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CONSTRAINING GALACTIC INFALL WITH DEUTERIUM OBSERVATIONS

T. PRODANOVIĆ[1] and B. D. FIELDS[2]

[1] *Department of Physics, University of Novi Sad, Trg Dositeja Obradovića 4,*
21000 Novi Sad, Serbia
E–mail: prodanvc@if.ns.ac.yu

[2] *Department of Astronomy, University of Illinois,*
1002 W. Green St., Urbana IL 61801, USA
E–mail: bdfields@illinois.edu

Abstract. Measurements of deuterium in the local interstellar medium have revealed large variations in D/H along different lines of sight. Recent *Far Ultraviolet Spectroscopic Explorer* measurements indicate that this is due to significant deuterium depletion onto dust grains. This in turn implies that the total deuterium abundance in the local Galactic disk could be as high as $D_{\rm ISM}/D_{\rm P} \sim 84\%$ of the primordial D abundance. Because deuterium is heavily destroyed in stars it was proposed that the infall/accretion of pristine gas is needed to explain such a high deuterium abundance.In this work we explore the infall rate of pristine material that is needed to maintain a high present-day D/H, but also test the consistency of this infall rate with observations of Galactic gas fraction. We find that FUSE deuterium observations and Galactic gas fraction estimates can be reconciled in some models that demand a significant infall rate of pristine material that almost completely balances the rate of star formation. These successful models also demand a relatively low average fraction $R \lesssim 0.32$ of gas to be returned by dying stars.

1. INTRODUCTION

Deuterium has played a crucial role in cosmology as a ”cosmic baryometer” being that it is only produced in the big bang nucleosynthesis (BBN) while all other processes (mostly stellar processing) destroy it (Epstein et al. 1976, Prodanović et al. 2003). Since the only source of deuterium is the BBN its abundance should monotonically decrease over the history. However, measurements of the D abundance in the interstellar medium (ISM) within the past decade have shown large (factor of 3!) variations over different lines of sight. Linsky et al. (2006) have analyzed the recent deuterium measurements in the Galaxy done by the Far Ultraviolet Spectroscopic Explorer (FUSE) and have proposed that these local D abundance variations are due to deuterium being efficiently depleted onto dust grains. As a result, Linsky et al. (2006) have determined what the true ISM deuterium abundance is and found it to be $(D/H)_{\rm ISM+dust} = (2.31 \pm 0.24) \times 10^{-5}$. However, this new estimate of the local D abundance is almost at the level of the primordial value, implying that almost no gas was processed through stars! For this high D abundance to be sustainable within galactic chemical evolution (GCE) models, some level of infall of primordial gas needs to be assumed (Romano et al. 2006). By adopting the Linsky et al. (2006) D abundance estimate as the true local value, and by combining it with a wide range of observed Galactic gas fractions, we place constraints on infall rates within different GCE models. In this work we demonstrate that our approach (Prodanović et al. 2008) places strong constraints on infall rates, and that based on the local deuterium and gas fraction observations, the infall rate almost balances out the star formation rate. Moreover, we demonstrate that our model can also be used to constrain the initial mass function, due to the fact that a parameter of our model that directly follows from the shape of the initial mass function, is very sensitive to the assumed infall rate when combined with deuterium and gas fraction observations.

2. MODEL

Following Larson et al. (1972), we construct a simple model of Galactic chemical evolution (GCE) where we assume infall with rate proportional to star-formation rate $\psi(t)$ with proportionality constant α. We also assume that no outflow is taking place in this picture. Thus, in such model, the total baryonic mass of the Galaxy increases with time according to

$$\dot{M}_{\rm baryon} = \alpha\psi \tag{1}$$

Further on we take that the infalling material is primordial in composition and that deuterium is completely destroyed in stars. If we define the ratio of gas at time t to the initial baryonic mass $M_{\rm baryon,0}$ as $\mu(t) \equiv M_{\rm ISM}(t)/M_{\rm baryon,0}$, we can find the deuterium evolution from its primordial $D_{\rm p}$ to present day value $D(t)$ as a function of the return fraction R the fraction of stellar mass that is returned to the ISM in the instantaneous recycling approximation, and α (Prodanović et al. 2008). Expressing the deuterium through a fraction of its primordial value $D_{\rm p}$ we find its evolution to have the following form

