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Implications of a high Population II B/Be ratio†

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ABSTRACT

The observed B/Be ratio in extreme Pop II stars has been interpreted as evidence of Be and B synthesis by early galactic cosmic rays. However, a recent reanalysis of the boron abundance in the Pop II halo star HD140283 suggests that B/H may be larger than previously reported, by as much as a factor of 4. This would yield a B/Be ratio lying in the range $14 \lesssim B/Be \lesssim 50$. The possibility of a high Pop II B/Be ratio stresses the importance of the upper limit to the B/Be ratio arising from cosmic ray production. It is found that the limit to cosmic ray-produced B/Be depends upon the assumed cosmic ray spectrum. For any Pop II comic ray spectrum that is a single power law in either total energy per nucleon or in momentum (both of which are consistent, for a particular spectral index, with the present observed flux) the B/Be ratio is constrained to lie in the range $7.6 \lesssim \mathrm{B/Be} \lesssim 14$. Thus, if the new B/Be ratio is correct, it requires either a bimodal cosmic ray flux with a large low energy component, or for another B source, possibly the proposed ν-process in supernovae, either of which may be helpful in explaining the observed $^{11}\mathrm{B}/^{10}\mathrm{B}$ ratio. Finally, it is noted that the boron reanalysis highlights the uncertainty in our knowledge of the B/Be ratio, and the need for additional data on Be and B abundances.

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In the last few years, new observations of Population II halo stars have led to the detection of B (Duncan, Lambert, & Lemke 1992 (DLL); Edvardsson et al 1994) and Be (Rebolo et al. 1988; Ryan et al. 1990, 1992; Gilmore et al. 1992a, 1992b; Boesgaard & King 1993). It is commonly believed (Reeves, Folwer, & Hoyle 1970; Meneguzzi, Audouze, & Reeves 1971 (MAR); Reeves, Audouze, Fowler, & Schramm 1973; Walker, Mathews, & Viola 1985; Steigman & Walker 1992 (SW); Prantzos, Cassé, & Vangioni-Flam 1992 (PCV); Walker et al. 1993 (WSSOF); Steigman et al. 1993 (SFOSW); Fields, Olive & Schramm 1994 (FOS)) that these elements have their origin in early cosmic ray activity. Spallation of carbon, nitrogen and oxygen by protons and α nuclei can for the most part account for the observed abundances of B and Be. Early cosmic rays can also produce some of the observed ^{7}Li as well as all of the now observed ^{6}Li (Smith, Lambert, & Nissen 1992; Hobbs & Thorburn 1994), in part by spallation but predominantly via the accompanying $\alpha + \alpha$ fusion.

A comparison of observed abundance ratios and their theoretical predictions is a good test of models of galactic cosmic-ray nucleosynthesis (SW; PCV; WSSOF; SFOSW; FOS) and galactic chemical evolution (PCV); it may have implications for big bang nucleosynthesis as well (WSSOF; Olive & Schramm 1992). The ratios of interest are ^{6}Li/^{7}Li, Li/Be, B/Be, and potentially ^{11}B/^{10}B. In the case of ^{6}Li/^{7}Li where the theoretical prediction of about 0.9 (from cosmic-ray nucleosynthesis) is robust, the observation of ^{6}Li (Smith, Lambert, & Nissen 1992; Hobbs & Thorburn 1994) is a good indication that Li is not strongly depleted in stars (at least not by nuclear burning (Brown & Schramm 1988; Deliyannis et al. 1989)). Though caution is still warranted due to the current paucity of data, the ^{6}Li/^{7}Li ratio found by both groups is consistent with standard models of cosmic-ray and big bang nucleosynthesis and standard stellar models which have minimal Li depletion (SFOSW). The Li/Be ratio which can be used to probe the compatibility between cosmic-ray and big bang nucleosynthesis (WSSOF; Olive & Schramm 1992) is much more model-dependent (FOS). There is as yet not data on the ^{11}B/^{10}B ratio in Pop II objects, but such data would be very interesting, as this ratio is anomalous even in Pop I objects, a point we will return to below. Finally that brings us to the B/Be ratio which like the ^{6}Li/^{7}Li ratio is robust (WSSOF; FOS) and is an excellent tool to probe theoretical models.

While there are many observations giving the Be abundance in halo stars (Rebolo et al. 1988; Ryan et al. 1990, 1992; Gilmore et al. 1992a, 1992b; Boesgaard & King 1993), there is data on B for only three stars (DLL; Edvardsson et al 1994) since the B lines reside well into the ultraviolet and thus require satellite observation. The data are summarized in Table 1. In the table we show the observed abundances of Be and B as well as Fe for the three halo stars. For each particular Be measurement we list the Fe abundance used for that measurement. Note that both the Be and the Fe abundances for each star vary among the different measurements.

