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

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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 of the right order of magnitude, allowing for further use in more extended sets of models.

Keywords: Supernova remnants; shock waves; non-thermal emission

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 ionization levels. Consequently, the spectra and lightcurves

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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, inhomogeneities in the surrounding interstellar medium (ISM), or magnetic fields. For a review on observations of SNRs, we refer to Reynolds (2008). 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 (Duncan and Green, 2000; Slane et al., 2001; Aharonian et al., 2007; Ivudin et al., 2007; Tanaka et al., 2011; Kishishita et al., 2013).

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 et al. (2014) performed a series of three-dimensional simulations of the expansion of supernova blast waves into a clumpy environment. 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 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 et al. (2013) 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 Lee et al. (2013), which couple hydrodynamics, non-equilibrium ionisation, non-linear diffuse shock acceleration, and cosmic-ray production in a fully self-consistent manner. We additionally note that our approach is at an approximate level related to the relativistic emission modelling of Mimica et al. (2004) and Mimica et al. (2010). 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 Obergaulinger et al. (2014) and an outline of our emission model in Sect. 2, then present results for the non-thermal radiation emitted by one of the models (Sect. 3), before summarising the main results and drawing further conclusions in Sect. 4.

2. Physical ingredients and numerical method

Following the implementation in the SPEV code outlined in Mimica et al. (2009), 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, justified by the low gas density, 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).

**Hydrodynamical models.** From the simulations of Obergaulinger et al. (2014), we select a model (model S25A) in which a bipolar supernova explosion ejects a mass of $M_{\text{SN}} = 6 M_\odot$ with a total explosion energy of $E_{\text{SN}} = 6.7 \times 10^{51} \text{erg}$ into an ISM of particle density $n_{\text{ISM}} = 0.25 \text{ cm}^{-3}$ and temperature $T_{\text{ISM}} = 10 \text{ K}$. The ISM contains four large high-density clouds placed in the NW, N, SE and S directions from the 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 $t \sim 700 \text{ yr}$, 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.

**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 $0^{\text{th}}$ moment of the distribution function of the electrons, $n^0(\gamma)$, i.e. the number density of particles per unit Lorentz factor, $\gamma$, follows a power-law distribution,

$$n^0(\gamma) = n_0^0 \left(\frac{\gamma}{\gamma_{\text{min}}}\right)^{-q} \quad \text{for} \quad \gamma_{\text{min}} \leq \gamma \leq \gamma_{\text{max}}.$$  \hspace{1cm} (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 $p = \gamma m_e c$ 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, $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$, 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, $\epsilon_b$, of the thermal energy density, $u_S$ (provided by our hydrodynamic models), i.e., $B = \sqrt{8\pi \epsilon_b u_S}$.

2. Following Reynolds (2008), 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), $E_{\text{max}} = 100 \text{ TeV} \ \alpha_{\text{acc}} \left(\frac{B}{1 \mu\text{G}}\right)^{-1/2}$, and thus, we shall specify the value of the parameter $\alpha_{\text{acc}}$.

3. Given $\gamma_{\text{max}}$, 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, $\epsilon_n$ and $\epsilon_e$, respectively.

In practise, we ignore all electrons below $\gamma_{\text{min,emi}} = 10$ 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 $[p_{\text{min}}, p_{\text{max}}] = [\gamma_{\text{min}}, \gamma_{\text{max}}] \times m_e c$ and initialise $n^0(p_i), i = 1, \ldots, n_p$ according to Eq. (1).

Afterwards, the electrons suffer radiative losses and gain or lose energy due to adiabatic compression or expansion, respectively. In the evolution equation for the $0^{\text{th}}$ moment,

$$D_t \ln n^0 + \left(\frac{-p}{3} \Theta + B\right) \partial_p \ln n^0 = -\frac{2}{3} \Theta - \partial_p B,$$  \hspace{1cm} (2)

these effects are accounted for by the expansion coefficient

$$\Theta = -D_t \ln \rho$$  \hspace{1cm} (3)

and the emission coefficient

$$B = \frac{4\sigma_T (u_B + u_{\text{ph}})}{3m_e^2 c^2} p^2.$$  \hspace{1cm} (4)
Here, $D$ denotes the Lagrangian time derivative, $\rho$ is the gas density, and $\sigma_T$ is the Thompson cross section. The emission coefficient is the sum of a synchrotron contribution, proportional to the magnetic energy density $u_B = B^2/2$, and an IC contribution, proportional to the energy density of the background photon field, $u_{\text{ph}}$. $u_B$ and $u_{\text{ph}}$ are, besides the efficiencies determining the initial distribution of non-thermal particles, the most important free parameters of our analysis.

