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Big-Bang Nucleosynthesis and Galactic Chemical Evolution

Craig J. Copi,[1,2] David N. Schramm,[1,2,3] and Michael S. Turner[1,2,3]

[1]*Department of Physics*
Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637-1433

[2]*NASA/Fermilab Astrophysics Center*
Fermi National Accelerator Laboratory, Batavia, IL 60510-0500

[3]*Department of Astronomy & Astrophysics*
The University of Chicago, Chicago, IL 60637-1433

ABSTRACT

Deuterium is the best indicator of the baryon density; however, only its present abundance is known (and only locally) and its chemical evolution is intertwined with that of ^{3}He. Because galactic abundances are spatially heterogeneous, mean chemical-evolution models are not well suited for extrapolating the pre-solar D and ^{3}He abundances to their primeval values. We introduce a new approach which explicitly addresses heterogeneity, and show that the decade-old big-bang nucleosynthesis concordance interval $\eta \approx (2-8) \times 10^{-10}$ based on D and ^{3}He is robust.

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1 Introduction

Big-bang nucleosynthesis is the earliest and most stringent test of the standard cosmology. The inferred primeval abundances of D, ^{3}He, ^{4}He and ^{7}Li are in accord with the big-bang predictions provided that the baryon-to-photon ratio η between about 2.5×10^{-10} and 6×10^{-10}, which corresponds to $\Omega_B \simeq 0.009h^{-2} - 0.02h^{-2}$, and the number of light (mass less than about 1 MeV) particle species, expressed as the equivalent number of massless neutrino species, $N_\nu \leq 3.4$ (Walker et al. 1991; Krauss & Kernan 1995; Copi, Schramm, & Turner 1995). Big-bang nucleosynthesis thereby provides the best determination of the density of ordinary matter and an important constraint to theories that attempt to unify the fundamental forces and particles of Nature.

Of the light elements D has the most potential as a "baryometer" because its production depends sensitively upon η, $D/H \propto \eta^{-1.7}$. On the other hand, its interpretation is challenging because D is burned in virtually all astrophysical situations and its abundance has only been measured in the solar vicinity. Because D is destroyed and not produced (Epstein, Lattimer, & Schramm 1976) a firm upper limit to η can be obtained by insisting that big-bang production accounts for the D observed in the local ISM, $D/H \geq (1.6 \pm 0.1) \times 10^{-5}$ (Linsky et al. 1993). This leads to the two-decade old bound, $\eta \lesssim 9 \times 10^{-10}$, which is the linchpin in the argument that baryons cannot provide closure density (Reeves et al. 1973).

Because D is so readily destroyed, it is not possible to obtain a lower bound to η based upon D alone. The sum of D and ^{3}He is more promising: Since deuterium is first burned to ^{3}He, and ^{3}He is much more difficult to burn, $(D + {}^3He)/H$ is much less sensitive to chemical evolution (Yang et al. 1984). This argument depends upon the fraction of ^{3}He that survives stellar processing (referred to as g_3), which itself depends strongly upon stellar mass: high mass stars destroy ^{3}He, $g_3 \sim 0.2$, whereas low-mass stars are believed to produce additional ^{3}He (Iben and Truran 1978; Dearborn, Schramm, Steigman 1986).

To obtain a lower bound to η, one needs good determinations of both D and ^{3}He in the same place, at the same time, as well as a lower bound to g_3. The only place where both abundances are known is the pre-solar nebula, $(D/H)_\odot \sim 2.7 \times 10^{-5}$ and $(^3He/H)_\odot \sim 1.5 \times 10^{-5}$. Arguing that the mean survival fraction $\bar{g}_3$ is greater than 0.25, the lower limit, $\eta \gtrsim 2.5 \times 10^{-10}$ has been derived (Yang et al. 1984). Thus, D and ^{3}He together define a big-bang consistency interval, $\eta \simeq (2.5 - 9) \times 10^{-10}$.

Our aim here is to provide a firmer basis for these arguments. To this end we introduce a new approach to the chemical evolution of D and ^{3}He which allows their primeval abundances to be extracted from pre-solar abundances, while explicitly including heterogeneity. By considering an extreme range of possibilities for the mean properties of galactic chemical evolution as well as heterogeneity we show that the consistency interval $\eta \approx (2 - 8) \times 10^{-10}$ based upon D and ^{3}He is robust. This strengthens the case for the nucleosynthesis determination of the baryon density as well as the limit to the number of light neutrino species.