In the case of HD140283, there are several independent observations of Be and two observations of B. In the table, we show the quoted value of [Be]. For [B], we have averaged the two measurements and, to minimize systematics, we have adjusted the B abundance quoted in Edvardsson et al. (1994) by assuming stellar parameters (temperature and surface gravity) as in DLL. To obtain the B/Be ratios we use the average B abundance and we have adjusted the Be abundances in each case to

TABLE 1. OBSERVED POP II ABUNDANCES OF BE AND B

STAR	[Fe/H]	[Be]	[B]	LTE B/Be	NLTE B/Be	SOURCE*
HD19445	-2.1	-0.14 ± 0.1	0.4 ± 0.2	3.5 ± 1.8	Unavailable	BK
HD140283	-2.7	-1.25 ± 0.4	-0.16 ± 0.14	12 ± 12	34 - 50	Ry
HD140283	-2.8	-0.97 ± 0.25	-0.16 ± 0.14	7 ± 5	23 - 33	G
HD140283	-2.7	-0.78 ± 0.14	-0.16 ± 0.14	5 ± 2	14 - 21	BK
HD140283	-2.5	< -0.90	-0.16 ± 0.14	> 7	> 21 - 30	M
HD201891	-1.3	0.65 ± 0.1	1.7 ± 0.4	11 ± 11	Unavailable	Re, BK

*BK = Boesgaard & King 1993; Ry = Ryan et al. 1990, 1992; G = Gilmore et al. 1992a, 1992b; M = Molaro et al. 1993 Re = Rebolo et al. 1988;

also match the DLL stellar parameters. For HD19445 we note that there are in addition upper limits of [Be] < 0.3 (Rebolo et al. 1988) and < -0.3 (Ryan et al. 1990) giving B/Be > 1.3 and > 5 respectively which have not been included in the table and for HD201891 the values of [Be] and B/Be given represent an average of the two published measurements.

One should be aware that most observational determinations have been made using different sets of parameters in their stellar atmosphere models. Though one can ascribe some uncertainty to chosen values of these parameters, it is not always clear to what extent these systematic errors have been incorporated into the quoted so-called "statistical error," and different authors make divergent assumptions on the uncertainty of their assumed stellar parameters. Thus some care is warranted in using this data. Since systematic errors due to assumed model parameters, etc., are probably not distributed in a gaussian manner, nor will they be decreased with the square root of the number of observations, one cannot reliably apply standard statistical techniques. (Perhaps future observational papers might consider separating the systematic portion of the stated error from the statistical portion as is now being done in many nuclear and particle physics papers.)

As one can see from the B/Be ratios in table 1, some of the LTE ratios are in agreement with standard cosmic-ray nucleosynthesis model predictions (B/Be $\simeq 12 - 14$), but most of them are on the low side of the prediction. For example, the overall average in the case of HD140283, gives B/Be $= 6 \pm 2$. (Though recall the caveat regarding systematic errors). Thus effort has been concentrated for the most part in determining how low the B/Be can be made within the context of cosmic-ray nucleosynthesis. In WSSOF, it was argued on the basis of spallation cross-sections that the extreme lower limit is B/Be $\gtrsim 7$. Both WSSOF and PCV have noted that a low Pop II B/Be ratio (between 7 and 10) would imply a steeper cosmic ray spectrum in the early Galaxy. which is suggested to have arisen from stronger cosmic ray confinement.

Recently, Kiselman (1994) has performed a reanalysis of the inferred B in HD140283 from the DLL data. In the original analysis of DLL, abundances based on the BI and BeII spectral lines were extracted using the assumption of local thermodynamic equilibrium (LTE). The beryllium abundance is believed to be relatively insensitive to this approximation. It was recognized by

DLL that a non-LTE (NLTE) analysis could be a potentially important correction to the boron abundance. Kiselman (1994) has in great detail attempted to account for the NLTE correction for the specific case of HD140283. Indeed he found an overall upward correction to the boron abundance of 0.56 dex or a factor $\gtrsim 3$. To test the reliability of his results, Kiselman perturbed his model and estimates that a reasonable NLTE correction to the boron abundance of HD140283 should lie between 0.46 and 0.62 dex. Recently the DLL measurement of B in HD140283 has been confirmed by Edvardsson et al. (1994). Within errors, there is very good agreement in the LTE abundances. Edvardsson et al (1994) argue for a similar NLTE correction to their derived abundance. In Table 1, we also give Kiselman's corrected B/Be ratio for the range 0.46-0.62 dex. The weighted average of the three positive observations of Be (again corrected for differing surface gravities) is [Be] = -0.93 ± .12, giving B/Be = 6 ± 2. After the Kiselman correction we find that B/Be = 17 - 25, using the central value of Be. The range here corresponds to the range in the correction factor, not to statistical errors.

The possibility of a high Pop II B/Be ratio can have interesting consequences. WSSOF compute an upper bound of B/Be $\lesssim 17$ for cosmic ray production in Pop II, but this result was not their main focus. In particular, whereas the WSSOF lower limit to B/Be is model-independent, their upper limit is not, as it was calculated in their "zeroth order" model. The question we ask here is, what is the true, model-independent upper bound to the B/Be ratio arising from cosmic rays? In this note we compute the range of B/Be produced in various models of cosmic ray synthesis of LiBeB, and we discuss the implications for alternate means of boron production.

