Simulation of Cosmic Ray Acceleration, Propagation and Interaction in SNR Environment

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Abstract. Recent studies of young supernova remnants (SNRs) with Chandra, XMM, Suzaku and HESS have revealed complex morphologies and spectral features of the emission sites. The critical question of the relative importance of the two competing gamma-ray emission mechanisms in SNRs; inverse-Compton scattering by high-energy electrons and pion production by energetic protons, may be resolved by GLAST-LAT. To keep pace with the improved observations, we are developing a 3D model of particle acceleration, diffusion, and interaction in a SNR where broad-band emission from radio to multi-TeV energies, produced by shock accelerated electrons and ions, can be simulated for a given topology of shock fronts, magnetic field, and ISM densities. The 3D model takes as input, the particle spectra predicted by a hydrodynamic simulation of SNR evolution where nonlinear diffusive shock acceleration is coupled to the remnant dynamics (e.g., Ellison, Decourchelle & Ballet [1]; Ellison & Cassam-Chenai [2]; Ellison, Berezhko & Baring [3]). We will present preliminary models of the Galactic Ridge SNR RX J1713-3946 for selected choices of SNR parameters, magnetic field topology, and ISM density distributions. When constrained by broad-band observations, our models should predict the extent of coupling between spectral shape and morphology and provide direct information on the acceleration efficiency of cosmic-ray electrons and ions in SNRs.

Keywords: Collisionless shocks, supernova remnants, particle acceleration, cosmic rays

INTRODUCTION

This work aims to develop a highly flexible platform for 3D SNR hydro and cosmic ray (CR) simulation, which is easily expandable to accept new physics, and adaptable to the complex environments of individual supernova remnants. As a preliminary work in progress, the simulation is tested under toy model configurations, in a cubic mesh with a relatively low resolution (21x21x21 binning). Several assumptions and simplifications are made in the physics of cosmic ray acceleration and diffusion. Once the framework becomes mature, however, we can immediately proceed to perform realistic modeling of any given SNR, match in broad-band with observations, and extract useful information.

SNR EVOLUTION AND PARTICLE ACCELERATION

The CR-Hydro code we employ in the simulation couples SNR hydrodynamics to cosmic ray acceleration interactively using a standard SN hydro code (VH-1) together with a semi-analytical CR kinetic model adapted to nonlinear diffusive shock acceleration (DSA) in non-relativistic shocks (Blasi et al [4]). In each time step the hydro code generates hydrodynamic parameter sets for the spherically symmetric SNR shells, which are inputted into the kinetic model to calculate proton and electron spectra in the shells. The changed ratio between energy density and pressure due to the freshly produced energetic CR population modifies the global effective ratio of specific heats, which is feedback to the hydro code and used for the next time step. With parameters taken specifically to model RX J1713.7-3946, the simulation is run for 1000 years in steps of 100 years. Magnetic field self-generation (amplification) due to the streaming CR protons in the plasma is not yet considered. The pressure term P_C due to CR protons modifies the shock structure and leads to non-linearity. Parametric thermal injection (i.e., Blasi, Gabici & Vannoni [5]) is used to set the particle acceleration efficiency. At each time step, proton spectra are obtained for

