

Ph 442 Problem Set 4

Due: Thursday, October 15, 2009

1. The observed energy spectrum for an X-ray source is the combined result of the intrinsic spectrum emitted by the source, the absorption by interstellar gas along the line of sight, and the energy resolution and varying sensitivity of the detector. This problem and the next uses the WebSpec tool from HEASARC (<http://heasarc.gsfc.nasa.gov/webspec/webspec.html>) to explore these effects.

- a. Sources whose emission is produced primarily by synchrotron emission, such as the Crab Nebula supernova remnant (SNR), emit a power-law spectrum: $F(E) = AE^{-s}dE$, where $F(E)$ is the number of photons with energies between E and $E + dE$ arriving per unit area and per unit time. The average index for the entire Crab SNR is $s = 2.1$. Use WebSpec to generate observed spectra for the RXTE PCA (3 PCUs and summing layers 1, 2, and 3) both with and without photoelectric absorption by an interstellar medium with $N_H = 3.3 \times 10^{21}$ atoms cm^{-2} . Use an exposure time of 10000 s and leave all of the plotting parameters at their default values. Show plots of both spectra and discuss their general features. In particular, discuss why the observed spectrum departs from a power law and where.
- b. Repeat part (a) for the EPIC PN CCD detector of the XMM satellite. Select the thin filter — this filter is needed to exclude the visible and ultraviolet photons to which the CCD is also sensitive. You may need to do some reading on the XMM website to identify the features in the spectrum. How does the energy resolution of the CCD compare to the PCA? (The HEASARC “Observatories” page has a useful comparison of the capabilities of different satellites.)
- c. Repeat part (a) for the Chandra Low-Energy Grating (LEG) operating in first order with the ACIS detector (a CCD). Use an exposure time of 100,000 s. You will probably need to do some reading in the Chandra website to identify the sources of the features seen in the spectra. The grating disperses the x-rays across the detector to provide a spectrum with better energy resolution than that available from the detector alone. What is the energy resolution of this instrument?

2. A collisionally-ionized and optically-thin plasma emits a spectrum containing both a continuum resulting from bremsstrahlung radiation and emission lines from atomic recombination. Raymond & Smith calculated a set of output spectra for this situation that are widely used. Use WebSpec to calculate spectra for this situation with a plasma temperature of 10 keV, a metal abundance of 1.0 (*i.e.*, solar abundances), and an exposure time of 100,000 s. Set photoelectric absorption by the interstellar medium to zero. Plot spectra for the RXTE PCA, the XMM EPIC pn, the Chandra LEG (order 1) with ACIS, and the Constellation X SXT. The last is a proposed “next-generation” X-ray telescope with large mirrors and a microcalorimeter detector. Is the Fe K line visible in the spectra? Comment on how the different energy resolutions of the different instruments affects the visibility of emission lines.

3. The mirrors in X-ray observatories such as Chandra operate at “grazing incidence”, in which X-ray photons undergo total internal reflection off of the metal-coated mirrors. A

simple approximate model for the optical properties of metals is to consider only the optical properties of the “free” conduction electrons and to ignore any bound electrons in the metal atoms. Then the metal can be approximated as a plasma of free electrons with the index of refraction derived in class. The Chandra mirrors are coated with the metal iridium. Assume that the optical properties of iridium are identical to those of a plasma with an electron density of $n_e = 6.4 \times 10^{23} \text{ cm}^{-3}$, which is the density of conduction electrons in iridium. (For hard X-rays, the effective free electron density is actually somewhat larger than this.)

- a. Calculate the plasma frequency ν_p for iridium (in Hz).
- b. Calculate the index of refraction n_m of iridium for an optical photon with an energy of 1 eV. What is the meaning of this value?
- c. Calculate the index of refraction n_m of iridium for an X-ray photon with an energy of 1 keV. Give the value of $\delta = 1 - n_m$ rather than n_m . Repeat for an energy of 5 keV.
- d. Calculate the maximum angle for grazing-incidence reflection, θ_c , in degrees for iridium for photons with energies of 1 keV; with energies of 5 keV.
- e. Consider an X-ray telescope with mirrors using a single reflection. (Note: actual X-ray telescopes use Wolter Type 1 optics with two reflections.) Assume that the mirrors have a diameter of 1 m and are made of iridium. Estimate the shortest possible focal length of the telescope if it were designed to reflect photons with energies of 1 keV; with energies of 5 keV.

4. Go to the Chandra Education Data Analysis Software and Activities page (<http://chandra-ed.harvard.edu>) and install ds9 on a computer to which you have access. Then work your way through the section on “Learning DS9.” In other words, do steps 1 and 2 on the original page.

Then work your way through the “Cas A: The Supernova as Cosmic Recycling Center” on the Chandra-Ed activities page. Print out and hand in the following.

- a. Answers to questions 1, 2, and 3 of Activity 3. Describe how you estimated the size of the remnant. Also decide whether the pulsar is centered in the remnant and justify your answer.
- b. Plots for the light curve of Cas A and a background region as described in Activity 4. Use the “Quick Light Curve Plot” tool with a time interval of 32.4104 s (this is exactly ten times the “native” Chandra binning of 3.24104 s; the program is not smart enough to handle non-integer multiples correctly). Estimate the expected standard deviation of the bin values around their mean. How does this compare to the actual variation? You may need to plot just pieces of the time interval to see the actual points.
- c. A plot of the radial profile as described in Activity 5. Also try a plot with 100 radial bins and an outer radius of 430 pixels. Is the edge of the supernova remnant apparent in this latter plot?
- d. Plots of the energy spectra for the two regions as described in Activity 6. Comment on differences between the two spectra.