**Cume #357**

4 Question Categories; 80 Points Possible; 60 Points (75%) is Guaranteed Pass
passes below this score are a possibility
Administered: November 13, 2010

**The Role of Sub-Damped Lyman-Alpha Absorbers in the Cosmic Evolution of Metals**
V. P. Kulkarni, P. Khare, C. Péroux,, D. G. York, J. T. Lauroesch, & J. D. Meiring (2007), ApJ, 661: 88-94

Please start each question (by number) on a new sheet of paper, write on only one side of the paper, and staple them together in order of question number when finished. Please present your results in the order that the individual questions appear.

1. **[20 pts] This Paper:**

   **(a)** [15 pts] As concise and polished as possible, and *in your own words*, limiting yourself to no more than ten sentences (maximum!), summarize this paper. Indicate an understanding that goes beyond the abstract; but avoid non-essential details: be sure to address: **(i)** the scientific motivation; **(ii)** the main methods; **(iii)** the results (including mention of Figure 1); **(iv)** the astrophysical implication of the result(s).

   **(b)** [2 pts] Definitions of DLAs and sub-DLAs

   **(b.i)** What is the numeric range of the quantity (measured property) that defines DLA absorption?

   **A:** [1 pt] As given in the first paragraph of the Introduction: DLAs are defined by the column density $N(\mathrm{H\,I}) \geq 2.0 \times 10^{20}$ neutral hydrogen atoms cm $^{-2}$, or $\log N(\mathrm{H\,I}) \geq 20.3$. it is a historical definition.

   **(b.ii)** What is the numeric range of the quantity (measured property) that defines sub-DLA absorption?

   **A:** [1 pt] Also as given in the first paragraph of the Introduction: Sub DLAs are defined by the column density $1.0 \times 10^{19} \leq N(\mathrm{H\,I}) < 2.0 \times 10^{20}$ neutral hydrogen atoms cm $^{-2}$, or $19.0 \leq \log N(\mathrm{H\,I}) < 20.3$.

   **(c)** [3 pts] Whereas [Fe/H] is a commonly employed standard measure of metallicity, the authors employ [Zn/H] to measure the metallicity in DLAs and sub-DLAs. Based upon discussion in the paper, state at least two reasons the authors provide to justify their use of [Zn/H]? There is a third reason that is mentioned only indirectly: What is it?

   **A:** [3 pts] The authors clearly list the following two reasons: (1) Zn traces Fe within $\pm 0.1$ dex in Galactic halo and disk stars; (2) Zn II has *two* absorption lines that are clear of the confusing absorption of the Ly$\alpha$ forest and these lines are often unsaturated; The third reason (more subtle in the paper) is that Zn does not suffer dust depletion (unlike Fe), so it provides a robust measure of the absorbing gas metallicity (not just the gaseous phase).

2. **[20 pts] The Experimental Configuration:**

   **(a)** [4 pts] The Origin of DLA Absorption:

   **(a.i)** For which type of atom (specifically, which species, ionization stage, and excitation state) does this absorption feature provide a measure of column density.

   **A:** [2 pts] The Ly$\alpha$ transition arises in neutral hydrogen in its ground state ($n = 1$ excitation state).

   **(a.ii)** Sketch a simple Bohr model of this atom; indicate and label the transition giving rise to Ly$\alpha$ absorption. What is the rest-frame wavelength (in angströms) of the Ly$\alpha$ transition?

   **A:** [2 pts] (1 pt) for an accurate and fully labeled drawing of the Bohr *model.* (1pt) The transition wavelength is 1215.6701 Å. [The transition wavelength is not given in the paper].

   **(b)** [12 pts] Schematic of Experiment:

   **(b.i)** From the side view, draw a schematic diagram of a $z_{\mathrm{em}} = 4$ quasar with a $z_{\mathrm{abs}} = 3$ absorbing structure in the line of sight to the observer at $z_{\mathrm{obs}} = 0$. Also, draw the light path (line of sight) and indicate the location of the observer. Label all parts.

