**NMSU Astronomy Cume #437** **Moire Prescott**
**October 26, 2019**

**Overview:**

This Cume is based on the paper "Secularly powered outflows from AGNs: the dominance of non-merger driven supermassive black hole growth" by Smethurst et al. 2019.

The exam contains 6 questions, worth 68 total points. The anticipated passing grade is 75%.

**Additional Instructions:**

- Please start each question on a new page (leaving enough room at the upper left for the staple) and put your name on each page. Staple your packet of pages together in question order at the end.
- If at any point you aren't able to remember or calculate a specific number, just introduce a variable and proceed with the rest of the question.

**Useful Information:**

- Speed of light $c = 3 \times 10^{10}$ cm s$^{-1}$
- $M_\odot = 2.0 \times 10^{33}$ g
- $L_\odot = 3.8 \times 10^{33}$ erg/s
- 1 pc $= 3.08 \times 10^{18}$ cm

# THE BIG IDEA

1. Let's start by considering the main conceptual result from this paper.
   (a) (4 points) Explain in a few sentences why the authors chose to focus on disk-dominated galaxies.

   *The authors are interested in the role of secular processes (non-merger processes, things happening just within the individual galaxy) in feeding the central black hole. Since galaxy mergers tend to produce bulge components, the authors focus on disk-dominated galaxies as a way to limit their sample to galaxies with minimal merger history.*

   (b) (6 points) Summarize in a few sentences (i) the differences between the two accretion scenarios mentioned in the paper, and (ii) how the measurements in the paper suggest both scenarios may be relevant for different samples of galaxies.

   *In one mode, which dominates in disturbed, merger systems, the accretion is quasi-spherical, which means the black hole is not spun up and accretion efficiency is not increased. The outflow will interact more directly with the inflowing material, potentially sweeping up extra mass into the outflow. This explains the lower black hole accretion rates and higher mass outflow rates of the merger-dominated sample.*

   *In the other mode, which is relevant for non-merging systems, accretion is smooth and nearly radial and the outflow is bipolar, and thus does not interact as much with the inflowing material. This leads to a spin-up of the black hole (as the accretion adds angular momentum), which increases the efficiency of the black hole accretion. This explains the high black hole accretion rates and lower mass outflow rates of the disk-dominated sample.*

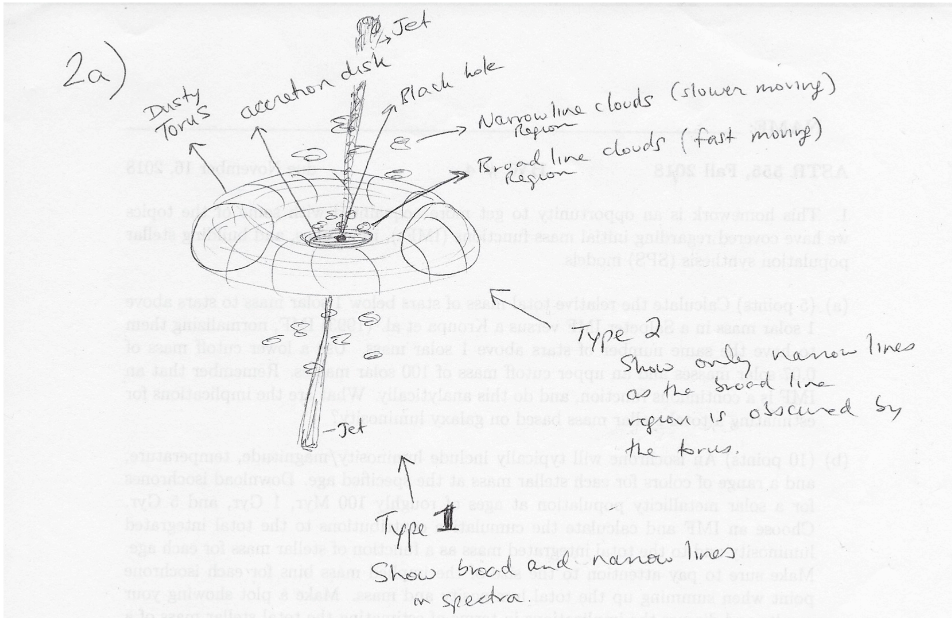


Figure 1: Sketch Unified Model of AGN.

# ACTIVE GALACTIC NUCLEI

2. The two samples that are compared in this paper are drawn from different AGN populations.

   (a) (6 points) Sketch and describe the Unified Model of AGN in a few sentences. In your description, be sure to clarify what distinguishes Type I and Type II observationally and how the Unified Model unifies them.