2 Stochastic Histories

The study of the evolution of the light-element abundances within the Galaxy has a long history (see e.g., Reeves et al. 1973; Audouze & Tinsley 1974). It is a difficult problem. Even at a given age, metal abundances in different places vary significantly. The light-element abundances are no different: The D abundance measured in the nearby ISM along different lines of sight varies significantly (Linsky 1995), and the ^{3}He abundance measured in different HII regions in the Galaxy varies by almost an order of magnitude (Bania, Rood and Wilson 1994). Since there is strong evidence that chemical evolution in different parts of the Galaxy has proceeded differently models for the mean chemical evolution cannot be trusted to accurately represent the history in a specific location.

Our new approach allows for heterogeneity in a most fundamental way: we follow the history of the material in the pre-solar nebula through stars back to its primeval beginning. We use a stochastic algorithm for generating histories; from each history the primeval D and ^{3}He abundances can be determined from pre-solar abundances. Taking an ensemble of histories, we construct "a fuzzy map" from local D and ^{3}He abundances to primeval D and ^{3}He abundances.

Histories are generated by a diagrammatic technique and set of rules (see Fig. 1). We suppose that the pre-solar material came from the primeval mix (fraction f_P) and from N other stars (fractions f_i, $i = 1, \cdots, N$). The fraction f_P is drawn from a linear distribution whose mean is $1-\epsilon$ ($\epsilon \sim 0.5$). The number of "first-tier stars" N is drawn from a flat distribution whose mean is $N_0 \sim 10$; if $N < 1$, there is no material from other stars and f_P is set equal to one. The fractions f_i are drawn from a flat distribution whose mean is $(1-f_P)/N$.

First-tier stars are made from primeval material and from material processed by "second-tier stars." Second-tier stars are made from primeval material and from material processed by "third-tier stars," and so on. A branch terminates when a star is made only of primeval material. The material from which any star is made is a fraction f_P primeval and fractions f_i from N other stars. At the nth tier, the expectation for f_P is $1-\epsilon_n$ and the number of stars N is drawn from a flat distribution whose mean is $N_0\epsilon_n/\epsilon$.

A star is assumed to do the following: (i) burn all its D to ^{3}He; (ii) return a fraction g_3 of its ^{3}He to the ISM; and (iii) possibly add some ^{3}He and heavy elements to the material it returns to the ISM. The amount of ^{3}He returned to the ISM by a star is related to the D and ^{3}He from which it is made

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{IN}} = f_P\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_P; \tag{1}$$

$$\left(\frac{^3\mathrm{He}}{\mathrm{H}}\right)_{\mathrm{IN}} = f_P\left(\frac{^3\mathrm{He}}{\mathrm{H}}\right)_P + \sum_i f_i\left(\frac{^3\mathrm{He}}{\mathrm{H}}\right)_{\mathrm{OUT}}; \tag{2}$$

$$\left(\frac{^3\mathrm{He}}{\mathrm{H}}\right)_{\mathrm{OUT}} = g_3\left[\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{IN}} + \left(\frac{^3\mathrm{He}}{\mathrm{H}}\right)_{\mathrm{IN}}\right] + h_3. \tag{3}$$

The quantities g_3 and h_3 are chosen from distributions that are adjusted to reflect the mix of stars and our knowledge about their processing of ^{3}He.

We use oxygen as a surrogate for the heavy elements. Massive stars produce oxygen quantified by the mass fraction $h_{16} \sim 0.10$ of the material they return to the ISM; low-mass stars preserve oxygen. We require that the oxygen mass fraction in the pre-solar material is between 0.5% and 2%. The oxygen constraint ensures that some material in the pre-solar nebula has been processed through massive stars, but not too much.

For a given history two linear equations relate the primeval and pre-solar D and ^{3}He abundances. The primeval D abundance is $1/f_P$ times the pre-solar abundance. The equation for the primeval ^{3}He abundance is more complicated, but straightforward to obtain. These two equations uniquely map pre-solar abundances to big-bang abundances. The primeval ^{3}He abundance can turn out to be negative, in which case the history must be discarded. This occurs when the primeval D abundance is large (i.e., small f_P) and illustrates the crux of the D + ^{3}He argument: if the primeval D abundance is large, it should lead to a large ^{3}He abundance today, and thus a negative primordial ^{3}He abundance may be required to account for the relatively modest pre-solar ^{3}He abundance.

Both the inherent uncertainty that arises from not knowing the precise history of the material in the pre-solar nebula (i.e., heterogeneity) and the uncertainty in the pre-solar abundances themselves are treated by Monte Carlo. Pre-solar D and ^{3}He abundances are drawn from distributions (see below); histories are constructed as described above.

