Cume #459

90 Points Possible; 65 Points is Guaranteed Pass

Administered March 5, 2022

Hydrogen reionization ends by $z = 5.3$: Lyman-α optical depth measured by the XQR-30 sample

Bosman, Sarah, E. I. et al. 2021, arXiv:2108.03699v1 (18 pages)

Be sure your solutions in your uploaded document presents in portrait mode. You may use a calculator, but no programmed formulae. Clearly start each question (by number) in the exact order the questions appear. IMPORTANT NOTE: The paper is long. You should not read the whole paper. I have place green boxes around the portions of the paper you should read and/or that are helpful for answering questions on this exam. You are not expected to read or familiarize yourself the other parts of the paper. There should be no loss of continuity due to this. HELPFUL COMMENT: before answering any problems, be sure to familiarize yourself with the full exam so that you can obtain some insight on how to partition your time management between problems. The approximate wavelengths of two key quasar absorption lines are Lyβ = 1025.72 Å and Lyα = 1215.67 Å. For any hand drawn diagrams, be sure to provide axes scales and labels very clearly.

1. **[18 pts]** Let's consider the overall roadmap of this paper (a) the scientific topic, (b) motivations, (c) observations, (d) analysis, and (e) results. Please read all the questions before answering any of the parts.

   (a) [6 pts] (i) Define and describe what the "Epoch of Reionization" is, including what physical process(es) are transpiring in the universe that defines the epoch. (ii) At what *approximate* redshift range does the Epoch of Reionization appear to come to an "end"?

   (b) [3 pts] In three sentences maximum, describe the big picture broader astronomical context motivating this work.

   (c) [3 pts] In three sentences maximum, describe the data employed and the observations.

   (d) [3 pts] In three sentences maximum, describe the scientific analysis performed (do not describe results or findings here).

   (e) [3 pts] In three sentences maximum, describe the *new* most important conclusion(s), i.e., central to the larger picture addressed by the paper, i.e., your "walk away" result(s).

2. **[22 pts]** Let's consider some of the main bits of background knowledge on which this paper is founded.

   (a) [2 pts] An absorbng gas cloud at $z = 5.5$ gives rise to Lyα absorption line. At what wavelength (in angströms) would you observe the Lyα line from this cloud? Show your work.

   (b) [6 pts] Describe the physical process gives rise to an Lyα absorption line. Include in your answer (i) whether this involves neutral atoms, ions, or neutral or ionized molecules (if so, which one(s)), and (ii) whether the physical process is/are vibrational, rotational, or electronic transition(s)? (iii) Draw a diagram of the process and label the relevant parts.

   (c) [9 pts] (i) What is the Gunn-Peterson (GP) trough feature in a quasar spectrum? (ii) Explain the physical processes that combine to give rise to the GP trough. (iii) State why it is seen only in the highest redshift quasars. (iv) Draw a $z = 7$ "typical" quasar spectrum with a GP trough feature that extends down to $z = 5.5$ and label your spectrum and the important features.

   (d) [5 pts] (i) What is the ultraviolet background (UVB) and what are its global properties? (ii) Why is it important to this scientific investigation?

3. **[18pts]** In Figure 1 (top of page 3) we see an example of an X-Shooter spectrum of one of the XQR-30 quasars. The uncertainty (red data, σ_{F_λ}) in the flux values, F_λ, and the estimated uncertainty (blue band, $\sigma_{F^c_\lambda}$) and estimated continuum flux of the quasar, F^c_λ. See the below footnote[1].

   (a) [8 pts] At wavelength λ, the relative flux is written $F_\lambda/F^c_\lambda = \exp\{-\tau_\lambda\}$, where τ_λ is the optical depth at wavelength λ. (i) If $F_\lambda/F^c_\lambda = 0.23$, what is the optical depth at λ? Show your work. (ii) How many mean free paths did this photon of wavelength λ travel (along the line of sight) through the absorbing gas cloud? Show your work or explain your answer.

   (b) [4 pts] Remember our Lyα absorption at $z = 5.5$ in Question 2(a)? (i) Studying Figure 4 (page 7), what is the mean effective optical depth centered on this redshift, i.e., $\langle z\rangle = 5.5$? Give your answer to at least the 0.1 decimal place. (ii) What is the redshift range (lower and upper redshift of the bin) over which this mean effective optical depth is measured?

   (c) [6 pts] (i) For this value of $\tau_{\rm eff}$ at $\langle z\rangle = 5.5$, use Equation 1 from Bosman et al. (Section 3, page 4), to compute the mean relative flux $\langle F_\lambda/F^c_\lambda\rangle$ you would expect to see in a random quasar spectrum in this redshift bin (wavelength range). Show you work. (ii) compare you answer to the entry tabulated as $\langle F_{\rm Ly\alpha}\rangle$ in Table 4 of the paper; is your answer within the $\pm1\sigma$ errors?

4. **[14 pts]** Let's consider how some of the key quantities measured and applied in the science analysis are measured and determined.

   (a) [8 pts] (i) For Lyα, what is the wavelength *range* corresponding to the $\langle z\rangle = 5.5$ redshift bin discussed in Problem 3(b)? (ii) Now, visually examine the representative quasar spectrum in Figure 1, focusing on the flux values in the wavelength range corresponding to the $\langle z\rangle = 5.5$ redshift bin. Let's say you want to compute mean transmitted flux $\langle F_\lambda/F^c_\lambda\rangle$ in the $\langle z\rangle = 5.5$ redshift bin for this particular quasar. Write down a mathematical expression that would appropriately compute $\langle F_\lambda/F^c_\lambda\rangle$ over the appropriate wavelength range in the spectrum. Include the information about the wavelength range for this redshift bin in your formula.

   (b) [6 pts] Let's say you had M quasar spectra covering this redshift bin. Write a modified version of your formula to compute the mean transmitted flux incorporating in all M quasars.

5. **[18 pts]** Let's see what we can put together here.

   (a) [12 pts] In Section 5, the authors compare their measurements to "mock" measurements made in cosmological simulations (Sherwood and Nyx). Consider Figure 13 (Section 5.3, page 13) in the paper, which illustrates the outcome of their likelihood analysis. (i) What does it mean when a data point is less than 1σ and what does it mean when it is greater than 3σ? (ii) Briefly describe what Figure 13 is saying scientifically.

   (b) [6 pts] In Section 5.3.2 (page 16), the authors introduce another set of simulations from Keating et al. (2013). (i) What is the main difference about this simulation compared to the Sherwood and Nyx simulations (ii) Very briefly, at a high level, what is Bosman et al. demonstrating by exploring and comparing the Keating simulations?

[1] Note that Bosman et al. uses the notation $F(\lambda)$ for F_λ, and $F_{\rm cont}(\lambda)$ for F^c_λ.