There are several factors which affect the maximum B/Be ratio that Pop II cosmic rays can produce. Ultimately, the predicted ratios are controlled by (well-measured) nuclear physics, in the guise of spallation/fusion cross sections. The model-dependent feature one may adjust is the Pop II cosmic ray flux spectrum, which one must decide how to parameterize. Given a choice of flux, its LiBeB yields are constrained to be consistent with the observed Pop II LiBeB abundances and ratios. To determine the maximum B/Be, then, the game is to choose a range of admissible Pop II cosmic ray spectra, and then to convolve it with the cross sections find the highest B/Be ratio these spectra can produce without violating observational constraints.

In the notation of FOS, the rate for producing nuclide A = LiBeB with a number density relative to hydrogen of $y_A = n_A/n_H$ is

$$\frac{\partial y_A}{\partial t} = \sum_{ij} y_j(t) \int_{T^0}^{\infty} dT \; \sigma_{ij}^A(T)\phi_i(T;t)S_A(T_A;t) \; . \tag{1}$$

were $y_j = n_j/n_H$ is the number density of ISM nuclei $j = p, \alpha$,CNO. The integral runs over cosmic ray kinetic energy per nucleon T, with ϕ_i the flux spectrum of cosmic ray species i, and σ_{ij}^A is the spallation/fusion cross section for $i + j \to A + \cdots$. The probability of the product nucleus A being thermalized and stopped in the ISM is measured by $S_A = \exp -R_A/\Lambda$, where R_A is the ionization range of A in the ISM (taken at the the energy T_A at which the product is produced), and $\Lambda = \Lambda(t)$ is the "escape pathlength."

The lower bound for the integral in eq. (1) is the threshold for the spallation/fusion process $i + j \to A$. The threshold energies are determined by Q values for the reactions. For our purposes, the most important fact about these thresholds is that for all spallation reactions $T_B^0 < T_{Be}^0$, i.e. *the threshold for boron production is lower than that for beryllium production.* This means that all the flux in the energy range $T_B^0 \leq T \leq T_{Be}^0$ (in our case, 3.13 MeV $\leq T \leq$ 17.5 MeV) will produce only boron. Clearly, one can make B/Be arbitrarily high by tuning the low-energy cosmic ray flux to exploit this difference in thresholds. We will address below the observational constraints on such a "designer" spectrum. Note as well that for boron isotopic production, we have $T_{11}^0 < T_{10}^0$, and so a large low energy flux will also have the effect of increasing the $^{11}B/^{10}B$ ratio.

The cosmic ray spectrum ϕ is propagated (in energy space) from a source spectrum q according to

$$\phi_i(T) = w_i(T) \int_T^\infty dT' \, q_i(T') \exp\left[-\frac{R_i(T') - R_i(T)}{\Lambda}\right] \tag{2}$$

where $w_i = \partial R_i / \partial T$. One must specify the source spectrum q to determine the (propagated) flux spectrum which fills the galaxy. Today we observe the propagated flux from contemporary sources, from which we can infer a source spectrum. However, observations of the present spectrum are limited by solar modulation to include only cosmic rays with kinetic energy per nucleon $T \gtrsim 100$ MeV/nucl. The observed spectrum is consistent, over this range, with a source law taking the form of a single power law, either in momentum per nucleon, $q(p) \propto p^{-\gamma}$, or in total energy per nucleon, $q(T) \propto (T + m_p)^{-\gamma}$. The observed galactic cosmic ray flux today corresponds to such a flux, with a spectral index of ~ 2.7, and a pathlength Λ which varies in energy around $\sim 10 \mathrm{g/cm}^2$.

We do not know directly how the cosmic ray flux behaves at low energy ($\lesssim 100$ MeV/nucl); this is an unfortunate state of affairs, as the B/Be ratio is very sensitive to the details of the flux at precisely this energy range. We will in this paper assume that we may extrapolate the cosmic ray flux from the measured high-energy region down to the low energy regime. We will for the moment also assume that the low energy flux obtained through this extrapolation is the only low energy component. We remind the reader, however, that while the data we are extrapolating from measures the present, Pop I cosmic ray flux, we wish to model its behavior in the Pop II epoch. As several authors have pointed out, in this epoch, the flux parameters, namely the spectral index and escape pathlength, are not well constrained, and indeed could have been different than those today. We therefore will allow for these parameters to vary within physically allowable ranges as done in FOS.

We have calculated LiBeB production rates using cosmic ray fluxes propagated from different source spectra that are either power laws in momentum or in total energy. For each source type we have allowed the escape pathlength to vary over the range $10 \mathrm{~g/cm}^2 \leq \Lambda \leq 1000 \mathrm{~g/cm}^2$, which encompasses the current values and extends up to values at which nuclear inelastic losses dominate the escape losses.

Note that the possibility of a high B/Be might change the outlook on the behavior of early cosmic ray confinement. Before the Kiselman (1994) result, it was argued that larger early confinement was needed to reproduce a low B/Be. Now we consider the opposite case, and so this motivation for a larger confinement disappears. (Though a large Λ still can help the Be-Fe slope (PCV).) Thus, we allow for the escape pathlength to take values both of order the present one as well as significantly larger.