The science in our approach comes in choosing the parameters ϵ, N_0 and the distributions g_3, h_3 and h_{16} to reflect our understanding of galactic chemical evolution. The parameter ϵ controls the fraction of material that has undergone stellar processing; conventional wisdom has it that about 50% of the pre-solar material has undergone stellar processing. The parameter N_0 controls the number of stars that contribute to the material from which a given star is made; we have tried values from 5 to 15.

Of more importance are the distributions chosen for g_3, h_3 and h_{16}. The distribution $f(g_3)$ determines the amount of ^{3}He that survives stellar processing; it in turn depends upon the stellar mass function and the rate of return of material from stars of a given mass to the ISM. We parameterize $f(g_3)$ by a minimum value, $g_{3\rm min} \sim 0.15$, and a power-law index m, $f(g_3) \propto g_3^m$ for $1 \geq g_3 \geq g_{3\rm min}$. A standard mass function and conventional stellar models correspond roughly to $m = 0$ (Truran 1995). The distribution $f(h_3; g_3)$ determines the amount of stellar ^{3}He production. It is parameterized by g_{3*}: only stars with $g_3 \geq g_{3*} \sim 0.8$ are assumed to produce ^{3}He, and the amount of ^{3}He production, h_3, which is chosen from a flat distribution with $0.5 \times 10^{-5} \leq h_3 \leq 2 \times 10^{-5}$.

Lastly, the distribution $f(h_{16}; g_3)$ quantifies heavy-element production by massive stars. The distribution is characterized by $g_{3\rm max} \sim 0.3$, only stars with $g_3 \leq g_{3\rm max}$ are assumed to produce ^{16}O, and $h_{16} = 0.025 - 0.20$, the mass fraction of oxygen produced by massive stars which is returned to the ISM. The range for these two parameters is based upon models for the yields of type II supernovae (Timmes, Woosley, & Weaver 1995).

By varying the parameters and distributions we can explore different models of chemical evolution, as opposed to different histories within a model. In this *Letter* we explore three models designed to span an extreme range of possibilities. Model 0 is chosen to be the plain, vanilla model for chemical evolution; it is characterized by $g_{3\min} = 0.1$, $g_{3*} = 0.8$, $g_{3\max} = 0.3$, $\epsilon_n = \epsilon^n$, $\epsilon = 0.5$, $N_0 = 10$, $h_{16} = 0.10$, and $m = 0$ for the first tier, $m = -1$ for the second tier and so on (corresponding to more massive stars contributing to the ISM in earlier stellar generations). Model 1 has extreme stellar processing and ^{3}He destruction; it is characterized by $g_{3\min} = 0.15$, $g_{3*} = 1$ (no stellar ^{3}He production), $g_{3\max} = 0.3$, $\epsilon_n = \epsilon^{2n-1}$, $\epsilon = 0.8$, $N_0 = 5$, $h_{16} = 0.025$ (corresponding to very little heavy-element return to the ISM, e.g., heavy elements ejected with high velocity), and $m = -2$ for the first tier, $m = -4$ for the second tier and so on. Finally, Model 2 has less stellar processing by massive stars, more primeval material (e.g., due to infall), and more stellar ^{3}He survival/production; it is characterized by $g_{3\min} = 0.2$, $g_{3*} = 0.8$, $g_{3\max} = 0.3$, $\epsilon = 0.25$, $\epsilon_n = \epsilon^{2n-1}$, $N_0 = 5$, $h_{16} = 0.20$, and $m = 2$ for the first tier, $m = 0$ for the second tier and so on.

These three models certainly do not exhaust the full range of possibilities for galactic chemical evolution, and we have studied a number of other possibilities. An example that illustrates the richness embodied in our approach is a variant of Model 1 which included very significant ^{3}He production by low-mass stars. Rather than shifting to lower primeval abundances, D and ^{3}He were shifted to higher values. This is because histories with many low-mass stars in their past were excluded by the relatively low pre-solar ^{3}He abundance. In any case, we find that Models 0, 1, and 2 serve well to illustrate the extreme range of possibilities.

