

## Cume #457

Welcome to the first cume of 2022 – Happy New Year! You will have received the corresponding paper, Peluso et al. (2021) 30 minutes prior to the receiving this exam. Herein, you will find questions on that paper and related topics.

There are 13 questions with 84 points possible. A score of 63 points or more will warrant an automatic pass.

As a reminder, references beyond this paper, notes, or communication (other than with me) are NOT permitted during this exam. You are permitted to use the basic functions of a calculator, i.e., not graphing or information stored prior to the exam.

Please make sure your writing is legible. As a general rule, I try to assign partial credit for good efforts, but I *cannot if the writing is illegible*. Also, please show all work and do attempt each problem, showing your thought process even if you can't solve it completely. Note that most questions have multiple parts, so make sure you answer the entire problem.

If anything needs clarification, please email me.

Possibly relevant information:

$$\begin{aligned}M_{\text{sun}} &= 1.988 \times 10^{30} \text{ kg} \\ G &= 6.674 \times 10^{-11} \text{ m}^3 / (\text{kg s}^2) \\ 1 \text{ pc} &= 3.08 \times 10^{16} \text{ m}\end{aligned}$$

1. (6pt, Knowledge/Comprehension) In two to three sentences (or one sentence and a drawing), describe the process of ram-pressure stripping and the environments where it is likely to happen. Ram-pressure stripping (RPS) is a mechanism wherein objects, such as galaxies, moving through a dense medium (such as the intercluster medium, ICM) experience a force opposite to the direction of motion and gas within the galaxy (interstellar medium, ISM) is compressed and/or removed from the galaxy.

2 pts for a reasonable description of process,  
2 pts for mentioning motion through dense medium  
2 pt for environment: galaxy clusters (and possibly groups)

2. (4pts, Knowledge/Comprehension) What are two of the observable morphological signatures of ram-pressure stripping?

2 pt for extended tails of gas and/or stars  
2 pt for truncated galaxy disks (also accept triggered star formation if specific about observational indicators; 1 pt for just mentioning quenching or AGN activity)

3. (6pts, Comprehension) In two sentences, describe the hypothesized process by which ram-pressure stripping induces active galactic nuclei.

4 pts for anything about gas funneling towards the SMBH

2 pt for compression of the ISM gas by the ICM

4. (4pts, Knowledge) The authors use emission-line diagnostics to identify regions in the AGN-dominated regions of the interstellar media (ISM) in their galaxy sample. Why might, e.g., the [NII]/H $\alpha$  ratio be sensitive to AGN activity?

2 pts for an explanation that involves the difference in source of ionizing photons between H II regions (hot stars) and radiation from accretion disks around supermassive black holes (AGN)

2 pt for a reasonable attempt

5. (10pts, Application) Referring to the BPT diagram in Figure 1, sketch galaxy spectra that are representative of the four classes: star-forming, composite, Seyfert, and LINER. Note: the hard-to-see dashed bright green line differentiates between the Seyfert and LINER regions of the more general AGN class. Your drawings do not have to be perfectly to scale with respect to the line fluxes, but they should be self-consistent with one another; exaggeration of features is okay!

Hint #1: Make two sketches per galaxy where each ‘zooms’ in on either the region around the [OIII] and H $\beta$  lines or the region around the [NII] and H $\alpha$  lines.

Hint #2: First, draw your star-forming spectrum for reference, then draw the others relative to this.

2 pt for something that looks like spectra with emission lines

4 pt for apparent changes in the relative strengths between the [OIII]/H $\beta$  line and [NII]/H $\alpha$  ratios

4 pt for plausibly correct spectra for the various classes one to another. Example: the composite spectrum showing intermediate [NII]/H $\alpha$  for fixed [OIII]/H $\beta$  between the star-forming and LINER spectra

6. (8pts, Analysis) From Figure 2, what might you conclude about the relationship between AGN fraction and galaxy stellar mass? Why or why not do these histograms justify the mass selection criteria for the samples compared in this study?

4 pts: The AGN fraction appears to increase with host galaxy mass.

4 pts: The authors exclude galaxies with  $M_* < 10^9 M_{\text{sun}}$ , which is justified because no AGN are found in galaxies with this mass. This choice mitigates a bias in their comparison from any differences in the mass distributions.

(or 1 pt for something more vague about selection bias)

**Note: Questions 7 through 9 relate back to the following paragraph:**

The ‘classical’ Gunn & Gott (1972) formulation of ram-pressure stripping takes the form

$P_{\text{ram}} \approx \rho (\Delta v)^2$  where  $\rho$  is the density of the intracluster medium (ICM) through which the galaxy is moving and  $\Delta v$  is the difference between the galaxy velocity and local velocity of the gas. For simplicity, we assume that there no net bulk motions in the ICM around the galaxy and

$\Delta v = v_{\text{sat}}$  where  $v_{\text{sat}}$  is the velocity of the galaxy.

7. (4pts, Application) Using dimensional analysis, show that the expression above indeed yields the expected units of pressure.

Expected units of pressure (in cgs):  $[P_{ram}] = g \frac{cm}{s^2} \frac{1}{cm^2} = g \frac{1}{cm} \frac{1}{s^2}$

$[\rho] = g/cm^3$ ,  $[v] = cm/s$

$$\rho v^2 = \frac{g}{cm^3} \left( \frac{cm}{s} \right)^2 = g \frac{1}{cm} \frac{1}{s^2}$$

2 pt: units of density and velocity (doesn't have to be cgs)

2 pt: correct result

8. (8pts, Synthesis) For simplicity, we could assume that the velocity of the galaxy is equal to the virial velocity of the galaxy cluster. Note that the virial theorem technically holds for average total kinetic and potential energies of systems. As an approximation, we will assume the individual galaxy motions satisfy the virial theorem as well.

