On the Deuterium-to-hydrogen Ratio of the Interstellar Medium

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Abstract

Observational studies show that the global deuterium-to-hydrogen ratio (D/H) in the local interstellar medium (ISM) is about 90% of the primordial ratio predicted by Big Bang nucleosynthesis. The high (D/H)ISM implies that only a small fraction of interstellar gas has been processed through stars, which destroy any deuterium they are born with. Using analytic arguments for one-zone chemical evolution models that include accretion and outflow, I show that the deuterium abundance is tightly coupled to the abundance of core collapse supernova (CCSN) elements, such as oxygen. These models predict that the ratio of the ISM deuterium abundance to the primordial abundance is \( \frac{X_D}{X_H^P} \approx (1 + rZ_O/m_{O^5}^{\text{cc}})^{-1} \), where \( r \) is the recycling fraction, \( Z_O \) is the ISM oxygen mass fraction, and \( m_{O^5}^{\text{cc}} \) is the population-averaged CCSN yield of oxygen. Using values \( r = 0.4 \) and \( m_{O^5}^{\text{cc}} = 0.015 \) appropriate to a Kroupa initial mass function and recent CCSN yield calculations, solar oxygen abundance corresponds to \( \frac{X_D}{X_H^P} \approx 0.87 \), consistent with the observations. This approximation is accurate for a wide range of parameter values, and physical arguments and numerical tests suggest that it should remain accurate for more complex chemical evolution models. The good agreement with the upper range of observed (D/H)ISM values supports the long-standing suggestion that sightline-to-sightline variations of deuterium are a consequence of dust depletion, rather than a low global (D/H)ISM enhanced by localized accretion of primordial composition gas. This agreement limits deviations from conventional yield and recycling values, including models in which most high-mass stars collapse to form black holes without expelling their oxygen in supernovae, and it implies that Galactic outflows eject ISM hydrogen as efficiently as they eject CCSN metals.

Key words: Galaxy: abundances – Galaxy: evolution – Galaxy: formation – Galaxy: general

1. Introduction

Most of the atoms of our everyday world were once inside a star. As astronomers, we are accustomed to explaining this remarkable fact in our undergraduate classes and popular lectures. Most atoms in the local interstellar medium (ISM), by contrast, were never inside a star. We know this because the deuterium-to-hydrogen ratio (D/H) measured from absorption lines through the ISM approaches 90% of the primordial (D/H) ratio (Linsky et al. 2006), and stars destroy 100% of the deuterium they are born with.1 Everyday objects are of course biased toward heavy elements, but even so, this stark difference between the history of atoms on Earth and those in the ISM may seem surprising at first glance.

In fact, as discussed in some detail by Tosi et al. (1998), Romano et al. (2006), and Steigman et al. (2007), chemical evolution models that reproduce other aspects of the local stellar and ISM abundances typically give good agreement with the observed ISM (D/H). In this paper I argue that the (D/H) ratio should be closely tied to the ISM oxygen abundance, and that for the roughly solar oxygen abundance the (D/H) ratio should be 85%–90% of its primordial value. This conclusion is consistent with previous findings about ISM deuterium, and it implies that they are robust to many details of the assumed chemical evolution model but sensitive to adopted supernova yields. My analysis makes use of an analytic formalism for chemical evolution presented by Weinberg, Andrews, & Freundenburg (2017, hereafter WAF). Because this paper focuses on oxygen as a metallicity tracer, it avoids the more complicated aspects of the WAF formalism that are connected to SNIIa elements. The modeling approach can be seen as a generalization of the one originally introduced by Larson (1972).

The (D/H) ratio measured from UV absorption spectroscopy shows large variations from sightline to sightline through the local ISM (Linsky et al. 2006). This variation most likely reflects variable depletion onto dust grains (Draine 2006; Linsky et al. 2006), a point I return to in Section 3. Linsky et al. (2006) estimate a global (D/H) in the ISM (2.31 ± 0.24) × 10⁻⁵, which is (90 ± 10)% of the value (2.58 ± 0.13) × 10⁻⁵ predicted by Big Bang nucleosynthesis (BBN) for the baryon density implied by cosmic microwave background observations (Cyburt et al. 2016; see also Nollett & Steigman 2014; Coc et al. 2015).

Before proceeding to a more careful derivation, it is worth giving an order-of-magnitude argument that explains this result. For a Kroupa (2001) initial mass function (IMF) truncated at 0.1 and 100 \( M_\odot \), and the supernova yields of Chiefi & Limongi (2004) and Limongi & Chiefi (2006), core collapse supernovae (CCSNe) produce an average of 1.5 \( M_\odot \) of oxygen for every 100 \( M_\odot \) of star formation (WAF; Andrews et al. 2017). For the same initial mass of stars, the total mass of gas returned from SN ejecta and the envelopes of AGB stars is 40 \( M_\odot \) after 2 Gyr and 45 \( M_\odot \) after 10 Gyr. If the ISM consisted entirely of material that had been through stars, then the predicted oxygen abundance would be approximately 1.5 \( M_\odot /45 M_\odot = 3.3\% \) by mass. Using the photospheric scale of Lodders (2003), the solar oxygen abundance is 0.56% by mass, about 1/6 of this value. Therefore, if the ISM oxygen abundance is approximately solar, the material returned from

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1 Protostars are fully convective and draw deuterium nuclei into layers hot enough to fuse them into helium (Bodenheimer 1966; Mazzitelli & Moretti 1980).
stars must have been diluted by five times as much unprocessed gas. The analysis in the next section treats inflow and outflow more explicitly and leads to the same conclusion.

