Analysis of Galactic chemical evolution model compatible with measurements of interstellar deuterium abundance

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Measurements of interstellar deuterium abundances (D/H) (Copernicus, HST, IMAPS, FUSE) have shown significant variations along different lines of sight. There is correlation between these variations and rates of dust depletion of refractory elements (Fe, Mg, Si), suggesting that differencies in D/H are due to deuterium depletion on dust. Relatively high deuterium abundance (~70-80% of primordial), according to its destruction in nuclear reactions in stars, is understood as a consequence of constant infall of deuterium rich and low-metallicity gas from Galactic halo. Furthermore, measurements of gas fraction in baryonic mass of Galactic disk show that only 7-30% of mass of the disk is in gas. Late estimates of average D/H abundance in Galactic disk and primordial D abundance, $(\mathrm{D/H})_{\mathrm{ISM}} = (2.0 \pm 0.1)\times 10^{-5}$, $(\mathrm{D/H})_{\mathrm{p}} = (2.8 \pm 0.2)\times 10^{-5}$ (used in this paper), together with gas fraction measurements, lead to determination of infall rate as a fraction of star formation rate in simple galactic chemical evolution models. Also, it was determined that return fraction of (deuterium free) gas is ~42% of initial stellar masses.

1. Introduction

Deuterium, as a primordial hydrogen isotope, is important to cosmology because all its amount was created in big bang nucleosynthesis. Later, during the evolution of the Universe, deuterium was only being destroyed, predominantly through the process of forming and evolution of stars (astration). Its abundance, therefore, monotonically decreases with time. Due to this unique nature, deuterium serves as an accurate baryometer, a test of chemical features of intergalactic medium, and also as a test of galactic chemical evolution (GCE) models, because measuring of its ISM abundance can lead to the fraction of gas which never ended up in stars.

Deuterium abundance is measured as the fraction of hydrogen abundance, from Lyman-α absorption lines of strong background objects. The graph of measured D/H abundances in galactic disk is divided in three zones by the distance from the Sun: Local Bubble, Solar Neighborhood and Galactic Disk. The average abundance is around $(\mathrm{D/H})_{\mathrm{gas}} = 1.5\times 10^{-5}$. The variation from average is smallest in Local Bubble region, but higher distance measures show variations by a factor of 3-4.

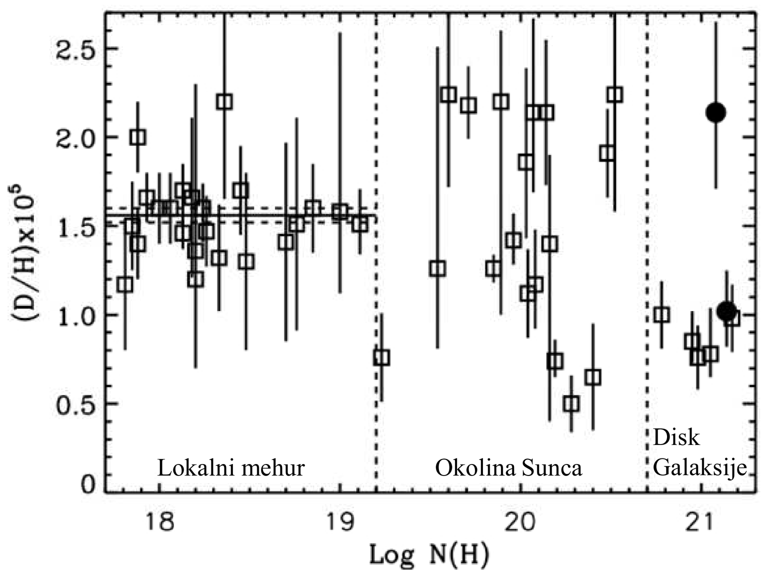

Fig. 1. D/H as a function of hydrogen column density for lines of sight observed with Copernicus, IMAPS, HST and FUSE.

