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Cosmic ray production and emission in M82

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Abstract. Starting from first principles, we construct a simple model for the evolution of energetic particles produced by supernovae in the starburst galaxy M82. The supernova rate, geometry, and properties of the interstellar medium are all well observed in this nearby galaxy. Assuming a uniform interstellar medium and constant cosmic-ray injection rate, we estimate the cosmic-ray proton and primary & secondary electron/positron populations. From these particle spectra, we predict the gamma ray flux and the radio synchrotron spectrum. The model is then compared to the observed radio and gamma-ray spectra of M82 as well as previous models by Torres (2004), Persic *et al.* (2008), and de Cea del Pozo *et al.* (2009). Through this project, we aim to build a better understanding of the calorimeter model, in which energetic particle fluxes reflect supernova rates, and a better understanding of the radio-FIR correlation in galaxies.

Keywords. galaxies: individual (M82), galaxies: starburst, cosmic rays, gamma rays: theory, radio continuum: galaxies

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1. Introduction

M82 is a nearby starburst galaxy. The supernova rate, geometry, and density and extent of the interstellar medium are all well observed. The galaxy is modeled as a calorimeter with a supernova-powered cosmic ray model. The calorimeter model for galaxies predicts that all the energy input from supernovae is expended within the galaxy and that both the far-infrared and radio synchrotron emission from cosmic rays are proportional to the supernova rate (Völk 1989). Thus, by starting with the supernova rate, the cosmic ray particle production can be determined.

Our objective is to build a simple model of cosmic ray interactions that reproduces the gamma ray flux and synchrotron emission of M82 and is readily scalable to other systems. Here we present preliminary results from this investigation.

2. Procedure

Our single zone model is based on the following assumptions: uniform density (180 cm^{-3}), magnetic field (120 μG), radius (300 pc), supernova rate (0.3/yr); equilibrium for particle injection and energy losses (no diffusion); a power-law injection spectrum (p $\sim$ 2.1); and a particle acceleration efficiency from supernovae (10% of SN energy, $E_{51} = E_{SN}/10^{51} erg$, to protons and 2% of the proton energy to electrons).

Assuming an equilibrium situation, we know that the particle spectrum is given by $N(E) = Q(E) \cdot \tau(E)$ where $\tau(E)$ is the loss lifetime. The source function is given by $Q(E) = AE^{-P}$ where the proportionality constant, A, is related to the supernova rate ν, the particle acceleration efficiency η, and the starburst region volume V, such that

$\int_{E_{min}}^{E_{max}} Q(E)EdE = \frac{\eta\nu E_{51}}{V}$. This provides the source function for the protons which can be related to the source function for the electrons, $Q_e = Q_p \cdot N_e/N_p$. From the proton spectrum, we calculate the pion source function by weighting the differential cross sections for pion production by the proton spectrum and integrating over the proton energy (Torres 2004).

$$q_\pi(E_\pi) = cn_H \int_{E_{th}}^{\infty} N_p(E_p) \frac{d\sigma(E_p, E_\pi)}{dE_p} dE_p \tag{2.1}$$

From the π^- and π^+ source functions, we can calculate the secondary electron and positron source functions by integrating over γ_π and γ_e (Schlickeiser 2002).

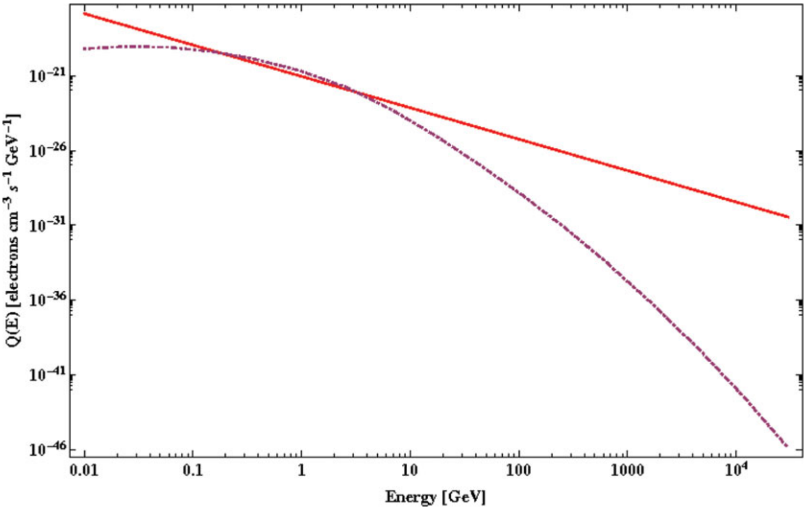


Figure 1. Electron source function: primary (solid) and secondary (dashed) electrons.