3 Pre-solar Abundances

The pre-solar D and ^{3}He abundances are derived from ^{3}He/^{4}He ratios measured in meteorites and in the solar wind. Because essentially all primordial D has been burned to ^{3}He in the solar convective zone and the convective zone is not hot enough to burn ^{3}He, the solar-wind value of ^{3}He/^{4}He reflects the pre-solar D + ^{3}He abundance. Measurements made using foil collectors on the moon and by the ICI instrument on the ISEE-3 satellite give ^{3}He/^{4}He ranging from 1×10^{-4} to 10×10^{-4}, depending on the phase of the solar cycle and other factors. Geiss and Reeves (1972) argue that they can correct for the variation and that the solar-wind value is $^3\text{He}/^4\text{He} = (4.1 \pm 1\,\text{stat}) \times 10^{-4}$. This agrees with the low-temperature component released from carbonaceous-chondrite meteorites in step-wise heating experiments, $^3\text{He}/^4\text{He} \simeq 4.5 \times 10^{-4}$, which is believed to be solar-wind material (Black 1972; Wieler et al. 1991). Most recently, measurements were made at high heliographic latitudes with the SWICS instrument on the ULYSSES spacecraft; the year-long average isotopic ratio was determined, $^3\text{He}/^4\text{He} = (4.4 \pm 0.4) \times 10^{-4}$, and fractionation effects were searched for and no evidence was found (Bodmer et al., 1995). Based upon this measurement we adopt $^3\text{He}/^4\text{He} = (4.4 \pm 0.4) \times 10^{-4}$; because some fractionation in the solar-wind cannot be excluded we assign a systematic error of 1×10^{-4}.

The pre-solar ^{3}He/^{4}He ratio is measured in meteorites. Black (1972) proposed that it is the high-temperature component released in step-wise heating of carbonaceous chondrites (also see Eberhardt 1978), $(^3\text{He}/^4\text{He})_{\text{hi T}} \simeq 1.5 \times 10^{-4}$. However, Wieler et al. have argued that the high-temperature component is dominated by gas trapped in pre-solar grains (diamonds) formed in locations far removed from the solar system and propose that the component known as "Q" is a better candidate. Fortunately, the difference between the high-temperature and Q components is small, $(^3\mathrm{He}/^4\mathrm{He})_Q = (1.6 \pm 0.04) \times 10^{-4}$. A systematic error arises since no component has been unequivocally shown to represent pre-solar ^{3}He. Taking $(^3\mathrm{He}/^4\mathrm{He})_Q$ as the pre-solar value, but allowing for a systematic error to include the range encompassed by all would-be pre-solar ^{3}He values yields $(^3\mathrm{He}/^4\mathrm{He})_\odot = (1.6 \pm 0.04 \pm 0.3) \times 10^{-4}$.

In order to convert to abundance relative to hydrogen one needs $(^4\mathrm{He}/\mathrm{H})_\odot$. We use $(^4\mathrm{He}/\mathrm{H})_\odot = 0.095 \pm 0.01$, based upon $Y_\odot = 0.27 \pm 0.01$ and $Z_\odot = 0.015 - 0.02$ as derived from standard solar models (Turck-Chieze et al. 1988; Bahcall & Pinsoneault 1992). From this we infer

$$\left(\frac{\mathrm{D} + {}^3\mathrm{He}}{\mathrm{H}}\right)_\odot = (4.2 \pm 0.7 \pm 1) \times 10^{-5}; \quad (4)$$

$$\left(\frac{^3\mathrm{He}}{\mathrm{H}}\right)_\odot = (1.5 \pm 0.2 \pm 0.3) \times 10^{-5}. \quad (5)$$

It is reassuring that the pre-solar D abundance, given by the difference of these two numbers, is in agreement with the HD/H_2 ratio measured in Jupiter, $\mathrm{HD}/\mathrm{H}_2 \sim (1-3) \times 10^{-5}$ (Smith, Schempp, & Baines 1989). Although planetary D/H ratios are subject to chemical fractionation, it is minimized in Jupiter since the bulk of the deuterium exists as HD (molecular-line blanketing does still leads to significant systematic uncertainties).

4 Discussion

By Monte Carlo we constructed around 300,000 histories for each of our three chemical-evolution models. For each history, we draw pre-solar ^{3}He and D + ^{3}He abundances from a distribution with a gaussian statistical error and top-hat systematic uncertainty. About half of the histories are acceptable: satisfy the oxygen constraint (pre-solar mass fraction between 0.5% and 2%) and have positive primeval ^{3}He abundance. In addition, to ensure that the primeval D abundance is large enough to account for that in the ISM today we weight each point with the probability that the primordial D abundance is greater than $(1.6 \pm 0.1) \times 10^{-5}$. Histograms of the fraction of pre-solar material that is primeval and has been processed through 1 and 2 generations of stars as well as the average ^{3}He survival fraction are shown in Fig. 2. The distribution of inferred primeval D and ^{3}He abundances are shown in Fig. 3; the spread in abundances due to histories alone is also shown and is seen to be very significant. From these distributions and the predicted big-bang abundances (see Copi, Schramm, and Turner 1995) likelihood functions for the baryon-to-photon ratio are generated (see Fig. 4).

