Ph 442   Data Analysis Project 1

Due: Tuesday, November 24, 2007

1. Run the program ds9 that you installed for homework set #4. Connect to the Chandra-Ed Archive Server on the Virtual Observatory page. Then load the image associated with Observation ID (ObsID) 1996 from the Chandra-Ed Archive. This image was taken for the program “Coordinated Chandra/HST Observations of the Crab Nebula”, which was also the subject of problem 4 in homework set #5. The image appears much smaller than the Cas A image that you previously analyzed because pixels have been binned together. Expand the image by zooming in by a factor of 8.

a. Move the cursor position vertically by 1 pixel in the image and note the change in the declination (δ) at the top of ds9. How big are the displayed pixels in arcseconds? If the original Chandra ACIS pixels were 0.5 arcseconds, what is the N of the $N \times N$ binning of this image?

b. Use a circular region that includes most of the flux in the image. 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 powerlaw, blackbody, bremsstrahlung, and mekal models. The mekal model is a hot, collisionally-excited plasma which produces strong emission lines. It assumes solar abundances for the elements. Give the center and radius of the circle that you used (in physical pixels). For each model hand in a plot of the data and fitted model and report the fitted model parameters: the flux in ergs cm^{-2} s^{-1} both before and after correction for “dust absorption” (really absorption by gas in the interstellar medium), the hydrogen column density (N_H, you will have to turn on the printing of the Sherpa logs to get this), and temperature for the blackbody, bremsstrahlung, and mekal models or the power-law index (the fitted function is E^{-index}) for the powerlaw model. Also report the chi-square and the chi-square divided by the number of degrees of freedom (called the “statistic” and “reduced statistic” in the output). Which model is the best fit?

c. Use the corrected flux from your best-fitting model of the previous part to calculate the luminosity of the Crab Nebula in the Chandra X-ray band. Report your value in solar luminosities.

d. Calculate the energy being lost by the Crab Nebula pulsar as it slows down (see Section 5.4 of the text). Assume that the moment of inertia of the neutron star is give by $I = 0.33MR^2$ (the leading coefficient is consistent with the most popular equations of state for nuclear matter). How does the energy being lost compare to the energy being emitted in the X-ray band that you found in the previous part?

e. Use a small circular aperture to fit a power-law spectrum to three regions of the image: the bright central regions of the nebula, the jet to the lower left, and the faint emission to the upper right. In each case, report the center and radius of the region and the fitted N_H and power-law index.

f. If the emission from the Crab Nebula is due to synchrotron radiation, calculate the power-law index of the electron energy spectrum implied by the three spectral indices measured in the previous part. If plasma is flowing from the center of the nebula outwards, come up with an explanation for why the electron energy spectrum is steeper in the outskirts of the nebula than in the center.

2. SN 1006, first observed on about 1 May 1006, was probably the brightest supernova for which we have recorded observations. At its peak it had an apparent magnitude of about -7.5 and it was visible in daylight for a time. Reconstructions of the light curve suggest that it was a SN Ia and the appearance today of the remnant in X-rays is of a partial bright shell surrounding emission from hot gas. The shell is also observed at radio wavelengths and this emission is significantly polarized, strongly suggesting synchrotron emission. The direction of polarization suggests that the ordered component of the magnetic field is approximately radial. However, the amount of polarization is less than would be expected for a purely ordered field and most of the field strength must be in a disordered component. Observations of the shell of SN 1006 have provided important, though also somewhat confusing, evidence about the acceleration of particles in supernova shocks.

a. Radio observations of the shell at $\nu = 1.0$ GHz yield a spectral index of $s = 0.6$. What is the exponent implied for the index of the power-law electron energy spectrum, p, assuming synchrotron emission? How well does this index compare with that predicted by the first-order Fermi mechanism?

b. Use ds9 to connect to the Chandra-Ed website and download ObsID 4391, which is part of a project titled "Studying High Mach Number Shocks in Young Supernova Remnants with Chandra" conducted by Rutgers's own Professor Hughes. This image is centered on bright filaments on the northeast side of the remnant. Estimate the width in arcseconds of the narrowest filaments, which are assumed to be segments of the shock seen edge-on. What is the width in parsecs if the distance to this remnant is 2.2 kpc?