2. Evolution of [O/H] and (D/H)

The WAF formalism applies to a one-zone model in which stars form from a reservoir of gas that is fully mixed at all times. The star formation rate (SFR) is \( M_\star(t) = M_\star(t)/\tau_\text{sfh} \), where \( M_\star(t) \) is the gas mass at time \( t \), and the star formation efficiency (SFE) timescale \( \tau_\text{sfh} \) is assumed to be constant in time to allow for analytic solutions. Constant \( \tau_\text{sfh} \) is equivalent to the “linear Schmidt law” adopted in many other analytic models of chemical evolution (e.g., Recchi et al. 2008). For the analytic calculations in this paper I adopt an exponential star formation history (SFH), \( M_\star(t) = M_\star(0)e^{-t/\tau_\text{sfh}} \), which approaches a constant SFR in the limit of long \( \tau_\text{sfh} \). Star formation is assumed to drive outflows with a constant mass-loading factor of \( \eta = M_\text{out}/M_\star \). I use numerical calculations to examine some more complex scenarios in Section 2.5.

2.1. Oxygen

In the instantaneous recycling approximation, the evolution equation for the total mass of oxygen in the ISM is

\[
M_\text{O} = m_\text{cc}Z_\text{O}M_\star - Z_\text{O}M_\text{M} - Z_\text{O}e^{-t/\tau_\text{out}}M_\star + M_\text{inf}M_\star,
\]

where \( Z_\text{O}(t) \) is the current ISM oxygen abundance by mass. The first term represents enrichment by CCSNe with an IMF-averaged yield of \( m_\text{cc} \), i.e., for each solar mass of star formation, \( m_\text{cc} \) solar masses of oxygen are produced by massive stars and are returned to the ISM. I adopt \( m_\text{cc} = 0.015 \) based on the IMF and yield assumptions described in Section 1. The second term represents depletion of oxygen already in the ISM into stars. The third term represents depletion by outflow, with a mass-loading factor of \( \eta \). Producing solar abundances at late times requires \( \eta \approx 2.5 \) (WAF). The fourth term represents recycling of the oxygen stars were originally born with, where \( r \) is the fraction of mass formed into stars that is returned to the ISM by supernovae and by the winds of evolved stars. For a Kroupa (2001) IMF the recycled fraction is \( r(t) = 0.37, 0.40, \) and 0.45 after 1, 2, and 10 Gyr, respectively. The approximation in Equation (1) treats this recycling as instantaneous with a single effective value of \( r \), and WAF show that for \( r = 0.4 \) this approximation reproduces numerical results with full time-dependent recycling quite accurately.

The gas mass in the ISM is depleted by star formation and outflow and is replenished by recycling and inflow, with time derivative of

\[
M_\text{s}(t) = -(1 + \eta - r)M_\star + M_\text{inf}(t).
\]

In the absence of accretion, star formation and outflow with \( M_\text{s}(t) = M_\text{s}(t)/\tau_\text{dep} \) would deplete the gas supply on an e-folding timescale of

\[
\tau_\text{dep} = \tau_\text{s}/(1 + \eta - r).
\]

More generally, the infall rate \( M_\text{inf}(t) \) is determined implicitly by the adopted SFE timescale and SFH. For constant \( \tau_\text{s} \) one can set \( M_\star = \tau_\text{s}M_\star \), and with an exponential SFH yielding \( M_\star = -M_\star/\tau_\text{sfh} \), one obtains

\[
M_\text{inf} = (1 + \eta - r - \tau_\text{s}/\tau_\text{sfh})M_\star.
\]

I assume below that infalling gas has primordial composition, i.e., no oxygen and the BBN value of (D/H).

For an exponential SFH, Equation (1) can be rewritten as

\[
M_\text{O} = \frac{M_\text{O}}{\tau_\text{dep}}M_\star + \frac{m_\text{cc}}{\tau_\text{sfh}} e^{-t/\tau_\text{out}},
\]

where \( \mu(t) = e^{t/\tau_\text{out}} \), \( f(t) \) is the driving term on the rhs of Equation (5), and an arbitrary integration constant has been set to zero to satisfy the boundary condition \( M_\text{O} = 0 \) at \( t = 0 \). The result is

\[
M_\text{O}(t) = m_\text{cc}Z_\text{O}M_\star e^{-t/\tau_\text{out}} - e^{-t/\tau_\text{out}},
\]

where I have introduced the notation,

\[
\tau = \left( \frac{1}{\tau_\text{dep}} - \frac{1}{\tau_\text{sfh}} \right)^{-1},
\]

for a “harmonic difference timescale” composed of the gas depletion and SFH timescales. (In WAF, where there are several such timescales, this particular quantity is denoted as \( \tau_\text{dep,shf} \).) To get the oxygen abundance, one divides \( M_\text{O}(t) \) by \( M_\star(t) = \tau_\text{s}M_\star(t) \), and with notation (8) one can express the result as

\[
Z_\text{O}(t) = m_\text{cc} \frac{\tau}{\tau_\text{s}} (1 - e^{-t/\tau}) = Z_\text{O,eq}(1 - e^{-t/\tau}).
\]

Here \( Z_\text{O,eq} \) is the “equilibrium” oxygen abundance approached at times \( t \gg \tau \):

\[
Z_\text{O,eq} = m_\text{cc} \frac{\tau}{\tau_\text{s}} = \frac{m_\text{cc}}{1 + \eta - r - \tau_\text{s}/\tau_\text{sfh}}.
\]

Once the ISM reaches this equilibrium abundance, enrichment from further star formation is balanced by dilution from inflow and depletion by star formation and outflow.