$$\frac{D(t)}{D_{\rm p}} = \frac{R}{R+\alpha}\left(\frac{\alpha}{R} + \mu^{\frac{\alpha+R}{1-R-\alpha}}\right) \tag{2}$$

where $D \equiv X_D = \rho_D/\rho_{\rm baryon}$ is the deuterium mass fraction for a given epoch. Although only an infall of material that is close to primordial in its composition would affect Galactic deuterium abundance, any kind of infall in the model without outflow, directly changes i.e. in this scenario, increases, the gas content of the Galaxy. Thus, present gas mass fraction defined as $\omega \equiv M_{\rm ISM}(t)/M_{\rm baryon}(t)$ is another observable that is directly sensitive to star formation and infall rates. Within our model, we can express the gas mass fraction as (Prodanović et al. 2008)

$$\omega(t) \equiv \frac{M_{\rm ISM}}{M_{\rm baryon}} = \frac{1-R-\alpha}{1-R-\alpha\mu(t)}\mu(t) \tag{3}$$

where $M_{\rm baryon} \equiv M_{\rm baryon}(t)$ is the total baryonic mass at a given epoch. Equations (2) and (3) now directly relate observables D and ω to the model parameters α and μ, which together respectively quantify the current and integrated rates of Galactic infall. Moreover, it can also easily be shown that at late times, D and ω have limiting minimum values. Limiting minimal values that follow from different assumed infall rates combine to give the limiting curve (for a set return fraction R) above which no solutions can be found. We find the limiting curve to be (Prodanović et al. 2008)

$$\frac{D_{\rm min}}{D_{\rm p}} = \frac{1}{1 + R(1-\omega)(1-R)} \tag{4}$$

The return fraction R that is a parameter in determining the limiting curve directly follows from the assumed initial mass function (IMF). It follows then that equation (4) can be used to discriminate between different IMFs by demanding that a limiting curve for a given R falls withing the observed range of deuterium abundances and gas mass fraction. It will be shown in the next section that only some values of R fit both high present-day interstellar deuterium and the observed gas fraction.

3. RESULTS

As demonstrated in (2) we can use deuterium and gas mass fraction observables to test GCE infall models. However, we first must specify those observables as well as their uncertainties.

In (2) we have presented deuterium abundance at a given epoch as a fraction of the primordial deuterium for which we adopt Cyburt et al. (2003) value of $({\rm D/H})_{\rm p} = 2.75^{+0.24}_{-0.19} \times 10^{-5}$. As noted in the introduction, measured ISM deuterium abundance varies significantly. Thus for a present day Galactic deuterium abundance we take the full range of observed values $({\rm D/H})_{\rm ISM} = (0.5 - 2.2) \times 10^{-5}$ (Linsky et al. 2006) with the central value of $({\rm D/H})_{\rm ISM} = (1.56 \pm 0.04) \times 10^{-5}$ (Wood et al. 2004). This of course, represents the old estimate of the disk D abundance. For the new estimated ISM deuterium abundance that corrects for significant depletion onto dust we take the value of $({\rm D/H})_{\rm ISM+dust} \geq (2.31 \pm 0.24) \times 10^{-5}$ (Linsky et al. 2006).

