Energetic Particles In Star Forming Galaxies

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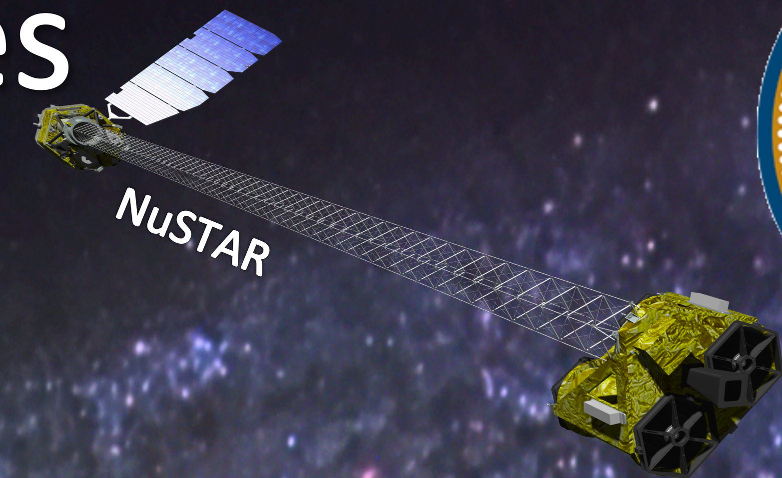
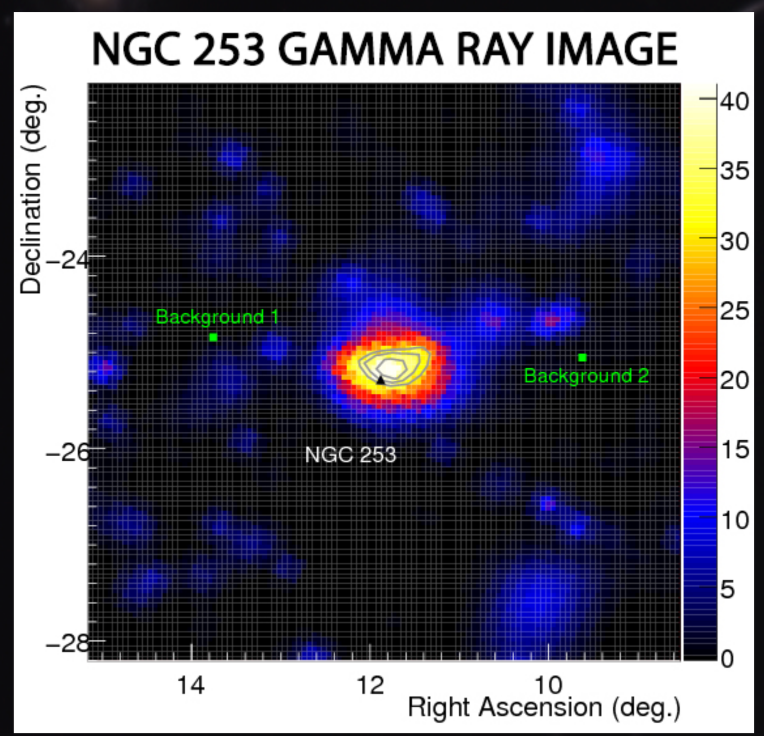
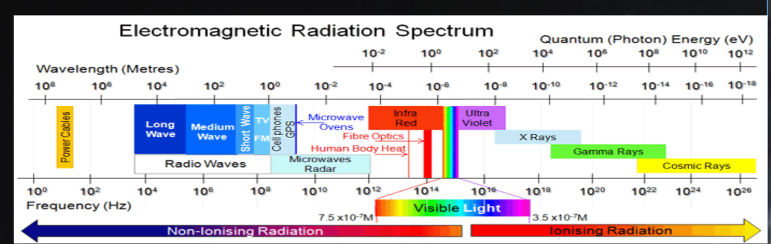


An exciting result from the Fermi Gamma-ray Space Telescope is the detection of star-forming galaxies at gamma-ray energies. In star-forming galaxies, gamma rays are produced through the interactions of highly energetic cosmic rays with interstellar gas and radiation. Nearby star-forming galaxies, such as NGC 253, have been the subject of multi-wavelength observations by telescopes such as Fermi (at GeV energies), NuSTAR (in X-rays), VLBA (radio), and HESS and VERITAS (at TeV energies). Even so, the details surrounding the mechanism for producing the gamma rays remain elusive. Do the gamma rays originate from interactions from interstellar gas and radiation and cosmic ray **electrons**, or cosmic ray **protons**? For this opportunity, we conducted a theoretical study of cosmic ray physics in star-forming galaxies and their resulting emission. Our goal is to make predictions for observations of starburst galaxy NGC 253 using Fermi and NuSTAR, as well as for telescopes operating in other wavebands.

