

Instructions

A hearty welcome to Cume #455! This exam will address subjects related to extragalactic astronomy, galaxy formation, and cosmology. It makes frequent reference to the paper, “Normal, Dust-Obscured Galaxies in the Epoch of Reionization.”

- There are 13 questions and 52 total points are possible. A score of 39 points is a guaranteed pass.
- Please show all work and use a nice new piece of paper for each section or problem.
- If the exam asks you to obtain a number from the paper, then please indicate the number that you obtained and where you obtained it from.
- Be very explicit. For example, if you need to invoke the concept of a “critical density”, don’t just use that phrase, write down what it actually means.
- If you cannot obtain an answer to one question that is necessary for a subsequent question, just assume something for the upstream problem and then move on.
- Please let me know if you’re hopelessly stuck; I may be able to help.

$$\begin{aligned}
 G &= 6.672 \times 10^{-8} \text{ cm}^3 \text{ g}^{-1} \text{ s}^{-2} \\
 c &= 2.99792458 \times 10^{10} \text{ cm/s} \\
 H &= 100h \text{ km s}^{-1} \text{ Mpc}^{-1} \\
 \text{Mpc} &= 3.0855 \times 10^{24} \text{ cm} \\
 \pi &= 3.14159265359 \\
 M_{\odot} &= 1.989 \times 10^{33} \text{ g}
 \end{aligned}$$

Schmidt-Kennicutt Law (Kennicutt+1998):

$$\Sigma_{\text{SFR}} = 2.5 \times 10^{-4} (\Sigma_{\text{gas}} / M_{\odot} \text{pc}^{-2})^{1.4} M_{\odot} \text{yr}^{-1} \text{kpc}^{-2}$$

1 Cosmology

1. (4 points) Suppose that a monochromatic luminous source is receding from an observer in an inertial reference frame at a speed $v \ll c$. Derive the relationship between the wavelength at which the light is observed λ_{obs} and the intrinsic wavelength λ_0 . You should find that the light from the source is observed at a wavelength that is redshifted by the ratio

$$\frac{\lambda_{\text{obs}} - \lambda_0}{\lambda_0} = v/c.$$

(Knowledge) In the source frame, two successive wave crests are separated by a distance λ_0 . The time between when they are emitted is $\Delta t = \lambda_0/c$, and during this time the source moves away from the observer by a distance $v\lambda_0/c$. In the observer’s frame, the wave crests are therefore separated by distance $\lambda_{\text{obs}} = \lambda_0 + v\lambda_0/c$, which is the desired result. Rubric: 2 points for a strong start, 2 points for a full solution. No points for writing down the answer.

2. (4 points) In cosmological applications, one usually quantifies this redshift as

$$z \equiv \frac{\lambda_{\text{obs}}}{\lambda_0} - 1$$

Using the measured redshift of REBELS-12 from Table 1, what is its recession velocity v ? Hint: (Combine the definition of z with the result from Problem 1.) (Application) For REBELS-12, $z = 7.347$. Combining the two previous relations yields $v = cz$, so $v = 7.347c$. Rubric: 1 point for grabbing the correct redshift, two points for noticing, remembering, or showing that $v = cz$, and 1 point for a correct answer.

3. (4 points) You should have found that $v > c$. Explain in 1–2 sentences why this is not a violation of Special Relativity. (Application) Special Relativity applies only in reference frames described by the Minkowski metric. An expanding universe is described by the Robertson-Walker metric, which reduces to Minkowski only if the expansion factor is near unity. In the more general case, the line element is given by

$$ds^2 = -c^2 dt^2 + a(t)^2 [dr^2 + S_k^2(r) d\Omega^2]$$

The proper distance between two events is given by setting $dt = 0$ to get $ds = a(t) dr$, where dr is a comoving distance. From this it can be shown that the growth rate of proper distance is $ds/dt = (da/dt)r$; that is, ds/dt is not constrained to be $< c$ and superluminal growth of proper distance results from uniform expansion. Rubric: All of this is not required for full credit. 2 points for writing something vaguely promising; full credit for noting that SR does not apply to expanding reference frames.

4. (4 points) If you were an observer at $z = 1$ studying REBELS-12, what would you measure its redshift to be? (Application) The observed redshift plus one equals the ratio of the cosmological expansion factors between the emitting and observed frame. For example, the redshift of a source at $z = 7$ is as viewed by an observer at $z = 0$ (today) is $(1 + 7)/(1 + 0) - 1 = 7$. For an observer at $z = 1$, this would mean a measured redshift of $(1 + 7)/(1 + 1) - 1 = 3$. Rubric: 1 point for writing down at least one factor of $(1 + z)$ to indicate some awareness that expansion factors are involved; 2 additional points for invoking the ratio of expansion factors; 1 final point for a correct answer.
5. (4 points) Review Section F of the Appendix. In 2–3 sentences of your own words, what is the authors' argument that the newly-discovered sources are physically associated with REBELS targets? (Comprehension) The newly-discovered sources are near REBELS targets both in projection and in redshift. Rubric: 2 points for just *mentioning* projected distance and/or redshift, and 2 more points for noting that this alignment is unlikely. Alternatively, 4 points for reviewing the discussion of probability of chance alignment in the Appendix.
6. (3 points) In the second-to-last paragraph of page 4, the authors provide an initial estimate of the cosmic star formation rate density by dividing the total star formation rates from the newly-discovered, dust-obscured galaxies by the total survey volume in the REBELS survey. In 2–3 sentences, what is potentially wrong with this particular estimate? (Comprehension) Because of the way in which galaxies cluster, galaxies of any type are more abundant in regions that are pre-selected to have bright galaxies, hence the REBELS survey volume is biased high almost by design. Rubric: 1 point for noting that galaxies are clustered, and 2 points for relating this fact to the nature of the REBELS survey volume.
7. (4 points) The general shape of the star formation density curves in Figure 3 all involve a peak around $z = 2$, when the Universe was only 3 Gyr old. Name and describe in 1–2 sentences each *two* effects that could lead the Universe's star formation rate density to decline at later times. (Analysis) There are many possibilities here including quenching of star formation in overdense regions (which itself comes from more than one cause); declining gas inflow rates; the onset of accelerated expansion; and declining merger rates. Rubric: 1 point each for naming an effect and describing it creditably.

