The deuterium abundance in the local interstellar medium

Tijana Prodanović, 1,† Gary Steigman2,† and Brian D. Fields3,†

1Department of Physics, University of Novi Sad, Trg Dositeja Obradovića 4, 21000 Novi Sad, Serbia
2Departments of Physics and Astronomy, Ohio State University, 191 W. Woodruff Avenue, Columbus, OH 43210-1117, USA
3Department of Astronomy and Physics, University of Illinois, 1002 W. Green Street, Urbana, IL 61801, USA

Accepted 2010 March 24. Received 2010 March 22; in original form 2009 November 4

ABSTRACT

As the Galaxy evolves, the abundance of deuterium in the interstellar medium (ISM) decreases from its primordial value: deuterium is ‘astrated’. The deuterium astration factor \( f_D \), the ratio of the primordial D abundance (the \( D \) to \( H \) ratio by number) to the ISM D abundance, is determined by the competition between stellar destruction and infall, providing a constraint on models of the chemical evolution of the Galaxy. Although conventional wisdom suggests that the local ISM (i.e. within \( \sim 1–2 \) kpc of the Sun) should be well mixed and homogenized on time-scales short compared to the chemical evolution time-scale, the data reveal gas-phase variations in the deuterium, iron and other metal abundances as large as factors of \( \sim 4–5 \) or more, complicating the estimate of the ‘true’ ISM D abundance and of the deuterium astration factor. Here, assuming that the variations in the observationally inferred ISM D abundances result entirely from the depletion of D on to dust, rather than from unmixed accretion of nearly primordial material, a model-independent, Bayesian approach is used to determine the undepleted abundance of deuterium in the ISM (or a lower limit to it). We find the best estimate for the undepleted, ISM deuterium abundance to be \( (D/H)_{\text{ISM}} \geq (2.0 \pm 0.1) \times 10^{-5} \). This result is used to provide an estimate of (or an upper bound to) the deuterium astration factor, \( f_D = (D/H)_P/(D/H)_{\text{ISM}} \leq 1.4 \pm 0.1 \).

Key words: ISM: abundances – Galaxy: evolution – galaxies: ISM.

1 INTRODUCTION

Deuterium is created in an astrophysically interesting abundance only during big bang nucleosynthesis (BBN) (Boesgaard & Steigman 1985; Steigman 2007), after which, in the post-BBN Universe, its abundance \( [Y_D] = 10^3 (D/H) \) decreases monotonically due to the processing of gas through succeeding generations of stars where deuterium is completely destroyed (Epstein, Lattimer & Schramm 1976; Prodanović & Fields 2003). Consequently, deuterium plays a special role in cosmology, nuclear astrophysics and in Galactic chemical evolution (GCE; Yang et al. 1984; Boesgaard & Steigman 1985; Steigman & Tosi 1992, 1995; Vangioni-Flam, Olive & Prantzos 1994; Tosi 1996; Schramm & Turner 1998; Romano et al. 2006; Steigman 2007; Steigman, Romano & Tosi 2007, hereafter; Prodanović & Fields 2008). Its relatively simple Galactic evolution permits us to use deuterium to determine the fraction of interstellar gas that has been processed through stars (Steigman & Tosi 1992, 1995). By comparing the primordial and Galactic deuterium abundances one can learn about and discriminate among different Galactic chemical evolution models (Vangioni-Flam et al. 1994; Tosi 1996; Romano et al. 2006; SRT; Prodanović & Fields 2008). Together with non-BBN constraints on the baryon (nucleon) density from observations of the cosmic microwave background (Spergel et al. 2007; Dunkley et al. 2009; Komatsu et al. 2009, 2010), the primordial deuterium abundance, \( Y_D^P \), is predicted by BBN (Cyburt, Fields & Olive 2003; Coc et al. 2004; Steigman 2007; Cyburt, Fields & Olive 2008; Simha & Steigman 2008). The predicted abundance is in excellent agreement with observations of deuterium in high-redshift, low-metallicity quasi-stellar object absorption-line systems (QSOALS; O’Meara et al. 2006; Pettini et al. 2008).

Since deuterium is destroyed in the Galaxy as gas is cycled through stars \( (D/H)_{\text{ISM}} \leq (D/H)_P \). However, all successful chemical evolution models require infall to the disc of the Galaxy of unprocessed (or nearly unprocessed) gas (Tosi 1996; Prodanović & Fields 2008), and such deuterium-rich (and metal-poor) gas would raise the interstellar medium (ISM) \( D/H \) ratio closer to the primordial value. As a result, a comparison of the primordial and ISM deuterium abundances provides a constraint on infall and, therefore, on chemical evolution models. Observations over the past decade and more of the deuterium abundance in the relatively local ISM reveal an unexpectedly large scatter in \( D/H \) (Jenkins et al. 1999; Sonneborn et al. 2000; Hébrard et al. 2002; Hoopes et al. 2003), challenging the conventional wisdom of a well-mixed ISM.
example, as shown in Fig. 1, the absorption-line measurements from the Far Ultraviolet Spectroscopic Explorer (FUSE) reveal variations of a factor of \(\sim 4 \left[0.5 \lesssim y_{\text{ISM}}(D/H) \lesssim 2.2\right] \) in the gas-phase D/H ratios over lines of sight (LOS) to background stars within \(~1–2\) kpc of the Sun. Moreover, the variations in the observed, gas-phase D/H abundances are found to correlate positively with the abundances of refractory elements such as Ti (Prochaska, Tripp & Howk 2005; Lallement, Hebrard & Welsh 2008), and a similar correlation is also found between D and other metals such as Fe and O (Linsky et al. 2006; SRT). However, this positive correlation between the abundances of D and the metals is opposite to the trend expected from stellar nucleosynthesis (D decreasing as the metals increase). Motivated by the observed correlations and by the very large spread in the D/H ratios inferred from the FUSE and other data sets, it has been proposed that the large variations in gas-phase D/H may be due to the depletion of gas-phase deuterium on to dust grains (Jura 1982; Draine 2004, 2006). If this is the case, then the FUSE (and other) gas-phase absorption-line measurements reveal that depletion has not been well mixed (homogenized) in the ISM and the data may only provide a lower limit to the true (undepleted) ISM deuterium abundance and, therefore, only an upper limit to the deuterium astration factor, \(f_0 \equiv y_{\text{ISM}}/y_{\text{ISM}}\).