2.2. Deuterium

The deuterium mass in the ISM changes because of accretion, which brings in gas at the primordial deuterium abundance, and because of star formation and outflows, which consume gas at the current ISM abundance. The evolution equation is

\[
M_\text{D} = X_\text{D}M_\text{inf} - \frac{M_\star(1 + \eta)}{1 + \eta - r - \tau_\text{s}/\tau_\text{sfh}}. \tag{11}
\]

Note that \( X_\text{O} \) and \( X_\text{D} \) refer to the deuterium mass fraction, while \((\text{D/H})\) and \((\text{D}/\text{H})_\text{py} \) refer to the \( \text{D}/\text{H} \) by number. The ratios \( X_\text{D}/X_\text{O} \) and \((\text{D}/\text{H})/(\text{D}/\text{H})_\text{py} \) are, of course, equal.
In contrast to oxygen evolution, there is no recycling term because any deuterium that enters a star is destroyed before being returned to the ISM. Using \(X_D M_* = X_D M_*/\tau_8 = M_D/\tau_8\) and Equation (4) for the infall rate with an exponential SFH yields

\[
M_D + \frac{1 + \eta}{\tau_8} M_D = X_D^p (1 + \eta - r - \tau_8/\tau_{sfh}) M_*, 0 \exp(-t/\tau_{sfh}.
\]

(12)

This equation can be solved by the same technique used previously for oxygen, with the boundary condition that \(M_D = X_D^p M_*\) at \(t = 0\). After some manipulation, the result can be expressed in the form of

\[
X_D(t) = X_D^p (1 + C)^{-1} [1 + C e^{-\eta/r - 1/f}],
\]

(13)

with the constant

\[
C = \frac{r}{1 + \eta - r - \tau_8/\tau_{sfh}} = \frac{Z_{O, eq}}{m^c_O},
\]

(14)

where \(Z_{O, eq}\) is the equilibrium oxygen abundance of Equation (10). For \(r = 0\), Equation (13) yields \(X_D = X_D^p\) at all times, which is as expected because in this case all of the hydrogen in the ISM is primordial by definition. The solution (13) can be verified by direct substitution into Equation (12), noting that the rhs of (12) can be written as \(X_D^p M_*(t) \times (r/C)\).

At \(t = 0\), Equation (13) yields \(X_D = X_D^p\) as expected. However, once \(r\) becomes large compared to either \(\tau_8/\eta\) or \(\tau\), then \(X_D\) approaches an equilibrium value of

\[
X_D_{eq} = X_D^p (1 + C)^{-1} = \frac{X_D^p}{1 + 2X_{O, eq}/m^c_O}.
\]

(15)

Continuing infall leads to an equilibrium in which the loss of deuterium to star formation and outflow is balanced by accretion of primordial composition gas. Equation (15) is the principal mathematical result of this paper, showing the relation between ISM deuterium and oxygen abundances in equilibrium, and the dependence of this relation on the physical parameters \(X_D^p\), \(r\), and \(m^c_O\).

2.3. Evolutionary Tracks

Figure 1 plots the evolution of the oxygen and deuterium abundances for a variety of parameter choices. The solid black curves show a case with an SFE timescale of \(\tau_h = 2\) Gyr, typical of that found for molecular gas in star-forming galaxies (Leroy et al. 2008), a slowly declining SFH with \(\tau_{sfh} = 6\) Gyr, and a mass-loading parameter \(\eta = 2.5\) chosen to yield \(Z_{O, eq}\) near solar. With a depletion timescale of 0.65 Gyr (Equation (3)), the oxygen abundance rises quickly to its equilibrium value, and deuterium declines to the corresponding equilibrium within 2 Gyr. The solid green curves have \(\tau_{sfh} = 2\) Gyr, which raises \(Z_{O, eq}\) because of the more rapidly declining gas supply. The equilibrium deuterium abundance is correspondingly lower. Magenta solid curves show a model with much lower SFE, \(\tau_h = 8\) Gyr. Here the approach to equilibrium is much slower, though both oxygen and deuterium are nearly constant after \(t = 10\) Gyr.

The dotted curves show the same cases but with a lower mass-loading factor of \(\eta = 1.0\). Here the equilibrium oxygen abundances are higher because more of the metals produced by stars are retained, and the equilibrium deuterium abundances are lower because a larger fraction of the ISM consists of stellar ejecta. The lower outflow rate also lengthens the gas depletion time, and for \(\tau_h = 8\) Gyr the abundances have not yet reached their equilibrium values by \(t = 12.5\) Gyr. For all of these models, the predicted trend of \([O/H]\) with time is nearly flat over the past 8–10 Gyr, in qualitative agreement with the
observed age–metallicity relation of stars (e.g., Edvardsson et al. 1993; Bensby et al. 2014; Feuillet et al. 2016), but explaining the detailed trends and the considerable scatter in the age–metallicity relation requires radial mixing of stellar populations, beyond the scope of the one-zone models used here (D. Feuillet et al. 2017, in preparation).}

Figure 2 plots the evolution of these models in the plane of $X_D/X_D^p$ versus [O/H]. Remarkably, they are nearly superposed on a universal curve. The circles show the obvious generalization of Equation (15),

$$X_D = \frac{X_D^p}{1 + rZ_O/m_O^{cc}},$$

which simply assumes that the equilibrium relation also applies at earlier times. This formula describes the model results very well, though it slightly overpredicts $X_D$ for super-solar [O/H]. I have tried other values of $r$ and $m_O^{cc}$ and find that they yield equally good agreement between full evolution and Equation (16).