The formal solution of Eq. (2), given by Mimica et al. (2009), lends itself straightforwardly to a discretisation on a time-dependent grid in momentum space. Given the momentum of an electron $p(t_0)$ at time $t_0$ and setting

$$\frac{\rho(t_1)}{\rho(t_0)} = \exp (3k_a \delta t)$$

and

$$\mathcal{B} = -k_e \delta t,$$  

we find the momentum of at time $t_1 = t_0 + \delta t$ as

$$p(t_1) = p(t_0) \frac{k_a \exp (k_a \delta t)}{k_a + p(t_0) (\exp (k_a \delta t) - 1)}.$$  

and the 0th moment as

$$n_0(t_1) = n_0(t_0) \left[ \exp (k_a \delta t) \left( 1 + \gamma(t_0) \frac{k_a}{k_e} (\exp (k_a \delta t) - 1) \right) \right]^2.$$  

Solving Eqs. [7] and [8] for each tracer particle that already passed by the shock wave, we obtain the time evolution of the distribution of non-thermal particles at discrete momentum values $p_i(t)$. Between these interface values, we approximate the function $n_0(\gamma)$ by piecewise power laws of index $q$, i.e.

$$n_0(\gamma) = n_0^i \left( \frac{\gamma}{\gamma_i} \right)^{-q} \text{ for } p_i \leq \gamma m_e c < p_{i+1}.$$  

This procedure does not directly yield the spectral distribution of the emitted radiation, which we can compute in an additional step using the expressions summarised by Böttcher and Reimer (2012). The synchrotron emission at frequency $\nu$ of non-relativistic electrons is described by the emissivity coefficient, i.e. the energy emitted per unit volume, unit frequency interval, and unit time

$$j_\text{syn}(\nu) = \frac{1}{4\pi} \int d\gamma n(\gamma) P_\nu(\gamma).$$  

For the power-law distribution Eq. (9), the radiative output of a single ultra-relativistic electron with Lorentz factor $\gamma$ can be approximated by

$$P_\nu(\gamma) = \frac{32c}{9\Gamma(4/3)} \left( \frac{u_c^2}{m_e c^2} \right) \frac{u_B^2 \gamma^{4/3} \nu^{1/3}}{\nu_c^{4/3}} \exp \left( -\nu/\nu_c \right).$$  

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with the critical frequency \( \nu_c = \frac{3q_eB}{2m_ec}\gamma^2 \) (\( q_e \) is the electron charge). For IC, we restrict ourselves to the simple case of a mono-energetic seed field of photons of frequency \( \nu_0 \), leading to an emission coefficient for the power-law spectrum of electrons with momentum \( p_i \leq \gamma m_ec < p_{i+1} \) approximately given by

\[
j_{i}^{\text{IC}}(\nu) = C \left( \frac{\nu}{\nu_c} \right)^2 \left\{ \max \left( \gamma_i, \frac{h\nu}{m_ec^2}, \sqrt{\frac{\nu}{2\nu_c}} \right)^{-q-3} - \gamma_{i+1}^{-q-3} \right\}
\]

(12)

if \( \gamma_{i+1} \geq \max \left( \frac{h\nu}{m_ec^2}, \sqrt{\frac{\nu}{2\nu_0}} \right) \) and \( j_{i}^{\text{IC}} = 0 \) otherwise; the normalisation is given in terms of the number density of seed photons, \( n_{\text{ph},0} \), by

\[
C = \frac{hc\sigma_T}{8\pi(q+3)\gamma_i^{-q}}.
\]

For each tracer particle and its non-thermal electron distribution, we evaluate the emission coefficients at discrete frequencies between infrared and TeV energies. We determine emission maps, i.e. the total spectral emissivity \( J_{\nu}(x, y; T) \) arriving at the position of an observer at distance \( D \) along the \( z \)-axis from gas at position \((x, y)\) on the celestial plane by integrating the emissivity along the trajectory of a ray of light at time \( T \),

\[
J_{\nu}^{\text{synlIC}}(x, y; T) = \int_{-\infty}^{D} dz \ j_{\nu}^{\text{synlIC}}(x, y, z; t = T - \frac{1}{c}(D - z)).
\]

(13)

For the spatial integration, we take into account the expansion of the gas by assuming that each tracer particle represents a uniform distribution of electrons centred at its position and with a volume \( V(t) = V(t_0) \frac{\rho(t)}{\rho(t_0)} \), where \( V(t_0) \) denotes the volume assigned to the particle at the start of the simulation. Finally, an integration of \( J_{\nu}(x, y; T) \) over \( x \) and \( y \) yields the total, spatially unresolved emission of the gas.