In Fig. 1, the logs of the deuterium abundances \([\log y_D \equiv 5 + \log N(D) \text{ } - \log N(H)]\) are shown as a function of the logs of the H\(_1\) column densities for the 49 LOS with D\(_1\) column densities from table 2 of Linsky et al. (2006), supplemented by data from Oliveira & Hébrard (2006) and Dupuis et al. (2009). Of these 49 LOS, 41 have iron abundance measurements (filled symbols); 21 of the 49 LOS are within the Local Bubble (LB; see Linsky et al. 2006 for a discussion of the LB) and the remaining 28 non-Local Bubble (nLB) LOS are towards stars beyond the LB (see Section 2.1).

The unexpectedly large spread among the observationally inferred ISM D abundances complicates any estimate of \(y_{\text{ISM}}\). Recognizing this point, Linsky et al. (2006) chose for their estimate of a lower bound to the true (undepleted) ISM deuterium abundance the mean of the five highest D/H ratios finding \(y_{\text{ISM}} \gtrsim 2.17 \pm 0.17\), or when including corrections (see the discussion in Section 2.1) for \(N(H)\) and \(N(D)\) for those LOS outside of the LB, \(y_{\text{ISM}} \gtrsim 2.31 \pm 0.24\). These estimates are quite close to the lower bound to the primordial abundance estimated from the QSOALS, \(y_{\text{BP}} = 2.82^{+0.20}_{-0.19}\) (Pettini et al. 2008),

suggesting a small upper limit to the D astration factor, \(f_0 \lesssim 1.30^{+0.14}_{-0.14}\), or an even smaller value, \(f_0 \lesssim 1.22 \pm 0.15\), for the LB-corrected, nLB deuterium abundances. To account for such a high ISM deuterium abundance and such a small D astration factor, a very high infall rate of pristine material would be needed, challenging many Galactic chemical evolution models (Romano et al. 2006; Prodanović & Fields 2008). By limiting themselves to the five highest D abundances, Linsky et al. (2006) ignore the lower deuterium abundances along many more LOS which are consistent with them within the errors, potentially biasing their estimates of \(y_{\text{ISM}}\) and of \(f_0\).

In an attempt to address this issue, SRT used the 18 highest D/H ratios from the FUSE data (see table 3 of Linsky et al. 2006), finding an ISM D abundance of \(y_{\text{ISM}} = 1.88 \pm 0.11\), corresponding to a D-astration factor \(f_0 \lesssim 1.50^{+0.14}_{-0.14}\), consistent with at least some of the otherwise successful chemical evolution models discussed in SRT. In fact, the data in table 2 of Linsky et al. (2006) reveal that there are 19 LOS with central values of \(\log y_D \geq 0.20\). The weighted mean (along with the error in the mean) for these 19 D abundances is \(\log y_{19} = 0.26 \pm 0.01\), corresponding to \(y_{19} = 1.8 \pm 0.1\). For these 19 LOS the reduced \(\chi^2 = 0.85\), confirming that the weighted mean provides a good description of their D abundances. As more LOS with lower D abundances are added, the weighted mean decreases but the reduced \(\chi^2\) increases, so that \(y_{\text{ISM}} \gtrsim 1.8 \pm 0.1\) is likely a robust lower bound to the ISM D abundance and \(f_0 \lesssim 1.5 \pm 0.1\) (log \(f_0 \lesssim 0.19 \pm 0.03\)) is a robust upper bound to the deuterium astration factor.

Surely, there must be a better way to find a reliable estimate of the maximum value of the deuterium abundance in the local ISM while accounting for the observational errors in the individual D abundance determinations. In Section 2, we describe a Bayesian analysis designed to find the best estimate of the maximum, gas-phase (undepleted), ISM deuterium abundance, \(y_{\text{ISM},\text{max}}\), from data with non-negligible errors and apply it to the FUSE data set. On the assumption that the spread in the observed D abundances is the

---

**Figure 1.** The logs of the deuterium abundances versus the logs of the H\(_1\) column densities (cm\(^{-2}\)) for the 49 FUSE LOS (see the text). The filled symbols are for the 41 LOS which have iron abundance data, while the open symbols are for the eight LOS which lack iron abundances. The squares (blue) are for the LOS within the LB and the circles (red) are for the non-LB (nLB) LOS. The solid line is the mean D abundance for the LB LOS (log \(y_{\text{LB}} = 0.19\)); the dashed line is its extension to the nLB LOS.

---

\(^1\) Since this estimate of \(y_{\text{BP}}\) relies on only seven high-redshift, low-metallicity LOS, and since the dispersion in deuterium abundances among them is unexpectedly large, some prefer to adopt a so-called ‘Wilkinson Microwave Anisotropy Probe (WMAP) D abundance’. WMAP does not observe deuterium. Rather, the WMAP-determined baryon density parameter may be used in a BBN code to predict the relic D abundance. If the Komatsu et al. (2010) estimate of the baryon density is adopted, the BBN-predicted primordial D abundance is \(y_{\text{BP}} = 2.5 \pm 0.1\). However, the WMAP collaboration also provides an estimate of the effective number of neutrinos, \(\Omega_{\text{nu}}\) which, when used along with their baryon density estimate in a BBN code, leads to a different predicted primordial D abundance \(y_{\text{BP}} = 3.0 \pm 0.4\). The difference between these two predictions reflects the difference between the standard model effective number of neutrinos expected and the WMAP observed value, which is within \(~1.5\) of expectations. So, which, if either, ‘WMAP D abundance’ is preferred? Here, we compare observations to observations, not to model-dependent predictions, and adopt the Pettini et al. (2008) value for \(y_{\text{BP}}\).
2 A BAYESIAN ANALYSIS OF THE ISM D ABUNDANCES