INTRODUCTION

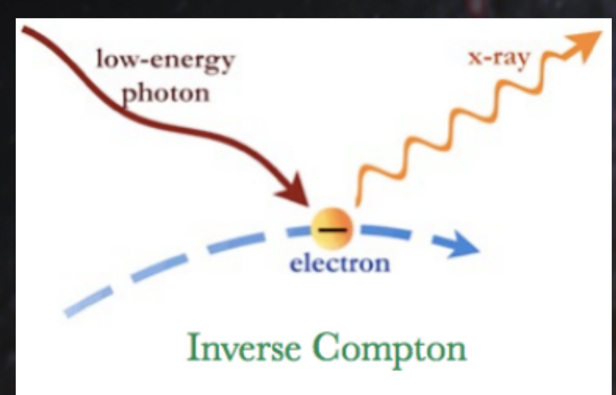


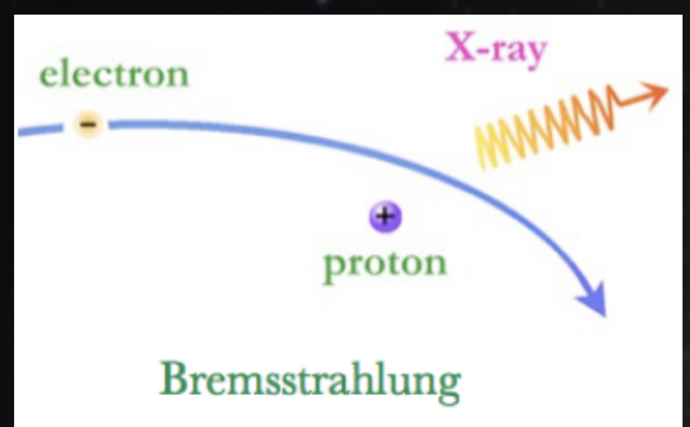
Starburst galaxies are galaxies with high rates of star formation, usually near the core of the galaxy. Because high star density leads to a higher rate of supernovae, the cosmic ray density is also higher, making starburst galaxies a prime source of gamma-ray emission as a result. The nearest starburst galaxies are M82 and NGC 253.



Even with data from Fermi (GeV) and NuSTAR (4-30 KeV), the origins of gamma rays within starburst galaxies remains elusive, since there are many particle processes that take place in starburst galaxies that can produce gamma rays:

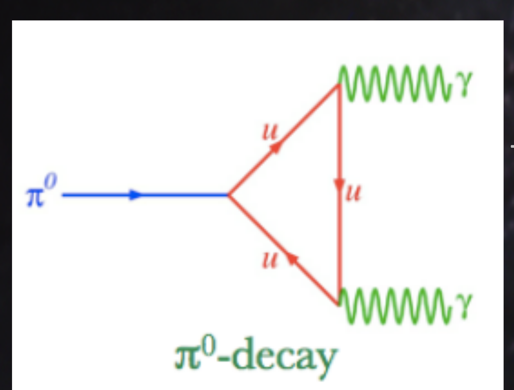
Inverse Compton Scattering: A charged particle transfers part of its energy to a photon, and the photon gains energy.



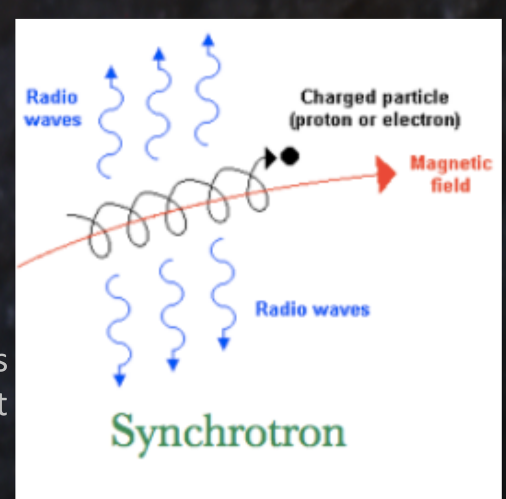


Bremsstrahlung: Radiation produced from the deceleration of a charged particle, typically an electron. The moving particle loses kinetic energy, which is converted into a photon.