2. Deuterium-depletion model

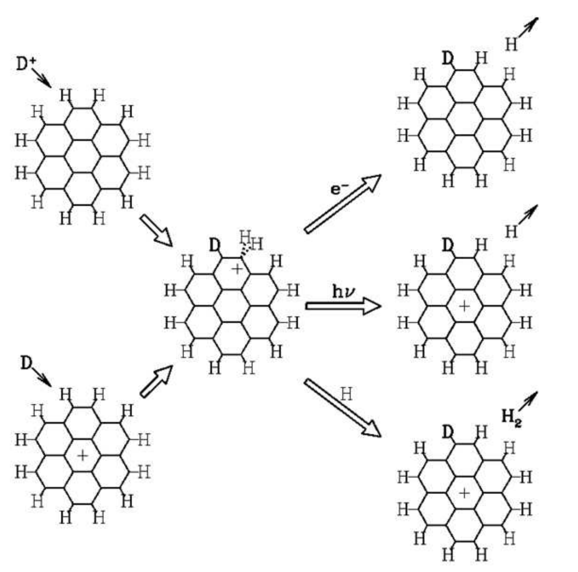

Fig. 2. The scheme of chemical reactions of D-H exchange in PAH molecules.

In order to explain significant variations of D/H along the various sight lines, Draine (2004, 2006) and Wood et al (2004) introduce the dynamic ISM model where D may suffer significant dust-depletion in conditions including dense ISM with low temperature. On the other side, if such region undergoes some external influence which heats the medium, then D incorporated in dust molecules can be brought back to the gas phase. Linsky et al (2006) confirm that in many sight lines D/H is correlated to H_2 rotational temperature and anticorrelated to dust-depletion rate of refractory elements such as Fe, Mg and Si. The relation of D/H in gas and depletion of D onto dust is based on the fact that D-C bond is stronger than H-C bond, so in required conditions H in envelope of dust molecules is replaced by D from gas, lowering the D/H ratio in the gas.

3. Galactic chemical evolution (GCE) model with infall

Questions of galactic chemical evolution can be answered through a model which uses the measurements of chemical abundances in combination with evolution of matter in Galaxy. The main such question is how much gas in galactic disk has never undergone the astration process. According to the fact that the evolution of deuterium abundance, from primordial to current, is affected only by the rate of its astration, we can say that the ratio $(\mathrm{D/H})_{\mathrm{ISM}}/(\mathrm{D/H})_{\mathrm{p}}$ (where $(\mathrm{D/H})_{\mathrm{ISM}}$ implies deuterium in *all* forms in ISM) is the fraction of the gas which never ended up in stars. Linsky et al (2006) suggested that $(\mathrm{D/H})_{\mathrm{ISM}}$, considering depletion of D onto dust, should be determined by several highest points on the graph from Fig. 1, so they obtained the value

$$(\mathrm{D/H})_{\mathrm{ISM}} = (2.31 \pm 0.24)\times 10^{-5}.$$

This is the value used in GCE model of Prodanović and Fields (2008) (further, PF (2008)) which will be presented here. They also used Steigman's value for the primordial D abundance,

$$(\mathrm{D/H})_{\mathrm{p}} = 2.75^{+0.24}_{-0.19}\times 10^{-5},$$

Dividing these two numbers we get the fraction of unastrated gas in galactic disk

$$\frac{(\mathrm{D/H})_{\mathrm{ISM}}}{(\mathrm{D/H})_{\mathrm{p}}} = 0.84 \pm 0.09.$$

According to the observations, the gas fraction in baryonic mass in galactic disk is

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

Such a high $(\mathrm{D/H})_{\mathrm{ISM}}/(\mathrm{D/H})_{\mathrm{p}}$ ratio can be explained by continuous galactic infall of (nearly) primordial gas from galactic halo. This model defines this infall as linearly proportional to star formation rate, as some simulations show such dependence, with infalling gas being primordial

$$\frac{dM_{\mathrm{baryon}}}{dt} = \alpha\psi,$$

where dM_{baryon}/dt is the change of baryonic mass in the galactic disk, α is the rate of infall and ψ is the star formation rate (SFR). The change of ISM mass in galactic disk is then

$$\frac{dM_{\mathrm{ISM}}}{dt} = \alpha\psi - (1-R)\psi,$$

where R is the return fraction, which represents the mass returned to ISM from stars (after the stars finish their evolution) and is taken as estimation in this model to be 0.2 and 0.3.