To avoid imposing any prior prejudice on which LOS should be included and which excluded in our analysis, or on how the observed D abundances may or may not correlate with iron (or other metals), we adopt a statistical, model-independent method for determining the undepleted Galactic deuterium abundance. Our approach closely follows the model-independent Bayesian analysis developed by Hogan, Olive & Scully (1997) to determine the primordial helium abundance. It is useful to recall the problem Hogan et al. (1997) addressed and how they solved it. Helium-4 is produced abundantly during BBN, and in the post-BBN Universe its abundance is enhanced by stellar produced He. As a result, the He mass fraction, YP, is expected to increase from its primordial value, Yp, along with the metallicity, Z. Extrapolation of the observed Y versus Z relation to zero metallicity results in an estimate of Ymin = Yp. The problem for He is that the form of the Yp versus Z relation is a priori unknown and may even differ from object to object (low metallicity, extragalactic H ii regions). This, in combination with the errors in the observed values of Yp and Z, complicates the derivation of Yp from the data. The challenge confronting Hogan et al. (1997) was to identify Ymin. The Bayesian approach they developed (Hogan et al. 1997) is described below. If, indeed, the observed spread in D abundances results from dust depletion, then their He problem is entirely analogous to the one we confront in using the D abundance data, with its errors, to infer the maximum, gas-phase D abundance.

Here, the FUSE set of Galactic ISM deuterium observations is analyzed assuming only that there exists a ‘true’, uniform, ISM deuterium abundance whose gas-phase value may have been reduced by the depletion of D on to dust grains, with the amount of depletion possibly varying from LOS to LOS. The a priori unknown distribution of depletions is characterized in terms of a Bayesian probability distribution (a ‘prior’), and the data themselves are used to determine both the true ISM deuterium abundance yD ISM = yD max or a lower bound to it, yD ISM ≥ yD max, and a measure of the amount of depletion, the depletion parameter w = yD max − yD min. No prior assumptions about which LOS may have been affected by dust depletion are imposed and the entire data set is analyzed in an unbiased Bayesian manner.

2.1 The data

In our analysis we use the FUSE ISM deuterium abundance data for 46 LOS from Linsky et al. (2006), together with three more recent measurements towards HD41161, HD53975 (Oliveira & Hébrard 2006) and REJ1738+665 (Dupuis et al. 2009). Of the 49 LOS with deuterium abundance measurements, 21 are within the LB (see Linsky et al. 2006 for a discussion of the LB); the remaining 28 are nLB LOS, towards stars beyond the LB. While the star 31 Com is more distant than all the LB stars, the LOS to it has a very low H i column density and an average H i volume density (NH i) = N(H i)/d much smaller than for all LB LOS. According to Piskunov et al. (1997) and Dring et al. (1997), the absorption feature towards 31 Com is at a velocity which is inconsistent with the LB and this LOS likely lies within the hot, ionized LB (which may account for the ‘high’ D and Fe abundances) in the direction of the North Galactic Pole. For a contrary point of view, see Redfield & Linsky (2008). In contrast to the assignment in table 2 of Linsky et al. (2006), we include 31 Com along with the nLB LOS (see Fig. 1). However, this assignment has negligible impact on our quantitative results. Linsky et al. (2006) also list D/H ratios for the nLB LOS corrected by them for assumed average foreground LB D and H abundance. If velocity information were available, it could be used to separate foreground absorption in the LB from that due to gas lying beyond the LB. In the absence of such data, Linsky et al. (2006) assume that the LB extends to N(H i)LB = 10^{19.2} and multiply N(H i)LB by an adopted average D/H ratio to find N(D)/N(H). These two average column densities are subtracted from the D and H i column densities observed for the individual nLB LOS and the ratio of the corrected column densities is used to find corrected D/H ratios. Linsky et al. (2006) base their assumed LB H i column density on the Na i observations of Lallement et al. (2003), who find tentative evidence for an LB ‘wall’ of cold dense gas with N(H i) = 10^{19.5}. This procedure can bias the ‘corrected’ nLB deuterium abundances. For example, it enhances the D abundances along those nLB LOS where the observed D abundance exceeds the adopted LB D abundance and decreases the D abundances for those LOS where the observed D abundance is less than the adopted LB value. The magnitude of the correction increases with the value of the ‘average’ H i column density adopted. In fact, the observed LB H i column and volume densities are distributed very inhomogeneously, varying by nearly a factor of 30 along different LB LOS. This results in a scatter plot for the column densities as a function of distance to the background star. Even for the subset of the most distant LB stars with d ~ 70–80 pc, N(H i) varies by a factor of ~16. 10^{19.5} < N(H i) < 10^{19.1}. The structure of the LB is very complex (Lallement et al. 2003) and the location of the LB ‘wall’ varies from 65 to 150 pc. Thus, the value for the LB H i column density adopted by Linsky et al. (2006) may be an overestimate, leading to an overestimate for their inferred value of yD max, since a smaller choice for the average foreground LB H i column density will result in a smaller correction to N(D) and a lower estimate of yD max. For these reasons, in our analysis, we use the uncorrected H i and D column densities for all nLB LOS.

Following Linsky et al. (2006), we adopt a working hypothesis that the large scatter in the observed gas-phase, ISM deuterium abundances is a reflection of the preferential depletion of deuterium (relative to hydrogen) on to dust grains. Therefore, it is assumed that in the ISM deuterium has a total LOS column density N(D)ISM = N(D)gas + N(D)dust, where the sum includes the observed, gas-phase component, N(D)gas = N(D)obs, and an unobserved, dust-depleted component, N(D)dust. Along any LOS, N(D)ISM ≥ N(D)gas. The data suggest, and we assume, that hydrogen is negligibly depleted on to...
dust and that the fraction of H tied up in molecules in the diffuse ISM probed by FUSE is usually negligible (when H$_2$ is observed, its column density is included in the budget for gas-phase hydrogen), so that $N$(H$_2$)$_{\text{ISM}} = N$(H$_2$)$_{\text{gal}}$.