   **A:** [3 pts] See attached diagram Fig. 2(b.i) "Side View Schmeatic".

**(b.ii)** What is the observed wavelength of the Ly$\alpha$ emission from the quasar in the quasar spectrum?

**A:** [2 pts] $\lambda_{\rm obs} = \lambda_r \cdot (1 + z_{\rm em}) = 1215.67 \cdot (1 + 4) = 6078.35$ Å.

**(b.iii)** What is the observed wavelength of the Ly$\alpha$ absorption from the absorber in the quasar spectrum?

**A:** [2 pts] $\lambda_{\rm obs} = \lambda_r \cdot (1 + z_{\rm abs}) = 1215.67 \cdot (1 + 3) = 4862.68$ Å.

**(b.iv)** Assuming the absorber is metal rich, what are the observed wavelengths of the Zn II doublet in the quasar spectrum?

**A:** [2 pts] The doublet is Zn II $\lambda\lambda 2026, 2062$. Using $z_{\rm abs} = 3$, for the $\lambda 2026$ transition, the observed wavelength is 8104 Å, and for the $\lambda 2062$ transition, the observed wavelength is 8248 Å.

**(b.v)** Draw a rough sketch of the quasar spectrum that includes the Ly$\alpha$ emission, Ly$\alpha$ absorption, and Zn II absorption [do not bother with other possible features in the spectrum; be sure your wavelengths are accurate].

**A:** [3 pts] See attached diagram Fig. 2(b.v) "Quasar Spectrum".

**(c)** [4 pts] DLA Profiles:

**(c.i)** Assuming the absorbing structure is a DLA, as *highly accurately as possible*, draw as detailed a damped Ly$\alpha$ absorption profile as you can (focused on an expanded region of the spectrum right at the absorption profile). You can assume a normalized continuum. Provide as *accurate* a wavelength scale in your sketch as you can.

**A:** [2 pts] See attached diagram Fig. 2(c.i,c.ii) "DLA profile". For full credit, one needs to draw the core with (i) zero flux, (ii) the accurate characteristic shape of the damping wings, (iii) have the wavelength centered at $\lambda = 4862$ Å, and (iv) have a fairly good estimate of the wavelength spread of the profile.

**(c.ii)** Indicate where on the profile the optical depth is unity, i.e., $\tau_\lambda = 1$.

**A:** [2 pts] The transmitted relative flux for pure absorption is given by $I_\lambda = e^{-\tau_\lambda}$. For $\tau_\lambda = 1$, we have $I_\lambda = e^{-1} = 0.368$. So, where the relative flux is 0.368, the optical depth is unity. There are two locations in wavelength on the profile that satisfy this condition. See the points labeled on the attached diagram Fig. 2(c).

3. **[18 pts] The Metallicity Estimates:**

**(a)** [3 pts] Definition of Metallicity:

**(a.i)** Write out the symbolic (mathematical) definition of [Zn/H], being sure to define each of the terms.

**A** [2 pts] The definition is

$$[\mathrm{Zn/H}] = \log\left(\frac{\mathrm{Zn}}{\mathrm{H}}\right) - \log\left(\frac{\mathrm{Zn}}{\mathrm{H}}\right)_{\odot} = \log\left(\frac{N(\mathrm{Zn})}{N(\mathrm{H})}\right) - \log\left(\frac{\mathrm{Zn}}{\mathrm{H}}\right)_{\odot},$$

where $\log(\mathrm{Zn/H}) = \log(N(\mathrm{Zn})/N(\mathrm{H}))$ is the measured ratio of zinc to hydrogen in the object of interest and where $\log(\mathrm{Zn/H})_{\odot}$ is the measured ratio of zinc to hydrogen in the solar photosphere.

**(a.ii)** In words, state what [Zn/H] $= -0.5$ means.

**A:** [1 pt] [Zn/H] $= -0.5$ means that the object of interest has a zinc abundance that is half a logarithmic decade (a factor of 3) less than the abundance of zinc in the solar photosphere.