### 3. Results

Keeping the hydrodynamical model fixed, we computed several model light curves, spectra, and emission maps. The goal of this series of models is not to provide a good fit to the observations of a particular SNR, but to assess in principle the viability of our model to reproduce the most important features of the non-thermal emission from SNRs and to explore the dependence of the results on the input physics and the free parameters governing the evolution of the non-thermal electrons and their emission, viz. the efficiency of particle acceleration, the magnetic field in the SNR, and the background photon field acting as seed for IC scattering. To facilitate our goal, we will qualitatively compare the models to the observations of the Vela Jr. SNR in radio (Duncan and Green, 2000), X-ray (ASCA GIS, Aharonian et al., 2007), Fermi-LAT (Tanaka et al., 2011), and HESS (Aharonian et al., 2007). We defer a more rigorous comparison with observational data to an upcoming study.

For a reference model serving as test case for our method, we assume that the spectrum of the shock-accelerated electrons follows a power-law of index
\( q = 2.2 \) and set the acceleration efficiencies to \( \epsilon_e = 0.4 \) and \( \epsilon_n = 0.075 \). We set the post-shock magnetic energy density to a fraction \( \epsilon_b = 10^{-3} \) of the local internal energy density and set the parameter for the maximum electron energy to \( \alpha_{\text{acc}} = 10 \).

The synchrotron emission then follows directly from the settings for the magnetic field. We represent the seed for IC scattering by a simple model for the cosmic microwave background (CMB), viz. a field of photons of temperature \( T_{\text{IC,0}} = 2.7 \) K with a uniform energy density of \( u_{\text{IC,0}} = 1 \) eV/cm\(^3\).

We show the spectral energy distribution of the radiation emitted by the shock-accelerated electrons at \( t = 300 \) yr with the blue lines in Fig. 1. Qualitatively, the shape of the spectrum is similar to the observational data. Synchrotron radiation dominates the total radiative output at low energies with a broad peak in the range of UV to soft X-ray energies. Most notably, the overall energy emitted in synchrotron appears to exceed the observational data, and the high-energy cutoff of the spectrum is at too high photon energies. IC radiation creates a second feature in the spectrum at energies of GeV and above. In agreement with the observations, IC does not show sharp peak, but rather a broad maximum. Again, the agreement between model and observations is only qualitative, and our set of parameters does not represent a good fit to the data.

The spectrum undergoes a considerable evolution with time, with different tendencies for the two contributions. The IC emission increases with time and its maximum shifts to lower photon energies. The latter trend can be observed in the synchrotron contribution, too, but the maximum value of the spectral energy distribution (SED) increases first (compare the green and dark blue lines), but then starts to decrease (red and yellow lines). The gradual softening of the spectra can be understood in terms of the decreasing energy of the population of non-thermal electrons as the shock wave expands, decreasing the thermal energy density available for acceleration.

We investigate the evolving appearance of the SNR in the series of emission maps presented in Fig. 2. Before hitting the four major clouds (top panels), the expanding shock wave maintains its ellipsoidal shape, and consequently the observational display of the SNR at low and high photon energies is dominated by the limb-brightened shock wave. The most prominent features are located at the shock wave along the semi-major axis of the ejecta. The non-thermal particles cool rather rapidly, and, hence, the interior regions of the SNR behind the shock wave remain dark. A few bright spots in the interior of the SNR indicate the positions of small clouds already hit by the shock wave. At a later time (bottom panels), the shock wave has already crossed the four main clouds, which now show up as additional emitters, in particular in the X-ray band. This enhanced emission reflects the rather high particle density and pressure at the shock-heated cloud surface as well as the reduced velocities in the flow hitting the cloud, where the fluid remains trapped for a fairly long time, thus reducing the adiabatic cooling of the non-thermal electrons.