On the assumption of a uniform D abundance (gas plus dust) in the local ISM, the dispersion among the observed gas-phase D abundances, $y_{D,i}$, reflects the observational errors in $N$(D) and $N$(H), along with any spatial variations in D depletion. Since deuterium may be depleted along ALL local ISM LOS, $y_{D,i} \leq y_{D,\text{max}}$, where $y_{D,\text{max}}$ is the maximum gas-phase (undepleted) deuterium abundance, consistent with the observational errors, and $y_{D,\text{ISM}} \geq y_{D,\text{max}}$. Within the local ISM there will be a depletion so that $y_{D,i} \geq y_{D,\text{min}}$.

Along the i-th LOS, the observed gas-phase D abundance, $y_{D,i}$, differs from the maximum undepleted abundance by an amount $w_i$, where $w_i = y_{D,\text{max}} - y_{D,i}$ and $0 \leq w_i \leq w \equiv y_{D,\text{max}} - y_{D,\text{min}}$. In the absence of observational errors, the observed D abundance along the i-th LOS would lie between $y_{D,\text{min}}$ and $y_{D,\text{max}}$ and would reflect the difference between the maximum undepleted ISM abundance $y_{D,\text{max}}$ and the spatially varying value of $w$, $w_i = y_{D,\text{max}} - y_{D,i}$. Observational errors complicate the task of using the data, $\{y_{D,i}\}$, to identify $y_{D,\text{max}}$ (and $y_{D,\text{min}}$ or $w$).

Since real data do have errors, the observationally inferred D abundance along the i-th LOS, $y_{D,i}$, will differ from the true gas-phase D abundance, $y_{D,i,T}$, by an amount $\delta_i(y_{D,i} = y_{D,i,T} + \delta_i)$. For an individual measurement, the difference between the observed and true D (gas-phase) abundances, $\delta_i$, is unknown. If it is assumed that $\delta_i$ is a random variable drawn from a zero-mean Gaussian of width $\sigma_i$, then the probability distribution for $y_{D,i}$, given a true gas-phase abundance $y_{D,i,T}$ along the i-th LOS is

$$P(y_{D,i}|y_{D,i,T}) = \frac{1}{\sqrt{2\pi}\sigma_i} e^{-(y_{D,i} - y_{D,i,T})^2/2\sigma_i^2}.$$  

(1)

In equation (1), we allow for asymmetrical measurement errors so that $\sigma_{i+}$ corresponds to $y_{D,i} > y_{D,i,T}$ and $\sigma_{i-}$ to $y_{D,i} < y_{D,i,T}$.

### 2.2 Bayesian formalism

For a set of data with errors $\{y_{D,i}, \delta_i\}$, the Bayesian approach described by Hogan et al. (1997) enables a determination of two parameters, $y_{D,\text{max}}$ and $w$ (or $y_{D,\text{min}}$). Along each LOS in the local ISM, the true abundance is related to $y_{D,\text{max}}$ by $y_{D,i,T} = y_{D,\text{max}} - w_i$.

The likelihood of finding particular values of $y_{D,\text{max}}$ and of $w$ (or $y_{D,\text{min}}$), $\mathcal{L}(y_{D,\text{max}}, w)$, from a sample of measurements $y_{D,i}$, with errors $\delta_i$, is

$$\mathcal{L}(y_{D,\text{max}}, w) = \prod_i P(y_{D,i}|y_{D,\text{max}}, w).$$  

(2)

$$\mathcal{L}(y_{D,\text{max}}, w) = \prod_i \int d y_{D,i,T} P(y_{D,i}|y_{D,i,T})$$

$$\times P(y_{D,i,T}|y_{D,\text{max}}, w),$$  

(3)

where $P(y_{D,i}|y_{D,i,T})$ is the probability distribution from equation (1), relating each observed abundance $y_{D,i}$ to its underlying true value $y_{D,i,T}$. $P(y_{D,i,T}|y_{D,\text{max}}, w)$ is the depletion probability distribution – the probability of finding the true, dust depleted, LOS deuterium abundance $y_{D,i,T}$, given the values of the maximum and minimum ISM deuterium abundances, $y_{D,\text{max}}$ and $y_{D,\text{min}} = y_{D,\text{max}} - w$, respectively. Our probability distribution, $P(y_{D,i,T}|y_{D,\text{max}}, w)$, determines the distribution of the $w_i$ to avoid any a priori model dependence and to limit ourselves to the fewest assumptions, following Hogan et al. (1997) we initially adopt the simplest form for this probability distribution – a top-hat function:

$$P(y_{D,i,T}|y_{D,\text{max}}, w) = \begin{cases} 1/w, & y_{D,\text{min}} \leq y_{D,i,T} \leq y_{D,\text{max}} \\ 0, & \text{otherwise} \end{cases},$$  

(4)

where $y_{D,\text{min}} = y_{D,\text{max}} - w$. The probability distribution is normalized to unity when integrated over $y_{D,i,T}$. Integrating over the range of possible deuterium abundances for $N$ data points, we find the likelihood distribution for the maximum gas-phase deuterium abundance in the local ISM, $y_{D,\text{max}}$, and for $w$

$$\mathcal{L}(y_{D,\text{max}}, w) = \prod_i \frac{1}{2w} \left[ \text{erf} \left( \frac{y_{D,i} - y_{D,\text{min}}}{\sqrt{2}\sigma_i} \right) - \text{erf} \left( \frac{y_{D,i} - y_{D,\text{max}}}{\sqrt{2}\sigma_i} \right) \right].$$  

(5)

Equation (5) is evaluated numerically for a range of $y_{D,\text{max}}$ and $w$ (or $y_{D,\text{min}}$) values to find the combination of these two parameters which maximize the likelihood. In this way the set of deuterium observations, including the errors, is used to find the most likely values of $y_{D,\text{max}}$ and the depletion parameter, $w$, avoiding any prior assumptions about which LOS may, or may not, be affected by depletion of deuterium on to dust, or about how the abundance of D may, or may not, be correlated with the abundance of iron or other metals.