For each source type (i.e. power law in momentum or in total energy) we plot the ratio of production rates, ∂_tLi/∂_tBe, as well as ∂_tB/∂_tBe. As noted in FOS, lacking a model for the galactic chemical evolution, one can only calculate the ratio of LiBeB production rates (as calculated from eq. 1), rather than the actual abundance ratios, e.g. B/Be or Li/Be. However, FOS note that evolutionary processes will serve to make ∂_tLi/∂_tBe a lower bound for the true Li/Be ratio, while evolutionary effects are unimportant in the B/Be ratio which can be identified with the ∂_tB/∂_tBe ratio.

Our results appear in figures 1 and 2. Note that the case of the momentum source spectrum, (figure 1) the ∂_tB/∂_tBe ratio does rise with increasingly steep spectra. This is expected: a featureless power law in momentum has a lot of power at low energies, and so the ∂_tB/∂_tBe ratio should be sensitive to the spectral index (though the steepness of the source law is greatly softened at low energies by ionization losses included in the propagation). However, while the ∂_tB/∂_tBe ratio linearly increases with the spectral index, the ∂_tLi/∂_tBe ratio increases exponentially. But a large Li/Be ratio is constrained by the observational data. If we demand that the cosmic rays do not wash out the Spite plateau, then we may very generously insist that $(\mathrm{Li/Be})_{CR} < (\mathrm{Li/Be})_{OBS} \simeq 1000$. Bearing in mind that the ∂_tLi/∂_tBe ratio *underestimates* the Li/Be, we see that the spectral index is strongly constrained. Even for a high confinement, the steepest allowed spectrum has $\gamma \lesssim 3.3$. In this range, for all confinement parameters, $\partial_t\mathrm{B}/\partial_t\mathrm{Be} \simeq \mathrm{B/Be} \lesssim 14$. A momentum source that is not otherwise enhanced at low energies cannot produce B/Be in the range of the Kiselman results.

Similar results for a source spectrum in total energy are shown in figure 2. Note here that there is much less of a problem with the ∂_tLi/∂_tBe ratio. However, this spectrum is doomed to fail to produce high B/Be. Because the source is a power law in total energy, $q \sim (T+m_p)^{-\gamma}$, the nucleon rest mass m_p introduces a low-energy cutoff which keeps the flux spectrum finite and sets the scale for the peak in the propagated flux to be around m_p, far above the tens of MeV at which one requires a large flux to fit B/Be. This effect is seen in the flatness of the ∂_tB/∂_tBe curve in figure 2. Applying the constraint $\partial_t\mathrm{Li}/\partial_t\mathrm{Be} < 1000$ gives $\partial_t\mathrm{B}/\partial_t\mathrm{Be} \lesssim 14$, the same constraint as for the momentum spectrum. Thus we have, for either spectral type, an upper bound of

$$\partial_t\mathrm{B}/\partial_t\mathrm{Be} \simeq \mathrm{B/Be} \lesssim 14, \tag{3}$$

a limit which is independent of the choice of confinement parameter Λ and allows for variation in spectral index.

If the NLTE correction to the B abundance in HD140283 is correct, then for this star $\mathrm{B/Be} \gtrsim 17$ (see table 1) and a single power law cosmic ray flux underestimates the observed B/Be ratio. We must therefore conclude that either (1) the cosmic ray flux is not well described by a single power law; (2) there has been significant stellar depletion in Pop II, which would preferentially destroy Be relative to B because of the difference in the coulomb barriers; or (3) that something other than or in addition to cosmic rays produce the observed ratio. We will address point (1), suggesting a possible non-power law spectrum. Regarding point (2), as it is argued in SFOSW, we do not expect significant depletion in these stars, as is indicated by the positive identification of ^{6}Li in halo stars.

Thus we will not consider this line of reasoning further. As for point (3), we note that no proposed source for Be (and for ^{6}Li) other than cosmic rays has stood the test of time, and thus lacking an alternative we will continue to assume that these nuclei do arise from cosmic rays processes. We will consider the possibility of additional sources to the boron abundance.

If we take the observed LTE B/Be ratio to be accurate (i.e. we assume that B and Be are undepleted), and we assume that cosmic rays (with a single power law spectrum) produced the Be (and inevitably some B as well), then the importance of the Kiselman (1994) result is that another source of boron is needed. As mentioned above one possibility frequently discussed is the superposition of a low energy component to the cosmic ray flux. Such a low-energy component to the cosmic rays is not directly observable, as solar modulation, i.e. the solar wind excludes cosmic rays with energies below $\sim$ 100 MeV/nucl from the solar system. Introduction of a low-energy component to the cosmic ray flux allows additional tuning of LiBeB production beyond the above considerations of adjusting the cosmic ray source type, or confinement.

Long before the recent Kiselman (1994) analysis, there has been another good reason for an additional source of B. Namely, the boron isotopic ratio. It is well known that standard cosmic-ray nucleosynthesis models predict (MAR) a value $^{11}\mathrm{B}/^{10}\mathrm{B} \simeq 2.5$, whereas the observed ratio (Cameron 1983; Anders & Grevesse 1989) is very close to 4. Interestingly, the same low energy flux that will make a high B/Be ratio will also make a large $^{11}\mathrm{B}/^{10}\mathrm{B}$ ratio. Indeed, this point has been noted by MAR as well as in subsequent cosmic ray nucleosynthesis calculations. MAR first suggested that the cosmic rays might have a low-energy component which could fix the (Pop I) boron isotopic problem, and possibly the Pop I lithium isotopic ratio as well. Authors since then have followed this lead in trying to reproduce the solar ratios of B and Li, and have been moderately successful in doing so, the most recent model being that of WMV.

