Personal Section

The summer before my junior year, I went to attend the Secondary Student Training Program at the University of Iowa. There, I interned for Professor Ugur Akgun to simulate the unfolding process of a fusion protein of the Para-influenza Virus 5. Although I struggled in the beginning to grasp the complicated processes of membrane fusion, not to mention the various steps needed to write the code that would make a realistic simulation, I eventually became comfortable with converting my scientific knowledge into simulations that could help determine the protein's unfolding process. From determining the correct input parameters to analyzing output models, I found the complex procedure of computer simulation exciting.

Yet even though I left the program feeling much more knowledgeable about computer codes and simulations, I found myself craving for another opportunity to participate in hands-on research, some place where I could study exotic topics that I had never heard of before. So I kept looking around for more opportunities to participate in cutting-edge research.

That is why the next summer I jumped at the opportunity to join Professor Charles J. Hailey's research lab at Columbia University, where Shell Supernova Remnants were under close examination. While I was familiar with the idea of a supernova, I was at first confused by the order of the study: shouldn't we observe the supernova *before* instead of *after* the explosion, since in a remnant the star had already exploded? As I read various research papers and explanations about supernovas, however, I began to understand how information from the remnants could provide an insight into the explosion mechanism of the original star. This new perspective made me realize how advances in science are sometimes made through non-intuitive methods.

Together with my time spent in Iowa, my second summer research experience made me realize the power of simulations in scientific research. From the molecular scale of proteins and membranes to the galactic scale of shell supernova remnants, simulations are powerful tools in making predictions based on current or novel scientific models. By utilizing simulations, scientists in turn can rule out the implausible and focus their investigation.

For anyone who is considering joining a research group but is worried that the topic might be too hard to grasp upon first try, I encourage that he or she take the opportunity nonetheless to explore topics that textbooks so often fail to cover. Without my summer experiences, it would have been hard for me to jump right into Computational Biophysics and Astrophysics, fields I once found foreign and obscure but have proven to be the ultimate fuel for my love of science.

Research Section

Introduction

Ever since Galactic Cosmic Rays were detected by Victor Hess 100 years ago (Hess 1912), their origin has been a mystery; what stellar object is powerful enough to accelerate particles into TeV energy ranges, and how does it release so much of them? Galactic Cosmic Rays are capable of releasing high energy X-rays and gamma rays, with energies up to GeV, as they travel through the interstellar medium. By studying the spectral patterns of the emitted X-rays and gamma rays, we can gain insight into the nature of the Cosmic rays themselves. To record such patterns, astronomers have used the *Chandra* telescope and the *Very Large Array* telescope to create high-resolution X-ray images of some sources of Cosmic rays. However, the low energy band of these pre-existing telescopes has limited our ability to detect high-energy X-ray emissions from the sources and to gain further understanding of their particle acceleration mechanisms (Reynolds 2008). But with the recently launched Nuclear Spectroscopic Telescope Array (NuSTAR), it is now possible to record these high-energy spectrum data with high resolution.

As a star goes supernova, it releases a shockwave along with the debris from its surface. The shockwave, as it travels through the interstellar medium, creates a reverse shock towards the source. The ejected debris is then shocked by the reverse shock, and emits thermal and non-thermal electromagnetic waves.

There are various models of particle acceleration in SNRs, but one of the most detailed and complex models is known as the Diffusive Shock Acceleration (DSA) model (Fig. 1). In this model, particles are accelerated by the reverse shock front, where the debris meets the reverse shock, is then shot ahead until they lose energy through collision and radiation, and comes back to be accelerated by the shock front again. This "jumping" back and forth across the shock front creates a large reservoir of high-energy electrons and protons, releasing X-rays and gamma rays (See e.g. Bell, 1978; Blandford & Ostriker, 1978). Shortly, in DSA particles are accelerated at the forward and the reverse shock.