In addition to adopting the top-hat depletion probability distribution, following Hogan et al. (1997) we also explore the consequences of choosing two other asymmetric probability distributions:

$$P(y_{D,i,T}|y_{D,\text{max}}, w) = \begin{cases} \frac{2(y_{D,i,T} - y_{D,\text{min}})}{w^2}, & y_{D,\text{min}} \leq y_{D,i,T} \leq y_{D,\text{max}} \\ 0, & \text{otherwise} \end{cases},$$  

(6)

$$P(y_{D,i,T}|y_{D,\text{max}}, w) = \begin{cases} \frac{2(y_{D,\text{max}} - y_{D,i,T})}{w^2}, & y_{D,\text{min}} \leq y_{D,i,T} \leq y_{D,\text{max}} \\ 0, & \text{otherwise} \end{cases},$$  

(7)

where equation (6) is a positive-bias distribution, favouring smaller depletion of deuterium, while equation (7) is a negative-bias distribution, favouring larger D-depletion. At the referee’s suggestion we have also analyzed the effects of another probability distribution – a bimodal, $M$-shaped bias distribution defined in equation (8), which favours both low and high depletion of deuterium, while moderate depletion is disfavoured. Finally, we also explored the complementary, $A$-shaped probability distribution presented in equation (9).

Both additional distributions are defined with respect to the midpoint $Y_M = (y_{D,\text{max}} + y_{D,\text{min}})/2 = y_{D,\text{max}} - w/2$.

$$P(y_{D,i,T}|y_{D,\text{max}}, w) = \begin{cases} \frac{2(Y_M - y_{D,i,T})}{w(Y_M + w - y_{D,\text{max}})}, & y_{D,\text{min}} \leq y_{D,i,T} \leq Y_M \\ \frac{2(Y_M + y_{D,\text{max}} - w)}{w(Y_M + w - y_{D,\text{max})}}, & Y_M \leq y_{D,i,T} \leq y_{D,\text{max}} \end{cases}.$$  

(8)

$$P(y_{D,i,T}|y_{D,\text{max}}, w) = \begin{cases} \frac{2(y_{D,\text{max}} - y_{D,i,T})}{w(Y_M + w - y_{D,\text{max}})}, & y_{D,\text{min}} \leq y_{D,i,T} \leq Y_M \\ \frac{2(Y_M + y_{D,\text{max}} - w)}{w(Y_M + w - y_{D,\text{max})}}, & Y_M \leq y_{D,i,T} \leq y_{D,\text{max}} \end{cases}.$$  

(9)

All probability distributions are normalized to unity when integrated over $y_{D,i,T}$.

Our Bayesian analysis determines two parameters, the best-fitting values of the maximum and minimum deuterium abundances, $y_{D,\text{max}}$.
and $y_{D,\text{min}} = y_{D,\text{max}} - w$, compatible with the errors in the data and the assumption that any spread in the observed abundances, above and beyond that expected from the errors, is real and reflects the variable ISM depletion of deuterium on to dust. Hogan et al. (1997) were mainly interested in the minimum $^4$He abundance, $Y_{\text{min}}$, and we are primarily interested in the maximum ISM D abundance, $y_{D,\text{max}}$. The likelihood in the $\{y_{D,\text{max}}, w\}$ plane is maximized to find the best estimate of the maximum undepleted D abundance, providing a lower limit to the ISM D abundance ($y_{D,\text{ISM}} \geq y_{D,\text{max}}$). We note that in the absence of observational errors, the depletion parameter, $w$, is restricted to $0 \leq w \leq y_{D,\text{max}}$, since $y_{D,\text{max}} \geq Y_{\text{min}}$. In Figs 2–4, $w$ starts at zero and the dashed lines show the boundary, $w = y_{D,\text{max}}$.

### 2.3 Results

As may be seen from Fig. 1, the distributions of the observed D abundances for the LB and nLB LOS are very different. The LB $y_D$ values show little gas-phase variation from LOS to LOS, in contrast to the nLB D/H ratios, whose variation accounts for most of the factor of ~4 spread in the observed ISM D abundances. Indeed, all 21 LB D abundances are consistent with no variation (within the observational errors) around a weighted mean of $\log(y_{D,\text{LB}}) = 0.19$, corresponding to $y_{D,\text{LB}} = 1.5$. Our Bayesian analysis for all five probability distributions is in agreement with this and yields $w \approx 0$ and $y_{D,\text{max}} \approx y_{D,\text{min}} \approx 1.5$. Our results for three distributions (top-hat, positive-bias, negative-bias), shown in Fig. 2, illustrate this result. A lower bound to the deuterium astration factor may be inferred from the upper bound to the LB deuterium abundances, $y_{D,\text{max}} = y_{D,\text{LB}}$, and the estimate of $Y_{\text{min}}$ from Pettini et al. (2008). For central values of $\log(y_{D,\text{LB}}) \geq 0.19$ and $\log(y_{D,LB}) = 0.45$ (Pettini et al. 2008), $\log(f_{D,\text{LB}}) \leq 0.26$, corresponding to $f_{D,\text{LB}} \leq 1.8$, consistent with the successful Galactic chemical evolution models identified in SRT. This value is also consistent with a wide range of chemical evolution models discussed in Prodanović & Fields (2008) with both low and high infall rates of nearly pristine gas, as well as with a variety of initial mass functions.