   *Sketch shown in Figure 1.*

   *A Type 1 AGN is one where the accretion disk of the black hole is viewed closer to face-on. This means that the dusty torus does not obscure the view of the accretion disks, and so the fast moving material in the very near vicinity of the black hole leads to broad Balmer emission lines (Hα, Hβ, etc.), i.e., the so-called "broad line region" (BLR). Material further out is also visible, so narrow emission lines of, e.g., [OIII], [NII], [SII] are visible from the "narrow line region" (NLR).*

   *A Type 2 AGN is one where the system is viewed closer to edge-on. In this orientation, the dusty torus obscures the view of the accretion disk and the broad emission lines are not seen in the spectrum. The narrow line region is still visible, so the spectrum shows narrow emission lines of, e.g., [OIII], [NII], [SII], but with ratios consistent with AGN powering.*

   (b) (4 points) The authors compare disk-dominated outflowing Type I AGN with merger-dominated Type II AGN (see Section 5.3 and footnote 3). Explain why you do (or do not) agree that these samples yield a legitimate "apples-to-apples" comparison.

   *The Unified Model of AGN suggests that different AGN types are manifestations of the same phenomenon, so to that extent comparing different AGN samples seems reasonable. However, the specific measurements in this paper, namely $r_{max}$ and $v_{[OIII]}$ are both orientation dependent quantities in the case of a bipolar outflow. $r_{max}$ will be larger for bipolar Type 2 systems, since we are seeing the full outflow in the plane of the sky, vs. in Type 1 systems, where the outflow is directed partially along the line of sight. Similarly, $v_{[OIII]}$*

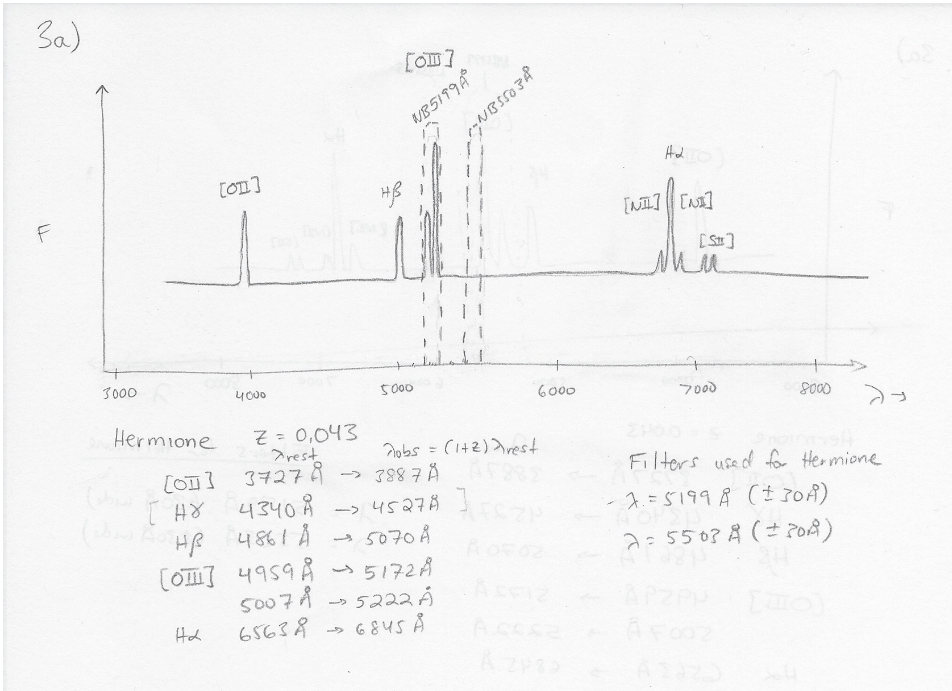


Figure 2: Sketch of optical galaxy spectrum with key emission lines and narrowband filter transmission curves used to observe Hermione.

*will be high for Type 1 systems, since the direction of the outflow will be primarily along the line of sight, and lower for Type 2 systems, where the outflow is moving closer to perpendicular to the line of sight. It would be better to choose AGN samples that do not have these geometric differences when attempting to investigate differences in accretion and inflow/outflow rates.*

(c) (4 points) Using the information in the paper, can you back out the measured bolometric luminosity of the AGN in galaxy Hermione?

*From Table 2, the estimated black hole accretion rate is 0.04* $M_\odot/yr$ *for galaxy Hermione. Some fraction of the accretion (the radiative efficiency* $\eta$*, which in this paper is assumed to be 0.15) leads to the bolometric luminosity of the AGN. As in equation 5, this translates to a* $L_{bol} = \dot{m}\eta c^2 = (0.04 M_\odot/yr)(1.99\times10^{33} g/M_\odot)(1yr/3.15\times10^7 s)(0.15)(3\times10^{10} cm/s)^2 = 3.42\times10^{44}\ erg/s = 8.8\times10^{10} L_\odot$

# OBSERVATIONAL TECHNIQUES

3. This study uses a combination of narrowband imaging and SDSS spectroscopy.

(a) (8 points) Sketch the full optical spectrum you would expect to observe for galaxy Hermione, given the information in Table 1, and label at least 4 key emission lines including approximate observed wavelengths. Add the transmission curves for the pair of narrowband filters used in this work.