For Models 0 and 2 (standard and high-infall model) the 95% confidence intervals are $\eta_{95\%} = (3.7 - 6.6) \times 10^{-10}$ and $\eta_{95\%} = (4.1 - 7.3) \times 10^{-10}$ respectively. For Model 1 (extreme ^{3}He destruction) the interval is shifted to lower values of the baryon-to-photon ratio, $\eta_{95\%} = (2.1 - 4.7) \times 10^{-10}$. This lower bound is slightly smaller than previous ones, because we have allowed for extreme ^{3}He destruction. In the many other models for chemical evolution we have explored, the likelihood function always drops precipitously at a value of η no smaller than 2×10^{-10}—some ^{3}He necessarily survives. While the D abundance measured in the local ISM leads to the upper limit, $\eta \lesssim 9\times10^{-10}$, consideration of the pre-solar D abundance improves this upper bound slightly since the pre-solar D abundance is larger. From all this we conclude that there is a robust concordance interval for D and ^{3}He, $\eta \approx (2-8)\times10^{-10}$.

This D and ^{3}He consistency interval encompasses those derived by others based upon a variety of chemical evolution models (see e.g., Hata et al., 1994; Olive, 1995; Casse and Vangioni-Flam 1995). Our results strongly suggest that the "generic," mean chemical evolution model of Hata et al. (1994), which is supposed to encompass the full range of possibilities for the chemical evolution of D and ^{3}He, is less generic than the authors claim: their 95% confidence interval corresponds to our Model 0.

A determination of the primeval D abundance by measuring D-Lyα absorption by high-redshift hydrogen clouds could both shed light on the chemical evolution of D and ^{3}He as well as accurately determine the baryon density. At the moment, there are conflicting measurements and upper limits, and the situation is very much unsettled (York et al. 1984; Carswell et al. 1994; Songaila et al. 1994; Tytler et al. 1995; Rugers et al. 1995). However, it seems likely that a definitive determination of the primeval D abundance will be made.

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Figure Captions

Figure 1: A typical history; boxes represent stars.

Figure 2: Fraction of solar-system material that has been processed through 0, 1, and 2 stars and the mean survival fraction of ^{3}He for Models 0 (solid), 1 (dotted) and 2 (long dash).

Figure 3: Scatter plot of primeval D and ^{3}He abundances for Model 0. The band represents the big-bang track (prediction including 2σ theoretical uncertainty); histograms show the distributions of predicted primeval D and ^{3}He abundances; dashed histograms illustrate the scatter that arises from heterogeneity alone (the central values of the D and D + ^{3}He abundances were used).

Figure 4: Likelihood functions for η based upon D and ^{3}He abundances for models 0 (solid), 1 (dotted) and 2 (long dash).

