

# ACCURATE MEASUREMENTS OF THE LOCAL DEUTERIUM ABUNDANCE FROM HST SPECTRA

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**Abstract.** An accurate measurement of the primordial value of D/H would provide a critical test of nucleosynthesis models for the early universe and the baryon density. I briefly summarize the ongoing HST observations of the interstellar H and D Lyman- $\alpha$  absorption for lines of sight to nearby stars and comment on recent reports of extragalactic D/H measurements.

## 1. The Importance of an Accurate Measurement of D/H

The Hubble expansion, microwave background, and light-element abundances are the main observational pillars upon which the standard Big Bang cosmology now rests. Of these three tests, the light-element abundances provide the main constraint on the total baryon density (luminous and dark matter). The D/H ratio provides the tightest constraint because of (1) the absence of any known significant sources of deuterium after about  $10^3$  s in the early universe, (2) the subsequent destruction by nuclear reactions in the cores of stars where D is the most fragile species, and (3) the steep monotonic slope between the primordial D/H ratio and the baryonic density in contemporary Big Bang nucleosynthesis models (e.g., Walker et al. 1991). Since none of the other light elements ( $^3\text{He}$ ,  $^4\text{He}$ ,  $^6\text{Li}$ ,  $^7\text{Li}$ , Be, or B) share these properties, their abundances provide more uncertain estimates of the baryon density of the universe. The importance of D/H has led to studies of D and deuterated molecules in many environments. See reviews by Boesgaard & Steigman (1985) and by Wilson & Rood (1994).

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The ratio of D to H column densities in warm interstellar gas ( $T \approx 7000$  K) as inferred from absorption in the Lyman series lines is now thought to provide the most accurate D/H ratios in the Galaxy. Although this gas has been chemically processed and the D/H ratio must be lower than primordial, the relative ionization fraction, molecular association fraction, and degree of condensation onto dust grains should be the same for D and H in this environment. For Galactic lines of sight, only the Lyman- $\alpha$  line can be studied by IUE and HST, but the overlap of the H and D lines ( $-0.33 \text{ \AA}$  from the H line) limits the use of the Lyman- $\alpha$  line to nearby stars where  $\log N_{\text{HI}} < 18.7$ . A reanalysis of the best available Copernicus and IUE data led McCullough (1992) to estimate that the mean value of D/H by number in the local interstellar medium (LISM) is  $(\text{D/H})_{\text{LISM}} = 1.5 \pm 0.2 \times 10^{-5}$ . Since these data have rather low S/N, the H line is very saturated, and the intrinsic shapes of the D and H lines are unresolved at the spectral resolutions of IUE and Copernicus, we initiated an observing program with the Goddard High Resolution Spectrograph (GHRS) on HST to obtain more accurate values of  $(\text{D/H})_{\text{LISM}}$ .

## 2. HST Observations of D/H in the Local ISM

On 1991 April 15 we obtained echelle spectra of the resonance lines of H and D (Lyman- $\alpha$  at  $1216 \text{ \AA}$ ), the FeII multiplet UV1 (at  $2599 \text{ \AA}$ ), and the MgII h and k lines (at  $2796 \text{ \AA}$  and  $2803 \text{ \AA}$ ) of the Capella binary system at orbital phase 0.26, very close to maximum radial velocity separation. A careful analysis of these Capella spectra by Linsky et al. (1993) showed that the neutral H column density is  $N_{\text{HI}} = (1.7\text{--}2.1) \times 10^{18} \text{ cm}^{-2}$  and  $(\text{D/H})_{\text{LISM}} = 1.65 (+0.07, -0.18) \times 10^{-5}$  for this line of sight.

A major systematic error in our analysis of the Capella phase 0.26 observations is the uncertain intrinsic Lyman- $\alpha$  emission-line profiles of the two stars in the Capella system, especially those portions of the emission lines that form the "continuum" against which the observed profile is compared to determine the interstellar column densities and broadening parameters for H and D. We therefore reobserved Capella on 1993 September 19 at orbital phase 0.80, close to the opposite orbital quadrature, to analyze the (assumed constant) interstellar absorption against the background of a somewhat different intrinsic emission line from the Capella system. Analysis by Linsky et al. (1994) of both Capella data sets, together with a more accurate representation of the instrumental point spread function, led to essentially the same D/H ratio,  $(\text{D/H})_{\text{LISM}} = 1.60 \pm 0.08 \times 10^{-5}$ .

Our second target was Procyon, an F5 IV-V star located 3.5 pc along a line of sight about  $54^\circ$  from Capella. We observed this star on 1992 December 21 in the same way as we observed Capella at phase 0.26, except

that the Lyman- $\alpha$  line was observed with the G160M grating through the small science aperture (SSA). The spectral resolution at Lyman- $\alpha$  was only 20,000 ( $15 \text{ km s}^{-1}$ ) instead of 84,000 ( $3.57 \text{ km s}^{-1}$ ) when we used the echelle-A grating. These observations and their analysis will be described in more detail by Linsky et al. (1994). Using a broadened solar profile for Procyon's intrinsic Lyman- $\alpha$  emission line, they concluded that Procyon data are consistent with but do not prove that  $(D/H)_{\text{LISM}} = 1.60 \times 10^{-5}$ .