MAR discussed the physical motivation for this additional component to the cosmic ray flux. Namely, it is imagined that the low energy particles are similar to those seen in solar flares, which indeed have steep spectra. MAR and subsequent authors have modeled this component with a power law in kinetic energy, $\phi(T) \propto T^{-\beta}$, with $3 \lesssim \beta \lesssim 7$. Solar flare power laws are indeed sometimes observed to have spectra of this general form, though there is a class of flares that have spectra that fall exponentially. As has been pointed out, such a component to the cosmic ray flux would be quite localized, as the ionization range is quite small at these energies. However, turbulent and diffusive processes in the ISM would presumably mix material synthesized by the local low-energy flux.

PCV also have some discussion of Pop II synthesis of LiBeB by including a low energy spectral component. They add a component $q(T) \propto T^{-5}$ to their usual source spectrum, and find that while addition of this component allows for a felicitous $^{11}\mathrm{B}/^{10}\mathrm{B}$ ratio, the flare component also leads to Li overproduction at low metallicities. PCV concluded that such a fix to the $^{11}\mathrm{B}/^{10}\mathrm{B}$ ratio problem, could only be implemented during the disk phase of the galaxy. As such, it can not account for a high B/Be ratio in halo stars.

WMV and earlier works have calculated the LiBeB yields for the case in which the low-energy flare component dominates the production. For this case of a LiBeB synthesis purely by flares (in a Pop I environment) . WMV find that such a flux does not reproduce elemental or isotopic ratios. In particular, they find that B/Be $\gtrsim$ 100 for a flare spectrum with index $\beta \gtrsim 5$, and they find that in all cases $^{11}B/^{10}B \gtrsim 5$. They also find that Li/B $\gtrsim$ 80, an overproduction that only becomes exacerbated in a Pop II environment. That these ratios fit the data poorly is indication that a flare spectrum alone cannot dominate the LiBeB production in a Pop I environment. Furthermore, since the Be and B production is insensitive to galactic evolution, these conclusions hold for a Pop II environment as well.

While we cannot observe a low-energy flux directly, there are two indirect observational constraints and signatures that have been suggested. One is its ionization of the ISM, which MAR employ as a constraint on the low-energy flux. Too many cosmic ray particles would ionize the ISM beyond the observed limits. Also, a low energy flux creates a distinctive γ-ray spectrum. These γ-rays are produced by inelastic collisions with CNO nuclei that leave the CNO in an excited state. The de-excitation of these states leaves a signature of distinctive lines. Until recently these lines, predominantly from the 4.44 MeV state of $^{12}C^*$, and at 6.13 MeV from $^{16}O^*$, have remained unobserved. However, the COMPTEL group on the Gamma Ray Observatory (Bloemen et al 1994) have observed the Orion complex at 0.75-30 MeV and report a detection of gamma ray emission in excess of background in the 3-7 MeV range (and only in this range).

Bloemen et al (1994) report a flux of $(1.01 \pm 0.15) \times 10^{-4} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (3-7 MeV). This is to be compared with the calculations of Meneguzzi & Reeves (1975), applied to Orion, for which one expects a flux at the $^{12}C^*$ peak of $\phi_\gamma \simeq (2.5 - 5) \times 10^{-7} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{MeV}^{-1}$ for a flare-type spectrum (and significantly less for a spectrum from a single component momentum or total energy source). Bloemen et al (1994) suggest that an enhancement in the low-energy cosmic ray proton flux sufficient to match the observation leads to a large rate for the ionization if the ISM. Consequently Bloemen et al argue that these γ-rays are not from energetic protons on interstellar C and O but instead from an enhanced component of low-energy cosmic ray C and O on ISM hydrogen.[1]

In either case, it is hard to understand how the COMPTEL measurement could be a detection of cosmic ray C and O nuclear lines, given the lack of observed lines (at lower energies) from, e.g., Ne, Mg, Si, and Fe. Furthermore, even if only C and O have a high, low energy flux, it would have to be much larger than the galactic cosmic ray flux. The low energy C and O would then completely dominate the production of LiBeB, which, occurring such a low energy, would very much reflect the threshold behavior of the LiBeB spallation production cross sections. As we have noted above, this leads to enhanced boron production, and indeed to B/Be and $^{11}B/^{10}B$ ratios above those measured

[1] However, as Meneguzzi & Reeves (1975) make clear, the lines from light cosmic rays on stationary CNO are very narrow–Meneguzzi & Reeves estimate the Doppler width to be $\Delta E_l \sim 40$ keV. On the other hand, the lines from heavy cosmic ray C and O on interstellar H and He are much broader, with a width dominated by the Doppler width $\Delta E_h \sim 0.5$ MeV. Bloemen et al urge against deriving linewidths from their preliminary results, and so we cannot yet compare these to the data. But in the absence of linewidth data it remains true that height ϕ_{max} of the peaks is related to their width ΔE, with $\phi_{max} \Delta E \sim const.$ Thus the peaks for the light cosmic ray kinematics are much higher than those for heavy cosmic rays, by a factor $\Delta E_h / \Delta E_l \sim 10$. Thus if the Bloemen et al data does arise from heavy cosmic rays then their flux must be much larger than a proton flux would be to create the same signature. Such a large CNO flux faces similar constraints regarding the overionization of the ISM as does the proton flux.

in the solar system.