In contrast to the LB, the nLB LOS do show large variations among the observed gas-phase D abundances (see Fig. 1). It is thus

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Likelihood contours (68 per cent, 95 per cent, 99 per cent) in the $w$–$y_{D,\text{max}}$ plane for the 21 LB LOS for the top-hat (top panel), the positive-bias (middle panel) and the negative-bias probability distribution (bottom panel). Where $w = y_{D,\text{max}} - y_{D,\text{min}}$ is the depletion parameter. The best-fitting values for all three probability distributions are at $y_{D,\text{max}} = 1.5$ and $w = 0$ ($y_{D,\text{min}} = y_{D,\text{max}}$), rounded off to two significant figures. The dashed line, $w = y_{D,\text{max}}$, represents the lower bound above which the results, in the absence of errors, are unphysical since $y_{D,\text{min}} = y_{D,\text{max}} - w$ becomes negative.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Likelihood contours (68 per cent, 95 per cent, 99 per cent) in the $w$–$y_{D,\text{max}}$ plane for all 49 LOS for the top-hat (top panel), the positive-bias (middle panel) and the negative-bias probability distribution (bottom panel). The dashed line is $w = y_{D,\text{max}}$ (see Fig. 2).

### Footnote

Significant figures and round off: the $H_1$ and D$_1$ column densities listed in Table 2 of Linsky et al. (2006) are typically given to two significant figures (the integers in front of the decimal place simply count the powers of 10). These column densities are used to find $\log(N_D) = 5 + \log(N(D)) - \log(N(H_1))$, where the errors in the logs of the column densities are added in quadrature. As a result, the values of $\log(N_D)$ (and their errors) are only known to two significant figures, and so also are the values of $y_D$ (and their errors) derived from them. However, in table 3 of Linsky et al. (2006) the values of $y_D$ are given to three (or more) significant figures. For our Bayesian analysis we use the data in table 3 of Linsky et al. (2006), but the results presented here are generally rounded to two significant figures. As an example, if we had first rounded the individual values of $y_{D,\text{LB}}$ and $y_{D,LB}$ to two significant figures, we would have found $y_{D,\text{LB}} = 1.5$ and $y_{D,LB} = 2.8$, leading to $f_D/y_{D,\text{LB}} = 1.9$, in contrast to the slightly different value quoted here, which follows from $\log(f_D) \leq \log(y_{D,LB}) - \log(y_{D,\text{LB}}) = 0.26$ and $f_D = 10^{0.26} = 1.8$. 

© 2010 The Authors. Journal compilation © 2010 RAS, MNRAS 406, 1108–1115
expected that the Bayesian analysis of this data subset will find evidence for $w > 0$ at a statistically significant level. This indeed is seen in Figs 4 (top-hat) and 5 (M-shaped bias) where our results are shown separately for the data of the LB (top panel), the nLB (middle panel) LOS, along with those for all 49 LOS (bottom panel). For the 28 nLB LOS, the best-fitting values, from a top-hat distribution, are $y_{D, \text{max}} = 2.1$ and $w = 1.5$. The top-hat Bayesian analysis for the complete FUSE data set (Fig. 4, bottom panel) finds maximum likelihood values of $y_{D, \text{max}} = 2.0$ and $w = 1.3$, corresponding to $y_{D, \text{min}} = 0.7$. The non-zero depletion parameter found for all 49 LOS is driven by the large variations in $y_D$ for the nLB LOS. This value of $y_{D, \text{max}}$ corresponds to $f_D \leq 1.4$, which, within the errors in the measurements of $y_{DF}$ and $y_{D, \text{max}}$, is marginally consistent with the fiducial chemical evolution model discussed in Prodanović & Fields (2008), where even larger infall rates are required for some initial mass functions. On the other hand, when the complete FUSE data set is analyzed with the M-shaped prior suggested by the referee (Fig. 5, bottom panel), the maximum likelihood is obtained for $y_{D, \text{max}} = 1.8$ and $w = 1.0$, corresponding to $y_{D, \text{min}} = 0.8$ and $f_D \leq 1.6$. This result is consistent with the fiducial model adopted in SRT, but not with some of the other Galactic chemical evolution models discussed by them (SRT). Similar to the nLB case, this result is also consistent with some of the models explored in Prodanović & Fields (2008), where the observations allow for both high and low infall rates depending on the choice of the initial mass function. However, the more recent initial mass functions are only consistent with larger infall rates.

As anticipated from Fig. 1, the bottom panels of Figs 4 and 5 confirm that the variation among the gas-phase D abundances for all 49 FUSE LOS is too large to be accounted for by the observational errors ($w \neq 0$ at much greater than 99 per cent confidence), for all adopted probability distributions. Indeed, for example for the top-hat probability distribution, the D abundances for all 49 LOS span a range of nearly a factor of 3, from $y_{D, \text{max}} = 2.0$, down to $y_{D, \text{min}} \equiv y_{D, \text{max}} - w = 0.7$.

The effects of the choices of the priors on the likelihood distributions for $y_{D, \text{max}}$ and $w$ are shown for the complete FUSE data set in Fig. 3 and in the bottom panel of Fig. 5. While the results for the top-hat and positive-bias distributions are quite similar, the negative-bias distribution is notably different. The best-fitting parameters $y_{D, \text{max}}$, $w$ and resulting astration factor $f_D$ are summarized in Table 1. Also presented in the table is $\Delta \ln \mathcal{L}_{\text{max}}$, the difference between the logarithms of the largest maximum likelihood and a maximum likelihood of a given probability distribution. While the M-shaped probability distribution has the largest maximum likelihood value, so that $\Delta \ln \mathcal{L}_{\text{max}} \equiv \ln \mathcal{L}_{\text{max},M} - \ln \mathcal{L}_{\text{max},\text{bias}}$, this

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Likelihood contours (68 per cent, 95 per cent, 99 per cent) in the $w-y_{D,\text{max}}$ plane for the 21 LB LOS (top panel), the 28 nLB LOS (middle panel) and all 49 LOS (bottom panel), using the top-hat probability distribution. The dashed line is $w = y_{D,\text{max}}$ (see Fig. 2).