Synchrotron Radiation: Radiation produced when relativistic charged particles spiral through a magnetic field.



Pion Production: The collision of cosmic ray protons and nuclei with interstellar medium particles produces excited states that lead to pion emission.



Data from gamma ray telescopes such as Fermi and Hess cannot distinguish among the many viable models for gamma ray emission in starburst galaxies such as NGC 253. Determining the origins of the gamma ray emission would reveal important properties, specifically, the magnetic field strength, the cosmic ray spectrum, and the density of the interstellar medium and interstellar radiation.

METHODS

As can be imagined, the proton spectrum established from a cosmic ray detector near Earth will have a different form than at its origin in a supernova remnant shock wave. However, the original proton spectrum can be inferred through the following diffusion loss equation:

$$\frac{\partial}{\partial E}[b(E)N(E)] = \frac{N(E)}{\tau(E)} - Q(E)$$

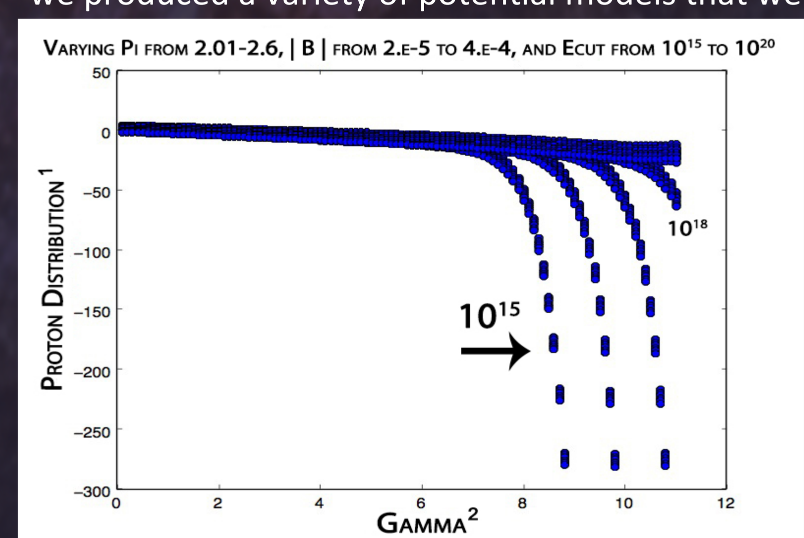
Where b(E) is a continuous loss term for protons as a result of ionization losses and pion production, tau(E) is an escape term for particles that leave the system, and Q(E) is a source term which describes the rate of injection of protons and their injection spectra into the source region.

