Highly Structured Models in High Energy Astrophysics

David A. van Dyk
Department of Statistics, University of California at Irvine

Astro-Statistics

In recent years, there has been an avalanche of new data in observational high-energy astrophysics. Recently launched or soon-to-be launched space-based telescopes that are designed to detect and map ultra-violet, X-ray, and γ-ray electromagnetic emission are opening a whole new window to study the cosmos. Because the production of high-energy electromagnetic emission requires temperatures of millions of degrees and is an indication of the release of vast quantities of stored energy, these instruments give a completely new perspective on the hot and turbulent regions of the universe. The new instrumentation allows for very high resolution imaging, spectral analysis, and time series analysis. The *Chandra X-ray Observatory*, for example, produces images at least thirty times sharper than any previous X-ray telescope. The complexity of the instruments, the complexity of the astronomical sources, and the complexity of the scientific questions leads to subtle inference problems that requires sophisticated statistical tools. For example, data are subject to non-uniform stochastic censoring, heteroscedastic errors in measurement, and background contamination. Astronomical sources exhibit complex and irregular spatial structure. Scientists wish to draw conclusions as to the physical environment and structure of the source, the processes and laws which govern the birth and death of planets, stars, and galaxies, and ultimately the structure and evolution of the universe.

Chandra X-ray Observatory

STS-93 Launch

CXC

Figure 1: The Launch of the *Chandra X-ray Observatory.*

X-ray Astronomy: The sky in X-rays looks very different from that in optical. X-rays are the signature of accelerating, energetic charged particles, such as those accelerated in very strong magnetic fields, extreme gravity, explosive nuclear forces, or strong shocks. Thus, X-ray telescopes can be used to study nearby stars (like our Sun) with active coronae, the remnants of exploding stars, areas of star formation, regions near the event horizon of a black hole, very distant but very turbulent galaxies, or even the glowing gas embedding a cosmic cluster of galaxies.

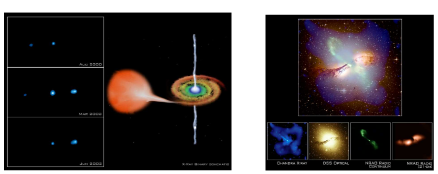

Figure 2: An X-ray image of an accreting black hole and a multi-wavelength image of two colliding galaxies.

Spectral Analysis

X-ray Spectra: An electromagnetic spectrum is the distribution of the energies of the photons that a source radiates. In X-ray astronomy photons are counted in each of a large number of energy bins. We explicitly model photon arrivals as a Poisson process, and thus have no difficulty with high resolution/low count high-energy spectral data.

The Basic Spectral Model: The spectral model has two components:

1. The *continuum*, a Generalized Linear Model for the baseline spectrum.
2. Several emission line profiles (i.e., a finite mixture of Gaussian or Lorentzian distributions added to the continuum).

An example of a simple spectral model of this form is given in Figure 3.

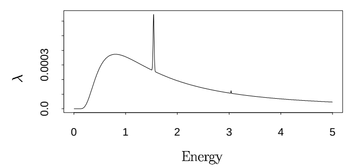

Figure 3: A Typical Spectral Model. The model includes a smooth continuum and two narrow Gaussian lines.

Distortion of the Data: Unfortunately, the photon counts reflect several layers of distortion in the data:

1. Photon absorption, stochastic partial non-homogeneous censoring;
2. Blurring of photons—energy and coordinates are recorded with error;
3. Photon pile up—if more than one photon arrives during the same time bin with the same sky coordinates, they are recorded as one photon with energy equal to the sum of their actual energies; and
4. Background contamination of the data.

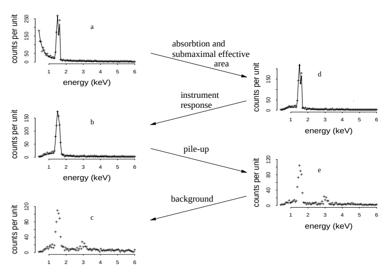

Figure 4: The Deterioration of Spectral Data.

BHiRXS: BHiRXS (Bayesian fitting of High Resolution X-ray Spectra) is a free statistical software that uses efficient EM-type algorithms, Markov chain Monte Carlo, and posterior predictive checks to:

- fit a variety of spectral models including several continuum models and allows for various added model components such as spectral lines,
- account for the data distortion processes described above,
- compute ppp-values to compare models of varying complexity, and
- preform model diagnostics such as residual plots based on the posterior predictive distribution.