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Likelihood contours (68 per cent, 95 per cent, 99 per cent) in the $w-y_{D,\text{max}}$ plane for the 21 LB LOS (top panel), the 28 nLB LOS (middle panel) and all 49 LOS (bottom panel), using the M-shaped probability distribution. The dashed line is $w = y_{D,\text{max}}$ (see Fig. 2).

| Bias shape | $y_{D,\text{max}}$ | $w$ | $f_D$ | $\Delta \ln \mathcal{L}_{\text{max}}$ |
|------------|-----------------|-----|------|----------------------|
| Top-hat    | $2.0 \pm 0.1$   | $1.3 \pm 0.2$ | $1.4 \pm 0.1$ | $0.5$ |
| Positive   | $1.9 \pm 0.1$   | $1.4 \pm 0.2$ | $1.5 \pm 0.1$ | $0.9$ |
| Negative   | $2.4 \pm 0.2$   | $1.7^{+0.3}_{-0.2}$ | $1.2 \pm 0.1$ | $2.7$ |
| M-shaped   | $1.8 \pm 0.1$   | $1.0 \pm 0.1$ | $1.6 \pm 0.1$ | $0.0$ |
| A-shaped   | $2.3^{+0.2}_{-0.1}$ | $1.8^{+0.3}_{-0.2}$ | $1.2 \pm 0.1$ | $1.4$ |

Table 1. Results for the different shapes of the adopted priors.
distribution is closely followed by the top-hat and positive-bias priors, suggesting that \( 1.8 \leq y_{\text{D, max}} \leq 2.0 \). The negative-bias prior, favouring large depletion, yields the poorest fit to the data. As may be seen from Fig. 1, the large errors in the data mask which of our priors might provide the best fit. Because the top-hat distribution requires the simplest assumption (no preference), and since its maximum likelihood is similar to that of the M-prior, we also adopt \( y_{\text{D, max}} = 2.0 \pm 0.1 \) as our best estimate for the maximum of the gas-phase, ISM D abundances.

3 SUMMARY AND CONCLUSIONS

In the decades prior to the current era of precision cosmology, the primordial abundance of deuterium provided the only quantitative cosmological baryometer (Boesgaard & Steigman 1985). Although, at present, the deuterium abundance is only measured along seven high-redshift, low-metallicity LOS to background quasars (O’Meara et al. 2006; Pettini et al. 2008), the inferred primordial D abundance, \( y_{\text{D,}} = 2.8 \pm 0.2 \), is in excellent agreement with the non-BBN inferred baryon density parameter (Steigman 2007). In the post-BBN Universe, deuterium is destroyed as gas is cycled through stars, so that comparing the abundance of deuterium in the ISM of the Galaxy with the primordial D abundance provides an estimate of the virgin fraction of the ISM (i.e. the amount of gas presently in the ISM which has never been cycled through stars), constraining models of Galactic chemical evolution (Steigman & Tosi 1992, 1995; SRT; Prodanović & Fields 2008). According to the conventional wisdom, the deuterium-free, metal-enhanced products of stellar nucleosynthesis should be well mixed in the local ISM. In contrast, the FUSE data on the abundances of deuterium and several metals (e.g. iron, oxygen, etc.) along LOS within \(~1–2 \text{ kpc}\) of the Sun reveal a much different picture. The FUSE (Linsky et al. 2006) and earlier observations (Jenkins et al. 1999; Sonneborn et al. 2000; Hébrard et al. 2002; Hoopes et al. 2003; Prochaska et al. 2005) reveal unexpectedly large gas-phase variations in \( y_{\text{D,}} \) (and in the abundances of iron, oxygen, etc.) within the local ISM, as shown for FUSE deuterium data in Fig. 1. It has been proposed that the large variations observed in the local ISM D abundances can be accounted for by preferential depletion of deuterium (relative to hydrogen) on to dust (Jura 1982; Draine 2004, 2006), although incompletely mixed infall of relatively unprocessed, deuterium-enhanced, metal-free material may have contributed to some of the observed variations (Steigman & Tosi 1992, 1995; SRT). The large variations among the ISM D abundances, along with observational errors and the possible contributions from dust depletion and infall, complicate using the D observations to provide a robust estimate of the ISM D abundance which, in combination with the primordial D value, can lead to a constraint on the deuterium astation factor, \( f_{\text{D}} \). The key question is, given the data (with its errors), how to find the best estimate of the ‘true’, undepleted, ISM D abundance?

Here, to address this question, the limits to the true, undepleted, ISM D abundance were investigated employing a model-independent Bayesian statistical analysis similar to that used by Hogan et al. (1997) to infer the primordial helium abundance from a set of helium abundance observations. It was assumed, along with Linsky et al. (2006), that the spread in the observed D abundances is the result of incompletely homogenized D depletion on to dust in the local ISM. In our analysis, this is modelled by five different probability distributions (priors) for the \( y_{\text{D,}} \) values. The \( y_{\text{D,}} \) (actually, \( \log y_{\text{D,}} \)) values shown in Fig. 1 suggest that, given the relatively large errors, a uniform (top-hat) distribution favouring neither low D nor high D may be a good approximation to the data. To explore the sensitivity of our result to the choice of the prior, we first considered two asymmetric distributions – a positive-bias prior favouring low depletion and a negative-bias prior favouring large depletion, as well as two other priors – an M-shaped distribution favouring both low and high depletions and a complementary, \( \Lambda \)-shaped distribution.