**(b)** [9 pts] Some Applied Concerns: The authors measure the column densities of Zn II and H I, i.e., $N(\mathrm{Zn\,II})$ and $N(\mathrm{H\,I})$, yet quote [Zn/H], for which one would assume they need to have measured $N(\mathrm{Zn})$ and $N(\mathrm{H})$.

**(b.i)** What physical conditions in the gas would have to hold for $N(\mathrm{Zn\,II})/N(\mathrm{H\,I}) = N(\mathrm{Zn})/N(\mathrm{H})$ to be a good approximation?

**A:** [2 pts] The ionization conditions in the gas would have to favor the condition in which zinc is primarily in its first ionization stage (singly ionized) and in which hydrogen was primarily neutral. If only 50% of the hydrogen is ionized, for example, than the ratio $N(\mathrm{Zn\,II})/N(\mathrm{H\,I})$ would be a factor of two larger than the ratio $N(\mathrm{Zn\,II})/N(\mathrm{H})$.

**(b.ii)** Qualitatively, briefly state the corrections that would have to be made in order to determine $N(\mathrm{Zn})$ and $N(\mathrm{H})$ from the measured $N(\mathrm{Zn\,II})$ and $N(\mathrm{H\,I})$. In practice, how are these corrections determined?

**A:** [2 pts] One needs to determine the so-called ionization corrections, i.e., the applicable ionization fractions. Basically, one needs to determine the fraction of zinc that is in the form of Zn II, and the fraction of hydrogen that is neutral, i.e., H I. In practice, these ionization correction factors are determined from photoionization models (like Gary Ferland's Cloudy code), which usually requires having some additional observational constraints on the gaseous conditions. [NOTE: (based upon student responses): the Boltzmann equation does not address relative ionization stages, only relative excitation states- so not relevant here; the Saha equation applies only in thermal equilibrium or approximately in local thermal equilibrium; Saha can be applied fairly well in stellar photospheres; however, the conditions of sub-DLAs and DLAs is such that the ionization balance is dominated by photoionization (ionization from the radiation field- due to the lower density)].

**(b.iii)** Now quantify these corrections by first defining the correction factors (assuming they can be determined), and then by writing down the equation that provides $N(\mathrm{Zn})/N(\mathrm{H})$ from the measured $N(\mathrm{Zn\,II})/N(\mathrm{H\,I})$.

**A:** [5 pts] Define the ionization fractions as

$$f_{\mathrm{ZnII}} = \frac{N(\mathrm{Zn\,II})}{N(\mathrm{Zn})} \qquad f_{\mathrm{HI}} = \frac{N(\mathrm{H\,I})}{N(\mathrm{H})}\,.$$

Then we obtain

$$\frac{N(\mathrm{Zn})}{N(\mathrm{H})} = \frac{f_{\mathrm{HI}}}{f_{\mathrm{ZnII}}}\frac{N(\mathrm{Zn\,II})}{N(\mathrm{H\,I})}$$

[NOTE(again): the ionization fractions are determined from a full model of the ionization balance of the gas, which is dominated by photoionization.]

**(c)** [6 pts] Weighted Means: The authors compute both the straight mean $\langle[\mathrm{Zn/H}]\rangle$ and the $N(\mathrm{H\,I})$ weighted mean $\langle[\mathrm{Zn/H}]\rangle_{N(\mathrm{HI})}$. If you had measured $[\mathrm{Zn/H}]_i$ and $N(\mathrm{H\,I})_i$ for the $i$th absorbing system and were going to compute the $N(\mathrm{H\,I})$ weighted mean $\langle[\mathrm{Zn/H}]\rangle_{N(\mathrm{HI})}$, write down the equation that you would employ to make this calculation from your sample.

