

Instructions

Welcome to Cume #418. This exam will address subjects related to extragalactic astronomy and cosmology and makes frequent reference to Mathews & Prochaska 2017. Do not read the paper in detail; that would take too long. I recommend just reading the abstract, the Introduction and the figure captions, and then referring back to the paper as the questions indicate.

- There are 40 possible points. A score of 28 is a guaranteed pass.
- Please show all work. I can't give partial credit for sparsely-shown work.
- In a number of places, the exam asks you to lift a number from the paper. Please indicate the number you lift and where you lifted it from; the ability to do this efficiently is one of the things that is being tested.
- Please let me know if you're hopelessly stuck; I may be able to help.

$$c = 2.99792458 \times 10^{10} \text{ cm/s}$$

$$M_{\odot} = 1.989 \times 10^{33} \text{ g}$$

$$\text{year} = 3.156 \times 10^7 \text{ sec}$$

1 Qualitative

1. I propose to confirm and extend the OVI measurements that are the basis of this paper using APO facilities.
 - (a) (3 points) Quote the rest-frame wavelength of the transition in question, and compute observed-frame wavelength. Note: You may simply choose one combination of wavelength and redshift to demonstrate that you understand the calculation.
 - (b) (2 points) Based on your result from the previous problem, why won't the APO TAC give me my time?

From the Introduction, the OVI doublet that they use is at a rest-frame wavelength of (1031.9, 1037.6Å). For galaxies at $z=0.1-0.4$ this corresponds to observed-frame wavelengths $\lambda_{\text{rest}} \times (1+0.4) < 1453\text{Å}$, which is inaccessible from the ground.

2. (4 points) This paper discusses L^* galaxies.
 - (a) Qualitatively, what is an L^* galaxy?
 - (b) How is L^* measured from a distribution of galaxy luminosities? It may help to sketch a galaxy luminosity function and point to L^* .

The distribution of galaxy luminosities is well-approximated by a Schechter function, or the product of a power-law (for faint galaxies) and an exponential (for bright ones). The luminosity at which the exponential becomes effective is L^* , hence an L^* galaxy can be thought of as a typical bright galaxy.

3. (3 points) The model assumes that the gas density profile is an NFW profile. Qualitatively, what is an NFW profile? Under what conditions is the gas likely to be distributed in this way?

Under quite general conditions, collisionless matter such as dark matter condenses into bound regions whose density profile $\rho(r)$ is well-characterized by the Navarro-Frenk-White profile. Gas will also do this if it does not cool and is not heated through feedback processes; that is, if it is also collisionless.

4. The Introduction to this paper distinguishes between models in which OVI-absorbing gas is in photoionization equilibrium, and models in which it is in collisional ionization equilibrium.
 - (a) (2 points) What is ionization equilibrium?
 - (b) (1 point) What is the difference between photoionization and collisional ionization equilibrium?
 - (c) (1 point) How might the gas temperature differ between these two scenarios?

Ionization equilibrium involves taking the differential equation governing the evolution in the abundance of a particular species such as OVI:

$$\frac{dn_{\text{OVI}}}{dt} = [\text{OVII recombination rate} + \text{OV ionization rate}] - [\text{OVI ionization rate} + \text{OVI recombination rate}]$$

and setting the left-hand side equal to zero. In the case of photoionization equilibrium, ionizations all owe to the local UVB and the gas is characteristically much colder than the ion's ionization potential. In the case of collisional ionization equilibrium, ionizations all owe to collisions with electrons, hence the gas must be hot enough for a significant population of electrons with more energy than the ionization potential.

2 Heating by SNe and Black Holes

A central assertion in this paper is the idea that supernovae cannot balance radiative losses. Let's explore that idea.

1. Let's step through how one would compute the number of Type II supernovae that blow up per total mass of stars formed. Suppose that all stars that initially reach the Main Sequence with masses between $8\text{--}40M_{\odot}$ explode as Type II SNe. Suppose also that the initial mass function is given by $\xi(m)$; that is, the number per mass of stars formed with masses between m and $m + dm$ is $\xi(m)dm$. (Note: you won't be able to evaluate these expressions because I'm not giving you the functional form for $\xi(m)$.)
 - (a) (2 points) Write down an expression for the number of Type II supernovae that form up if the IMF extends from masses 0 to ∞ .
 - (b) (2 points) Write down the total mass in stars that form over the same mass range.
 - (c) (1 point) How would you combine answers to (a)–(b) to get the number of supernovae per mass of stars formed?