Image Analysis

The Basic Image Model: Image reconstruction is similar to spectral analysis in that the basic model involves Poisson counts (but in a 2D array of pixels) and must account for similar data distortion processes. The image model, however, is far less structured than the spectral model. Instead of a highly parameterized model we use a multi-scale wavelet-like smoothing prior distribuiton on the image.

An Example: Figure 5 shows optical and X-ray images of NGC 6240, a galaxy that is the product of the collision of two smaller galaxies. The X-ray image is produced using Gaussian smoothing which blurs details but highlights the two bright blackholes near the center.

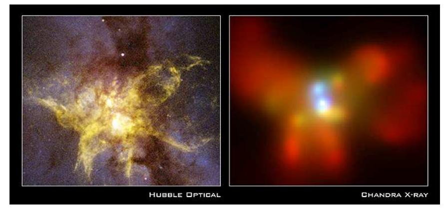

Figure 5: Optical and X-ray images of NGC 6240.

The raw data ("original"), the posterior mean under our model-based method ("EMC2 image"), and two Maximum Likelihood ("R-L") images appear in Figure 6. The ML reconstructions become more grainy with more EM iterations. Thus, EM is stopped before convergence in practice.

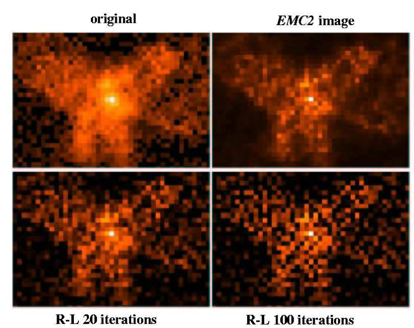

Figure 6: Model based reconstructions of the NGC 6240 X-ray image.

Chandra (blue) and HST H-alpha (red)

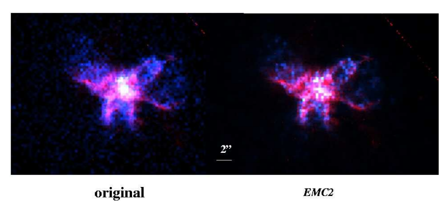

Figure 7: A comparision of the optical iamge and our reconstruction of the NGC 6240 X-ray image.

We can use our MCMC simulation of the posterior distribution of the image to expore the variablity of structures in the image. These are illustrated in the movies on the compute screen.

Exploring the Environment of a Stellar Corona

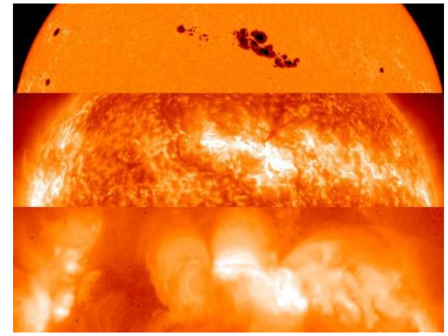

Figure 8: The Sun in Three Wavelengths.

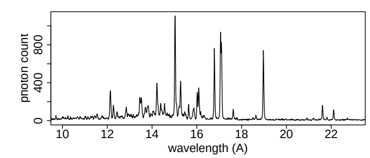

Figure 9: Capella.

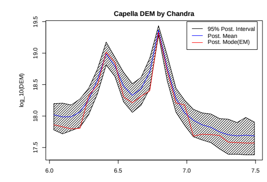

Figure 9: Capella DEM.

Hybrid-Chromosphere Supergiant Star Alpha TrA: As an example, we have applied our method to the high-energy tail of an *ASCA*/SIS spectrum (24 ksec) of the Hybrid-Chromosphere supergiant star Alpha TrA (see e.g., Kashyap et al. 1994, ApJ 431, 402).

The model we fit included

- an exponential continuum (representing Bremsstrahlung) emission,

$$\frac{\alpha}{\sqrt{T}} e^{-\text{energy}/kT} [\text{counts}/(s \cdot cm^2 \cdot \text{keV})], \text{ and}$$

- ten narrow Gaussian profiles located at the positions of strong lines.

We find evidence for the existence of a high-temperature (i.e., T greater than 10 MK) component in the quiescent emission and that the metallicity [Fe/H] ~ 0; this value is however not constrained and requires a more complete accounting of the strong lines in the spectrum. However, it is consistent with the photospheric abundances reported by Taylor (1999, A&AS 134, 523).

The Bayesian analysis is summarized in Figures 4-7.