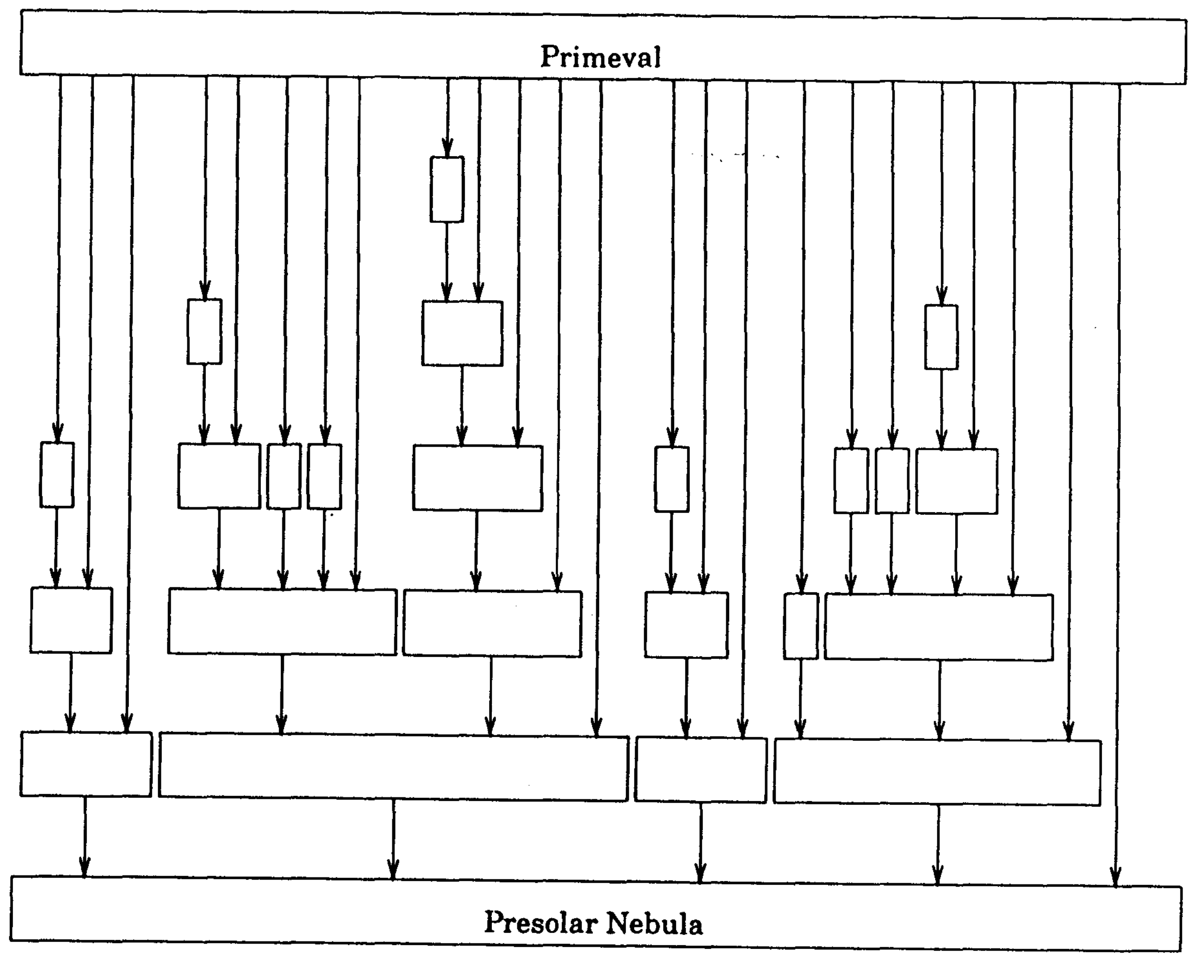

FIG. 1

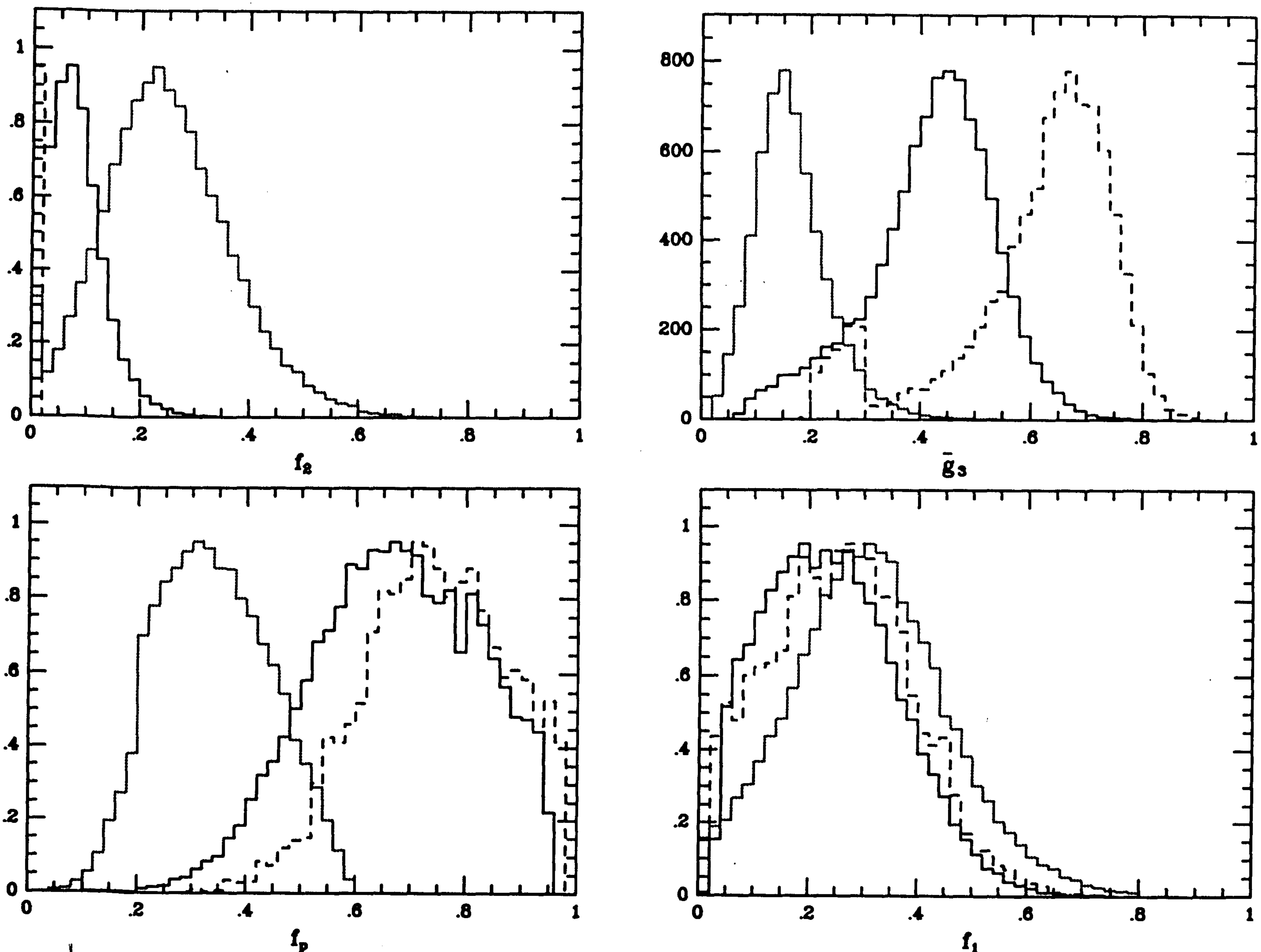

FIG 2

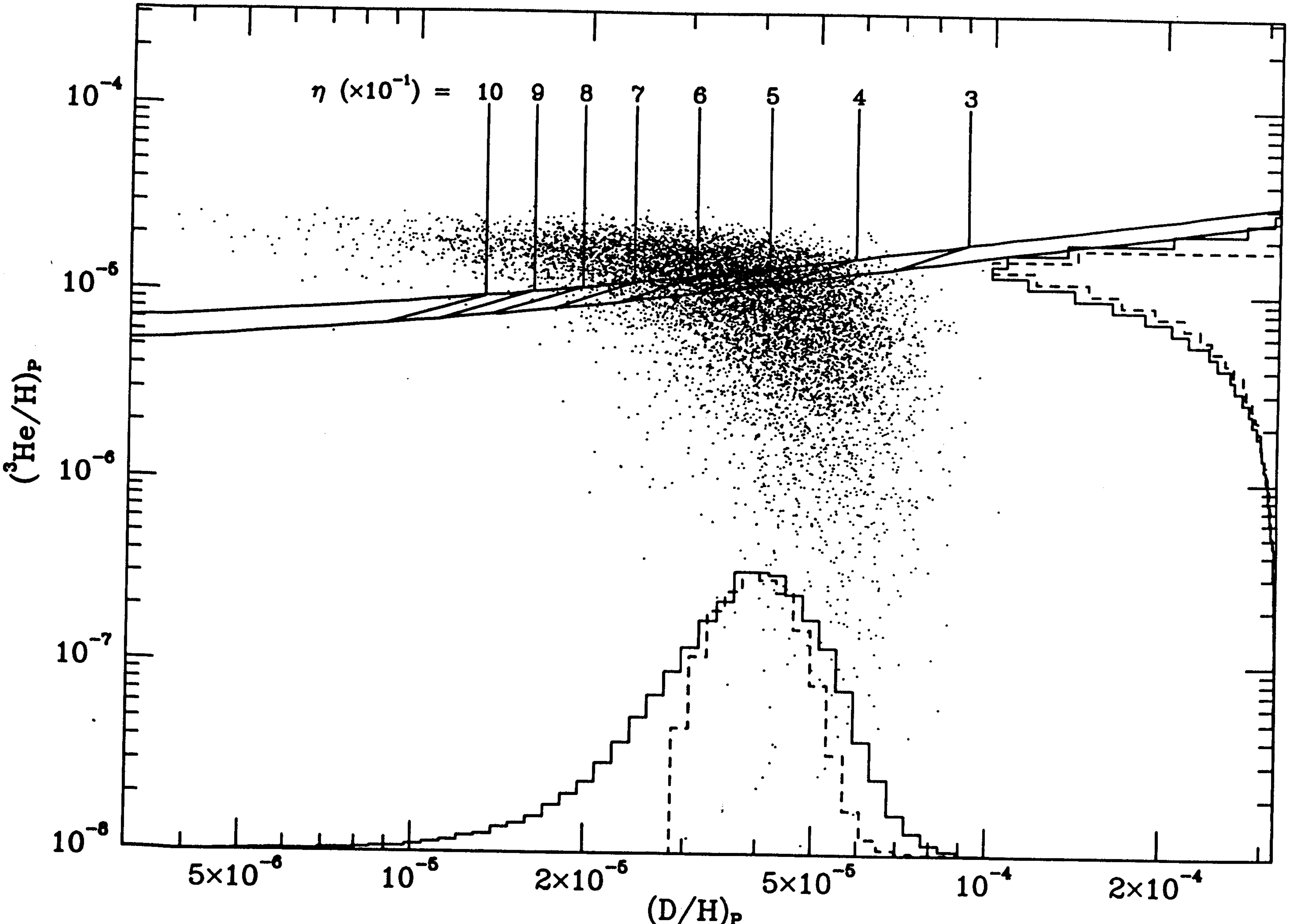
$\eta\ (\times 10^{-1})$ =
10
9
8
7
6
5
4
3
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
$(^3He/H)_P$
5×10^{-6}
10^{-5}
2×10^{-5}
5×10^{-5}
10^{-4}
2×10^{-4}
$(D/H)_P$