- Write down the virial theorem.  $U + 2T = 0$  (2pt)
- Now rewrite the virial theorem in terms of the mass of the satellite galaxy ( $M_{sat}$ ), mass of the cluster ( $M_{clust}$ ), virial radius of the cluster ( $R_{clust}$ ), and velocity of the satellite galaxy ( $v_{sat}$ ).
- Show that  $v_{sat}$ , the virial velocity of the satellite galaxy, can be expressed as follows:

$$v_{sat} = \sqrt{\frac{GM_{clust}}{R_{clust}}}$$

$$2 \frac{1}{2} M_{sat} v_{sat}^2 = \frac{GM_{clust} M_{sat}}{R_{clust}}$$

$$v_{sat}^2 = \frac{GM_{clust}}{R_{clust}}$$

$$v_{sat} = \sqrt{\frac{GM_{clust}}{R_{clust}}}$$

4 pts: correct kinetic and potential energy relations

2 pt: correct result

9. (8pts, Application) For the density of the cluster, assume that it follows the profile of an isothermal sphere, so  $\rho \propto r^{-2}$ . Calculate the timescale required for a galaxy moving at the virial velocity to experience a doubling in ram pressure on path starting from the cluster radius  $R_{clust}$ . Assume a cluster with  $M_{clust} = 10^{14} M_{sun}$  and  $R_{clust} = 1500$  kpc.

(2 pt) First, set  $P_2 = 2P_1$ , where  $P_1$  is the ram pressure at  $R_{clust}$ , which leads to

$$\frac{R_{clust}^2}{R_2^2} = 2$$

$$R_2 = \frac{1}{\sqrt{2}} R_{clust}$$

(4 pts) Then, timescale to travel  $R_{clust} - \frac{1}{\sqrt{2}} R_{clust} \approx 0.29 R_{clust}$  can be found by setting  $v_{sat} t = 0.29 R_{clust}$ . Substitute expression for  $v_{sat}$ :

$$\sqrt{\frac{GM_{clust}}{R_{clust}}} t = 0.29 R_{clust}$$

$$t = 2.5 \times 10^{16} \text{ s} \sim 0.8 \text{ Gyr}$$

2 pt for correct result.

10. (4pts, Analysis) Referring to Figure 3, what might one infer about the relationship between AGN activity and the degree of ram-pressure stripping as indicated by the Jstage (if anything)?

2 pt: The AGN fraction is highest for Jstage = 2.

2 pt: Including the physical meaning of the Jstages, i.e., that the AGN fraction is highest for galaxies in a fairly advanced state of ram-pressure stripping: they exhibit tails longer than the stellar disk diameter.

11. (6pts, Analysis) Considering the information in Table 2, would you conclude that this relationship is or is not monotonic? Why or why not?

2 pt: Some reasoned argument for why the relationship is or is not monotonic.

2 pt: Inclusion of the error bars in the discussion.

2 pt: The AGN fractions for Jstage = 2 and Jstage = 3 are within the error bars of each other, so one cannot conclude that the relationship is not monotonic.

12. (10pts, Evaluation) You are at a conference where one of the authors of this paper is presenting the results. One proponent of AGN-driven quenching speaks up and says, “So you’ve shown that AGN are more prominent where environmental interactions are taking place. This proves that even in dense environments like galaxy clusters, it’s the AGN that quenches star formation. Ram-pressure activates the AGN, and the AGN either ejects the gas supply from the galaxy altogether or heats it up so that stars cannot form.”

Critique this argument by drawing on your own knowledge and information from within the paper to assess the logic at play here. Do you agree or disagree?

The argument appears to suffer from confirmation bias. Indeed, the fraction of galaxies that are quenched increases in dense environments such as those studied in this paper where the ram-pressure signatures are observed. Also, the results of this paper indicate that AGN are more prominent in galaxies also undergoing ram-pressure stripping. However, ram-pressure stripping itself is *directly removing* the gas supplies in these galaxies, as it is the stripped ISM of the galaxy that is observed in the H $\alpha$  tails. While the data indicate connection between AGN and

ram-pressure stripping, it is far more likely that the dominate quenching mechanism for these galaxies will be either the direct removal of their gas reservoirs for star formation or rapid consumption of the gas due to star formation triggered by the gas being compressed due to ram pressure. Furthermore, although we are witnessing a period of AGN activity, we do not know how long these episodes might last or their duty cycle.

4pts: A critical breakdown of the logic whether agreeing or disagreeing

4pts: Mentioning one of the alternate quenching mechanisms

2pt: Affirmatively saying whether they agree or disagree, regardless of logic

13. (6pts, Analysis) What is the primary observational difference between the ‘LIT-RPS’ sample and the ‘GASP-RPS’ and ‘MaNGA-Ref’ samples? What uncertainties might this introduce?

4 pts: The ‘LIT-RPS’ sample is not comprised of objects identified through integral field spectroscopy, whereas the other two (GASP and MaNGA) originate from integral field unit (IFU) surveys. (3 pts for differences in redshift)

2 pt: Given that the ‘LIT-RPS’ will be spatially sampled differently than the IFU surveys, possibly with only a single fiber placed on the galaxies, regions with AGN-like line ratios might be missed by the data and the objects incorrectly classified as not having AGN.

(1 pt for some attempt at describing corresponding uncertainties)