Astronomy 485 — Problem Set 7 — Weeks 14 and 15

Niel Brandt

All problems are worth 10 points.

1. Please read the articles 'Where are the Baryons?' by Cen & Ostriker and 'Chandra and FUSE Views of the WHIM: The Local Group and Beyond' by Nicastro; both are available from the course World Wide Web page. Then please write an ≈ 2 page essay describing the main results of these articles. You should address issues such as the following:

- Where are the baryons at $z = 0$ and $z = 2$? Why are the predictions and observations about the location of these baryons thought to be reliable?
- How is the warm/hot gas discussed in these articles related to the hot gas in clusters of galaxies? What are the relative size scales involved? Roughly how big would a 'filament' of warm/hot gas appear on the sky?
- How is the warm/hot gas discussed in these articles heated?
- What is the current status of X-ray observational efforts to detect the warm/hot gas? What observational techniques are being used? Why are these observations challenging?

If you have any difficulties with these articles, feel free to drop by and ask questions.

2. (a) How long (in years) does a stellar mass (say 7 $M_\odot$) black hole have to accrete matter at the Eddington limit in order to reach a luminosity of 10^{47} erg s^{-1}? To determine this, write down and solve a simple differential equation for how the mass changes with time due to accretion. You may assume a radiative efficiency of $\eta = 0.1$. Please compare the timescale you derive to the Hubble time (the age of the Universe).
2. (b) If a galaxy with 10^{11} stars contains a dead quasar that grew as in the previous part until reaching 10^8 $M_\odot$, compare its total gravitational and thermonuclear (from stellar fusion) energy release during the time it took for the black hole to grow. You may take the stars to each have a mass of 1 $M_\odot$.
2. (c) A quasar has a luminosity of 10^{47} erg s^{-1} and varies on the timescale of a day. Deduce a mass and a radius for the emitting region using the Eddington limit and light-crossing-time arguments. How does the implied density compare with that of the Earth? What is the mass accretion rate assuming a radiative efficiency of 10%? How does the amount of mass eaten per second compare with the mass of the Earth?

3. The jet in the nearby active galaxy M87 is probably inclined at 40° to the line of sight. Superluminal motion has been seen by radio astronomers within the core of the jet with $v_{\rm app} = 2.5c$. Estimate the velocity of the jet (β), the bulk Lorentz factor of the jet (γ), and the Doppler factor for each side of the jet ($D_{\rm approach}$ and $D_{\rm recede}$; see the Fabian notes). Why might the receding side of the jet be difficult to detect? Note that even the approaching side has a Doppler factor smaller than 1; what is the physical reason for this? You may assume a radio spectral index of $\alpha = 1$.

4. M87 is a giant elliptical galaxy in the core of the Virgo cluster. It contains a central supermassive black hole with a mass of $\approx 3 \times 10^9$ $M_\odot$. The nuclear region of this galaxy also contains a diffuse, hot interstellar medium with density 0.5 cm^{-3} and sound speed 500 km s^{-1}. Some of this hot interstellar medium will accrete onto the black hole. Show that, to order of magnitude, the expected accretion rate is 0.1–0.2 $M_\odot$ per year. What fraction of the Eddington accretion rate is this (for an efficiency of $\eta = 0.1$)? If the hot interstellar medium accretes with $\eta = 0.1$, what would be the luminosity produced? Observations show that the luminosity is much lower than this (the observed luminosity is $\sim 10^{42}$ erg s^{-1}), suggesting the presence of a low-efficiency accretion flow (perhaps dominated by advection).

5. The energy density of radiation from quasar light is $\sim 10^{-16}$ J m^{-3} now. What is the mean mass density in dead black holes? How does this compare to the critical density for $H_0 =$ 70 km s^{-1} Mpc^{-1}? What is the mean black hole mass per galaxy if the density of galaxies is 10^{-2} Mpc^{-3}? You should adopt an accretion efficiency of $\eta = 0.1$. If needed, you may assume that most quasars occurred at a redshift of $z = 2$.

6. (a) What is the column density at which matter starts to become optically thick to Thomson scattering?
6. (b) The rapid and large-amplitude X-ray variability seen from Seyfert galaxies and quasars can be used to place constraints on X-ray emission mechanisms. Consider a Seyfert galaxy with a mean X-ray luminosity of $L = 2 \times 10^{43}$ erg s^{-1} that varies by a factor of 2 in X-ray luminosity in 1000 s. Show that optically-thin thermal bremsstrahlung emission with a temperature of 2 keV cannot explain this X-ray variability. Assume a homogeneous spherical emission region and pure hydrogen gas. Your line of attack should be to show that the assumption of optical thinness breaks down.
If you are having difficulty, have a look at *The Astrophysical Journal*, 378, 537 for a somewhat more detailed discussion of this argument.

7. The Coma cluster of galaxies (see figure 14.1 of your book) is pervaded by a hot intergalactic medium which emits thermal bremsstrahlung X-rays at a temperature of 10^8 K. The luminosity between 0.5 and 10 keV is 5×10^{44} erg s^{-1} (the emission in this energy band dominates the total bremsstrahlung luminosity). The radius of the cluster is 2×10^{24} cm.
7. (a) Assuming a uniform distribution of gas, calculate the electron number density, the total mass of the plasma (in $M_\odot$), the total thermal energy, and the cooling time.
7. (b) If the thermal velocity of the protons in the gas is equal to the root mean square velocity of the galaxies in the cluster (a 'velocity equipartition'), estimate the total mass of the cluster (in $M_\odot$). This number is about right, but the total mass can be somewhat higher in reality (see page 319 of your book for the total mass of the Coma cluster).