After putting in required mass fractions D and integrating from D_{p} to $D(t)$ we get equation of evolution of D

$$\frac{D(t)}{D_{\mathrm{p}}} = \frac{R}{\alpha+R}\left(\frac{\alpha}{R} + \mu(t)^{\frac{\alpha+R}{1-\alpha-R}}\right), \qquad (1)$$

where $D \equiv X_{\mathrm{D}} \cong 2\left(\frac{\mathrm{D}}{\mathrm{H}}\right)X_{\mathrm{H}}$ and $\mu(t) \equiv \frac{M_{\mathrm{ISM}}(t)}{M_{\mathrm{baryon},0}}$, which is independent variable in this model, while α and R are constants.

The evolution of gas fraction in baryonic mass (ω) is

$$\omega(t) \equiv \frac{M_{\mathrm{ISM}}(t)}{M_{\mathrm{baryon}}(t)} = \frac{1-R-\alpha}{1-R-\alpha\mu(t)}\mu(t). \qquad (2)$$

The variables $D(t)/D_{\mathrm{p}}$ and ω from equations (1) and (2) are observables and they can be used to constraint the model in order to obtain the range of required infalls. Therefore, these two variables are placed on two axes on the diagrams on Fig. 3. and their mutual evolution is showed with red curves (each one for different α). Two diagrams stand for different R, for the left one $R = 0.2$ and for the right one $R = 0.3$.

