

Cume ... by R. Walterbos is based on the paper "Cold Molecular Gas along the Cooling X-ray Filament in A1795", by McDonald et al, 2012, ApJ Letters, L24.

Please write clearly and explain your answers. Each (sub)question is worth 5 points. Passing grade anticipated to be 70%.

1. Let us first investigate what the "cooling flow problem" (e.g. abstract, last line) for hot gas in galaxy clusters is.

a. What are the radiative cooling mechanisms for the hot gas? I am not just looking for the wavelength regime(s) at which radiation occurs, but the radiation mechanism(s) as well. Describe these mechanisms and address how the radiation produced depends on the plasma density.

(looking for: bremsstrahlung or free-free radiation, recombination lines and highly excited lines in heavy elements. Dependence for both is on product of $n(e)$ and $n(ions)$.)

b. Where would the cooling rate be highest and why would there be a "flow" expected to go along with the cooling?

(hydrostatic equilibrium for hot gas would imply highest density in cluster core, hence highest cooling rate there, so gas cools faster in core, leading to drop in pressure and inflow of gas from outside).

2a. Calculate the rest wavelength of the CO 1-0 line from information given in the paper on page 2. What kind of a transition is this (electronic, vibrational, or rotational?).

(paper gives observed frequency and redshift. Need to turn that into a rest wavelength. This is a rotational line transition).

2b. Why is CO emission used as a tracer for molecular hydrogen gas? In your answer, also address why the H_2 molecule itself is not observed directly.

(hydrogen molecule does not have dipole moment and does not radiate. CO is best tracer since C and O are next highest abundance elements (other than He) and form a suitable molecule that is easily excited by collisions with hydrogen molecules).

2c. What is the "X-factor" cited on page 3, left column? Explain its rather peculiar units.

(The conversion of CO into molecular mass needs to be calibrated. The

result is the "X-factor". It states the conversion of the observed intensity (CO spectrum integrated over velocity so brightness temp in K times km/s as units) to column density of molecules per cm²).

3. There are some interesting figures in this paper.

a. Consider Figure 1. If one had no prior knowledge of previous observations of region A that are cited in the paper, how many of the features you see in the spectrum for region A might be considered a significant detection as to opposed to possible noise or other systematics? Explain your reasoning.

(The spectra of the background regions show systematic variations in baseline level and noise features such that at best two of the lines in the spectrum for A might be considered significant detections.)

b. The correlation in Figure 3a looks pretty good. It becomes less convincing if one realizes a certain commonality between the two quantities plotted on the X- and Y-axis. What is that commonality? (You don't need the color version of the figure to address this question).

(The figure shows a classic distance squared vs distance squared plot. Both the mass and the Halpha luminosity depend on distance squared. Thus, only the scatter around the line provides any useful information.)

4. While the detections may not look all that spectacular, the results are nevertheless intriguing since it has been difficult to find much concrete evidence of cool gas in these types of environments. The following two questions probe the early part of the discussion section of the results in the paper.

a. The discussion mentions that " $L_{H\alpha}$ will decrease by a factor of ~ 100 during the first 10 Myr of a typical starburst". Why would it decrease so rapidly? What produces the $H\alpha$ emission?

(For a starburst all stars are formed instantaneously. The massive hot stars produce the ionizing radiation responsible for Halpha emission. These stars have life times less than 5Myr so the Halpha emission will drop off quickly.).

b. The paper discusses a "classical cooling rate" (dM/dt) at the bottom of page 4 and gives an expression for that. Explain what the basic factors are that go into that expression, and hence explain the equation (μ is the mean atomic weight of the ions in the plasma, m_p the mass of the proton) in its proportionalities (it is not a long derivation but follows from a few basic quantities).

(The cooling time is roughly equal to the thermal energy content divided by the luminosity. We can turn this into a mass deposit rate by taking $dM/dT \sim \text{Mass}/(\text{cooling time})$. This leads to the right dependence in the equation given).

4b $\left(\frac{dM}{dt}\right)_{\text{classical}} = \frac{2L \mu m_p}{5kT} ?$

Derivation:

Thermal energy content: $E_{\text{th}} = V \cdot \left(\frac{5}{2}\right) n_p kT$

(actually bit strange. $\left(\frac{3}{2} \times 2n_p\right)$ is correct I think.)

Mass of this gas: $M = V \cdot \rho$

$= V \cdot \mu m_p n_p$

Cooling time: $\tau = \frac{E_{\text{th}}}{L} = \frac{V \cdot \frac{5}{2} n_p kT}{L}$

$\frac{dM}{dt} \sim \frac{M}{\tau} = \frac{V \cdot \mu m_p n_p}{V \cdot \frac{5}{2} n_p kT / L} = \frac{2L \mu m_p}{5kT}$

2a redshift $z = 0.06325$

obs freq: $\sim 108.4 \text{ GHz}$

$\nu_{\text{obs}} = \frac{\nu_0}{(1+z)} \rightarrow \nu_0 \approx 115 \text{ GHz}$

$\lambda = \frac{c}{\nu} = 2.6 \text{ mm}$