Why does a formula derived for equilibrium abundances hold so well for systems that have not yet reached equilibrium? The mathematical answer is not obvious, but the ansatz of Equation (16) is closely connected to the approximate argument given in the introduction. Suppose that the ISM consisted of a mix of primordial gas, with zero oxygen abundance, and gas that had been through stars precisely once, with oxygen abundance of $m_O^{cc}/r$. The overall ISM oxygen abundance in this case would be $Z_O = f_{rec}m_O^{cc}/r = (1 - f_{prim})m_O^{cc}/r$, where $f_{rec}$ and $f_{prim} = 1 - f_{rec}$ are the mass fractions of recycled and primordial material, respectively. The deuterium abundance is $X_D f_{prim}$, and substituting for $f_{prim}$ gives

$$X_D \approx X_D^p(1 - rZ_O/m_O^{cc}),$$

which is equal to Equation (16) at the first order in $rZ_O/m_O^{cc}$. Equation (17) is approximate because some of the gas in the recycled component has been through stars more than once, making the oxygen abundance in this component higher than $m_O^{cc}/r$ and it is somewhat less accurate than Equation (16) at super-solar [O/H]. Nonetheless, the accuracy of Equation (16) appears to be rooted in fairly basic accounting, and it becomes exact in the limit of equilibrium.

2.4. Metal-enriched Winds

Equation (1) implicitly assumes that the gas ejected in winds has the current ISM abundance of $Z_O(t)$. If winds are driven by the energy or momentum input from supernovae and massive stars, then it is possible that the metallicity of ejected material is higher than that of the ambient ISM, with significant impact on the chemical evolution predictions (e.g., Pilyugin 1993; Marconi et al. 1994; Recchi et al. 2008; Spitoni 2015). In the extreme limit, CCSN ejecta could escape from the galaxy without entraining ISM gas at all. The relation between ISM oxygen and deuterium abundances can set constraints on the degree of metal enhancement in winds.

If the metallicity (specifically, the oxygen abundance) of ejected material is higher than that of ambient ISM gas by a factor of

$$\xi_{enh} = \frac{Z_{wind}}{Z_{ism}},$$

then the third term on the rhs of Equation (1) is multiplied by $\xi_{enh}$ while other terms are unchanged. The solution for oxygen evolution is the same as before except that $\eta$ is replaced by $\xi_{enh} \eta$, the effective mass-loading factor for oxygen ejection, in both the equilibrium abundance (Equation (10)) and the depletion timescale (Equation (3)). Thus, for $\xi_{enh} > 1$ and a given $\eta$, oxygen evolves to a lower equilibrium abundance and reaches that equilibrium more quickly.

Deuterium evolution depends on the overall mass outflow rate, independent of $\xi_{enh}$, so Equation (13) and the first equality of Equation (14) are unchanged. However, metal-enhanced winds alter the relation between the equilibrium deuterium and oxygen abundances to

$$X_{D,eq} = \frac{X_D^p}{1 + \beta rZ_O,eq/m_O^{cc}},$$

where $Z_{O,eq}$ represents the equilibrium oxygen abundance in the metal-enhanced case and

$$\beta = \frac{1 + \xi_{enh} - \tau_s/\tau_{enh}}{1 + \eta - \tau_s/\tau_{enh}}.$$
Figure 3. Ratio of equilibrium deuterium abundance to the primordial abundance as a function of the enhancement factor $\xi_{\text{enh}} = Z_{\text{wind}}/Z_{\text{ISM}}$, the ratio of wind metallicity to ISM metallicity. Solid, dotted, and dashed curves show cases in which the equilibrium oxygen abundance is solar, $[\text{O}/\text{H}]_{\text{eq}} = -0.2$, and $[\text{O}/\text{H}] = +0.1$, respectively. All of the cases assume $\tau_h/\tau_{\text{th}} = 1/3$.

Figure 3 illustrates the magnitude of this effect, where I have adopted $\tau_h = 2.0$ Gyr and $\tau_{\text{th}} = 6.0$ Gyr. For each value of $\xi_{\text{enh}}$, the value of $\eta$ is chosen to yield a solar equilibrium abundance (solid curve) or $[\text{O}/\text{H}]_{\text{eq}} = -0.2$ (dotted curve) or $+0.1$ (dashed curve). The equilibrium deuterium abundance decreases with increasing $\xi_{\text{enh}}$, as implied by Equation (19). For example, achieving solar oxygen abundance in the standard case of $Z_{\text{wind}} = Z_{\text{ISM}}$ requires $\eta = 2.4$, with an equilibrium of $X_{D,\text{eq}}/X_{D}^P = 0.87$. However, with a metal-enhancement factor of $\xi_{\text{enh}} = 2$, the required value of $\eta$ is 1.2, and the implied $X_{D,\text{eq}}/X_{D}^P = 0.79$. Unfortunately, dust depletion uncertainties make precise determinations of $(\text{D}/\text{H})_{\text{ISM}}$ challenging, but this value is probably at the lower limit of the acceptable range from Linsky et al. (2006). Metal enhancement with $\xi_{\text{enh}} \gtrsim 3$, implying $X_{D,\text{eq}}/X_D^P \lesssim 0.73$, would be difficult to reconcile with the observed deuterium abundance. There is no obvious physical mechanism for producing metal-depleted outflows ($\xi_{\text{enh}} < 1$), but if they occurred they would lead to higher $X_D$ at a given $[\text{O}/\text{H}]$.