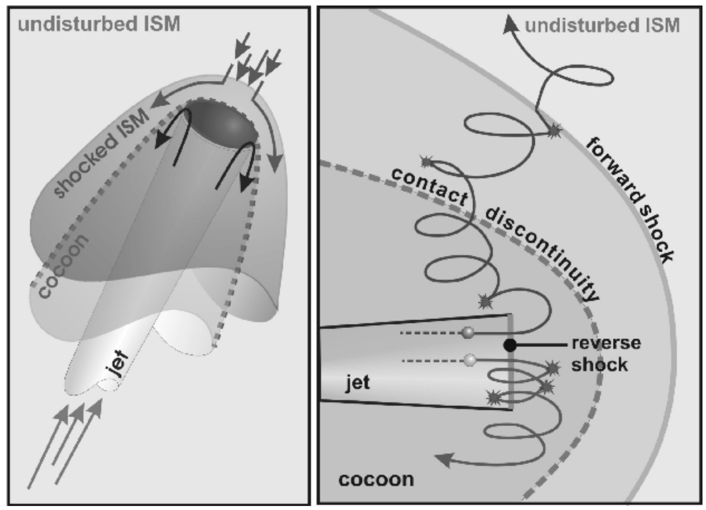
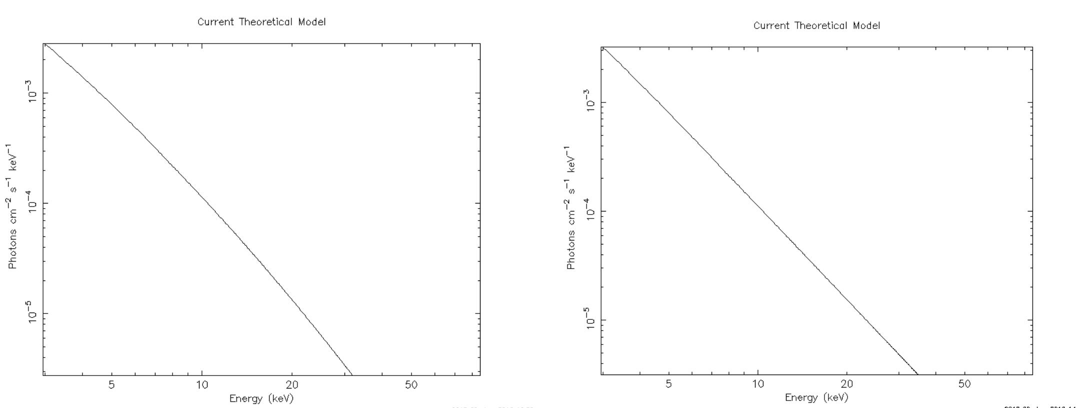


Image credit: Heinz & Sunyaev 2002

Fig. 1 Illustration of the Theory of Diffusive Shock Acceleration
As the jet of debris travels through the Interstellar Medium (ISM), the particles are accelerated by diffusing back and forth across the reverse shock front, until they reach relativistic speeds high enough to travel ahead of the forward shock front.

The accelerated electrons, now referred to as Cosmic rays, release radiation through processes such as Inverse-Compton scattering, Bremsstrahlung, and synchrotron radiation.

Detailed Theories of Shell Supernova Remnant emission



SRcut Power-Law

Fig. 2 Graphs of the SRcut and Power-Law models.
The SRcut model has a noticeable dip at its tail, in comparison to the linear Power-Law model.

There are many predictions for the spectral shape of non-thermal emission from SNRs, based on various models of explosion mechanism and shock front particle acceleration. Two of the predictions, the Power-Law and the SRcut, have been used to analyze the data for this investigation (Fig. 7). A Power-Law is the generic model, which can be derived from many theories but does not provide much detailed information about the shock structure. A SRcut is a simplified formula of a more complete and detailed model, which was derived from the DSA model, and describes the output of synchrotron radiation with respect to numerous parameters. Although the SRcut is not as complex, it requires much less computing power to fit onto data, as there are fewer degrees of freedom, and still outputs a very good approximation. The parameter values from the SRcut model can provide key information about the structure and magnitude of the shock front.

