Ph 442 Problem Set 3

Due: Thursday, October 8, 2009

1. Use the data in the table http://www.nndc.bnl.gov/masses/mass.mas03 and the information in the interactive chart of the nuclides available at http://www.nndc.bnl.gov/chart/ to answer this problem.

a. For mass $A = 56$, what is the most tightly bound nucleus in terms of binding energy per nucleon (*i.e.*, what is its name? how many protons does it have)? How many different $A = 56$ nuclei are stable against all modes of decay, strong and weak? How many different mass 58 nuclei are stable?

b. What is the most tightly bound nucleus of all (in terms of binding energy per nucleon)? Is it ^{56}Fe or something else? (Hint: it has an A somewhere between 55 and 65.)

c. If one considers only nuclei with $Z = N$, what is the most tightly bound nucleus (again, it is between $A = 55$ and 65).

d. Sketch a chart of the nuclides for $N = 78$ to 83 and $Z = 53$ to 58. Indicated which nuclei are stable and sketch the path taken by the s-process. Indicate which stable nuclei are produced by the s-process, the r-process, and by both processes.

e. The element La is mostly produced by the s-process. Can you give a reason why the production of La by the s-process is particularly large?

2. A feature of detectors which record the arrival of individual photons is detector dead time. If the count rate from a bright X-ray source is high enough, the X-ray detector may miss a legitimate count because it is still processing a previous count. This is known as detector dead time; the detector is "dead" (insensitive to further counts) for a time Δt after registering a count. Work out a simple equation for the actual count rate R' in terms of the measured count rate R and Δt. Counts that are missed do not themselves cause dead time. If we measure a source to have a count rate of $R = 100$ counts s^{-1} and the dead time is $\Delta t = 1$ ms, what is the actual count rate?

3. This problem explores the sensitivity of various X-ray detectors and the factors that influence that sensitivity.

a. At X-ray energies of 2–10 keV the brightest (relatively) steady source in the sky (excluding the Sun) is Sco X1 with a flux of 3×10^{-7} erg s^{-1} cm^{-2} in the above bandpass. Calculate the approximate flux from this source in photons s^{-1} assuming an average photon energy of 4 keV. Use your calculated photon flux for Sco X1 to estimate the count rates expected for the following two detectors, each consisting of a proportional counter behind a collimator: Uhuru (the first satellite X-ray observatory; proportional counter effective area = 280 cm^2, which is a third of the geometric area of 840 cm^2 due to less than 100% efficiency in detecting photons) and the proportional counter array (PCA) of RXTE (effective area = 920 cm^2 for one of the five units; the geometric area of the unit is about 1580 cm^2). Here we are ignoring the slightly different photon-energy bandpasses of the different detectors. Repeat the above calculations for the Crab Supernova remnant (flux= 2×10^{-8} erg s^{-1} cm^{-2}), Perseus cluster of galaxies (flux= 1×10^{-9} erg s^{-1} cm^{-2}), and quasar 3C273 (flux= 8×10^{-11} erg s^{-1} cm^{-2}). These are all among the brightest objects in their class. The dead-time for each PCA unit is 8.8 μs. Are dead-time corrections important for the PCA when observing Sco-X1?

b. Consider a detector with a count rate for the background of B. If photons from a source are detected at the rate R, then the signal (*i.e.*, the total number of counts) detected in time t is $S = Rt$ and noise in this signal is $N = \sqrt{Rt + Bt}$. This last assumes that the detector adds no noise of its own to that resulting from the Poisson arrival of photons. Using your results from part (a), calculate how long an integration time the Uhuru satellite needed to measure the brightness of 3C273 with $S/N = 100$ (an accuracy of 1%). Make the calculation using both $B = 0$ and with the true value of $B = 10$ counts s^{-1}. Note that the above estimate of the noise assumes that B is known perfectly, which is not the case in X-ray astronomy because B varies with the position of the satellite in its orbit and with time.

c. The Einstein X-ray Observatory had mirrors with a total collecting area of 350 cm^2. If the Imaging Proportional Counter (IPC) at the focus of the mirrors detects half of the photons incident on the mirrors (due to losses in the mirrors and IPC), calculate the count rate expected for 3C273 using your photon flux from part (a). (Note that this ignores the somewhat different passband, 0.1–4 keV, of Einstein.) If a background of 10 counts s^{-1} is uniformly spread throughout the IPC, which had an approximately square field of view with a side of 75 arcminutes, and all of the counts from 3C273 are concentrated in a spot 1 arcminute across (the resolution of the IPC), will the background contribute significant uncertainty to the measurement of the flux from 3C273?

d. The High Energy Astrophysics Science Archive Research Center (HEASARC) provides a number of web-based tools for high-energy astrophysics. Use the WebPIMMS tool (http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html) to calculate the expected count rates for the following satellite/detector combinations: Einstein IPC, RXTE PCA, Chandra ACIS-I, and XMM PN with a medium window. Use an input flux of 8×10^{-11} erg s^{-1} cm^{-2} in an input energy range of 2–10 keV (*i.e.*, 3C273), a power-law model for the source with a photon index of 1.9, and a Galactic $N_H = 1.8 \times 10^{20}$ cm^{-2}. How do the rates for the Einstein IPC and RXTE PCA compare with what you calculated above?

4. Consider an iron atom that has been stripped of all but one of its electrons.

a. Using the Bohr atomic model (or a more sophisticated one, if you prefer), calculate the energy (in keV) of the line photon created when the electron falls from its $n = 2$ to its $n = 1$ atomic level. This is the famous iron Kα line that is frequently used in x-ray astronomy and it is worth remembering this energy.

b. Now calculate the threshold energy of the absorption edge created when the electron is photoionized from the $n = 1$ level. This is the famous iron K edge.

c. If the atom had two electrons instead of just one, would the edge threshold energy be higher or lower (no need to calculate the exact number here, just reason it out using physics)? Please explain your answer.

d. The iron Kα line is one of the strongest emission lines studied by X-ray astronomers. One of the reasons for its strength is the relatively high abundance of iron. Based on your reading of the Garmire notes pages 1–8, state another reason for the strength of this line. Please fully explain the reasoning behind your answer. There are actually two possible answers and either one will do.