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Deuterium Link:
From Interstellar Medium and Chemical Evolution to Cosmology and Structure Formation

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Deuterium has a special place in cosmology, nuclear astrophysics, and galactic chemical evolution, because of its unique property that it is only created in the big bang nucleosynthesis while all other processes result in its net destruction. However, a large scatter found in the interstellar medium (ISM) deuterium abundance measurements indicates that deuterium might be preferentially depleted onto dust grains, which complicates the use of deuterium as a probe of galactic chemical evolution (GCE) models. We have applied a model-independent, statistical Bayesian method and determined the true, undepleted ISM D abundance. Having found the ISM D abundance one can identify the successful GCE models, which can then be used to learn about nucleosynthesis in the ISM, but can also be placed in cosmological context to learn about the infall rates of the primordial gas to our Galaxy, which bares implications for models of galaxy formation. Here we present our results and their implications for discriminating between different GCE models, for our understanding of the nature and physics of interstellar dust grains, as well as implications for cosmological evolution.

§1. Introduction

❑ Deuterium is only created in Big Bang Nucleosynthesis (BBN) [1] while all other processes destroy it [2,3] – its abundance $y_D \equiv (D/H)\times 10^5$ should monotonically decrease with redshift.
❑ Current BBN models along with WMAP observations set the **primordial D abundance** to be [4]. $y_{Dp} = 2.82^{+0.20}_{-0.19}$
❑ Measurements of the D abundance in the **local ISM** reveal **large variations** – by a factor of 4 over different lines of sight (LOS) $0.5 \le y_{D,ISM} \le 2.2$ - a problem for many sucessful GCE models!
❑ A solution proposed in the form of preferential deuterium depletion onto dust grains relative to hydrogen [5,6] - measured *gas phase* value is only a lower limit to the true, total ISM D abundance.
❑ Linsky et al. 2006 [7] thus revised a current estimate of the true, undepleted ISM D abundance and found it to be $y_{D,ISM+dust} \ge 2.31 \pm 0.24$ which is at the ~ 82% level of the primordial value!
❑ This result was based on the 5 LOS (of 46 available) which have the highest D abundances, and are thus, by assumption, least likely to suffer from depletion onto dust.
❑ Such high present ISM abundance requires $f_D \equiv y_{Dp}/y_{DISM} \le 1.22 \pm 0.15$ astration factor -- inconsistent with most GCE models that require $1.4 \le f_D \le 1.8$.

§2. Galactic Chemical Evolution Models and Infall

❑ High ISM D abundance [7] implies that ~80% of the initial interstellar gas was never been processed through stars - most of the GCE model require significant infall of (close to) pristine material
❑We construct a simple GCE model with infall and no outflow [8].
❑ Infall rate was assumed to be proportional to the star-formation rate, with a proportionality constant α.
❑ Deuterium abundance and galactic gas fraction affected by infall.
❑ Predictions of this model constrained by two observables : ISM-to-primordial deuterium mass fraction D_{ISM}/D_p, and present day gas fraction ω.

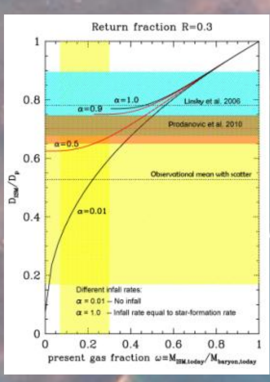


Figure 1
Presented are the results of Prodanović & Fields (2008) [8]: the ratio of the total present-day to primordial deuterium mass fraction D_{ISM}/D_p as a function of the present gas mass fraction ω. Shaded areas represent observations, while solid lines are model results for different assumed infall parameter α. Cyan band reflects the Linsky et al. (2006) [7] ISM D abundance, horizontal yellow band reflects measured D variations in the ISM, while the red band reflects the most recent prediction by Prodanović et al. (2010) [9] of the true, undepleted ISM D abundance. The adopted primordial D abundance is that of Cyburt at al. (2003) [10].

❑ Results depend on assumed return fraction *R* – a fraction of the initial stellar mass that is returned to the ISM .
❑ Return fraction reflects assumed initial mass function – adopted *R*=0.3 follows from Salpeter IMF .
❑ Results of this GCE model [8] are presented on Figure 1 – solid curves reflect different infall rates.
❑ Shaded horisontal bands – D observation constraints : cyan – Linsky et al. (2006) [7] estimate of the true ISM D, red – Prodanović et al. (2010) estimate of the true ISM D, yellow - range of observed D variations.
❑ Shaded vertical band – observed range of gas mass fraction.
❑ See that Linsky et al. (2006) [7] proposed ISM D abundance requires **large infall rates** that would have to almost completely **balance star-formation rate** $0.5 \le \alpha \le 1.0$.
❑ Sill in tension with most of the modern, successful GCE models.