3. Results

Then, from the π^0 source function, we can calculate the gamma ray emissivity as follows (Schlickeiser 2002).

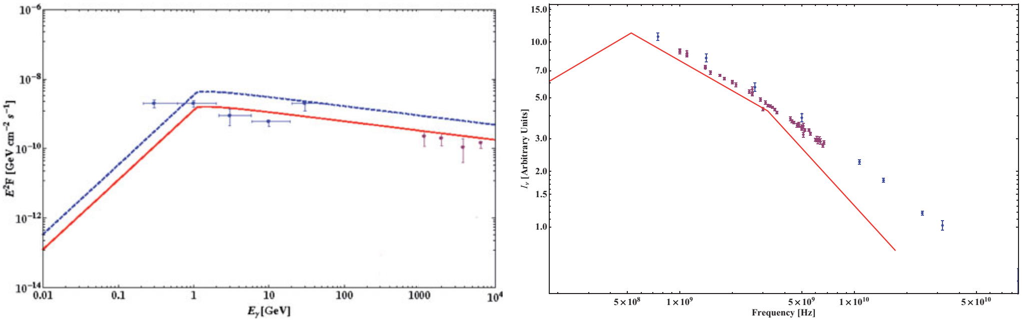
$$q_\gamma(E_\gamma) = \int_{E_{min}}^{\infty} \frac{q_{\pi^0}(E_{\pi^0})}{2\sqrt{E_{\pi^0}^2 - m_{\pi^0}^2 c^4}} dE_{\pi^0} \tag{3.1}$$

From the source function,we can calculate the predicted flux as $F = q_\gamma V/(4\pi d^2)$, where d is the distance to M82. Thus, we see that a simple one zone model can provide a reasonable fit to the gamma ray flux from M82, see Fig. 2a.

To calculate the synchrotron spectrum, we know that $J(\nu)d\nu = -\frac{dE}{dt}N(E)dE$, where N(E) includes the electron spectrum (both primaries and secondaries from pion decays) and the secondary positron spectrum (Longair 2011). The energy loss due to synchrotron emission is given by

$$-\frac{dE}{dt} = \frac{4}{3}\sigma_T c \left(\frac{E}{m_e c^2}\right)^2 \frac{B}{2\mu} \tag{3.2}$$

In the synchrotron spectrum, we also include an estimate of free-free absorption for a completely ionized medium. In recent work, we have found that the addition of free-free



(a) Gamma Ray Flux (b) Synchrotron Spectrum

Figure 2. Left: Gamma ray flux from M82. Observational data points between 0.1 GeV and 100 GeV were observed with Fermi and data points above 1 TeV were observed with VERITAS. Right: Synchrotron spectrum for M82. Observation data points taken from Klein *et al.* (1988) and Williams & Bower (2009).

emission required us to develop a multi-zone density model. It is assumed that there is a constant source function and no self-absorption for the preliminary discussion.

4. Conclusions

Because of the dense molecular interstellar medium, intense radiation field, and high magnetic field in M82, the particle energy loss lifetimes are very short, supporting the calorimeter model. Due to the short lifetimes most protons interact producing pions which decay making $e^{+/-}$, and so we find that the secondary electron densities are comparable to those for primary electrons. Our predicted gamma ray flux matches well with data from Fermi and VERITAS. We also find that the predicted synchrotron spectrum begins to turn over at lower frequencies due to free-free absorption. The results from our simple and intuitive model compare well with the results of more complex models.

Acknowledgments

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