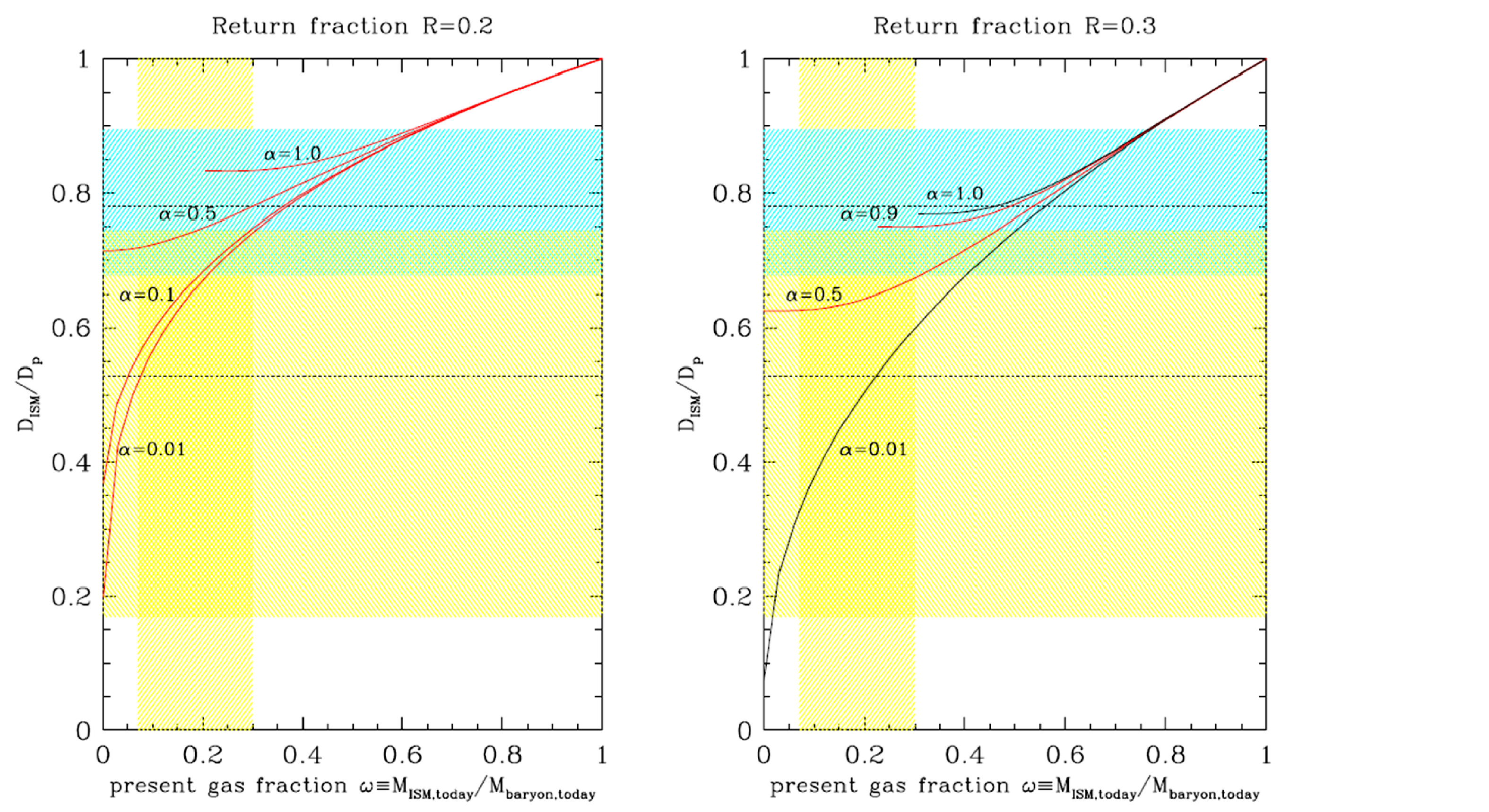

Fig. 3. Model PF (2008). On the left, R = 0.2, on the right R = 0.3. Red curves are for different infalls. Cyan bar represents constraint for $D(t)/D_{\mathrm{p}}$ and vertical yellow bar represent constraint for ω.

4. The initial mass function and the new estimation of return fraction R

The return fraction, in PF (2008) taken to be 0.2 and 0.3, is not yet fully investigated value. It represents the fraction of the mass locked in stars which is constantly being returned into the ISM during the recycling process of star evolution. The gas is returned through stellar winds, ejecting envelopes of giant stars and supernovae. R is determined using the initial mass function (IMF) and final mass function (FMF) as

$$R = 1 - \frac{\int_{0.01}^{150} m_{\mathrm{rem}}\xi(m)\,dm}{\int_{0.01}^{150} m\xi(m)\,dm},$$

where $\xi(m)$ is IMF, m is star mass (in solar masses) and m_{rem} is final (remaining) mass of the star, after its evolution is done. In this paper canonical IMF from Kroupa et al (2012) is used. Masses that in product with $\xi(m)$ give the FMF are

$$m_{\mathrm{rem}} = \begin{cases} m, & m \le 0.8 \\ 0.11m + 0.45, & 0.8 < m \le 8 \\ 1.4, & 8 < m \le 11 \\ 0.47m - 3.77, & 11 < m \le 40 \\ 15, & m > 40 \end{cases}$$

