NMSU Astronomy Cume #454 **Moire Prescott**
October 2, 2021

Overview:

This Cume is based on the paper "An Ancient Massive Quiescent Galaxy Found in a Gas-rich $z \sim 3$ Group" by Kalita et al. 2021.

The exam contains 9 questions, worth 68 total points. The anticipated passing grade is 75%.

Additional Instructions:

- Please start each question on a new page and write legibly.
- Aim to answer questions completely but **concisely**, generally in a few statements.
- Be careful with your time management. Do not spend too much time on any one question. I recommend that you try to get through all the questions within ~ 90 minutes, and then use the remaining ~ 30 minutes to go back and complete any parts you skipped.
- Calculators may be used for calculations, but you may not use any other outside resources (i.e., no stored equations, notes, books, internet access, etc.).
- If at any point you aren't able to remember or calculate a specific value, just introduce a variable or state your assumption and proceed with the rest of the question.
- At the end of the exam, put your responses in question order and either hand them in directly or upload them to Canvas.

Useful Information:

- The AB magnitude zeropoint is -48.6.

MORPHOLOGY

1. (6 points) The authors use morphological model fitting to obtain a Sérsic index of $n \sim 2$ for Galaxy-D (Section 4.1), which they suggest indicates the galaxy contains both a disky component and a significant bulge component.

   (a) What is a Sérsic index?

   [Knowledge] A Sérsic profile is an analytic function that is commonly used to fit the light profile of galaxies. The exponent of the Sérsic profile, called the Sérsic index n, is often used as a proxy for the morphology of the galaxy, with $n = 1$ indicating an exponential, disk-like profile, and $n = 4$ indicating the de Vaucouleurs profile characteristic of an elliptical galaxy. An index of $n = 2$ suggests a galaxy that is intermediate between exponential and de Vaucouleurs, hence the authors suggestion of a composite with both disky and bulge components. [3pt describe fitting surface brightness profile with Sérsic function with exponent n; only 1.5pt if only give key n values; 0pt for simply saying it quantifies morphology as that is implied by the statement of the question]

   (b) How could the authors have modified their approach to quantify the relative contribution of these two components, assuming sufficient signal-to-noise and high enough spatial resolution?

   [Synthesis] Assuming sufficient signal-to-noise and high enough spatial resolution, a multi-component parametric fit (e.g., an exponential for the disk plus a Sérsic profile for the bulge) could have been attempted to determine the bulge-to-disk ratio. [3pt describe multi-component fit; only 1.5pt if just mention bulge-to-disk ratio without saying how this would be derived]

2. (8 points) In Section 4.1, the authors use matched aperture photometry to derive isophotal fluxes in several HST/WFC3 filters (F606W, F814W, F125W, F160W), and then scale those measurements up using the results from model fitting in the F160W image.

   (a) What are isophotal versus model fluxes?

   [Knowledge] An isophotal flux is the total flux down to a given isophote (contour of constant surface brightness), whereas a model flux is the total flux of the derived parametric model. [2pt describe isophotal flux; 2pt describe model flux]

   (b) What assumption are the authors making in doing this scaling?

   [Analysis] Since they apply the scaling between the F160W isophotal and model fluxes to all of the filters, they are making the implicit assumption that the profile of the galaxy, i.e., the relative constribution from the central region versus the outskirts, is the same in all filters. [4pt same profile in all bands]

MAGNITUDES AND DISTANCES

3. (8 points) Using the information provided in Section 4.1 (second paragraph), what is the angular diameter distance to this galaxy (in Mpc)?

   [Application] The text mentions that Galaxy-D has an effective radius of $r_e = 0.14''$, which corresponds to 1.1 kpc at $z = 2.9$. This scaling is the angular diameter distance, with some unit conversions.

   $s = d_A\theta$ where s is the physical radius in kpc, θ is the angular radius in radians, and d_A is the angular diameter distance in kpc. Therefore,

   $d_A = s/\theta$

   $\theta(radians) = r_e('') \times 1°/3600'' \times \pi/180°$

   $d_A = 1.1\ kpc/[0.14'' \times 206265\ radians/''] \ d_A = 1.621E6\ kpc = 1621\ Mpc$

   [3pt grab r_e in arcsec and kpc; 3pt use $s = d_A\theta$ correctly; 1pt unit conversion to radians; 1pt answer]

4. (10 points) Based on Figure 3 (top left), what is the AB magnitude of Galaxy-D at $\lambda_{obs} = 2$ μm?

   [Application]

   $F_\lambda = 0.009 * 2 \times 10^{-17} erg/s/cm^2/Å$

   $F_\nu = F_\lambda * \lambda^2/c$

   $F_\nu = 0.009 * 2 \times 10^{-17} erg/s/cm^2/Å \times [(2 \times 10^{-6} m \times 1 \times 10^{10} Å/m)(2 \times 10^{-6} m)]/(3 \times 10^8 m/s)$

   $F_\nu = 2.4 \times 10^{-29} erg/s/cm^2/Hz$

   $m_{AB} = -2.5 * Log_{10}(F_\nu) - 48.6 = 22.9\ AB\ mag$

   [2pt F_λ value; 3pt use $F_\nu = F_\lambda\lambda^2/c$; 2pt unit conversion of λ; 2pt AB mag equation using provided zeropoint; 1pt answer]

STELLAR POPULATION AGE

5. (8 points) According to the authors, the variable t_{50} signifies the time elapsed between the epoch of "half-mass formation" and the time of observation (Section 4.3). They report a best-fit value of $t_{50} = 1.6$ Gyr.