Using the FUSE deuterium observations along all 49 LOS (Linsky et al. 2006; Oliveira & Hébrard 2006; Dupuis et al. 2009), we found the likelihoods in the \([y_{\text{D, max}}, w]\) plane for the five choices of the Bayesian priors (see Figs 3 and 5). For all priors, the Bayesian analysis of the full data set requires significant depletion (e.g. \( w \neq 0 \) at greater than 99.9 per cent confidence). Comparing the maximum likelihood values for the five different distributions, we find that the bimodal, M-shaped distribution provides the best fit to the observed data (see Table 1). However, it is important to note that the shapes of the priors require an additional assumption in our analysis, so that the M-shaped distribution is the most model-dependent.

In contrast, the top-hat prior is the least model-dependent, favouring all levels of depletion equally. Given our ignorance of the detailed depletion mechanisms responsible for the observed scatter in the gas-phase ISM deuterium abundances, we prefer to adopt for our estimate of the undepleted, ISM deuterium abundance, the result of the simplest, top-hat prior, whose maximum likelihood is similar to that of the best-fitting M-distribution,

\[ y_{\text{D, ISM}} \geq y_{\text{D, max}} = 2.0 \pm 0.1 = 2.0(1 \pm 0.05). \]

This value is our best estimate of the true ISM D abundance based on the available deuterium observations in the local ISM and is independent of any model-dependent assumptions about galactic chemical evolution. Combining our result with \( y_{\text{D,}} = 2.8 \pm 0.2 = 2.8(1 \pm 0.07) \) (Pettini et al. 2008) (which, recall, provides a lower bound to the primordial abundance) yields a limit to the deuterium astation factor, \( f_{\text{D}} \leq 1.4 \pm 0.1 \) (for the M-prior, \( f_{\text{D}} \leq 1.6 \pm 0.1 \), consistent with most, but not all, Galactic chemical evolution models (SRT; Prodanović & Fields 2008; Romano 2010). If, on the other hand, we compared this \( y_{\text{D, ISM}} \) value to the BBN + WMAP inferred primordial D abundance, for example \( y_{\text{D,}} = 2.5 \pm 0.1 \) (Steigman 2010), \( y_{\text{D,}} = 2.5 \pm 0.2 \) (Cyburt et al. 2008) or the prediction inferred when including the WMAP-determined effective number of neutrino species (Komatsu et al. 2010), \( y_{\text{D,}} = 3.0 \pm 0.4 \), the resulting deuterium astation factor would be somewhat lower in first two cases, \( f_{\text{D}} \approx 1.3 \pm 0.1 \), which is marginally problematic for some GCE models. In contrast, for the Komatsu et al. (2010) value of \( y_{\text{D,}} \), \( f_{\text{D}} \leq 1.5 \pm 0.2 \), which is entirely consistent with GCE models.

As seen in Figs 1–4, for the LB there is little scatter among the gas-phase D abundances. The small scatter is entirely consistent with the observational errors (\( w = 0 \)) and all LB D abundances are consistent, within the errors, with \( y_{\text{D, LB}} = 1.5(1 \pm 0.03) \). This suggests that for the LB, \( y_{\text{D, ISM}} \geq y_{\text{D, LB}} \) and \( f_{\text{D, LB}} \leq 1.8 \pm 0.1 \), consistent with all the successful chemical evolution models identified in SRT. However, while the uniform LB D abundance suggests that

\[ \text{3 The M-shaped prior favours both low and high levels of D depletion while strongly disfavouring intermediate depletion, suggesting that two competing processes may be at work: depletion on to dust and evaporation from dust, perhaps due to exposure to shocks. To fit the M-prior scenario, both processes would have to be efficient and rapid to account for the deficit of intermediate D abundances. The distribution of the presently available data (with its errors) is inconclusive and does not strongly favour any of the adopted prior distributions. When more data become available, the Bayesian approach presented here may be used to learn more about the mechanism of deuterium depletion on to dust.} \]
D may be undepleted in the LB, for all LOS, \(Y_{D,\text{max}} \approx 1.3 \, Y_{D,\text{LB}}\), suggesting either that D is depleted uniformly in the LB or that outside of the LB the gas-phase deuterium abundance may have been enhanced along some LOS by the addition of nearly primordial gas which has recently fallen into the disc of the Galaxy in the form of cloudlets which take some time to mix with the pre-existing gas in the ISM. Does \(Y_{D,\text{LB}} = 1.5\) or \(Y_{D,\text{max}} = 2.0\) provide the best estimate of the lower bound to the ISD D abundance? If deuterium is depleted on to dust, why is there not a strong correlation between deuterium abundance and iron depletion \(^4\) (Linsky et al. 2006) and which refractory element is then best to use as proxy for determining deuterium depletion on to dust? These questions cannot be answered by the analysis presented here. In a companion paper (Steigman & Prodanović, in preparation), abundances of refractory elements are used in concert with the deuterium abundances in an attempt to resolve this question.

**ACKNOWLEDGMENTS**

We are grateful to the referee (J. L. Linsky) for a constructive and valuable report which has helped us to improve on our original manuscript. GS acknowledges valuable discussions with D. Romano and M. Tosi, and we thank M. Tosi, C. Hogan and V. Pavlidou for helpful remarks on an earlier version of this manuscript. The work of TP is supported by the Provincial Secretariat for Science and Technological Development and by the Ministry of Science of the Republic of Serbia under project number 141002B.

The research of GS is supported at The Ohio State University by a grant from the US Department of Energy. Some of the work reported here was carried out when GS was a Humboldt Awardee at the MPI and the LMU for hospitality. GS is grateful to the AvH for its support and the Max Planck Institute for Physics and the Ludwig Maximilians University in Munich. This paper has been typeset from a TeX file prepared by the author.

---

\(^4\) As pointed out by the referee, shock strength may play a role in accounting for the scatter observed in the correlation between the gas-phase D and Fe abundances. If deuterium is loosely bound to the grain mantle while iron is locked into the core of the dust grain, deuterium would be more easily returned to the gas than iron when grains are exposed to shocks of modest strength, while iron might be removed from dust grains only by stronger shocks. The scatter in the correlation between the gas-phase D and Fe abundances may be an indicator of shock strength.