2.5. Numerical Examples

The analytic solutions here apply to a restricted class of models, so to investigate other cases I have written a simple numerical code that integrates the governing differential Equations (1) and (11). Figure 4 compares three different models to a fiducial analytic model with a constant SFE timescale of $\tau_h = 2$ Gyr, an exponential SFH with $\tau_{\text{th}} = 6$ Gyr, and $\eta = 2.5$. Observed star formation laws (Schmidt 1959; Kennicutt 1998) show a nonlinear relation between SFR surface density and total gas surface density, approximately $\Sigma_{\text{SFR}} \propto \Sigma_g^{1.5}$. If we think of a one-zone chemical evolution model as representing an annulus of the Galactic disk, we might therefore expect the SFE timescale to grow as the gas surface density decreases, with $\tau_h \propto M_g^{-0.5}$. The red curves show a numerical model with this SFE scaling and the same exponential SFH. The predicted evolutionary track of $X_D/X_D^P$ versus $[\text{O}/\text{H}]$ is indistinguishable from that of the constant $\tau_h$ model and is in excellent agreement with Equation (16).

The green curves show a model with constant $\tau_h = 2$ Gyr and a constant mass infall rate of $1 M_\odot$ yr$^{-1}$, again with $\eta = 2.5$. With zero initial gas mass, the SFR of this model rises linearly at early times and asymptotes to an equilibrium value of $M_h = M_{\text{inf}}/(1 + \eta - r)$. Despite the very different SFH (as shown in the right panel), the track of this model in the $X_D-[\text{O}/\text{H}]$ plane is indistinguishable from those of the exponential models. A linear-exponential SFH, similar in form to that modeled by Spitoni et al. (2017); see Appendix B of WAF for the relation between these models), also yields a very similar result (not shown). The blue curves show a model with a sharp transition of parameters at $t = 2$ Gyr, from efficient early star formation with low outflow mass loading ($\tau_h = 1$ Gyr, $\tau_{\text{th}} = 3$ Gyr, $\eta = 1$) to slower star formation and higher outflow efficiency ($\tau_h = 4$ Gyr, $\tau_{\text{th}} = 8$ Gyr, $\eta = 2$) at later times. Because of the low initial $\eta$, this model first evolves to super-solar $[\text{O}/\text{H}]$ and $X_D/X_D^P$ approximately but not exactly reversing its original evolutionary track.

Although these examples are not exhaustive, they suggest that the behavior of Equation (16) applies to a wide range of models, provided that outflows eject gas at the ISM metallicity. Further support for this view comes from van de Voort et al. (2017), who investigate deuterium evolution in 3D cosmological hydrodynamic simulations of galaxy formation, which automatically lead to complex outflows and gas mixing processes and produce gas with a wide range of oxygen and deuterium abundances. They find that the median relation between $X_D/X_D^P$ and $[\text{O}/\text{H}]$ is in excellent agreement with Equation (16), and that the $1\sigma$ scatter about this median relation is small.

2.6. Supernova Yields and the IMF

The key parameters influencing the relation between oxygen abundance and deuterium abundance are the oxygen yield $m_{\text{SN},O}^S$ and the recycling fraction $r$. For a Kroupa (2001) IMF truncated at 0.1 $M_\odot$ and 100 $M_\odot$, the solar metallicity supernova yields of Limongi & Chieffi (2006) yield $m_{\text{SN},O}^S = 0.017$, assuming that all stars above 8 $M_\odot$ explode as CCSNe (see Andrews et al. 2017 for details of the IMF-averaged yield calculation). However, the predicted oxygen production is a steeply increasing function of progenitor mass, and if the most massive stars collapse to form black holes instead of exploding, then the IMF-averaged yield can be significantly reduced. The left panel of Figure 5 shows the predicted value of $X_D/X_D^P$ at solar $[\text{O}/\text{H}]$, computed from Equation (16), assuming that all stars with $M > M_{\text{SN, max}}$ collapse to form black holes and release no oxygen.4 I have used the recycling fraction $r = 0.4$, appropriate for a Kroupa (2001) IMF after 2 Gyr, and I have ignored the small impact of black hole formation on $r$ under the assumption that massive stars still return most of the mass they were born with. For a cutoff of $M_{\text{SN, max}} < 37 M_\odot$, the predicted

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4 I am grateful to Brett Andrews for providing me with IMF-averaged yields as a function of $M_{\text{SN, max}}$ calculated using the Limongi & Chieffi (2006) supernova yield tables.
The Kroupa (2001) IMF scales as $M^{-2.3}$ for $M > 0.5 \, M_\odot$ and as $M^{-1.3}$ for $M = 0.1-0.5 \, M_\odot$. A pure $M^{-2.3}$ power-law IMF has more low-mass stars, increasing the total mass of the stellar population by a factor of $\approx 1.3$ for the same number of high-mass stars. (A Salpeter (1955) IMF has a slightly steeper, $M^{-2.35}$ slope.) The dashed curve in Figure 5 shows the value of $\eta$ implied by Equation (21) after reducing both $m_\odot$ and $r$ by this factor of 1.3. Adding low-mass stars does not change the $X_D/X_D^P$ results shown in the left panel because the changes to $m_\odot$ and $r$ cancel in Equation (16). A bottom-heavy IMF reduces the level of outflow required to achieve a solar ISM oxygen abundance, but reducing $\eta$ to zero is still not possible without an observationally unacceptable level of deuterium depletion. A bottom-heavy IMF of this sort also conflicts with the observed stellar populations of the local disk (Kroupa 2001; Chabrier 2003) and with the dynamical mass-to-light ratios of spiral galaxies (Bell & de Jong 2001).

