Nonthermal X-ray emission from young Supernova Remnants

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Abstract. The cosmic-ray spectrum up to the knee ($E \sim 10^{15}$ eV) is attributed to acceleration processes taking place at the blastwaves which bound supernova remnants. Theoretical predictions give a similar estimate for the maximum energy which can be reached at supernova remnant shocks by particle acceleration. Electrons with energies of the order $\sim 10^{15}$ eV should give a nonthermal X-ray component in young supernova remnants. Recent observations of SN1006 and G347.3-0.5 confirm this prediction. We present a method which uses hydrodynamical simulations to describe the evolution of a young remnant. These results are combined with an algorithm which simultaneously calculates the associated particle acceleration. We use the test particle approximation, which means that the back-reaction on the dynamics of the remnant by the energetic particles is neglected. We present synchrotron maps in the X-ray domain, and present spectra of the energies of the electrons in the supernova remnant. Some of our results can be compared directly with earlier semi-analytical work on this subject by Reynolds [1].

INTRODUCTION

The number of supernova remnants (SNRs) with an observed nonthermal X-ray component is slowly increasing (Allen et al.[2]). This confirms the theory of diffusive shock acceleration (DSA), which predicts the production of relativistic particles at SNR shocks in the required energy range. Furthermore it strengthens the evidence that SNR shocks are indeed the sites where cosmic rays are accelerated up to the knee of the observed cosmic ray spectrum ($E \sim 10^{15}$ eV). It is expected that with the current observational facilities like Chandra and XMM, the details about SNRs with a nonthermal component and, hopefully, the number of SNRs identified as sources of nonthermal X-ray emission will increase. This motivates the extension of the current models of nonthermal X-ray emission of SNRs, in order to keep up with the status of observational work on this subject. We present a model which consists of a hydrodynamics code calculating the flow of an evolving SNR coupled with an algorithm which simulates simultaneously the transport and acceleration of relativistic particles.
HYDRODYNAMICS

The evolution of a single supernova remnant (SNR) can be divided into four different stages (Woltjer [3]): the free expansion stage, the Sedov-Taylor stage, the pressure-driven snowplow stage and the momentum-conserving stage. We will only focus on the first two stages. In later stages, both synchrotron losses and the efficiency of the acceleration process, prevent particles to be accelerated to energies where they can emit X-rays by the synchrotron mechanism. In the free expansion stage the material of the SNR is dominated by expanding ejecta from the progenitor star, bounded by a shock which is driven into the interstellar medium (ISM). Due to deceleration by the ISM, a reverse shock accompanies the forward shock (McKee [4]). When the SNR has swept up a few times the ejected mass of the progenitor star, this reverse shock is driven back into the interior of the SNR. This marks the stage where the expansion of the SNR shock will make the transition to the Sedov-Taylor stage. We have performed hydrodynamical simulations for a young supernova remnant up to this transition. All the hydrodynamical simulations were performed with the Versatile Advection Code 1 (VAC, Tóth [5]). The calculations are performed on a spherically symmetric, 1D, uniform grid. As an initial condition we deposit thermal energy and mass in the first few grid cells. This leads to the formation of both the reverse shock and the forward shock, discussed above. The grid resolution is such that the forward and the reverse shock are both resolved, and give the right compression factor ($r = 4$) for a non-relativistic strong shock. We make the model of the SNR 2D axially symmetric by imposing a uniform magnetic field in the ISM, aligned with the symmetry axis, at the start of the simulation. By using the condition of a frozen-in magnetic field (ideal MHD) the magnetic field lines are dragged along with the fluid, determining the configuration of the magnetic field at later times.

PARTICLE ACCELERATION

In principle, the acceleration and propagation of particles in a flow can be investigated by solving a Fokker-Planck equation for the particle distribution in phase space (e.g. Skilling [6]). Instead, we employ a method which uses Itô stochastic differential equations (SDEs). The SDE method simulates the random walk trajectory of a test particle in a given flow. By considering many realizations of the SDE in the same flow one constructs the distribution of particles in phase space. This corresponds to the solution of the Fokker-Planck equation (Achterberg and Krülls [7]).

By performing hydrodynamical simulations of a young SNR, and by using the flow from these simulations as an input for the SDE method, we simultaneously describe both the particle acceleration and the hydrodynamical evolution. Losses due to synchrotron radiation and inverse Compton radiation are easily included in

1) See http://www.phys.uu.nl/~toth/
FIGURE 1. Synchrotron map for $\nu = 10^{17}$ Hz.

the SDE method. In this way, we get the electron distribution in phase space for a young SNR which realistically describes: (1) acceleration at the forward shock, (2) adiabatic losses due to the expansion of the SNR, (3) synchrotron losses due to the presence of magnetic fields and (4) inverse Compton losses due to the interaction of the electrons with the photons of the cosmic microwave background.

RESULTS

We present the results from a simulation of a SNR with a total mechanical energy of $E_0 \simeq 0.93 \times 10^{51}$ erg and an ejected mass of $M_{ej} = 5.6 M_\odot$. This expands into an uniform medium with density $\rho_0 = 10^{-24}$ g/cm$^3$ and an axially symmetric magnetic field with strength $B_0 = 10\mu$G. We continuously inject particles at the forward shock of the SNR, starting at an age of $t = 100$ years up to the end of the simulation at an age of $t = 1000$ years. A total of $\sim 3.7 \times 10^6$ test particles were injected during the simulation. The injection was at a fixed momentum, and proportional with the area of the remnant, with a particle weight which takes into account the increase in the amount of material processed by the shock as it expands. At the end of the simulation we have the position and the momentum of each particle in the simulation box. Because the magnetic field strength throughout this box is also known, we can produce synchrotron maps at different frequencies. One example is shown in figure 1, which is reminiscent of the synchrotron maps presented by Reynolds [1]. Furthermore, figure 2 shows the spectrum of all the particles in the remnant. At low frequencies one can see the expected value of the spectral index for acceleration at a strong shock (compression ratio $r = 4$), i.e. $S_\nu \propto \nu^{-0.5}$. In the roll-off part of the spectrum, where the synchrotron and inverse Compton losses
start to compete with the energy gain due to the acceleration process, we get a power-law index of $S_\nu \propto \nu^{-1.0}$ at a frequency of $10^{18}$ Hz.

CONCLUSION

We have presented results from a method using a combination of hydrodynamical simulations and an algorithm simultaneously simulating particle acceleration in a SNR. The results are comparable with earlier work on this subject by Reynolds[1]. Future work will consider the evolution of a SNR in an ISM which is not uniform, like stellar wind cavities or molecular clouds. The combination of the SDE method and hydrodynamics is a strong tool to investigate the resulting morphology of the synchrotron emission.

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