As NuSTAR was still in its initial stages of its calibration, my work focused on choosing which targets the telescope should focus on during its first round of observations, with which the telescope can demonstrate its capabilities to the science community. As there were no pre-existing high-energy X-Ray images of the target candidates, I used a simulation tool on the existing low-energy X-Ray images of three SNRs to generate hypothetical high-energy X-Ray images with extrapolated emission lines based on the two models and determine whether NuSTAR will be able to discern the correct model from both images.

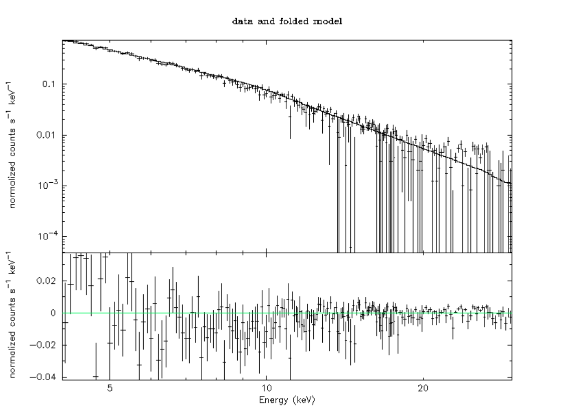
In predicting NuSTAR's capability in detecting the Power-Law and SRcut emission lines, I used a Chi-squared test. A Chi-squared test is a statistical tool that determines whether the model can be discarded or not, by using this equation $X^2 = \sum_{i=1}^{n} \frac{(E_i - T_i)^2}{T_i}$, where E is the experimental, or observed data and T is the theoretical or expected data. By dividing this value by the degrees of freedom, we get the reduced chi-squared value. If this value is close to 1, then the hypothesis cannot be discarded. However, if the value is much greater than or less than 1, the hypothesis can be discarded as unlikely: the null hypothesis.

The major factors in choosing certain targets over others were whether the SNR would provide important scientific information, which was in this case whether the telescope will be able to distinguish between the Power-law and the SRcut from the emission lines, and how quickly the telescope will get that result with confidence.

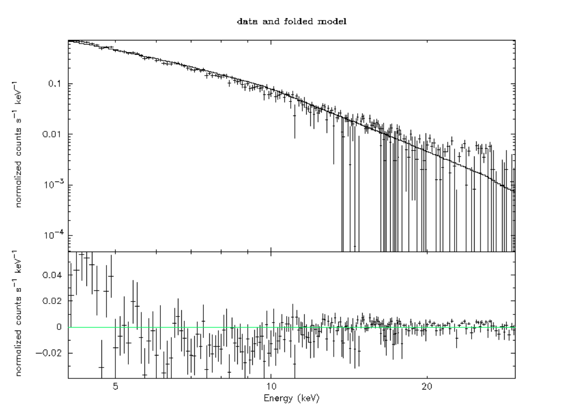
Results

Tycho;