Many models of the galaxy mass-metallicity relation find that strong outflows are required to reproduce observed ISM metallicities (e.g., Finlator & Davé 2008; Peeples & Shankar 2011; Zahid et al. 2012), as implied by Figure 5. However, some Galactic chemical evolution models reproduce properties of the solar neighborhood and the Milky Way disk without invoking outflows. Older papers often treated population-averaged yields as effectively free parameters, and some that did use computed supernova yields overpredicted the solar neighborhood abundance by a factor of two or more even for a Salpeter IMF (e.g., Matteucci & Greggio 1986). Radial gas flows can mitigate the need for outflows by driving enriched gas from the solar annulus inward and replacing it with lower metallicity gas from the outer Galaxy. Fountains of ejected gas that fall back to the disk can also mimic the impact of permanent outflows provided that returning gas is diluted by enough entrained primordial material to reduce its metallicity by a substantial factor. Some no-outflow models with and without radial gas flows yield reasonable agreement with

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**Figure 4.** Evolutionary tracks of $X_D/X_D^P$ vs. [O/H] (left) for models with star formation histories shown in the right panel. The black curves show our fiducial exponential model with constant $\tau_0$, the red curves a model with the same star formation history and “Schmidt Law” $\tau_0$ scaling, the green curves a model with constant mass infall rate, and blue curves a model in which star formation parameters and $\eta$ change suddenly at $t = 2 \, \text{Gyr}$ (see the text). Evolutionary tracks are nearly indistinguishable and agree well with Equation (16) shown by the open circles, but one can see that the two-phase model loops back to lower [O/H] and higher $X_D/X_D^P$ after $\eta$ changes from 1 to 2.

**Figure 5.** (Left) Influence of the upper mass cutoff for supernovae on the predicted deuterium abundance at solar metallicity, computed for a Kroupa (2001) IMF with the oxygen yields of Limongi & Chieffi (2006). A value of $M_{\text{SN, max}} = 37 \, M_\odot$ yields $X_D/X_D^P = 0.8$, the 1σ lower bound on the ISM deuterium abundance from Linsky et al. (2006). (Right) The value of $\eta$ required to yield solar oxygen abundance at equilibrium, as a function of $M_{\text{SN, max}}$. The solid curve shows results for a Kroupa (2001) IMF and the dashed curve for an $M^{-2.3}$ power-law IMF that extends down to $0.1 \, M_\odot$. A 37$M_\odot$ supernova cutoff corresponds to $\eta = 1.0$ or 0.54 in these two cases. Changing the IMF at low masses (below the main sequence turnoff) does not influence the predicted $Y_D$ because it has canceling effects on $m_\odot$ and $r$.

$X_D/X_D^P$ falls below 0.8, in tension with the Linsky et al. (2006) ISM estimates.

The right panel of Figure 5 shows the value of $\eta$ required to produce $Z_{\odot, \text{eq}} = Z_{\odot, \odot}$,

$$\eta = \frac{m_\odot}{Z_{\odot, \odot}} \left( r - 1 - \tau_0/\tau_{\text{sh}} \right),$$

assuming $r = 0.4$ and $\tau_0/\tau_{\text{sh}} = 1/3$ as in the fiducial model. As $m_\odot$ decreases with decreasing $M_{\text{SN, max}}$, the required value of $\eta$ also drops. However, values of $M_{\text{SN, max}}$ that imply $\eta \lesssim 1$ also imply $X_D/X_D^P \lesssim 0.8$, so one cannot eliminate the need for outflows by reducing the oxygen yield without running afoul of the deuterium constraint.
observed ISM oxygen abundances (Mollá & Díaz 2005; Spitoni & Matteucci 2011; Cavichia et al. 2014). It is difficult to tell how much of the difference from one-zone models is a consequence of the yields, since most papers detail their calculations but do not summarize them in a form (such as the $m^{2\chi}$ parameter given here) that enables straightforward comparison. Given the arguments presented here, it would be especially interesting to investigate the deuterium predictions of no-outflow models that reproduce the observed ISM oxygen abundance.

3. Implications

The results in Section 2 agree with those of more sophisticated models of galactic chemical evolution (GCE), which generally yield ISM deuterium abundances only moderately below the primordial abundance when they are tuned to reproduce observations of the solar neighborhood (e.g., Tosi et al. 1998; Romano et al. 2006; Steigman et al. 2007; Lagarde et al. 2012). The simplicity of the arguments leading to Equations (15) and (16) implies that this behavior should be robust to details of the GCE model, and it shows that the most important assumptions are likely those that affect the oxygen yield $m^{2\chi}$ and the recycling fraction $r$. The numerical examples illustrated in Figure 4 and the hydrodynamic simulation results of van de Voort et al. (2017) provide further support for the robustness of this prediction. A mixture of gas from zones that individually obey Equation (16) will also follow Equation (16) if $rZ_\alpha/m^{2\chi} \ll 1$ (allowing a linear Taylor expansion) and the level of deuterium depletion is therefore small in each zone. However, a mixture of high-metallicity, highly deplete gas with low-metallicity, low depletion gas would initially lie above this locus (high deuterium abundance relative to $[O/H]$), then return to it as further star formation drove the system toward equilibrium. It is thus likely but not guaranteed that Equation (16) will remain accurate in more sophisticated GCE models that incorporate ingredients such as radial gas flows and fountain recycling.

The close links predicted between oxygen and deuterium abundances strengthen arguments (Draine 2006; Linsky et al. 2006; Steigman et al. 2007) that sightline-to-sightline variations of $(D/H)$ absorption are caused by depletion of deuterium onto dust, as originally proposed by Jura (1982). This explanation requires a large fraction of the available sites on polycyclic aromatic hydrocarbon molecules to be occupied by deuterium rather than hydrogen, but the energy differences associated with the heavier deuterium nucleus permit this preferential outcome in the cool ISM, and reaction rates appear high enough to achieve it (Draine 2006). Producing factor-of- two variations in $(D/H)$ by differential astration, on the other hand, would induce enormous variations in $(O/H)$, since it would require a much larger fraction of the ISM on low $(D/H)$ sightlines to be comprised of stellar ejecta. The alternative of setting the mean ISM $(D/H)$ to $\sim 1-1.5 \times 10^{-5}$ and producing high $(D/H)$ by localized infall of primordial gas would require a major revision of oxygen yields to avoid overproducing oxygen. With our adopted $m^{2\chi} = 0.015$, reaching $(D/H) = 1.0 \times 10^{-5}$ implies $[O/H] = +1.0$, and $(D/H) = 1.5 \times 10^{-5}$ implies $[O/H] = +0.7$.