Nevertheless, if the important and provocative COMPTEL measurement holds up, it could be the first evidence for a very large low-energy cosmic ray component. However, given the tentativeness of the Bloemen result and its interpretation, we will in what follows consider the case in which there is not a significant low-energy cosmic ray flux, at least in the early galaxy.

Because of the difficulty in producing the observed isotopic ratio of ^{11}B/^{10}B in standard cosmic-ray nucleosynthesis models, it has been suggested that alternative astrophysical sites for the production of ^{11}B must be found. One such site is at the shock front of type II supernovae, as suggested by Dearborn et al. (1989): when the shock hits the hydrogen envelope, it burns the ambient ^{3}He and ^{4}He producing ^{7}Be. Some of the resulting ^{7}Be combines with alpha particles to produce ^{11}C which decays to ^{11}B. The primary goal of that work was to explore an alternative site for the production of ^{7}Li to reach Pop I abundances. They noted however that significant ^{11}B production might also take place. Subsequent calculations (Brown et al. 1991) have shown that these hydrodynamic processes were not sufficient producers of these light elements for currently preferred parameter values.

A potentially more important source for ^{11}B production has been found to result from neutrino induced nucleosynthesis in type II supernovae (Woosley et al. 1990). The core collapse of a massive star into a neutron star creates a flux of neutrinos so great that in spite of the small cross sections involved, it may still induce substantial nucleosynthesis. Neutrinos, including also ν_μ and ν_τ, are copiously produced in the hot collapsed core during a supernova (see eg., Mayle, Wilson and Schramm 1987). Because of their higher temperature, ν_μ and ν_τ neutral current reactions are dominant. The inelastic scattering of these neutrinos leads to unstable excited states which decay by p,n or α emission. These processes were included in supernova nucleosynthesis calculations by Woosley et al. (1990) where it was found that considerable ^{11}B production can result as the flux of neutrinos passes through the He, C, and Si shells of the stellar envelope, primarily by neutrino spallation of ^{12}C. The dominant product is ^{11}B since it is favored for ν-spallation to knock out a single nucleon. In addition, some synthesis of ^{7}Li and ^{10}B takes place by this process but the production rate seems quite low.

An important aspect of the calculation of Woosley et al. (1990) is the full treatment of pre- and post-shock nucleosynthesis. Since the duration of the neutrino burst exceeds the time scale for the passage of the shock through the inner layers of the exploding star, ν-process nucleosynthesis can continue after the passage of the shock. In the outer layers, however, the destruction of fragile isotopes is a significant effect and is, for example, responsible for the destruction of ^{9}Be. Uncertainties in calculation arise primarily from the assumed neutrino temperature and the cross sections for boron production. This process is attractive however as it naturally creates ^{11}B without much ^{10}B, and so provides the needed source of ^{11}B to augment GCR production and so reproduce the ^{11}B/^{10}B ratio.

Indeed the ^{11}B yields from these processes (Woosley et al. 1993; Timmes et al. 1993) were incorporated in a chemical evolution model (Olive, Prantzos, Scully, & Vangioni-Flam 1994). Respecting the overall constraints imposed by the LiBeB observations in halo stars, they were able to obtain a solar isotopic ratio $^{11}B/^{10}B \simeq 4$. Using the boron isotopic ratio to normalize the ν-process yields, they showed that neutrino process nucleosynthesis leads to a relatively model independent prediction that the B/Be elemental ratio is large (> 50) at low metallicities ($[Fe/H] < -3.0$), assuming still that Be is produced as a secondary element as is the case in the conventional scenario of galactic cosmic-ray nucleosynthesis. (Despite earlier conjectures (Malaney 1992), ^{9}Be is not significantly produced by the ν-process). In particular, at the metalicity corresponding to that of HD140283, [Fe/H] $\simeq$ -2.6, Olive et al. (1994) predicted that the B/Be ratio should be close to 40. Though still on the high side, this is in overall good agreement with the NLTE corrected values shown in Table 1.

To summarize our results: the Kiselman (1994) analysis of the B abundance in HD140283 suggests that in this star the B/Be ratio is potentially higher than can be accounted for by cosmic ray nucleosynthesis with a single power law source spectrum. This is best understood as arising from a overabundance of boron. If indeed the boron is high, then it must have a source that was active in the Pop II epoch, either low-energy cosmic rays in the early galaxy, or an alternative, non-cosmic ray process. The former might be suggested by the data of Bloemen et al(1994), while the latter has a promising candidate in the ν-process. These two alternatives should be distinguishable by getting more B/Be ratios, particularly in extremely metal deficient ([Fe/H] $\lesssim$ 3) stars, for which the ν-process should be dominant and hence the B/Be should be much larger than in HD140283 (Olive et al 1994).