Input Spectrum: Power-Law

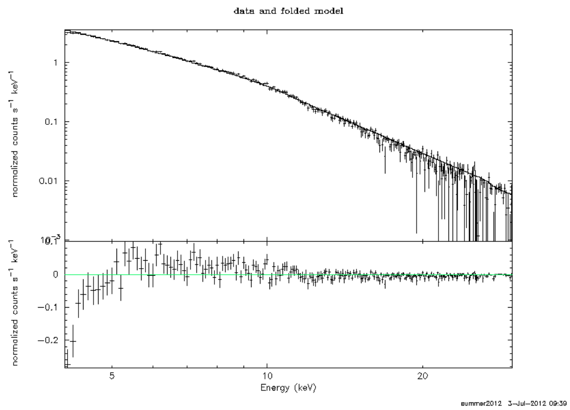


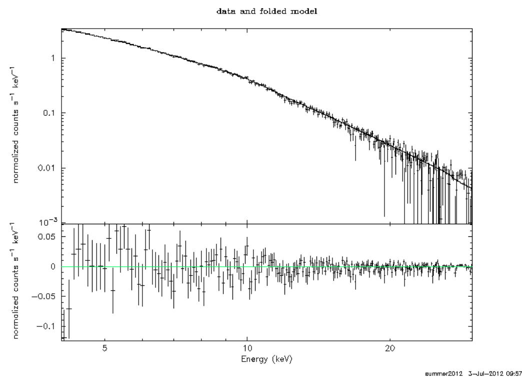
Power-Law fit



SRcut fit

Input Spectrum: SRcut





Power-Law fit SRcut fit

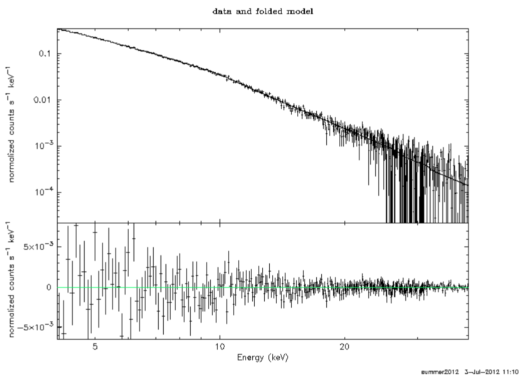
Fig. 3
The output spectra of the simulation along with the model-fit curves, generated through XSPEC. The energy band was limited to 4-30keV to improve statistical fit, as the background noise began to dominate in the higher energy levels. The nH levels were frozen at 0.7e22, as other studies had already determined them; we used *Chandra* X-Ray observatory's SNR catalogue. Integrated for 20ks.

Input Spectrum	**Model**	**Reduced Chi-Squared**	**Degrees of Freedom**	**Null-Hypothesis Probability**
Power-Law	Power Law	1.38	187	0.04%
	SRcut	1.92	186	<0.001%
SRcut	Power Law	2.01	249	<0.001%
	SRcut	1.04	248	31.8%

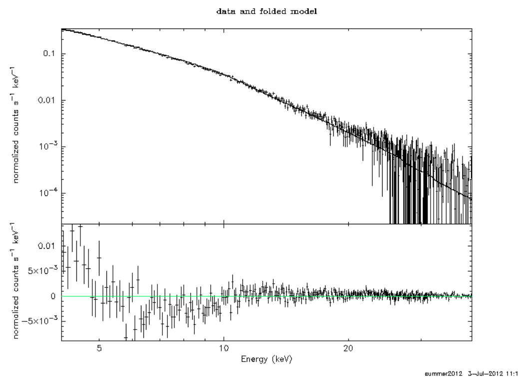
Table 1 The summarized results from the simulations for Tycho.
The difference in the reduced chi-squared values in the Power-Law simulation is not significant, but is enough to show that SRcut can be rejected while the Power-Law cannot be completely disregarded. On the contrary, the difference in the reduced chi-squared values in the SRcut simulation is very clear, and shows that Power-Law can be rejected while the SRcut cannot.

Kepler;