The number of SNe is simply the number of stars that form in the given mass range, or $\int_8^{40} \xi(m)dm$. The total mass in stars that form is similar, given by a mass-weighting of $\xi(m)$: $\int_0^{\infty} m\xi(m)dm$. The number of Type II SNe per mass of star formed is just the ratio of these integrals, or

$$\frac{N_{\text{SNe}}}{M_*} = \frac{\int_8^{40} \xi(m)dm}{\int_0^{\infty} m\xi(m)dm} \quad (1)$$

2. Let's consider the SN heating rate in more detail.

- (a) (3 points) The paper gives an observational estimate of this number in the form of SNe yr^{-1} per late-type galaxy as well as an estimate of the total SN heating rate in ergs s^{-1} . Find (and write down) the SN rate from Section 2 of the paper, assume that each SN releases 10^{51} ergs, and reproduce their estimated SN heating rate.

The SN rate is actually in Section 3; students were given extra time owing to this error. The SN rate on page 3 is 1–3 per century. The SN heating rate is therefore:

$$\begin{aligned} H_{\text{SN}} &= 10^{51} \text{ergs SN}^{-1} \times \frac{2 \text{ SN}}{100 \text{ yr}} \times \frac{1 \text{ yr}}{3.155 \times 10^7 \text{ sec}} \\ &= 6.3 \times 10^{41} \text{ergs sec}^{-1} \end{aligned}$$

- (b) (3 points) There is speculation (Nomoto et al. 2006) that as many as half of core-collapse SNe are actually “hypernovae”, which release 10–40 times as much energy as the conventional 10^{51} ergs per supernova assumed in the previous estimate. Suppose that this increases the overall SN heating rate by $5\times$. Would this bring the SN energy output into balance with the X-ray cooling losses implied by the modeling in this paper? (Note: your solution should quote the inferred X-ray luminosity from the paper, compute the SN heating rate if half of SNe are hypernovae, and compare the two rates.)

Boosting the heating rate in the previous problem by a factor of five brings it up to $3.2 \times 10^{44} \text{ergs s}^{-1}$, which is within the range of X-ray luminosities implied by Figure 4.

3. (4 points) A conclusion of the paper is that a central black hole must provide this heating rate. Of course black holes grow as they radiate. Let’s evaluate whether the required luminosity gives a black hole that is too massive. Suppose that black holes that accrete mass at a rate $\dot{M}$ radiate with luminosity $L = \eta \dot{M} c^2$ where the efficiency parameter $\eta = 0.1$. Suppose further that an L^* galaxy’s SMBH has been radiating at a rate that equals the X-ray luminosity implied by this paper for 10^{10} years. How does the resulting black hole’s mass compare to that of our Milky Way’s SMBH (which is in the paper)?

The luminosity L and final mass M are as follows:

$$\begin{aligned} M &= \dot{M} \Delta t \\ L &= \eta \dot{M} c^2 \end{aligned}$$

Solving the second equation for $\dot{M}$, substituting into the first equation yields

$$M = \frac{L \Delta t}{\eta c^2}$$

For $L = 1.6 \times 10^{42} \text{ergs s}^{-1}$, this is $2.8 \times 10^6 M_{\odot}$, remarkably close to the measured mass of the MW’s black hole given the uncertainty in the efficiency parameter η .

3 Chemical Evolution

Let’s think a little about the metal mass fractions that are implied by the modeling in this paper.

1. (2 points) Section 2 makes reference to a “closed box model” of chemical evolution. What does that mean?

This is a one-zone chemical evolution model in which no gas or metals enters or leaves the system, and the gas starts out with zero metallicity.

2. (2 points) What observational evidence is there that galaxies (as opposed to halos) are not closed boxes?

The G-dwarf problem, and the direct observation that gas and metals are ejected from galaxies.

3. (5 points) When SNe blow up, they release metals into the ISM. The ratio of the mass of newly-formed metals to the mass of long-lived stars is the “metal yield” y . In a closed box, the metal mass fraction in gas Z famously varies with the mass fraction of baryons in the gas phase μ as $Z = y \ln(1/\mu)$.

- (a) Assuming an oxygen yield of $y = 0.015$ and a solar oxygen mass fraction of $Z_{O\odot} = 0.01$, what is the gas fraction μ implied by the medium-feedback (red) model at 10kpc?
- (b) Why does this calculation probably underestimate the halo's overall gas fraction?

From Figure 3, $Z \approx 9Z_{O\odot} = 0.09$, so $\mu = \exp(-Z/y) = \exp(-0.09/0.015) = 0.0025$. However, only a fraction of the halo lies within 10 kpc and there are clearly metals at larger radii, where Z is inferred to be lower, so the halo's overall gas fraction is almost certainly higher.