The NLTE reanalysis of the boron abundance also underscores the difficulty of Pop II Be and B abundance measurements. Clearly there is a need for continued scrutiny of these abundances, as well as for further boron data in more stellar environments, some presumably not having the same NLTE effects and so amenable to a test of the possibility of high B/Be.

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FIGURE CAPTIONS

Figure 1: Ratios of LiBeB production rates for a source spectrum $q(p) \propto p^{-\gamma}$, plotted as a function of spectral index γ. For both plots we use CNO abundances [C/H] = [N/H] = [Fe/H] = [O/H] - 0.5 = -2.5, and ^{4}He/H = 0.08.

(a) The ∂_tB/∂_tBe ratio; the solid curve is for $\Lambda = 10\mathrm{g/cm}^2$, the broken curve is for $\Lambda = 1000\mathrm{g/cm}^2$. Note the very restricted, linear scale in the ordinate, showing the insensitivity of ∂_tB/∂_tBe to the spectral index.

(b) As in (a), for the ∂_tLi/∂_tBe ratio. Here we see that ∂_tLi/∂_tBe is exponentially sensitive to the spectral index, in contrast to the results of plot (a). As discussed in the text, the observational constraint Li/Be $\ll$ 1000 implies that ∂_tB/∂_tBe $\simeq$ B/Be $\lesssim$ 14.

Figure 2: Calculated as in figure 1, for a source spectrum $q(T) \propto (T + m_p)^{-\gamma}$. ($a$) The ∂_tB/∂_tBe ratio; note the larger range in γ compared to that of figure 1, and the even slower dependence of ∂_tB/∂_tBe on the spectral index.

(b) The ∂_tLi/∂_tBe ratio. Here again ∂_tLi/∂_tBe is sensitive to γ, but less so than for a source spectrum in momentum (figure 1). Note also that Li/Be $\ll$ 1000 again gives ∂_tB/∂_tBe $\simeq$ B/Be $\lesssim$ 14.

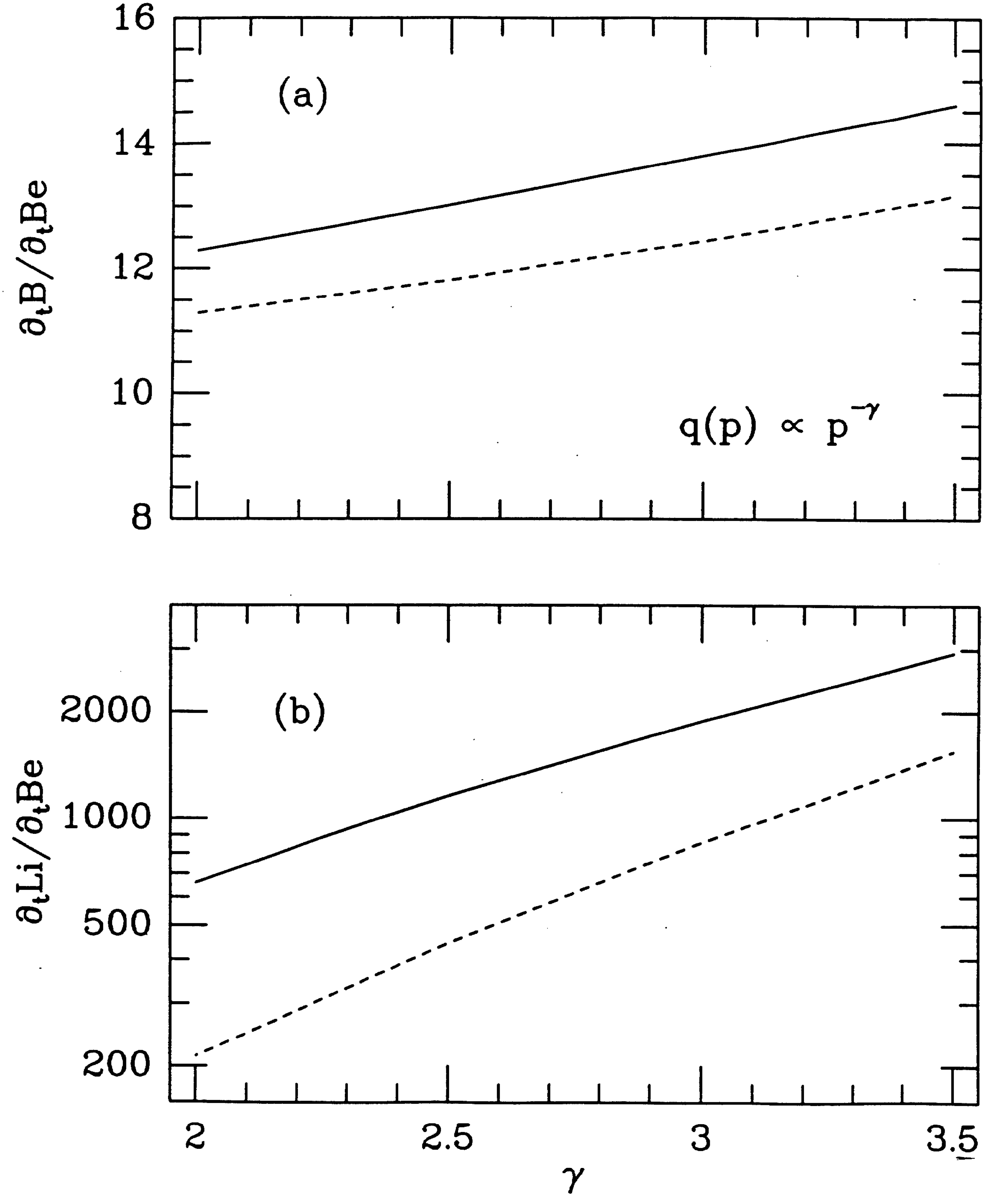
16
14
12
10
8
(a)
$q(p) \propto p^{-\gamma}$
$\partial_t B/\partial_t Be$
(b)
2000
1000
500
200
$\partial_t Li/\partial_t Be$
2
2.5
3
3.5
γ