Many studies have used $(D/H)$ in low-metallicity, extragalactic Ly$\alpha$ absorption systems to estimate the primordial $(D/H)$ ratio and thereby constrain the mean baryon density (e.g., Cooke et al. 2014 and references therein). The baryon density inferred from observations of the cosmic microwave background (Hinshaw et al. 2013; Planck Collaboration et al. 2016) agrees well with that inferred from $(D/H)$ observations, an important cosmological consistency test that constrains non-standard BBN models (Nollett & Steigman 2015; Cyburt et al. 2016). Equation (16) implies that evolutionary corrections to $(D/H)$ should be small in systems with sub-solar oxygen abundance, and there is no need to seek out ultra-low-metallicity systems to eliminate these corrections. The primary reason to concentrate on low-metallicity sightlines for cosmological $(D/H)$ studies is to reduce uncertainties associated with dust depletion. Dvorkin et al. (2016), using more sophisticated chemical evolution models based on cosmologically motivated dust rates, reach similar conclusions about the small impact of deuterium depletion to damped Ly$\alpha$ systems and the tight expected correlation between oxygen and deuterium abundance.

Like deuterium, $^3$He is produced in BBN at fairly high abundance, $(^3\text{He}/\text{H})_0 \approx 10^{-5}$ (Cyburt et al. 2016). In contrast to deuterium, $^3$He can be produced in stars as well as destroyed (Iben 1967; Truran & Cameron 1971; Rood et al. 1976; Dearborn et al. 1996), so even the sign of evolutionary corrections is not obvious without detailed modeling. The arguments presented here suggest that the magnitude of $^3$He destruction should be small because most ISM gas has not been processed by stars at all. Observations indicate an ISM $^3$He abundance that is not far from the BBN value (Gloeckler & Geiss 1996; Bania et al. 2002). In concert with minimal destruction, this small amount of evolution implies that production of $^3$He by stellar nucleosynthesis must be small. As discussed in detail by Lagarde et al. (2012), this result is a challenge to conventional stellar evolution models but is well explained by models that incorporate thermonuclear mixing.

The robustness of the $(D/H)$ prediction to detailed assumptions implies that deuterium observations provide only limited constraints on standard GCE models; most models that produce solar $[O/H]$ should predict $(D/H)$ that matches current observations within their uncertainties. However, if dust depletion uncertainties can be controlled, then precise $(D/H)$ measurements could provide a useful test of yield and recycling values, especially if deuterium can be mapped over a wide enough range of metallicity to demonstrate the behavior predicted by Equation (16). As shown in Figure 5, the constraint $X_D/X^0_D \gtrsim 0.8$ is already enough to challenge otherwise plausible scenarios in which most stars above $3M_\odot$ collapse to black holes instead of releasing oxygen in supernovae (see discussions by, e.g., Pejcha & Thompson 2015; Sukhbold et al. 2016).

As discussed in Section 2.4, the prediction of Equations (15) and (16) is violated in models where outflows preferentially drive out CCSN ejecta while retaining the AGB ejecta returned over longer timescales. This scenario allows more return of deuterium-depleted hydrogen for a given amount of oxygen, so it predicts lower $(D/H)$ as a function of $[O/H]$. The agreement of observed abundances with simple predictions disfavors metal-enhanced winds with $\xi_{\text{env}} \gtrsim 2$. Models in which radiation pressure ejects galactic dust with minimal gas entrainment (e.g., Aguirre et al. 2001) could also violate $(D/H)$ constraints, though here one must take account of the potentially high fraction of deuterium residing in ejected dust.

The analytic models presented here adopt the instantaneous recycling approximation, and models in which the SFR or
outflow efficiency change rapidly compared to the ~1 Gyr timescale of AGB recycling could lead to significantly different (D/H) predictions. For example, even with constant $\eta$ and $\xi_{\text{enh}} = 1$, a 100 Myr starburst could eject most of the oxygen produced by its supernovae while allowing deuterium-depleted gas to return from AGB envelopes after the burst has ended. Consistent with this picture, the models of Dvorkin et al. (2016) that incorporate extreme early star formation predict lower (D/H) than their smoother models. We leave the numerical investigations of bursty models with continuous AGB recycling to future work.

Theoretical models of galaxy formation require feedback from star formation to reproduce observed galaxy properties, and vigorously star-forming galaxies at low and high redshift show abundant evidence of outflows that eject a large fraction of supernova metals with little entrainment of the ambient ISM.

The robust link between oxygen and deuterium abundances should also inform the lectures that we give to our introductory astronomy students. In the H$_2$O molecules that make up two-thirds of our body mass, every oxygen atom was born in the nuclear furnace of a stellar interior. But the hydrogen atoms? 90% of them come straight from the Big Bang.