Elemental abundances are generally defined as ratios of the number density of some element and the number density of hydrogen. However, chemical evolution models usually use mass fractions as an abundance measure, thus we transform these D/H abundance ratios into mass fractions and find the ratios of ISM-to-primordial deuterium mass fractions to be (Prodanović et al. 2008)

$$\frac{D_{\rm ISM}}{D_{\rm p}} = 0.53^{+0.22}_{-0.36} \tag{5}$$

$$\frac{D_{\rm ISM+dust}}{D_{\rm p}} = 0.78^{+0.11}_{-0.10} \tag{6}$$

As already noted, the other observable that is highly sensitive to infall models is the gas mass fraction. For the present observed Galactic interstellar gas mass we adopt a full range of measured values (Holmberg et al. 2004, Flynn et al. 2006)

$$\omega_{\rm obs} \equiv \left(\frac{M_{\rm ISM,MW}}{M_{\rm baryon,MW}}\right)_{\rm obs} \sim 0.07 - 0.30 \tag{7}$$

We see that uncertainties in these measured values are large. Still, we will demonstrate that even in that case our approach places strong constraints on different GCE infall models.

As a parameter of our model we have the return fraction R , i.e. the mass fraction of stellar population that is returned to the ISM, which must be specified. The return fraction follows directly from the assumed initial mass function (IMF) – if a stellar population (i.e. IMF) includes more low-mass stars, the overall average return fraction will be lower than the one that would follow from a stellar population that includes more high-mass stars. More specifically, if we adopt the standard Salpeter (1955) IMF we find $R \approx 0.30$ (Prodanović et al. 2008), which, to the first decimal, does not change with changing mass ranges of a given stellar population. However, by adopting a more modern and more realistic IMF (e.g. Baldry et al. 2003) that is flatter in the higher-mass regime yields a larger return fraction closer to $R \sim 0.4$.

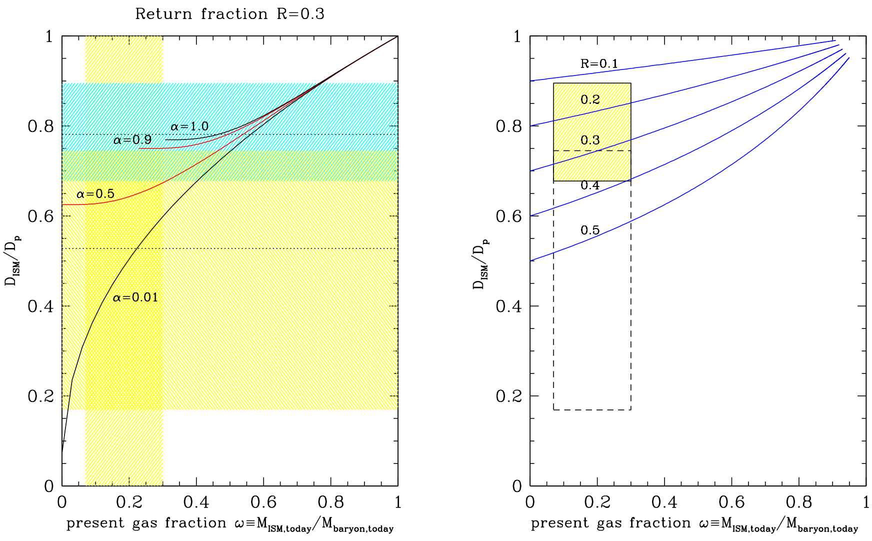

Figure 1: Left panel: The ratio of the total present-day to primordial D mass fraction $D_{\rm ISM}/D_{\rm p}$ as a function of the present gas mass fraction ω, for assumed return fraction $R = 0.3$. Dot-dashed black line along with the top (cyan) band corresponds to the ratio of the D mass fractions for the ISM D measured by FUSE and corrected for depletion onto dust (Linsky et al. 2006) and primordial D (Cyburt et al. 2003) as given in (6). Bottom (yellow) band with the central value of (5) (Wood et al. 2004) given as a dot-dashed black line corresponds to scatter of D abundances observed along different lines of sight. Vertical (yellow) band reflects the observed range of present gas mass fraction $\omega_{\rm obs}$ from (7). Different solid curves correspond to infall rates with proportionality constant: $\alpha = 0.01, 0.5, 0.9, 1.0$. Right panel: The ratio of the limiting present-to-primordial D mass fraction $D_{\rm ISM}/D_p$ as a function of the limiting gas mass fraction. The boxes present the overlap regions between the observed range of the present gas mass fraction $\omega_{\rm obs}$ (7) and measured ISM D abundances with (top, yellow box) and without (bottom, dashed box) depletion onto dust (Linsky et al. 2006). Different solid curves correspond to return fractions labeled.