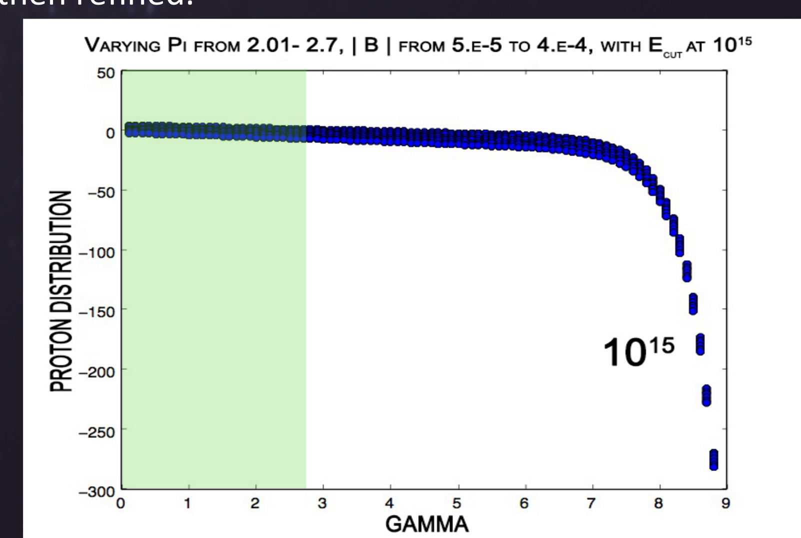
$$N = \propto E^{P_f}$$

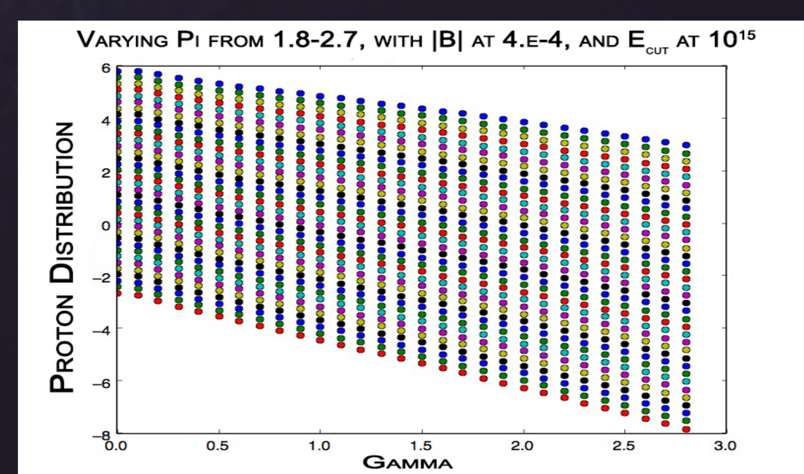
To create a theoretical proton spectrum, we needed to ultimately solve this equation for N(E), which we can do by solving for the proton index (pf), the number of protons per gas particles, to give an estimate of the energy loss as a result of particle interactions. We are trying to solve for and match the theoretical expectation, where P_f ~ 2.1. We have a code that will solve this equation, and we are trying to compare the output spectrum of code to the theoretical expectation. The steps for completing this process included running through a Monte Carlo simulation to apply the diffusion loss equation over a range of possible parameters that would output the particle spectra for different models. We used the method of least squares to fit the model points to a power law, and determine the power law index, that we could then compare to the theoretical P_f .

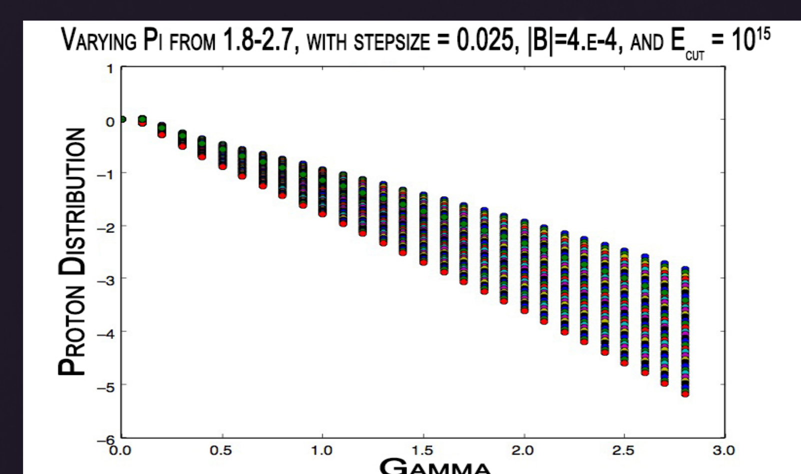
RESULTS

There were three variables, magnetic field, energy of the exponential cutoff, and power law index, that had a range of acceptable values which have been observed in other galaxies. Looping over all variables, we produced a variety of potential models that were then refined.