I dedicate this paper to the memory of Gary Steigman, a pioneer in the study of cosmic deuterium and its Galactic evolution, from whom I learned much of what I know about the subject. I am also grateful to Bruce Draine and Marc Pinsoneault for informative conversations about deuterium over the course of many years, to Irina Dvorkin for a discussion of her results, to Todd Thompson for comments on an early draft of the manuscript, and to two anonymous referees whose questions and suggestions led to significant improvements in the paper. I also thank my GCE collaborators Brett Andrews, Jenna Freundenburg, Jennifer Johnson, and Ralph Schönrich for insights and valuable background discussions. This work was supported by NSF grant AST-1211853.

**References**

Aguirre, A., Hernquist, L., Katz, N., Gardner, J., & Weinberg, D. 2001, *ApJL*, 556, L11

Andrews, B. H., Weinberg, D. H., Schönrich, R., & Johnson, J. A. 2017, *ApJ*, 835, 224

Balser, D. S., Rood, R. T., Bania, T. M., & Anderson, L. D. 2011, *ApJ*, 738, 27

Bania, T. M., Rood, R. T., & Balser, D. S. 2002, *Natur*, 415, 54

Bell, E. F., & de Jong, R. S. 2001, *ApJL*, 550, 212

Bensby, T., Feltzing, S., & Oey, M. S. 2014, *A&A*, 562, A71

Bodenheimer, P. 1966, *ApJ*, 144, 103

Cavichia, O., Mollà, M., Costa, R. D. D., & Maciel, W. J. 2014, *MNRAS*, 437, 3688

Chabrier, G. 2003, *ApJL*, 586, L133

Chieffi, A., & Limongi, M. 2004, *ApJ*, 608, 405

Coc, A., Petitjean, P., Uzan, J.-P., et al. 2015, *PhRvD*, 92, 123526

Cooke, R. J., Pettini, M., Jorgensen, R. A., Murphy, M. T., & Steidel, C. C. 2014, *ApJ*, 781, 31

Cyburt, R. H., Fields, B. D., Olive, K. A., & Yeh, T.-H. 2016, *RvMP*, 88, 015004

Dearborn, D. S. P., Steigman, G., & Tosi, M. 1996, *ApJL*, 465, 887

Draine, B. T. 2006, in ASP Conf. Ser. 348, Astrophysics in the Far Ultraviolet: Five Years of Discovery with FUSE, ed. G. Sonneborn, H. W. Moos, & B.-G. Andersson (San Francisco, CA: ASP), 58

Dvorkin, I., Vangioni, E., Silk, J., Petitjean, P., & Olive, K. A. 2016, *MNRAS*, 458, L104

Edvardsson, B., Andersen, J., Gustafsson, B., et al. 1993, *A&A*, 275, 101

Feuillet, D. K., Bovy, J., Holtzman, J., et al. 2016, *ApJ*, 817, 40

Finlator, K., & Davé, R. 2008, *MNRAS*, 385, 2181

Gloeckler, G., & Geiss, J. 1996, *Natur*, 381, 210

Hinshaw, G., Larson, D., Komatsu, E., et al. 2013, *ApJS*, 208, 19

Iben, I. Jr. 1967, *ApJ*, 147, 624

Jura, M. 1982, in NASA Conf. Publication 2238, ed. Y. Kondo, J. M. Mead, & R. D. Chapman (Greenbelt, MD: NASA/GSFC), 54

Kennicutt, R. C., Jr. 1998, *ApJ*, 498, 541

Kroupa, P. 2001, *MNRAS*, 322, 231

Lagarde, N., Romano, D., Charbonnel, C., et al. 2012, *A&A*, 542, A62

Larson, R. B. 1972, *Natur*, 236, 21

Leroy, A. K., Walter, F., Brinks, E., et al. 2008, *AJ*, 136, 2782

Limongi, M., & Chieffi, A. 2006, *ApJL*, 647, 483

Linsky, J. L., Draine, B. T., Moos, H. W., et al. 2006, *ApJ*, 647, 1106

Lodders, K. 2003, *ApJL*, 591, 1220

Marconi, G., Matteucci, F., & Tosi, M. 1994, *MNRAS*, 270, 35

Matteucci, F., & Greggio, L. 1986, *A&A*, 154, 279

Mazzitelli, I., & Moretti, M. 1980, *A&A*, 109, 273

Mollà, M., & Díaz, A. I. 2005, *MNRAS*, 358, 521

Nollett, K. M., & Steigman, G. 2014, *PhRvD*, 91, 083505

Peeples, M. S., & Thompson, T. A. 2015, *ApJL*, 801, 90

Pilyugin, L. S. 1993, *A&A*, 277, 42

Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016, *A&A*, 594, A13

Pejcha, O., & Thompson, T. A. 2015, *ApJL*, 801, 90

Schmidt, M. 1959, *ApJ*, 129, 243

Spitoni, E. 2015, *MNRAS*, 451, 1090

Spitoni, E., & Matteucci, F. 2011, *A&A*, 531, A72

Spitoni, E., Vincenzo, F., & Matteucci, F. 2017, *A&A*, 599, A6

Steigman, G., Romano, D., & Tosi, M. 2007, *MNRAS*, 378, 576

Sukhbold, T., Ertl, T., Woosley, S. E., Brown, J. M., & Janka, H.-T. 2016, *ApJL*, 821, 38

Tosi, M., Steigman, G., & Matteucci, F. 1998, *ApJ*, 498, 226

Truran, J. W., & Cameron, A. G. W. 1971, *Ap&SS*, 14, 179

van de Voort, F., Quataert, E., Faucher-Giguère, C.-A., et al. 2017, *MNRAS*, (arXiv:1704.08254)

Weinberg, D. H., Andrews, B. H., & Freundenburg, J. 2017, *ApJ*, 837, 183

Zahid, H. J., Dima, G. I., Kewley, L. J., Erb, D. K., & Davé, R. 2012, *ApJ*, 757, 54