High Energy Density Physics 17 (2015) 92–97

Contents lists available at ScienceDirect

High Energy Density Physics

journal homepage: www.elsevier.com/locate/hedp

A method for computing synchrotron and inverse-Compton emission from hydrodynamic simulations of supernova remnants

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ARTICLE INFO

Article history:
Available online 18 November 2014

Keywords:
Supernova remnants
Shock waves
Non-thermal emission

ABSTRACT

The observational signature of supernova remnants (SNRs) is very complex, in terms of both their geometrical shape and their spectral properties, dominated by non-thermal synchrotron and inverse-Compton scattering. We propose a post-processing method to analyse the broad-band emission of SNRs based on three-dimensional hydrodynamical simulations. From the hydrodynamical data, we estimate the distribution of non-thermal electrons accelerated at the shock wave and follow the subsequent evolution as they lose or gain energy by adiabatic expansion or compression and emit energy by radiation. As a first test case, we use a simulation of a bipolar supernova expanding into a cloudy medium. We find that our method qualitatively reproduces the main observational features of typical SNRs and produces fluxes that agree with observations to within a factor of a few allowing for further use in more extended sets of models.

1. Introduction

Supernova remnants (SNRs) are characterised by electromagnetic emission across a wide spectral range, which is generated by several different emission mechanisms such as (thermal) bremsstrahlung, synchrotron and inverse Compton scattering (IC), and the line emission of many different chemical elements in various ionisation levels (see, e.g. Gould and de Jager [4,7]. Similar processes play an important role in many other astrophysical objects (e.g. Zdziarski [22]. Consequently, the spectra and light curves depend on many physical processes, some of which can be—within a broad range of uncertainties—inferred from observational data (explosion energy, properties of the environment. Unfortunately, there are other key processes which may be not fully understood such as the physics of radiative shocks and the associated particle acceleration. Furthermore, many SNRs show a complex geometry with deviations from spherical symmetry that may be attributed to combinations of asymmetries in the explosion, instabilities during the propagation of the shock wave such as Rayleigh—Taylor, Vishniac (thin shell) or unstable cooling (see, e.g. Chevalier [3], inhomogeneities in the surrounding interstellar medium (ISM), or magnetic fields. For a review on observations of SNRs, we refer to [19]. Among the galactic remnants, SNR RX J0852.0-4622 (Vela Jr.) is a particularly interesting case, with observations from radio to TeV energies revealing a complex emission geometry [1,5,8,9,20,21].

The complexity of the radiation processes and the hydrodynamics of the SNR restrict a straightforward interpretation of observations and require the use of increasingly complex models in order to understand the physics of SNRs in general and of individual objects. Depending on the objective, models may focus on different effects, while making simplification in other sectors of physics. For instance, Obergaulinger [14] performed a series of three-dimensional simulations of the expansion of supernova blast waves into a clumpy environment (for models of simular settings, see Refs. [15,16]. Paying attention in particular to the case of Vela Jr., they concentrated their efforts on an accurate modelling of the hydrodynamics of the interaction between the shock wave and clouds in the ISM. Their model for the electromagnetic emission, on

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http://dx.doi.org/10.1016/j.hedp.2014.11.004
1574-1818/

the other hand, was relatively limited and accounted only for thermal bremsstrahlung, leaving out some of the most important contributions to the emission coming from SNRs.

Our goal now is to remedy this limitation by modelling the non-thermal emission of the simulated SNRs. To this end, we propose a method for post-processing the existing simulations. We assume that particle acceleration at the shock wave generates a population of high-energy electrons that subsequently cool by synchrotron and inverse-Compton radiation. The advantage of our approach is that it can provide and quick estimate of the non-thermal emission, but at a cost of several simplifications w.r.t., e.g. the spectra of the shock-accelerated electrons, the seed photons for IC, and the magnetic field in the SNR. Furthermore, we neglect ionisation and line emission. Kishishita [9] used similar methods to interpret observations of the Vela Jr. SNR, but coupled the emission model to spherically symmetric analytic hydrodynamical models, whereas we will use self-consistent hydrodynamical simulations to determine the evolution of the shock wave. Our method is, however, less accurate than, e.g. the simulations of Ref. [10]; which couple hydrodynamics, non-equilibrium ionisation, non-linear diffuse shock acceleration, and cosmic-ray production in a fully self-consistent manner. We also refer to the work of Ref. [17] for computations of the non-thermal emission in SNRs based on multi-dimensional simulations. We additionally note that our approach is at an approximate level related to the relativistic emission modelling of Ref. [12,13]. By virtue of its simplicity, the method lends itself easily to an investigation of the impact of variation of the input physics, e.g. of the spectra of accelerated electrons or the seed photons for the IC process.

We will begin the presentation in this article with a brief recap of the hydrodynamical simulations of Ref. [14] and an outline of our emission model in Section 2, then present results for the non-thermal radiation emitted by one of the models (Section 3), before summarising the main results and drawing further conclusions in Section 4.