With observables specified, we present our results on Fig. 1 (Prodanović et al. 2008). On the left panel we present deuterium mass fraction as a function of the gas mass fraction where the curves come from equation (2), for adopted retun fraction $R = 0.3$. Shaded horizontal bands represent the observed D values with – top, cyan (6), and without – bottom, yellow (5) accounting for the dust depletion . Shaded vertical yellow band represents the observed range of gas mass fractions (7). For a GCE infall model to be consistent with observations, the curves that come from (2) must go through overlap region between the observed D and gas fraction bands. These allowed curves are colored in red and we see that infall is required and in fact almost comparable to the star formation rate with the infall parameter $0.5 \lesssim \alpha \lesssim 1$. On the right panel of Fig. 1 we plot limiting curves that follow from equation (4) and above which no solution can be found. We plot 5 limiting curves, each for some adopted value of the return fraction $0.1 \leq R \leq 0.5$. Similarly, in order to be consistent with observations, a given limiting curve must go through the overlap region between observed D and ω, which are presented as boxes. We see that the *only* return fractions that are allowed are $0.1 < R \lesssim 0.4$. This constraint could provide hints about the IMF, its mass limits, and the physics of stellar gas return.

4. CONCLUSIONS

Large variations were found between measured deuterium abundances along different lines of sight in the Galactic disk. These variations are too large to be explained by conventional chemical evolution models since the only source of deuterium is in the big bang nucleosynthesis and its abundance should, thus, monotonically decrease with time. As a resolution of this conflict, a new solution has recently been proposed in the form of severe depletion of deuterium onto dust grains (Linsky et al. 2006), where now different measured D abundances result from different amounts of dust present. Consequently one could ask what the true, undepleted, deuterium abundance in the Galaxy is. Linsky et al. (2006) estimate this true D abundance to be very high – at a level 85% of the primordial value. In order to explain such high D abundance, most GCE models require some level of infall of primordial material into Galaxy, which would replenish Galactic deuterium content.

In this work we have further tested the level of infall of pristine gas that is needed for a GCE model that is consistent with such high D abundance. We have found that two observables – deuterium abundance and gas mass fraction, can be used together to place strong constraints on the allowed infall rate. By using this approach we have found (Prodanović et al. 2008) that not only does the new D abundance estimate of Linsky et al. (2006) requires some infall of pristine gas, it, in facts, *demands significant* infall rate with proportionality constant $0.5 \lesssim \alpha \lesssim 1$, which in some cases completely balances out the star formation rate. This result is consistent with hierarchical assembly of galaxies by accretion.

One parameter of our model is the return fraction R which directly follows from the adopted IMF. We have found that modern IMFs (Baldry et al. 2003) which demand high return fractions $R \sim 0.4$ are just marginally allowed by observations (Fig. 1, right panel). Thus our approach can also be used to discriminate and constraint different forms of the initial mass function.

Our analysis was done within the framework of a conventional Galactic chemical evolution model. Thus, we note here that our conclusion that significant infall is required, might be avoided within a class of non-standard GCE models (see eg. Romano et al. 2006 and references therein). Such models, prefer low astration factors where only a small fraction of gas was processed through stars, contrary to the standard view, and can, within errors, be consistent with recent results of Linsky et al. 2006 without the need to invoke infall of pristine material.

Besides direct consequences that these deuterium variations and the new high estimate of the true ISM D abundance have for the history of our Galaxy, we also have to note that these dust depletion effect might be important, and at least have to be considered, when measuring deuterium in the high-redshift systems. Though it is generally expected that high-redshift systems do not have large amounts of dust, if the opposite was found to be true, i.e. that in fact measured deuterium abundances needed to be corrected for significant depletion onto dust grains, standard BBN theory could allow a small upward correction to the deuterium abundance, before running into problems.

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