The GHRS has been used by Lemoine to study interstellar H and D absorption toward the hot white dwarf G191-B2B (50 pc) and by Alexander for the line of sight toward  $\lambda$  And (24 pc), but the analyses of these data are not yet published. We have requested GHRS spectra to observe  $\alpha$  Cen A and B (1.3 pc) and the binary system HR 1099 (33 pc). Observations at both quadratures in the orbit of HR 1099 should help remove the uncertainty of the intrinsic stellar Lyman- $\alpha$  emission line. Other lines of sight should be explored through the use of the GHRS echelle-A grating. HST programs to obtain D/H ratios for extragalactic lines of sight have been approved, but as yet there have been no reports of results from these difficult observations.

### 3. The Range of $\Omega_B$ Implied by D/H Measurements

An accurate determination of the primordial number ratio,  $(D/H)_p$ , should tell us the number density of baryons during the period 100–1000 s after the Big Bang when the temperature became low enough for the light nuclei to form. This conclusion follows from the density sensitivity of nuclear reaction rates that yield a higher abundance of  $^4\text{He}$  and lower abundance of D for larger densities at that time. Since the Hubble expansion relates the baryon densities then and now,  $(D/H)_p$  also determines the mean baryon density in the universe today and the ratio  $\Omega_B$  of the baryon density to the critical density needed to eventually halt the expansion. Thus  $(D/H)_p$  is a critical parameter for experimental cosmology.

Although our data do not allow us to measure  $(D/H)_p$  directly, we can infer its value from our measurement of  $(D/H)_{\text{LISM}}$  and chemical evolution calculations for the Galaxy. Steigman & Tosi (1992) and others have calculated the survival fraction of D as the primordial D is converted to heavier elements in the cores of stars and this deuterium-depleted gas is dispersed into the interstellar medium from which later generations of stars are formed. Their calculations indicate that  $(D/H)_p = (1.5\text{--}3.0) \times (D/H)_{\text{LISM}}$ , so that  $(D/H)_p = (2.2\text{--}5.2) \times 10^{-5}$ . Comparison of the Capella value for  $(D/H)_p$  with recent Big Bang nucleosynthesis calculations (Walker et al. 1991) indicates that  $\eta_{10} = 3.8\text{--}6.0$ , where  $\eta_{10}$  is  $10^{10}$  times the ratio of nucleons to photons by number. This range in  $\eta_{10}$  leads to the very important result that  $0.06 \leq \Omega_B h_{50}^2 \leq 0.08$ , where  $h_{50}^2$  is the Hubble constant in

units of  $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . Thus, no matter what value one assumes for the Hubble constant,  $\Omega_B \ll 1$ , and the universe must be open if the cosmological constant is zero and if only baryons are present. Tremaine (1992) and others, however, have argued that  $\sim 90\%$  of the universe consists of dark nonbaryonic matter. Thus whether  $\Omega = 1.0$  remains an open question.

#### 4. Comments on Recent Reports of Extragalactic D/H

One way to avoid the uncertainties in Galactic chemical evolution models is to measure D/H in warm gas with very low metallicity. The measured D/H ratio should therefore be close to zero metal abundance, the primordial value. Songaila et al. (1994, and, independently, Carswell et al. 1994) has reported on observations of the line of sight toward the  $z_{\text{em}} = 3.42$  quasar Q0014+813, which has a metallicity of  $< 10^{-3.5}$  solar. The proposed D feature has a column density of  $2 \times 10^{12} \text{ cm}^{-2}$ , a factor of  $2.5 \times 10^{-4}$  times that of the most opaque H cloud. Is this feature D or H? If it is D, then  $(\text{D}/\text{H})_p \approx 2.5 \times 10^{-4}$ , a factor of 5–10 times larger than  $(\text{D}/\text{H})_{\text{LISM}}$ , whereas Galactic chemical evolution calculations (e.g., Steigman & Tosi 1992) indicate that this factor should lie in the range 1.5–3.

The major uncertainty in the estimates of D/H in absorbing clouds toward Q0014+813, and by implication other distant lines of sight, is the possibility that a low-column-density H-absorbing cloud at the predicted D velocity is masquerading as D. This possibility was recognized by Songaila et al. (1994) and Carswell et al. (1994). I will discuss how to test this hypothesis elsewhere, but the possibility of H masquerading as D is high if an increasing number of clouds are present in the line of sight with decreasing values of  $N_{\text{HI}}$ , and the velocity centroid of the cloud distribution is centered on the mean velocity of the observed clouds.

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