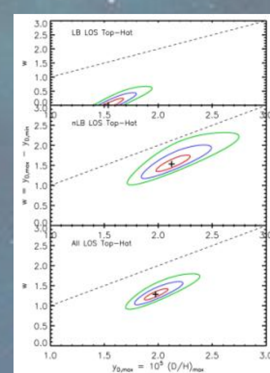
§3. Determining the True ISM Deuterium Abundance: A Bayesian Approach

❑ Take a fully statistical approach to determine the true ISM D abundance - Prodanović et al. (2010) [9].
❑ **Model-independent Bayesian analysis** on all 49 available LOS (following Hogan et al. (1997) [11])
❑ Only assumption --(dust) depletion may be possible .
❑ Find a two-parameter maximum likelihood function that best fits the available data.
❑ **Output two parameters** - find those that give largest maximum likelihood
- ○ $y_{D,max}$ - **maximal undepleted deuterium abundance** consistent with the data, which is a lower limit to the true ISM D abundance $y_{D,\max} \le y_{D,ISM}$,
- ○ **depletion parameter** $w \equiv y_{D,\max} - y_{D,\min}$

❑Adopt some **form of a depletion distribution** -- tested 5 different :
- ○ Top-hat bias , where all levels of depletion are equally probable,
- ○ Negative bias, which favors large depletion,
- ○ Positive bias, which favors low depletion,
- ○ M-shaped bias, where both high and low depletion levels are equally favorable while moderate depletion levels are suppressed,
- ○ Λ–shaped bias, which strongly favors moderate depletion levels.

❑ Two data subsets: LOS that are within the **Local Bubble (LB)** where their D abundances show very little scatter , and LOS that are **outside of the Local Bubble (nLB)** that show large scatter in D abundances [7].
❑ Apply Bayesian analysis on the two subsets of data separately and on all 49 LOS together (Figure 2) .

Figure 2
Likelihood contours (68%, 95%, 99%) in the $y_{D,max}$ -- w plane for the 21 Local Bubble LOS (top panel) , the 28 non-Local Bubble LOS (middle panel) and all 49 LOS (bottom panel) using the top-hat depletion distribution.



❑ **Results on all 49 LOS show – top-hat depletion distribution has largest maximum likelihood**
❑ **Best estimate of the true, undepleted ISM D abundance [9]:**

$$(D/H)_{ISM} \ge (D/H)_{\max} = (2.0 \pm 0.1)\times 10^{-5}$$

❑ Consistent with some of the successful GCR models - a lower $f_D \le 1.4 \pm 0.1$ astration factor.
❑ Figure 1, red band -- the new ISM D abundance [9] requires somewhat lower infall rates with infall parameter now $0.4 \le \alpha \le 0.9$.

❑§4. Conclusion

❑ Observed large variations of the ISM deuterium abundance – potential solution: deuterium depletion onto dust grains preferentialy relative to hydrogen.
❑ Some new estimates of the true, undepleted ISM D abundance yield values that are close to primordial [7] -- conflict with many of the successful GCE models.
❑ **Our Bayesian statistical approach yields lower value $(D/H)_{ISM}$ = 20 ppm -- relieves the tension with GCE models [9,12]**
❑ **Significant infall rates of close-to-pristine material [8] still required.**
❑Remaining questions – will be addressed in future work:
- ○ Why is the Local Bubble deuterium abundance so uniform and depleted from the ISM value, while iron depletion shows significant scatter?
- ○ Is ISM D abundance really so high or some of the high measured values reflect recent unmixed infall of pristine gas?
- ○ Should high-redshift observations of deuterium also be corrected for the potential depletion onto dust?

[1] Boesgaard A.M., Steigman G., 1985, ARA&A, 23, 319
[2] Epstein R.I., Lattimer J.M., Schramm D.N., 1976, Nat, 263, 198
[3] Prodanović T., Fields B.D., 2003, ApJ, 597, 48
[4] Cyburt R.H., Fields B.D., Olive K.A., 2008, J. Cosmol. Astropart. Phys., 11, 12
[5] Jura M., 1982, Kondo Y. , Mead J., Chapman R.D., eds, Advances in Ultraviolet Astronomy. NASA, Washington, p. 54
[6] Draine B.T., 2006, Astrophysics in the Far Ultraviolet: Five Years of Discovery with FUSE. Vol., 348, p. 58
[7] Linsky J.L. et al., 2006, ApJ, 647, 1106
[8] Prodanović T., Fields B.D., 2008, J. Cosmol. Astropart. Phys., 9, 3
[9] Prodanović T., Steigman G., Fields B.D., 2010, MNRAS, 724
[10] Cyburt R.H., Fields B.D., Olive K.A., 2003, Phys. Lett. B, 567, 227
[11] Hogan C.J., Olive K.A., Scully S.T., 1997, ApJ, 489, L119
[12] Steigman G., Romano D., Tosi M., 2007, MNRAS, 378, 567

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