   (a) To visualize this, make a sketch of Figure 4 (right panel) with just the best-fit $\tau = 0.2$ Gyr curve, and indicate on this figure what time t_{50} refers to.

   [Comprehension] The quantity t_{50} refers to the time between the time of observation, i.e., the epoch corresponding to $z = 2.9$, where the ALMA upper limit is plotted, and the time at which half of the stellar mass had been formed. Since the time of observation corresponds to about 2.2 Gyr after the Big Bang, the time of half-mass formation was $2.2Gyr - 1.6Gyr = 0.6Gyr$. Therefore, we can draw a bar from 0.6 to 2.2 Gyr to indicate t_{50} (see attached sketch). [2pt t_{50} bar on sketch starts at ∼0.6 Gyr; 2pt bar ends at ∼2.2 Gyr]

   (b) Use your sketch to argue that the reported value of $t_{50} = 1.6$ Gyr is indeed the epoch of "half-mass formation."

   [Application] Since this plot shows star formation rate (SFR) in solar masses per year versus time in Gyr, the total mass formed by a given time is simply the integral under the curve. It is clear by eye that a vertical line drawn at 0.6 Gyr splits the area under the curve into two equal areas, meaning that half the mass did indeed form prior to that time and half after (see attached sketch). [2pt something about how total mass is integral under the SFR vs t curve; 2pt show half areas before and after end of t_{50} line at ∼0.6 Gyr]

6. (6 points) In Section 4.3 (second paragraph), the authors describe how their derived t_{50} varies with different assumed metallicities. Name and describe the well-known degeneracy that is responsible for the trends they report, and explain why this degeneracy occurs generally.

   [Knowledge/Comprehension] This is the well-known age-metallicity degeneracy, whereby a stellar population will be red either if it is old or if it is metal-rich. Older stellar populations are dominated by lower mass, redder stars. Metal-rich populations have higher stellar photospheric opacities and more prominent metal lines in the blue which lead to a redder spectrum. [2pt name age-metallicity degeneracy, 2pt describe how a stellar population can be red either because it is old or because it is metal-rich; 1pt reason for old being redder; 1pt reason for metal-rich being redder]

RARITY AND ENVIRONMENT

7. (10 points) The authors estimate the probability of a chance alignment of Galaxy-D and the center of the galaxy group in Section 4.4. Taking their estimate of $2-20$ galaxies like Galaxy-D within the 2 square degree COSMOS survey area, recreate this calculation to show why the authors claim the probability is vanishingly small.

   [Application]

   There are between 2 and 20 galaxies similar to Galaxy-D in the COSMOS survey area, $A_{COSMOS} =$ 2 square degrees. The surface density is therefore $n = 2 - 20/2$ square degrees $= 1 - 10$ per square degree. Galaxy D is within 10" from the center of the galaxy group, which corresponds to an area on the sky of $A_{Galaxy-D} \sim \pi * (10''/(3600''/degree))^2 = 2.4 \times 10^{-5}$ square degrees.

So the probability that Galaxy-D would happen to fall within this 10" radius circle by coincidence is:

$P = n \times A_{Galaxy-D} = (1 - 10/sq.degree) \times 2.4 \times 10^{-5} sq.degree = 2.4 \times 10^{-5} - 2.4 \times 10^{-4}$

Since the authors are only confident about 2 galaxies similar to Galaxy-D, they quote the smaller of these two probabilities.

Equivalently, compute the relative areas (area within the group center / area of COSMOS) and multiply by the number of similar galaxies that would be expected within the COSMOS area.

[2pt use number of similar galaxies; 2pt use area within group; 2pt use area of COSMOS); 1pt unit conversion arcsec to degree; 2pt correct answer; 1pt compare to/comment on "vanishingly small" answer in paper]

8. (6 points) In Figure 5, Galaxy-D appears to be one of the only galaxies at its redshift and relatively old age. In Section 5.1, the authors describe three possibilities for why this might be. Choose one possibility and explain how it would lead to there being very few galaxies near Galaxy-D in Figure 5. (Make sure to describe where else a galaxy would end up in Figure 5 as a result of your chosen scenario.)

   [Comprehension]

   Option 1 - Most old massive galaxies at $z \sim 3$ experience re-accretion of gas and return to the star-forming population. This would give them a younger age, pushing them lower on Figure 5.

   Option 2 - Most galaxies with ages similar to Galaxy-D may simply not have assembled yet by $z \sim 3$, making them truly rare and therefore they would not appear on Figure 5 at all because they don't yet exist.

   Option 3 - Most galaxies similar to Galaxy-D are harder to detect and study because they are fainter in the NIR than younger post-starburst galaxies, which makes them less likely to be appear in Figure 5 even though they exist.

   [3pt chose one of the three scenarios in paper; 3pt why would lead to fewer galaxies near Galaxy-D / where would galaxy be in Figure 5]

9. (6 points) Given that Galaxy-D is relatively old for $z \sim 3$, what is surprising about the presence of a large Lyman-alpha (Lyα) nebula surrounding the galaxy group (Figure 1)?

   [Comprehension] The Lyα nebula means that there is a healthy supply of cold gas in the vicinity. One might have expected that the presence of lots of cold gas would have led to Galaxy-D restarting star formation, which would have decreased its measured age. Instead it appears that Galaxy-D has been able to shut down star formation and stay quenched despite living in an environment with abundant cold gas. [3pt nebula indicates presence of cold gas; 3pt something about how expect gas to lead to accretion/trigger star formation which would lead to younger age than observed]