Ph 442 Problem Set 7

Due: Thursday, December 10, 2009

1. Rosswog & Brüggen problem 8.5

2. Rosswog & Brüggen problem 8.9

3. The object 3C273 is the nearest and brightest quasar, with a visual magnitude that ranges between about 13.5 and 12.0. Its redshift of 0.1583 places it at a distance of 640 Mpc. As the name indicates, 3C273 is a strong radio source and has been detected at all wavelengths from radio to soft (GeV) gamma rays. Roughly equal amounts of energy are emitted per decade of frequency between photon energies of about 0.1 milli-eV (radio waves with 3 cm wavelength) and 100 MeV (see, for example, the compendium of 40 years of observations at many wavelengths in http://isdc.unige.ch/3c273/). This is fairly typical of quasars as is the strong variability at most wavelengths. The optical spectrum of 3C273 shows broad emission lines from hydrogen and a few other elements and a bright continuum between the lines. Sudden flares in brightness at radio wavelengths sometimes extend up to optical frequencies. These results cause 3C273 to be classified as a blazar, which means that we are probably looking down a jet which is beamed nearly at us. A jet displaying superluminal motion is seen very close to the quasar at radio wavelengths with very-long-baseline interferometry (VLBI). A bright jet is also seen much further to one side of the quasar and is detected from radio to x-rays. The jet may emit gamma rays, but our gamma-ray telescopes do not have sufficient angular resolution to separate the quasar and jet. This problem has you examine Chandra X-ray observations of the quasar and jet.

Run ds9, connect to the Chandra-Ed Archive Server on the Virtual Observatory page, and load the image associated with ObsID 1712. This is an image of 3C273 obtained during the early calibration phase of observations with Chandra. The bright source in the middle of the field is the quasar. The quasar is so bright that at the center of its image counts arrived so quickly that they could not be individually counted and were lost, a phenomenon called pile-up. This is the reason that the image of the quasar is dark at its center. The jet extends diagonally to the lower-right of the quasar. The faint line going through the quasar from the lower left to the upper right of the image was created by the bright quasar during the brief time when the charge was being shifted from the imaging part of the CCD to the storage region.

a) Use a circular region that includes most of the flux from the quasar but not the jet. Use the CIAO/Sherpa Spectral Fit from the Chandra-Ed Analysis Tools to fit different models for the spectrum to the data using the default 0.3 – 10 keV energy range. Try the power-law, blackbody, and bremsstrahlung models. For each fit, use values in the Sherpa logs to report the fitted temperature or power-law index, the hydrogen column density (a1.nH), the flux in the 0.3 – 10 keV band corrected for hydrogen absorption (in ergs $\text{cm}^{-2}\ \text{s}^{-1}$), and the reduced chi-square (the chi-square divided by the number of degrees of freedom). Which model is the best fit?

b) Use the fitted flux for the best-fitting model to calculate the luminosity of the quasar in 0.3 – 10 keV X-rays. Assume isotropic emission by the quasar. Note that this measurement is an underestimate because of the pile-up losses.

c) At what distance from the quasar does the bright portion of the jet begin, in arcseconds, and what is the corresponding projected distance in parsecs? Traveling at the speed of light, how long (in years) would it take to cover this projected distance? Note that the actual time for material to reach that point in the jet will be longer if the jet is not perpendicular to our line of sight (which it is almost certainly not).

d) What is the appearance of the jet in X-rays? Which end of the bright portion of the jet is brighter — that closest to the quasar or that furthest away? Examine the figure linked under this problem set on the class web page, which compares the jet at X-ray, optical, and radio wavelengths. How does the jet compare at these different wavelengths?

e) Use a polygonal region and a power-law spectrum to measure the X-ray flux from the bright portion of the jet. Also report the spectral index. Calculate the implied luminosity in the 0.3 – 10 keV band assuming isotropic emission, even though this is not a very good assumption.

4. The origin of the X-ray emission from the bright jet of 3C273 is still controversial. The two leading candidates are synchrotron radiation and inverse Compton scattering of microwave background photons. This problem examines some of the related issues. The radio and optical emission are generally accepted to be synchrotron emission because they are both polarized. However, the optical emission has a steeper spectral index than the radio. This argues that the energy spectrum of the electrons is already cutting off at the energies which generate optical synchrotron photons. Thus, one would not expect X-ray synchrotron photons and a single population of electrons cannot simultaneously produce both the X-ray, optical, and radio emission by the synchrotron mechanism. Thus, there must either be another population of electrons or another mechanism is required (or both). Even whether the optical emission should be associated with the radio or the X-ray emission is still unclear.

a) VLBI observations detected a superluminal velocity of $(14.2 \pm 1.2)c$ (using the current accepted value for the Hubble constant to get the distance to 3C273). What is the implied minimum value for the relativistic γ_{jet} of the bulk motion in the jet?

b) There is presumably a counter-jet in 3C273 that is invisible because of relativistic beaming. The limit on the ratio of the brightness of the jet to that of the counter-jet is $>$5800 from VLBI observations. Use the result in Chapter 8 of the text for the intensity of a beamed jet to show that your limit on γ_{jet} from part a) is easily able to produce this much suppression of the counter-jet (assume that the jet is pointed directly at us, for simplicity).

c) Calculating the minimum-energy magnetic field assuming synchrotron emission is more complicated than for supernova remnants because of the relativistic beaming of radiation from the jet. Calculations have yielded a value of $B = 10\ \mu$G. Using this magnetic field strength, calculate the energy of the electrons that would produce synchrotron X-rays with an *observed* energy of 5 keV. Start by calculating the emitted photon energy in the rest frame of the jet material, using your limiting value for γ_{jet} from part a). Note that the electron energy your derive is in the jet rest frame. What is the characteristic time for these electrons to lose their energy due to synchrotron losses (again in the jet frame)?

d) The typical microwave background photon has an energy of $2.8kT$, where $T = 2.7$ K, or about 7×10^{-4} eV. What is the relativistic γ_{el} required by an electron to produce an *observed* average photon energy of 5 keV by inverse Compton scattering? Again, your γ_{el} will be in the jet rest frame. Note that you need to calculate both the energy of the scattered photon in the jet rest frame and the energy of the microwave background photon that the electron will see in the jet frame. Calculate the characteristic Compton cooling time for these electrons in the jet frame. The energy density of the microwave background is $u_{CMB} = 4.2 \times 10^{-13}$ erg cm^{-3} in our rest frame. However, the energy density in the frame of the jet is is boosted to $\gamma_{jet}^2 u_{CMB}$ (approximately; the CMB is not isotropic in the jet frame and this alters some details of the Compton scattering, which we ignore here).

e) Compare your cooling times from the previous two parts to the minimum time to reach the bright part of the jet that you calculated in 3c). Could the electrons be accelerated in the core of the quasar to produce the emission seen in the jet? Or must they be re-accelerated by shocks within the jet?