Problem 1 - Ay 216 Interstellar Medium, Spring 2008

Determining the Abundance of Deuterium with FUSE

Far ultraviolet (FUV) spectroscopy is an important astronomical tool because the strong diagnostic lines of the cosmically abundant elements are found in this part of the spectrum. This requires satellite observations because the Earth's atmosphere is opaque at these wavelengths. Although there were several earlier FUV satellite observatories, the advent of the *Far Ultraviolet Spectroscopic Explorer* (FUSE) is particularly significant because of its capacity for high spectral resolution observations well below the Lyman α line (1216 Å).

The first results from FUSE were published in the spring of 2002, and this problem assignment is based on the overview paper by Moos et al. (ApJS 140, 3, 2002) and the paper by Kruk et al. (ApJS 140, 19, 2002) on measurements of hydrogen, deuterium, and other elements for the line of sight toward the nearby white dwarf HZ 43A. Measuring the D/H ratio accurately is important for pinning down its primordial value and for understanding Galactic chemical evolution. Deducing its value toward nearby bright white dwarfs is complicated, however, by the fact that the Sun is itself located in an interstellar cloud (the Local Interstellar Cloud or LISC) that is embedded in a hot bubble of an old supernova remnant (see Figs. 1 and 2 in Moos et al. 2002 and the review of the local interstellar medium (LISM) by Frisch (Sp Sci Rev 72, 499, 1995).

Download and read the Moos et al. and Kruk et al. papers and then, focusing on the latter, answer the following questions. In addition to these two FUSE papers and Frisch's review, two other sources may be useful: the UV spectral line atlas of Morton (ApJS 77, 119, 1991) and the review of HST results by Sembach & Savage (ARAA 34, 279,1996). Now would also be a good time to become familiar with the NIST data base that provides the atomic data essential for astrophysics (click on PhysRefData at physics.nist.gov).

1. What are the rest wavelengths and oscillator strengths of the Ly α lines of HI and DI? Make a simple estimate of the isotope shift of the line and compare your result with the measured laboratory value.

2. Evaluate optical depth effects for the main cloud toward HZ 43A by estimating the optical depth at line center for both the HI and DI Ly α lines, assuming that $b = (b_{\rm th}^2 + b_{\rm turb}^2)^{1/2}$. Here b is Spitzer's Doppler velocity parameter, related to the variance σ by $b = \sqrt{2}\sigma$. Be careful to track down the value of $b_{\rm turb}$ used by Kruk et al. and understand where it comes from.

3. Mg II is a hydrogen-like ion important in many kinds of nebulae. Construct a simple energy-level diagram of this ion [1], emphasizing the resonance transitions (allowed electronic transitions connected to the ground state), including energies, wavelengths, and Einstein A-values. Explain

[1] A simple 1-d diagram, as opposed to a Grotrian diagram which uses the horizontal dimension to give the configuration (angular momentum properties) of the levels.

why the first resonance transition of Mg II is a doublet in contrast to the essentially singlet H I Ly α line. Referring to Fig. 1 of Kruk et al., estimate carefully the equivalent widths (EWs) of the Mg II 2800 Å doublet and estimate the maximum column density of Mg for this line of sight. Compare with the results given in the observational paper and explain any differences.

4. Use the D I Lyman alpha profiles in Figs. 1 and 4 in Kruk et al. to estimate its EW and column density, using the same $b_{\rm turb}$ for D I as for H I. Make an estimate of the total b-value by determining the full-width at half maximum of the D I line in Fig. 1. Does the result imply any change in your estimate of the column density? Explore the uncertainty in the measured EW of the D I line by trying different extrapolations of the red-side of the line, which is obliterated by geocoronal Lyman α. Again compare your results with those given by Kruk et al. (Be sure you understand what the geocoronal emission is and where it comes from.)

5. Summarize the results of the Kruk et al. for the D/H ratio, and list the most important observational and interpretational uncertainties for both D and H. Is their quoted 2σ uncertainty of 17% reasonably conservative?
N.B. Some further work on the D/H ratio and its variation in the ISM include: C. Oliveira & G. Hébard. ApJ, 653, 345, 2006; J. Linsky et al. ApJ, 647, 1106, 2006; R. Lallement et al. astro=ph 0801.0457.

6. Look at the trend of the higher Lyman absorption lines in Fig. 5. What is the cause of the fadeout of the flux approaching the Lyman limit at 912 Å? Show that your explanation has the right order of magnitude to be correct.