Input Spectrum: Power-Law

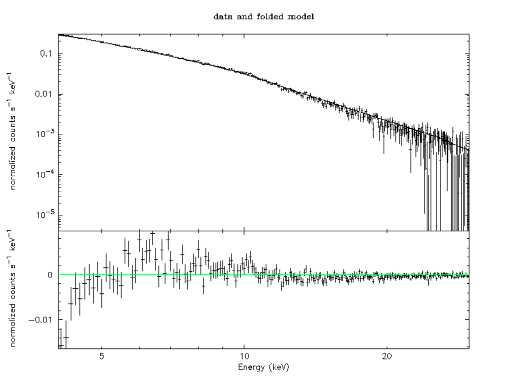


Power-Law fit

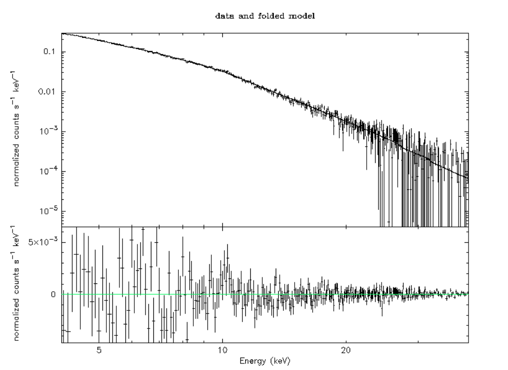


SRcut fit

Input Spectrum: SRcut



Power-Law fit



SRcut fit

Fig. 4

For the Kepler simulations I created a simulation with SRcut as the input spectrum, and found the best-fit Power-Law. Than, I created a new simulation with the best-fit Power-Law parameters. The energy band was limited to 4-30keV to improve statistical fit, as the background noise began to dominate in the higher energy levels. The nH was frozen at 0.5e22. Integrated for 200ks.

Input Spectrum	**Model**	**Reduced Chi-Squared**	**Degrees of Freedom**	**Null-Hypothesis Probability**
Power Law	Power-Law	0.98	312	56.61%
	SRcut	1.56	311	<0.001%
SRcut	Power-Law	1.64	242	<0.001%
	SRcut	1.04	283	30.71%

Table 2
The summarized results for Kepler. The difference between the reduced chi-squared values in both simulations is very significant, and shows that the wrong models can be completely disregarded. However, this simulation took 200ks to detect, which is much longer than the other two sources.

The results from the simulations are very promising for the NuSTAR telescope. In each graph, the residuals, located at the bottom of each graph, show the "goodness of fit". Residuals show the vertical distance of each point from the best-fit curve, and thus the more points are distributed evenly along above and below the middle line, the better the fit. For example, in the Tycho simulation with the SRcut input (Fig. 3), the initial part of the residual for the Power-Law fit is concentrated underneath the line, while the residual for the SRcut fit is spread evenly. And the reduced-chi squared values of each fit, shown in Table 1, confirms that the Power-Law fit is very poor, while the SRcut fit is good.

For the Tycho simulation with Power-Law input, the Power-Law model's reduced chi-squared value was 1.38, while the SRcut model's value was 1.92, as shown in Table 1. This suggests that if Tycho had Power-Law spectra, NuSTAR would be able to discard SRcut and faintly detect Power-Law from the data. For the SRcut simulation, the Power-Law model gave a value of 2.01 while the SRcut model gave a value of 1.04. This shows that if Tycho had SRcut spectra, NuSTAR would be able to discard Power-Law and clearly detect the SRcut.

Similarly, for the Kepler Power-Law simulation as shown in Table 2, the Power-Law model had a reduced chi-squared value of 0.98 while the SRcut model a value of 1.56. For the SRcut simulation, NuSTAR was able to reject the Power-Law model with a reduced chi-squared value of 1.64 while keeping the SRcut model with a value of 1.04. Thus, NuSTAR will be able to correctly discard the wrong model with high confidence if Kepler has either the Power-Law or the SRcut spectra (Fig. 4).

Conclusion

The simulations of the three Shell Supernova Remnants have shown that NuSTAR will be capable of detecting the correct model and disregarding the other, no matter what the input model is. This powerful result confirms NuSTAR's observational capabilities and makes Tycho a high priority target, as it is predicted to provide useful information about its shock structure in relatively short time; the required integration time for Tycho was 20ks, which is less than the average observation time for NuSTAR.

It is important to keep in mind, however, that these results are based on simulations, not measured data. Although the spectra have been logically deduced from previously recorded data, the actual patterns of high-energy emissions may turn out to be different than the simulated models. That finding, however, will still provide insight into the structure of particle acceleration among SNRs, as new theories maybe developed to explain such differences. So when the actual observed data from these SNRs are recoded, we may have a completely different understanding of their shock acceleration mechanism.

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