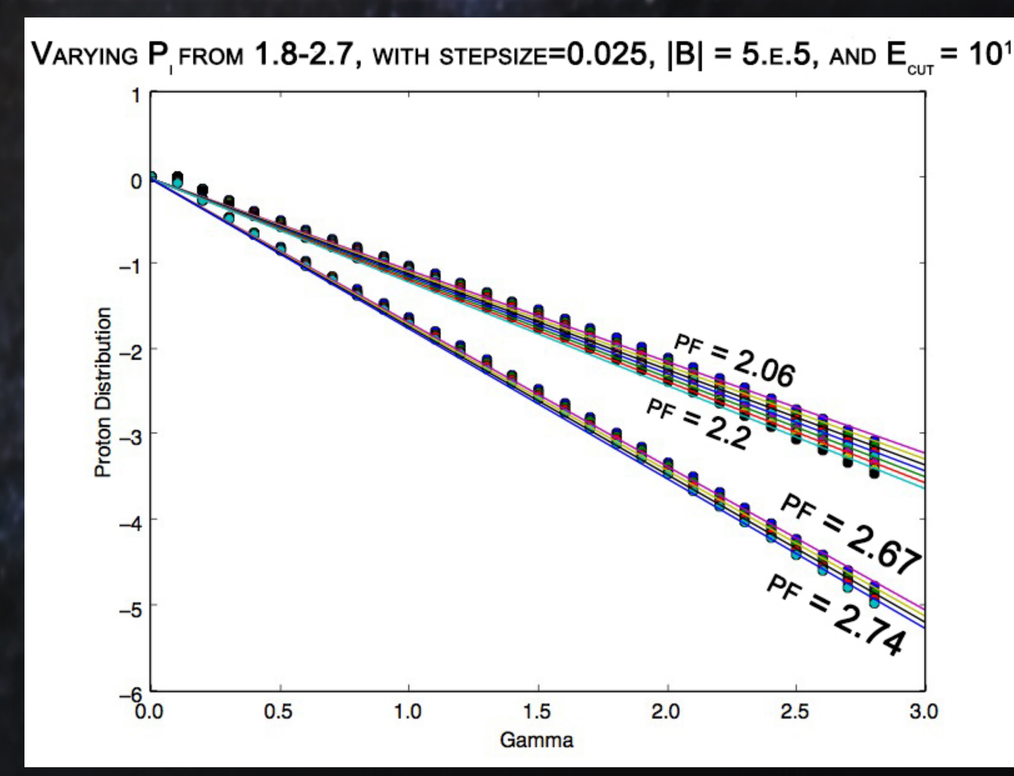


The initial plots of all potential models is illustrated by Graph1. We then picked a conservative value for the magnetic field to narrow down the number of models (Graph2), and discovered that over large scales, there is no noticeable effect on the models by varying the energy of the exponential cutoff. To find the resulting proton spectrum, we needed to find the best fit line for these models, and narrowed our focus to eliminate the exponential cutoff from our calculations (Graph3). By normalizing all models to be plotted through the origin, (Graph 4) we were able to compare differences between slopes, which would be our pf values.

[1] Proton Distribution is the number of protons per unit volume per logarithmic bin of energy (arbitrary units)

[2] (Gamma)mc^2 = Energy where (Gamma) is the Lorentz factor of the proton.

RESULTS cont.



pi	pf
1.9	2.068887918
1.925	2.09172791
1.95	2.114626031
1.975	2.137587525
2	2.160601338
2.025	2.183675319
2.05	2.206803994
2.55	2.678075674
2.575	2.701978365
2.6	2.725905212
2.625	2.749857725

The best fit line for each model is overlaid onto their model points. The slope of the best fit line corresponds to the value of pf for the fitted model. The input pi value for each model is displayed beside its corresponding pf value. We were then able to compare our output pf values to theoretical expectations (2.1 for M82 and 2.7 for the Milky Way), and remove models that were not around these values. We can now restrict our models to pi values between 1.9-2.05, and 2.55-2.625. We use these values to draw comparisons between NGC 253 and the Milky Way. These are the models we would calculate xray and gamma ray emission and compare with NuSTAR, Fermi, and HESS data.

DISCUSSION

With further work, future steps would include calculating the secondary particles created from pion production and the resulting gamma ray emission, allowing comparison between the models and data from Fermi, NuSTAR, and HESS. Comparing the models to the data would give us a broader understanding of the processes occurring within NGC 253.

With models alone, we can never definitively understand the conditions within NGC 253 without incorporating actual datasets, thus future steps would use data from Fermi and NuSTAR. There are many parameters in this problem, and we have many classes of models, so we would like to constrain on as many data points as possible.

As a final note, I would like to take this opportunity to thank my mentor, Toni Venters, for the support and guidance of this project.

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