**A:** [6 pts] This is derived from the basic equation for weighted means, $\langle x\rangle = (\sum w_i x_i)/\sum w_i$, where $w_i = N(\mathrm{H\,I})$ is the weight. We cannot directly weight [Zn/H] because it is logarithmic; we must weight $x_i = 10^{[\mathrm{Z/H}]_i}$, which provides the metalicity with respect to solar, and then take the logarithm of the result to convert back to $\langle[\mathrm{Zn/H}]\rangle_{N(\mathrm{HI})}$. Assuming $M$ systems in the sample, the equation is

$$\langle[\mathrm{Zn/H}]\rangle_{N(\mathrm{HI})} = \log\left\{\frac{\sum_{i=1}^{M} N(\mathrm{H\,I})_i \cdot 10^{[\mathrm{Z/H}]_i}}{\sum_{i=1}^{M} N(\mathrm{H\,I})_i}\right\} = \log\left\{\sum_{i=1}^{M} N(\mathrm{H\,I})_i \cdot 10^{[\mathrm{Z/H}]_i}\right\} - \log\left\{\sum_{i=1}^{M} N(\mathrm{H\,I})_i\right\}.$$

For comparion, the unweighted results would be obtained from

$$\langle[\mathrm{Zn/H}]\rangle = \log\left\{\sum_{i=1}^{M} 10^{[\mathrm{Z/H}]_i}\right\} - \log M\,.$$

4. **[22 pts] The quantity $\Omega$:**

**(a)** [2 pts] Definition of $\Omega$: Write down the *fundamental* mathematical definition of $\Omega_b$, where $b$ denotes baryons? Define your terms.

**A:** [2 pts] The definition is $\Omega_b = \rho_b/\rho_c$, where $\rho_b$ is the mean mass density of baryons in the universe and $\rho_c$ is the present-epoch critical density of the universe. Since $\rho_c$ is the present-epoch value, it is constant ($\rho_c = 3H_0^2/8\pi G$).

**(b)** [4 pts] Steps to the Result: Given that the $\Omega$ of metallicity from sub-DLAs [in units of $\Omega(Z_\odot)$] is written

$$\Omega_{\rm Z}^{\rm sub\text{-}DLA} = f \times 10^{[\langle {\rm Z/H}\rangle]} Z_\odot \Omega_{\rm HI}^{\rm sub\text{-}DLA}/\Omega(Z_\odot)\,, \qquad (1)$$

[FYI: The factor $f = f_{\rm HI}/f_{\rm ZnII}$ is the ratio of the correction factors from your answer to (b.iii)] the authors need to know the values of $\Omega_{\rm HI}^{\rm sub\text{-}DLA}$ and $\Omega_{\rm HI}^{\rm DLA}$ to estimate $\Omega_{\rm Z}^{\rm sub\text{-}DLA}$ and $\Omega_{\rm Z}^{\rm DLA}$.

**(b.i)** From where do the authors draw the information that $\Omega_{\rm HI}^{\rm sub\text{-}DLA} = 0.18 \times 10^{-3}$, and that $\Omega_{\rm HI}^{\rm DLA} = 0.85 \times 10^{-3}$? For what redshift regime do these values apply?

**A:** [2 pts] They quote this result from the paper Péroux et al. (2005). It applies for $z \sim 2.5$, which corresponds to the higher redshift range of the author's sample.

**(b.ii)** What assumption do the authors employ in order to make estimates at the other redshift bin(s) of their sample?

**A:** [2 pts] They simply must assume that these $\Omega$ values apply for lower redshifts. [see solution for 4(d)]

**(c)** [12 pts] The Result: The authors quote (last paragraph page 89) that $[\langle {\rm Z/H}\rangle] = -0.82 \pm 0.15$ for $0.1 < z < 1.2$ for DLAs. Using their tabulated "primary sample" results from Table 2, they show that $\Omega_{\rm Z}^{\rm sub\text{-}DLA}/\Omega_{\rm Z}^{\rm DLA} \sim f \times 1.5$ for this lowest redshift bin.