In order to show the sensitivity of the computed synthetic light curves to some of the parameters of our models, we also consider a very weakly magnetised model with \( \epsilon_e = 0.3 \), \( \epsilon_n = 0.1 \), and \( \epsilon_b = 10^{-4} \). The reduction of the...
magnetic field strength has fairly strong consequences for the emission. First, a lower magnetic field strength places the cut-off of the non-thermal electron distribution at higher energies. Furthermore, it drastically reduces the synchrotron emission of the electrons. The resulting SED for a time $t = 900 \text{ yr}$ is presented in the left panel of Fig. 3, clearly showing the strong suppression of the synchrotron peak, which now has the same magnitude as the IC peak. The latter has lost its more complex plateau shape. An opposite variation of the magnetisation to $\epsilon_b = 10^{-2}$ (right panel) has a small effect on the height of the synchrotron and IC peaks, but reduces the synchrotron cutoff energy. This finding seems to indicate that clearly different fluxes in both parts of the spectrum and a flat maximum in the IC contribution points towards a fairly strong magnetic field in the SNR. We defer a more thorough investigation of this effect and similar dependencies as well as the impact of the hydrodynamic model to a future study.

4. Summary and conclusions

Explaining the radiation observed in many galactic SNRs, characterised by non-thermal emission across a very broad band of photon energies as well as by a complex geometry, requires an approach combining multi-dimensional hydrodynamical simulations and a detailed modelling of the non-thermal radiation processes. To this end, we have adapted the methods used previously for computing the non-thermal emission of relativistic outflows to the situation of multi-dimensional non-relativistic SNRs expanding into a clumpy ISM. A fraction of the electrons in the gas are accelerated to extremely relativistic energies when the shock wave passes across a fluid element and they subsequently emit synchrotron and inverse-Compton radiation. We apply a simple post-processing tool, SPEVita, based on the relativistic code SPEV

Mimica et al. (2004). We follow the evolution of Lagrangian tracer particles advected with the flow. Upon passage of the shock wave, we set up a power-law distribution of the electrons. Starting from these initial states, we evolve the distribution taking into account adiabatic compression/expansion by the flow and energy losses due to synchrotron and IC radiation. We finally compute the detailed spectra of these two radiative processes by integrating the corresponding emissivities for all tracer particles. From these, we can straightforwardly obtain, e.g. spectra or two-dimensional emission maps.

Our method is less elaborate than, e.g. the scheme of Ellison et al. (2007); Patnaude et al. (2009); Lee et al. (2013) treating diffusive shock acceleration self-consistently. Therefore, as a first main step, we assessed its applicability in SNR models by computing a small set of emission models based on the same hydrodynamical simulation and varying some of the free parameters of the physics of non-thermal particles and their emission. We selected one of the three-dimensional simulations by Obergaulinger et al. (2014), consisting of an energetic bipolar explosion expanding into an ISM containing several large clouds. Although this particular hydrodynamical model was designed as a possible scenario for the observational appearance of SNR RX J0852.0-4622 (Vela
Figure 1: Broadband SED of our reference model for different times, distinguished by line colour. The total emission and the synchrotron and IC contributions are displayed by solid, dashed, and dash-dot-dot-dotted lines, respectively. For comparison, we include observations for the Vela Jr. SNR in radio (data points to the left; [Duncan and Green, 2000]), X-ray (ASCA GIS; shaded region around 2 keV; [Aharonian et al., 2007]), Fermi-LAT (data points in the GeV range; [Tanaka et al., 2011]), and HESS (shaded region to the right; [Aharonian et al., 2007]).
Figure 2: Emission maps in the X-ray and TeV bands at $t = 300 \, \text{yr}$ (top) and $t = 900 \, \text{yr}$ (bottom).
Figure 3: *Left:* SED for the weaker magnetised model at $t = 900$ yr. *Right:* SED for the stronger magnetised model at $t = 900$ yr.

Jr.), we do not intend to match the observational data of this or any other individual SNR here. We do, however, try to roughly reproduce the main features characteristic of most SNR.

While the results of this first set of models show only poor quantitative agreement with the data of the Vela Jr. SNR, they are nevertheless qualitatively compatible with the main observational findings. In particular, we clearly find the broad-band non-thermal emission with peaks in the UV-to-X-ray and GeV-to-TeV energies, produced by synchrotron and inverse-Compton scattering, with fluxes that are of the right order of magnitude. Geometrically, the emission is dominated by the immediate post-shock region. In addition, large clouds hit by the shock wave, can show up prominently, in particular in soft X-ray bands, after the shock wave has swept across them.

Having found a qualitative agreement between models and general observational features of SNRs, we plan to extend the present analysis by considering a wider range of physical parameters for the acceleration and emission processes and apply it to a larger set of (magneto-)hydrodynamical simulations in order to investigate the observational consequences of different sources for asymmetries in SNRs.

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