2 The Schmidt-Kennicutt Law

Let's use the information in Figure 1 along with Appendix E to estimate the star formation rate of REBELS-12-2 using the Schmidt-Kennicutt Law. Remember that, if you can't solve any of the next few problems, you may *assume* an answer and then use that one downstream.

8. (3 points) Compute the object's proper surface area in kpc^2 . (Application) From Figure 1, the diameter is $\sim 10 \text{ kpc}$, which yields a surface area of 75 kpc^2 . Rubric: 1 point for grabbing a length scale, 1 point for attempting to apply $\pi d^2/4$, 1 point for a correct answer.
9. (4 points) Compute its gas surface density Σ_{gas} in units of **solar masses per square parsec**. (Application) From Appendix E, the gas mass is $60\% \times 9.4 \times 10^{10} M_{\odot} = 5.6 \times 10^{10} M_{\odot}$; dividing this by the surface

area gives $750M_{\odot} \text{ pc}^{-2}$. Rubric: 1 point for grabbing the correct gas mass; 2 points for setting up the math correctly; 1 point for a correct answer. No points off if they do not apply the 60% gas fraction, but 1 point off if they do not convert kpc $\rightarrow$ pc.

10. (4 points) Use the Schmidt-Kennicutt law (given above) to compute its star formation rate surface density in **solar masses per year per square kiloparsec**. (Application) Applying the S-K law gives $2.64 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$. Rubric: 2 points for anything more substantial than just writing down the correct relationship between star formation rate surface density and gas surface density that is given at the top of the exam; 2 additional points for an answer within 20% of correct.
11. (4 points) Compute the star formation rate of REBELS-12-2. Locate the reported star formation rate given in Table 1 of the paper and comment on whether your estimate agrees with it (spoiler: they won't agree perfectly). (Application) Multiplying the star formation rate surface density by the surface area gives $198M_{\odot} \text{ yr}^{-1}$. This is larger than either of the estimates in Table 1. Rubric: 2 points for a calculation, 1 point for noting one of the measurements in the paper, and 1 point for verbally comparing in a way that is internally consistent even if their calculations are wrong.

3 Dust

12. (4 points) The authors use dust continuum emission to trace a galaxy's star formation rate. In no more than three sentences, describe conceptually why dust continuum emission is an effective tracer of a galaxy's star formation rate. (Knowledge) Some of the light from energetic young stars heats dust, which then re-radiates it; the bolometric dust luminosity is therefore a tracer of the bolometric luminosity of stars whose light is absorbed. As the brightest stars are short-lived, their abundance is proportional to the SFR. Connecting their abundance to their total luminosity indicates a connection between luminosity and SFR. Rubric: 2 points for some mention of dust re-radiation; 2 points for connecting this luminosity with the luminosity of short-lived stars.
13. (5 points) Name and describe in 2–4 sentences one assumption that must be made in order to relate a galaxy's dust continuum emission to its star formation rate (there are many). (Analysis, but also knowledge) Possible answers include star formation history; initial mass function; metallicity; subgrid stellar population parameters such as binarity, rotation, and mixing; dust temperature; and the escape fraction of high-energy flux. Rubric: 1 point for mentioning something sensible; 4 points for a good explanation.
14. (5 points) The authors advocate strongly for an unbiased survey for more dust-obscured galaxies. However, it is also very clear that the observed sample of dust-obscured galaxies is very poorly-understood. Suppose that the authors could *either* apply for further or deeper measurements of the current objects, *or* plan a blind survey. Which approach do you think would be more useful? Please describe at least two separate arguments in support of your preferred approach. (Synthesis) Arguments for learning more about these systems:

- constrain dust temperature, stellar mass, stellar age, or metallicity
- determine whether their spatial relationship to the REBELS sample implies that their deeply-obscured nature originates in an interaction (this would argue that few would be found in the field)
- constrain inclination angle to learn about dynamical mass

Arguments for a blind survey:

- suppress cosmic variance uncertainty
- constrain luminosity function of epoch-of-reionization dust-obscured galaxies

Rubric: 1 point for choosing an approach; 2 points each for naming and describing arguments in favor of their chosen approach.