*Sketch shown in Figure 2.*

(b) (4 points) The authors don't say exactly how they determined the empirical cut-off for [OIII] coming from star formation versus from outflows in Section 3.1 and Figure 7. Write a couple sentences describing what you think their method might have been.

*The authors seem to be drawing a distinction between the slowly rising profile of the extended (star-forming) disk and the spikier profile of the outflow in the center right around the location of the AGN. Perhaps they used some measure of the slope of the profile, and then set the threshold where the slope changed from shallow to steep by some substantial amount.*

# ANALYSIS

4. Let's look at some of the analysis done in this study.

   (a) (5 points) Using the spectra in Figure 1, estimate $v_{[OIII]}$ for the outflow in galaxy Hermione. Tip: make sure to read the Figure 1 caption carefully before you begin.

   *The wavelength offset between the outflow (blueshifted) component and the narrow (central) component at ∼5164Å is* $d\lambda \sim 5\AA$ *for galaxy Hermione, from Figure 1. This corresponds to an outflow velocity* $v_{[OIII]} \sim (d\lambda/\lambda)(c) = (5\AA/5164\AA)(3\times10^5 km/s) \sim$ *290 km/s.*

   (b) (4 points) Using your answer above, the tabulated values in Table 2, and equation 2, back out what the measured $r_{max}$ must have been for the galaxy Hermione.

   *The reported* $t_{outflow} = 9\times10^6$ *years for galaxy Hermione. Since* $t_{outflow} = rmax/v_{[OIII]}$, $r_{max} = (9\times10^6 years)(290 km/s)(3.15\times10^7 s/yr) = 8.2\times10^{16}$ *km ∼2.6 kpc.*

   (c) (5 points) Estimate the apparent magnitude of the [OIII] outflow in galaxy Hermione. To do this, estimate the area of the outflow in Figure 8 and use the tabulated surface brightness in Table 1. Note that the blue circles in Figure 8 represent the SDSS 3" diameter fiber.

   *Using the SDSS 3" diameter fiber as a reference, the outflow appears to have an area of roughly 1/4 of the fiber, so the area is* $A = 0.25\pi(3/2)^2 \sim 1.76 arcsec^2$. *The reported surface brightness is 31.85 mag/arcsec*$^2$. *Therefore, the apparent magnitude of the outflow is m = SB - 2.5 Log10(A) = 31.85-2.5Log10(1.76) = 31.23 mag.*

# LIMITATIONS

5. The authors comment that the issue with the PSF is a key limitation of their study. While they assert that this issue is not severe enough to cause the differences they find in outflow rates, they don't actually demonstrate this.

   (a) (4 points) Explain how the PSF issue could potentially affect their results.

   *They use a PSF subtraction to remove the contribution from the central AGN and then sum up the remaining [OIII] flux above some threshold to get the luminosity of the outflow, which they then use to get an outflow mass. If the PSF they use is incorrect, however, then they will over or undersubtract, leading to an over or under estimate of the outflow luminosity.*

   (b) (4 points) Describe what plot or numbers you would have liked the authors to provide to better justify their claim.

   *I would like to have seen at least some numbers quantifying how badly the PSF is under or oversubtracting the core profile. Perhaps they could have used several different PSFs and found the resulting scatter on the measurement. Or perhaps they could shown the cross-cuts of the PSF-subtracted data (as in Figure 7) but for several different PSF profiles.*

# FUTURE WORK

6. In the future, the authors plan to use integral field spectroscopy from the Keck Cosmic Web Imager (KCWI) to improve on this work. Let's think about what their KCWI data will look like for one of the objects, Hermione, using what we know from the existing data.

   (a) (4 points) Take a look at galaxy Hermione in Figures 3. What morphological information can you use to guess the direction of rotation of the galaxy? That is, is it most likely rotating clockwise or counter-clockwise from our perspective, and how do you know?

   *Galaxy Hermione is a barred spiral. It has been demonstrated that almost all galaxies rotate with trailing spiral arms. Therefore, based on the image in Figure 3, it is most likely that Hermione is rotating counter-clockwise from our perspective.*

   (b) (6 points) Suppose we know that the lower (Southern) half of galaxy Hermione is closer to us. Given the information about the galaxy in Figures 1 and 8, describe in a few sentences what would you expect to see in the full [OIII] velocity field derived from KCWI intregral field spectroscopy. Make sure to include a mention of what you would expect to see in the core, the disk, and the outflow.

   *It appears that galaxy Hermione is inclined roughly along the bar. If the Southern half of galaxy Hermione is closer to us and the arms are trailing, then the lower rightside end of the bar is redshifted and the upper leftside end of the bar is blueshifted. In the KCWI data, the central core of the galaxy would be at the systemic velocity of the system, by definition. The lower rightside would be redshifted, and the upper leftside blueshifted due to the rotation of the disk. Finally the outflow would appear as a little blueshifted region mostly to the lower left of the central core. The velocity of the outflow would be comparable to the maximum rotation velocity of the disk (so more blueshifted that the rest of the inner disk region).*