This calculation gave the return fraction $\boxed{R = 0.42.}$

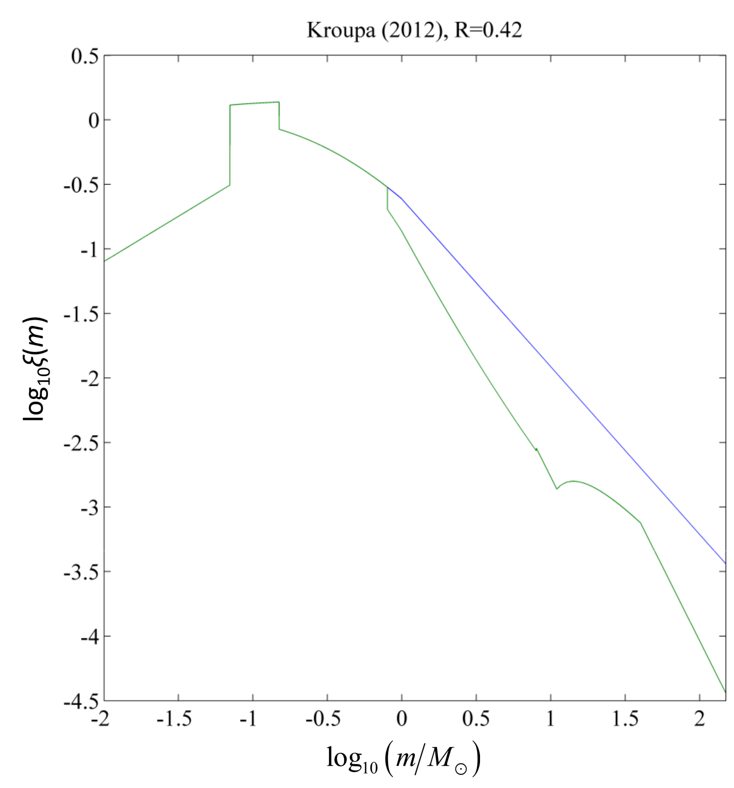

Fig. 4. Canonical IMF from Kroupa et al (2012). FMF is showed as the green line. The range of masses is from 0.01 to 150 solar masses.

5. The new value of $D(t)/D_{\mathrm{p}}$. Results

Prodanović, Steigman and Fields (2010) determined the new $(\mathrm{D/H})_{\mathrm{ISM}}$ value using Bayesian statistical analysis and adopted new value for $(\mathrm{D/H})_{\mathrm{p}}$ from Pettini et al (2008)

$$(\mathrm{D/H})_{\mathrm{ISM}} = (2.0 \pm 0.1)\times 10^{-5}, \qquad (\mathrm{D/H})_{\mathrm{p}} = (2.8 \pm 0.2)\times 10^{-5}$$

which gives new constraint for $D(t)/D_{\mathrm{p}}$

$$\boxed{\frac{D_{\mathrm{ISM}}}{D_{\mathrm{p}}} = 0.66^{+0.09}_{-0.08}}$$

The new results are shown in Fig. 5.

