neutron capture processes, and deuterium evolution in our Galaxy.

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