2. Physical ingredients and numerical method

Following the implementation in the SPEV code outlined in Ref. [11]; we model the evolution of a population of non-thermal electrons accelerated by the shock wave and their subsequent emission of synchrotron and IC radiation using the post-processing algorithm *SPEVita* based on three-dimensional hydrodynamic simulations. Such a two-step approach requires that the radiative energy losses do not significantly alter the structure and evolution of the remnant. This condition is satisfied in our cases because the total amount of energy carried away by photons is small w.r.t. the total kinetic and internal energy of the remnant.

We furthermore work in the limit of low optical depth of the gas in the SNR. This assumption is justified by the low gas density. If we estimate the optical depth of the SNR using the Thomson scattering cross section, $\sigma_{\rm Th} = 0.66 \times 10^{-24}$ cm^2, we find that even the densest clouds in our simulations (densities up to 1000 cm^{-3}, size up to 10 pc) have optical depths of less than 0.01, and most of the gas is much more optically thin. This fact allows us to directly obtain the radiation arriving at an observer location from the emissivity at the source location instead of solving the much more complex equations of radiative transfer. Furthermore, we neglect synchrotron self-absorption since it is unimportant in the frequencies considered here (above the optical band).

2.1. Hydrodynamical models

From the simulations of Ref. [14]; we select a model (model `S25A`) in which a bipolar supernova explosion ejects a mass of $M_{\rm SN} = 6M_\odot$ with a total explosion energy of $E_{\rm SN} = 6.7 \times 10^{51}$ erg into an ISM of particle density $n_{\rm ISM} = 0.25$ cm^{-3} and temperature $T_{\rm ISM} = 10$ K. The ISM contains four large high-density clouds placed in the NW, N, SE and S directions from the centre of the explosion at positions where X-ray bright features are suggestive of an interaction between the shock wave and overdense structures in the ISM.

The expanding shock wave roughly maintains its initial bipolar shape with an interior consisting of a hot, tenuous gas with very little substructure. This changes once, after a time of about $t \sim 700$ yr, the interaction between the shock wave and the clouds channels the expanding gas between the gas clouds and enhances the mixing of post-shock fluid elements. On the time scales under consideration here, i.e. up to 1500 years after the explosion, the clouds are not disrupted by the shock, but experience considerable deformation and, most importantly, heating of the shocked surfaces, which, as a combination of high temperature and high density, show up as prominent emitters of thermal radiation.

2.2. Non-thermal emission

The passage of the shock wave across a fluid element generates a population of relativistic non-thermal electrons. Without modelling the acceleration process in detail, we assume that the 0th moment of the distribution function of the electrons, $n^0(\gamma)$, i.e. the number density of particles per unit Lorentz factor, γ, follows a power-law distribution,

$$n^0(\gamma) = n_0^0 \left(\frac{\gamma}{\gamma_{\rm min}}\right)^{-q} \quad \text{for} \quad \gamma_{\rm min} \le \gamma \le \gamma_{\rm max}. \tag{1}$$

For further reference, we note that the Lorentz factor is related to the particle momentum and energy via the electron mass, m_e, as $p = \gamma m_e v$ ($p = \gamma m_e c$ for the case of ultrarelativistic electrons considered in the following) and $e = \gamma m_e c^2$, respectively. Aside from the power-law index q, there are three *free* parameters that specify the electron energy distribution, namely, the minimum and maximum Lorentz factors, $\gamma_{\rm min}$ and $\gamma_{\rm max}$, and the normalisation n_0^0. The following conditions allow us to fix these three parameters:

1. We first estimate the value of the stochastic magnetic field energy density generated at shocks assuming that it is a fraction, ε_b, of the thermal energy density, u_S (provided by our hydrodynamic models), i.e. $B = \sqrt{8\pi\varepsilon_b u_S}$.
2. Following Ref. [19]; we relate the cut-off energy of the electron distribution to the magnetic field strength at the site of acceleration (computed in point 1, above), $E_{\rm max} = 100$ TeV $\alpha_{\rm acc}(B/1\,\mu{\rm G})^{-1/2}$, and thus, we shall specify the value of the parameter $\alpha_{\rm acc}$.
3. Given $\gamma_{\rm max}$, the normalisation n_0^0 and the minimum Lorentz factor are direct functions of the efficiency of the acceleration process, i.e. the fraction of electrons accelerated in the shock wave and the fraction of total energy they carry, ε_n and ε_e, respectively.

In practise, we ignore all electrons below $\gamma_{\rm min;emi} = 10$ when computing synchrotron and IC emission to be consistent with the approximations we will employ in their respective emissivities.

We consider only a single episode of particle acceleration. Upon passage of the shock wave across one of our tracer particles, we define a momentum grid of n_p zones distributed logarithmically spanning the range $[p_{\rm min}, p_{\rm max}] = [\gamma_{\rm min}, \gamma_{\rm max}] \times m_e c$ and initialise $n^0(p_i)$, $i = 1,\ldots,n_p$ according to Eq. (1).