**(c.i)** Duplicate the result $\Omega_{\rm Z}^{\rm sub\text{-}DLA}/\Omega_{\rm Z}^{\rm DLA} \sim f \times 1.5$ for the lowest redshift bin by computing both $\Omega_{\rm Z}^{\rm sub\text{-}DLA}$ and $\Omega_{\rm Z}^{\rm DLA}$ from the authors' data.

**A:** [8 pts] The general required quantities for both sub-DLAs and DLAs is the solar metal mass fraction $Z_\odot = 0.0126$, and the present $\Omega$ of metals assuming solar abundances, $\Omega(Z_\odot) = 5.5 \times 10^{-4}$ (both values are given in the paper). The latter is required because the $\Omega_{\rm Z}$ we are computing are in units of $\Omega(Z_\odot)$ (because the term $10^{[{\rm Z/H}]} Z_\odot$ appearing in Eq. 1 above is in solar units). The ratio $Z_\odot/\Omega(Z_\odot) = 22.9$, yielding

$$\Omega_{\rm Z}^{\rm sub\text{-}DLA} = 22.9 \cdot f \cdot 10^{[\langle {\rm Z/H}\rangle]} \Omega_{\rm HI}^{\rm sub\text{-}DLA}\,.$$

For sub-DLAs: from Table 2 of the paper, $[\langle {\rm Z/H}\rangle] = 0.05$, and from Péroux et al. , $\Omega_{\rm HI}^{\rm sub\text{-}DLA} = 0.18 \times 10^{-3}$. We have

$$\Omega_{\rm Z}^{\rm sub\text{-}DLA} = 22.9 \cdot f \cdot 10^{0.05} (0.18 \times 10^{-3}) = 0.00462 \times f\,.$$

Thus, they estimate that the mass density of metals in sub-DLAs is $0.46f$% of the present-epoch critical density, $\rho_c$. For DLAs: from Table 2 of the paper, $[\langle {\rm Z/H}\rangle] = -0.82$, and from Péroux et al. , $\Omega_{\rm HI}^{\rm sub\text{-}DLA} = 0.85 \times 10^{-3}$. We have

$$\Omega_{\rm Z}^{\rm DLA} = 22.9 \cdot (1) \cdot 10^{-0.82} (0.85 \times 10^{-3}) = 0.00294\,.$$

Thus, they estimate that the mass density of metals in DLAs is 0.29% of the present-epoch critical density, $\rho_c$. The ratio is $0.00462 \cdot f/0.00294 = 1.57 \times f$. Note that the authors assume that $f = 1$ for DLAs, i.e., no ionization correction.

**(c.ii)** What does this result (a greater than unity value of the ratio $\Omega_{\rm Z}^{\rm sub\text{-}DLA}/\Omega_{\rm Z}^{\rm DLA}$) imply astrophysically? What astrophysical quandary is resolved if it is substantially greater than unity?

**A:** [4 pts] It implies that, at the lower redshift regime (later cosmic times), the cosmic mass density of metals in sub-DLAs exceeds the cosmic mass density of metals in DLAs by at least the factor 1.5. If true, this resolves the quandary that the metallicity of galaxies is predicted by theory/models to be much higher than is observed in DLAs (which were thought to be representative star forming galaxies).

**(d)** [4 pts] A Hole in the Logic?: What is the major source of uncertainty (I am not alluding to statistical uncertainty due measurement errors or observational bias) in the author's low redshift result that makes their final conclusion less than robust?

**A:** [4 pts] I quote the paper: "The statistics for sub-DLAs and hence the comoving density of H I gas ($\Omega_{\rm HI}$) in sub-DLAs are not yet known at $z < 1.7$. However, one could assume that the relative H I contributions of DLAs and sub-DLAs at low $z$ are similar to those at high $z$." In short, the authors don't have the data to be making the claims about the ratio $\Omega_{\rm HI}^{\rm sub\text{-}DLA}/\Omega_{\rm HI}^{\rm DLA}$ at low redshifts! In my view, this is a significant weakness in their arguments, rendering their results fairly unrobust.