FIG 1

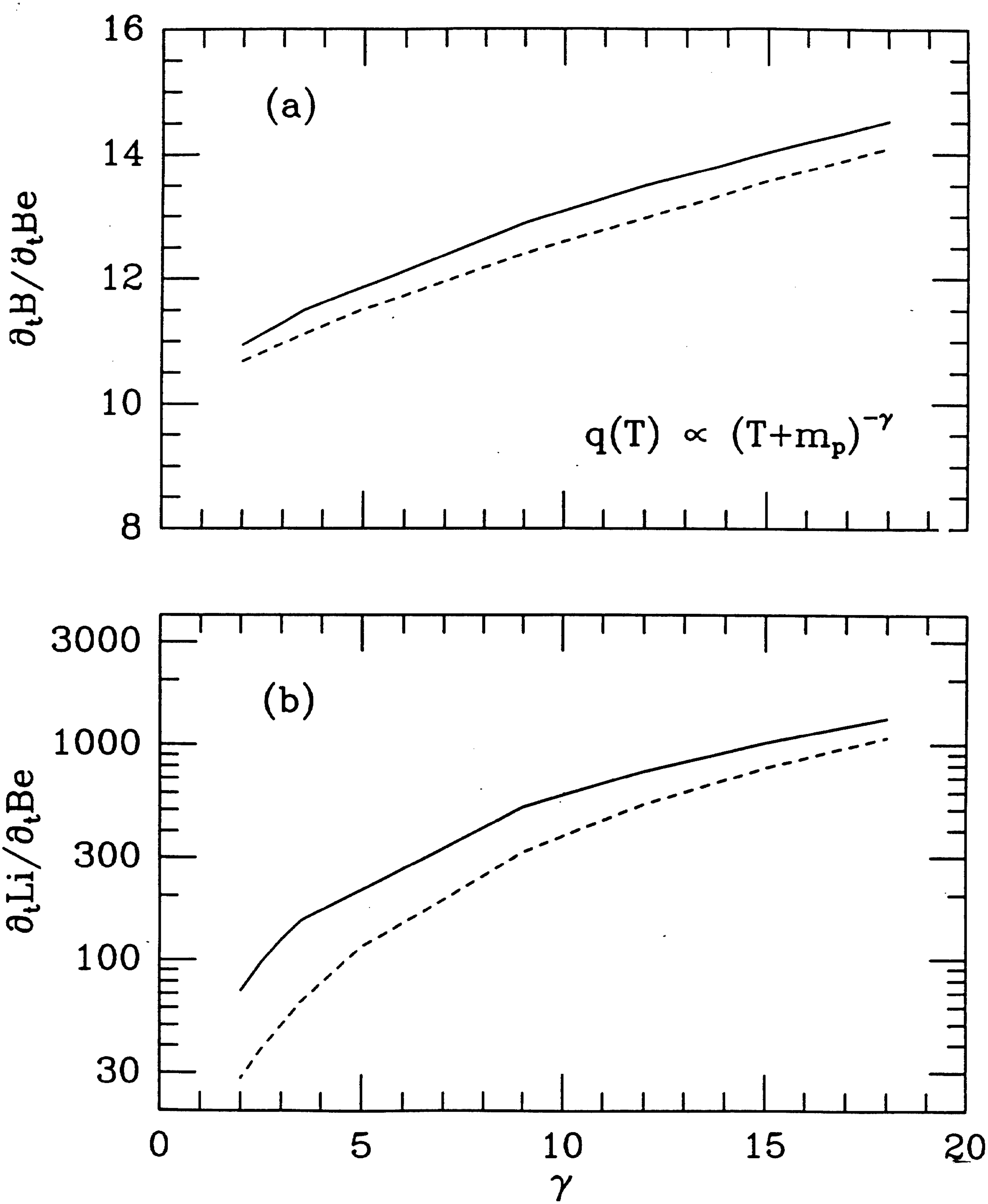
(a)
16
14
12
10
8
$\partial_t B/\partial_t Be$
$q(T) \propto (T+m_p)^{-\gamma}$
(b)
3000
1000
300
100
30
$\partial_t Li/\partial_t Be$
0
5
10
15
20
γ

FIG 2