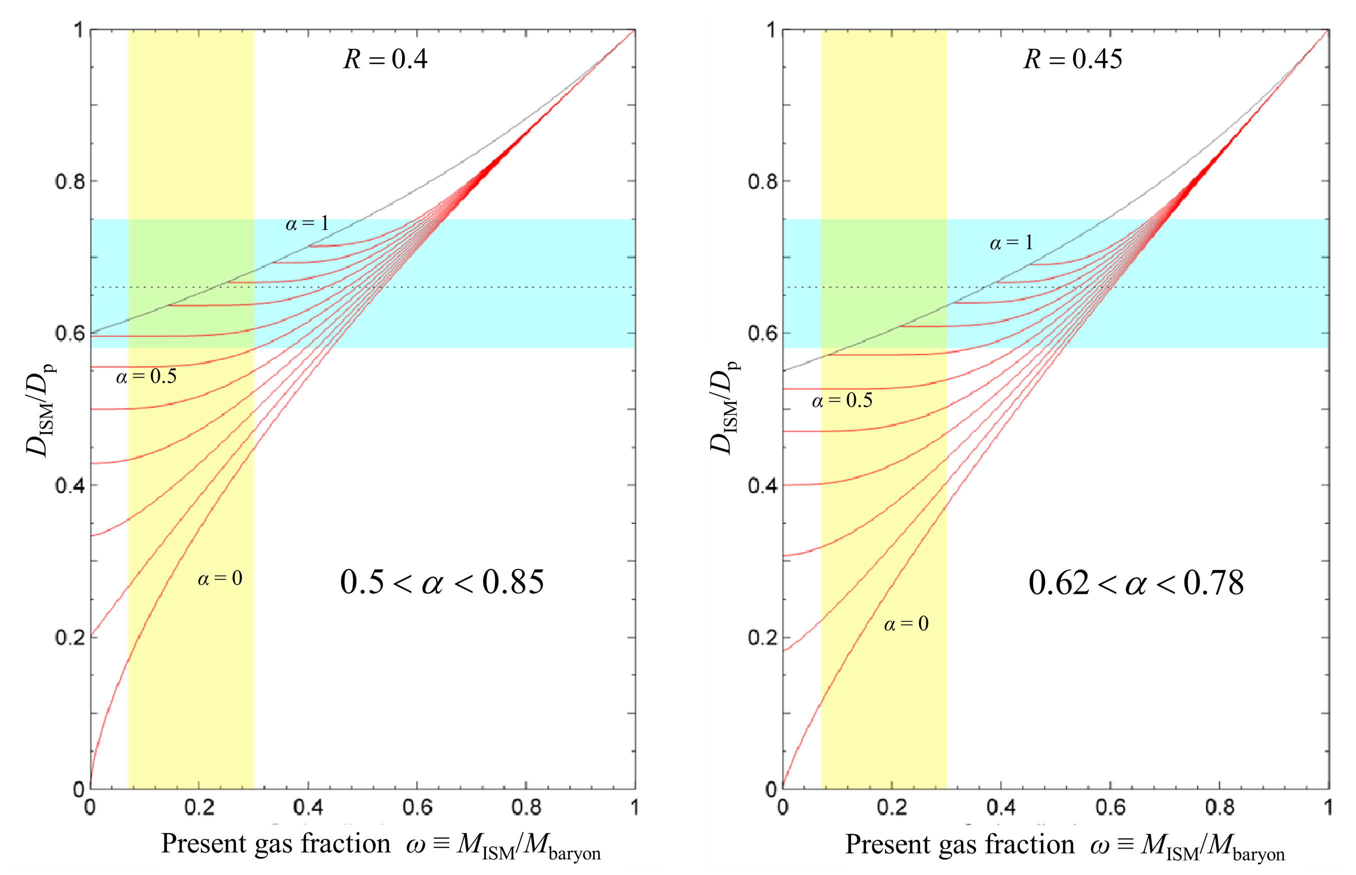

Fig. 5. On the left, R = 0.40, on the right R = 0.45. Red curves are for different infalls. Cyan bar represents the new constraint for $D(t)/D_{\mathrm{p}}$ and vertical yellow bar represent constraint for ω.

$$\text{For } R = 0.42 \quad \Rightarrow \quad \boxed{0.56 < \alpha < 0.83}$$

6. Conclusions

- This model stands for galactic disk
- Results show the infall in range [0.56, 0.83]
- Using a modern IMF, obtained R is in range [0.40, 0.45]
- Approximations which simplify the model
  - Infall is linearly proportional to SFR
  - Instantaneous recycling approximation
  - Non-variable IMF during evolution of the Galaxy
- There is a need for more (precise) D/H measurements

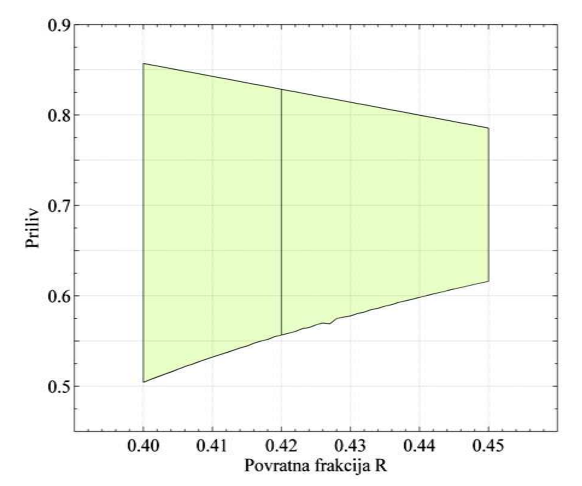

Fig. 6. Constraint on α in function of R.