FIG 3

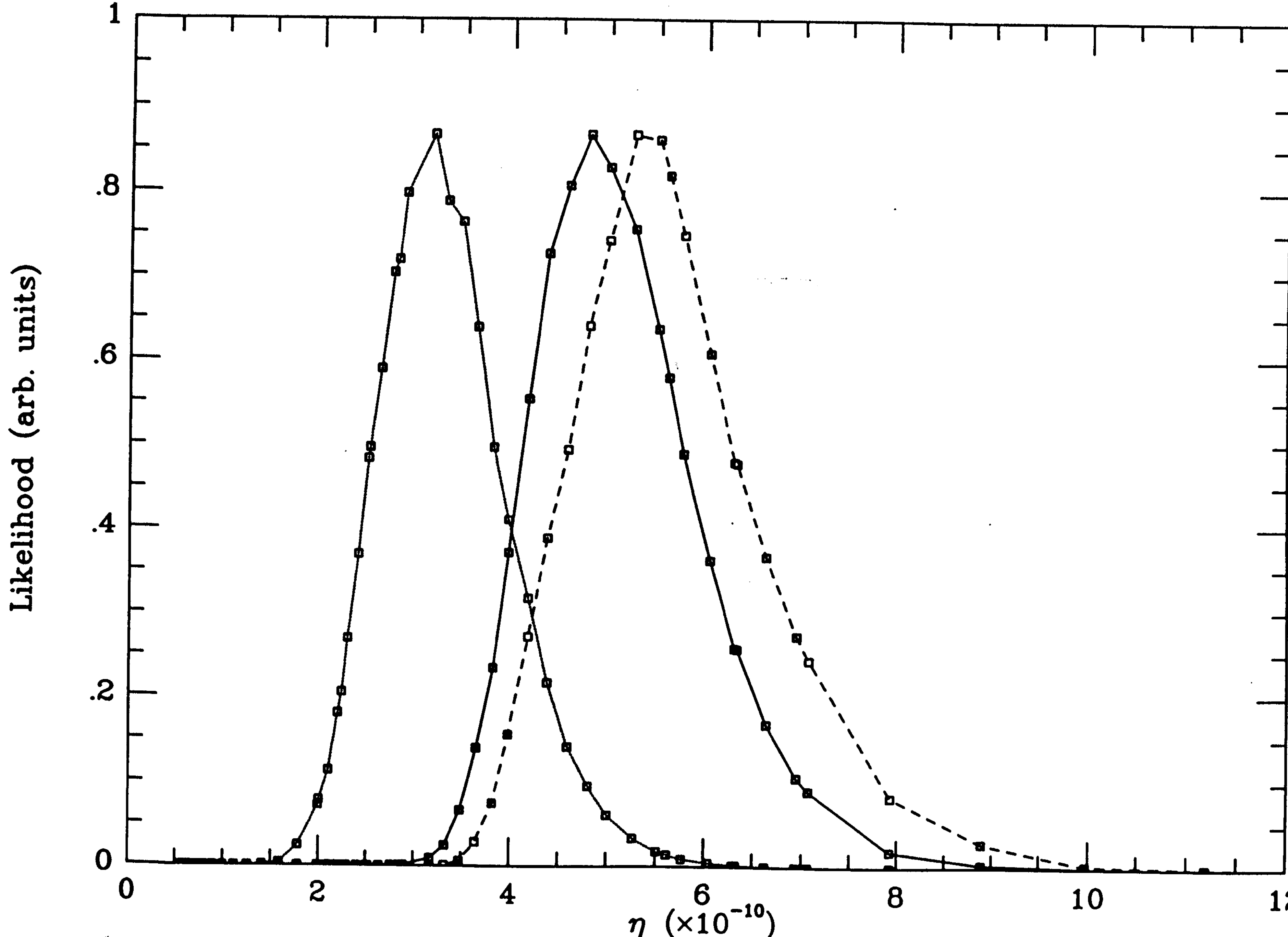

FIG 4