c. Use a polygon-shaped region to measure the spectrum for one of the bright filaments. Give the approximate location in physical pixels of the filament. Report the chi-square per degree of freedom (the "reduced statistic" in the Sherpa log) for a power-law, bremsstrahlung, and a mekal fit and so demonstrate that the power-law model is the best fit. Report the exponent and N_H for the power-law fit. What is the implied exponent for the electron energy spectrum assuming that the X-rays are produced by synchrotron emission?

d. The much steeper spectrum observed in the X-rays as compared to the radio could have several explanations. One is that we are actually seeing the high-energy cutoff of the first-order Fermi acceleration mechanism. Calculate the energy (in eV) of the electrons producing the synchrotron X-ray photons with $E_\nu = 5$ keV. In order to get a more accurate value (or, at least, a more definite value), adopt $\langle \sin(\alpha) \rangle = \pi/4$ (the value for an isotropic distribution of velocities) and assume that electrons produce most of their emission at $0.29\nu_c$. Assume a magnetic field strength of 40 μG. We will explore one possible way of estimating this number in the next problem. The above picture is actually the explanation of the steeper X-ray spectrum favored by most researchers in the field, partly because low upper limits on the emission of X-rays with somewhat higher energy than detected by Chandra suggest that the spectrum really is cutting off. However, note that the energy that you calculate for the cutoff is about 100× below the energy of the "knee" in the cosmic ray spectrum. This leaves the origin of the "galactic" cosmic rays with the highest energies unexplained. Maybe protons can be accelerated to higher energies than electrons?

e. Calculate the characteristic timescale for energy loss by synchrotron emission for the electrons producing the 5.0 keV X-rays. Compare this to the age of the supernova remnant. Energy loss may be having some effect on the distribution of highest electron energies, though the timescale is long enough that one would expect to see some region immediately behind the shock where the loss was unimportant.

f. Could the synchrotron energy losses be responsible for determining the width of the shock as seen in X-rays? In other words, as the relativistic electrons are advected away from the shock they lose energy and eventually no longer emit at X-ray wavelengths. The observed proper motion of the shock and detailed analysis of optical spectra of the shocked gas both imply $v_{sh} = 2900$ km s^{-1}. Assume a strong non-radiating shock to calculate the velocity down-stream of the shock and calculate the width of the region emitting synchrotron X-ray radiation implied by the energy-loss time. The width yielded by this calculation is somewhat larger than that of the narrowest filaments that you found in 1 b). By what factor would you have to increase the assumed magnetic field strength to make the calculated and observed width match? If this explanation for the width of the filaments is correct, how would you expect the power-law index of the emitted X-rays to vary with distance behind the shock?

g. Calculate the minimum energy needed to generate the synchrotron emission coming from the SN 1006 remnant using the formula given in class:

$$W_{min} = (1.1 \times 10^6 \text{ erg})\eta^{4/7} \left(\frac{V}{1 \text{ cm}^3}\right)^{3/7} \left(\frac{\nu}{1 \text{ Hz}}\right)^{2/7} \left(\frac{L_\nu}{1 \text{ erg s}^{-1}\text{Hz}^{-1}}\right)^{4/7} \tag{1}$$

Use the radio flux at $\nu = 1$ GHz of 19 Jansky $= 1.9 \times 10^{-22}$ erg s^{-1} cm^{-2} Hz^{-1} to calculate L_ν. Assume that the emission comes from a thin spherical shell whose thickness is given by the value you found in 1 b) and whose radius is given by the 30 arcminute angular *diameter* of the remnant. Leave η in your answer as a free parameter. How does your W_{min} compare to the 10^{51} erg of kinetic energy present in the typical supernova remnant? Is there enough energy present to produce the observed synchrotron emission?

h. Calculate the strength of the magnetic field implied by the W_{min} calculation. What value of η would make the field strength that you calculate equal to $B = 40$ μG? Dr. Cassam-Chanai, a postdoc working with Professor Hughes, tells me that his analysis of the observations of the SN 1006 and other shell-type remnants finds magnetic field strengths even larger than 40 μG and $\eta = 50 - 100$.