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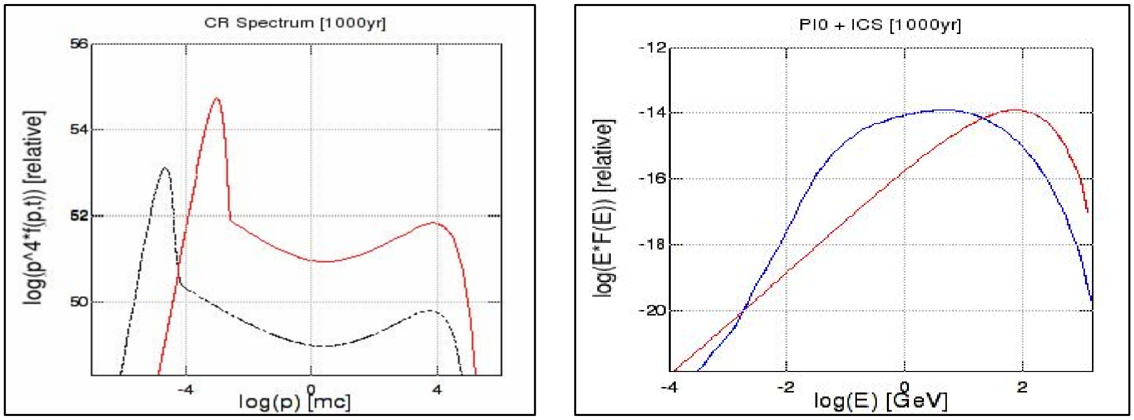

FIGURE 1. (Left) Proton (red) and electron (black) spectra at 1000 year for outermost shell where f(p) is momentum phase space distribution, m is the proton mass. Both thermal and non-thermal parts are shown. Exponential turnover before cut-off is due to particle escape upstream from shock. (Right) Spectral shape comparison between pion decay (blue) and IC (red) emission for the toy SNR model. The GLAST-LAT has the perfect energy sensitivity to discriminate between the two emission models.

each SNR shell from the kinetic calculation. Electron spectra are derived from the corresponding proton spectra, with radiative losses (synchrotron and inverse Compton) considered. The flux $(e/p)_{rel}$ and temperature Te/Tp ratios are free parameters in the model which can be obtained from observations. We assume these to be 0.01 and 1 (immediately behind the forward shock) respectively for our preliminary study. B-field in the downstream region evolves according to Reynolds [6], and is compressed at the shock according to Volk et al [7]. Strong turbulence in B-field is assumed such that Bohm diffusion is used. Adiabatic losses are taken into account, affecting the evolution of all particle spectra downstream.

Toy Model

We do a calculation for a toy model SNR and predict photon emission spectra and profile to illustrate the general methodology of the simulation framework. At the beginning of every time epoch, CR proton and electron spectra are calculated and assigned to spherical SNR shells defined in a cubic mesh. The cosmic rays are then allowed to diffuse out of the shells with D proportional to p/B(x,t), where D is the diffusion coefficient and p is momentum. Ambient B-field in the unshocked ISM outside the SNR is assumed to be 3 μG. Protons escaping upstream from the shock during acceleration are assumed to have a delta function distribution at p_{max}. To model emission contributed by pion decay, we can define a molecular cloud distribution in the mesh with a density profile inferred from observations for any SNR system being studied. Here a spherical shell with a Gaussian matter density distribution in the radial direction separated from the SNR shells is used for illustration. The calculation of photon emissivity uses the parameterized model of pp inclusive cross section from Kamae et al (2006). For inverse Compton, a monoenergetic, isotropic ambient photon field is allowed to be up-scattered by the accelerated CR electrons. Cross section is given by Jones (1968). The photon spectra are shown in Fig. 1(b).

CONCLUSION

Here we have developed a fast and expandable 3D computational platform capable of making predictions to be matched with observations, once we put in realistic parameters and physics for any specific SNR to be studied.

REFERENCES

1\. Ellison, Decourchelle & Ballet, A&A **413**,189-201 (2004)
1\. Ellison & Cassam-Chenai, ApJ **632**, 920-931 (2005)
2\. Ellison, Berezhko & Baring, ApJ **540**, 292-307 (2000)
4\. Amato & Blasi, Mon. Not. R. Astron. Soc. Lett. **364**, 76 (2005)
5\. Blasi, Gabici & Vannoni, Mon. Not. R. Astron. Soc. **361**, 907-918 (2005)
6\. Reynolds, ApJ, **493**, 375-396 (1998)
7\. Volk, Berezhko, Ksenofontov & Rowell, A&A **396**, 649-656 (2002)