Particle propagation in clumpy supernova remnants

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Abstract. The presence of dense clumps in the environment where a supernova remnant expands might have a strong impact in shaping the observed hadronic gamma-ray spectrum. A detailed numerical study about the penetration of relativistic protons into clumps which are engulfed by a supernova remnant shock is here presented, taking into account the magneto-hydrodynamical properties of the background plasma. This has strong implications for the formation of the spectrum of hadronic gamma rays, which does not reflect anymore the acceleration spectrum of protons, resulting substantially modified by propagation effects. A hadronic scenario including dense clumps inside the remnant shell is shown to adequately reproduce the broadband gamma-ray spectrum of the Galactic supernova remnant RX J1713-3946.7 from GeV to TeV energies.

1 Introduction

During the latest years, numerous detections of supernova remnants (SNRs) in TeV gamma rays have confirmed the theoretical predictions that SNRs can operate as powerful CR accelerators. However, the details of how particles propagate within the SNR, escape the shock and are released into the interstellar medium (ISM) are poorly understood, though these processes strongly influence the very-high-energy emissions observed. In the following, the effects of the presence of dense non homogeneities in the circumstellar medium (CSM), where the shock expands, are investigated. In particular, dense molecular clouds constitute potential sources of both gamma rays and neutrinos, in that the protons accelerated at the SNR shock might interact with the dense gas contained in clumps (in the so-called *pp* interaction) and produce both neutral pions and charged pions. The methods developed for the computation of the spectrum of protons penetrated inside the clump, from both the point of view of the background plasma and of the accelerated particles, are described in Sec. 2. This spectrum results much harder than that in the diffuse inter-clump medium: as a consequence, the gamma-ray spectrum resulting from pp interactions will reflect this hardening. The cumulative contribution of a uniform clump distribution within the remnant shell is able to reproduce the hard GeV spectrum observed in the SNR RX J1713-3946.7, as explained in Sec. 3. Finally, conclusions are derived in Sec. 4.

2 Shocks expanding in non-homogeneous media

Observations of the ISM have revealed a strong non homogeneity, particularly inside the Galactic Plane. For instance, the environment where type II SNe explode is likely populated by molecular clumps: in fact, given their fast evolution, the explosion happens in an environment rich of molecular

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clouds, the same that generated the star. Moreover, given their massive progenitor, strong winds in the giant phase of the star evolution accelerate the fragmentation of clouds into clumps, while creating a large cavity of hot and rarified gas around them. If the mass of the cool clouds does not exceed the Jeans mass, clouds can remain in pressure equilibrium with the surrounding hot phase. The physical size of these ISM inhomogeneities results from MHD simulations which include interstellar cooling, heating and thermal conduction. These have been conducted by [1], who found that the characteristic length scale of clumps amounts to $R_c \simeq 0.1$ pc, corresponding to the smaller scale where thermal instability is effective. Such a scale will be fixed in the following. This scenario could be similar to the one in which the remnant of RX J1713.7-3946 is evolving. In the following, a simplified scenario is realized, where a single clump much denser than the circumstellar plasma is engulfed by a shock. In such a configuration, two different kinds of processes amplify the magnetic field. Around the clump, the regular field results to be compressed reaching a value up to ~ 10 times the original value, in a layer that is found to be about half of the clump size, i.e. 0.05 pc, similar to the results obtained by [1]. This region will be referred to as the *clump magnetic skin*. In addition, in the region behind the clump, turbulence develops and the associate vorticity further amplifies the magnetic field. It is also shown that if the density contrast between the clump and the surrounding medium is very large, the clump can survive for long time before evaporating, even longer than the SNR age.

2.1 MHD simulations with PLUTO

The description of the thermal properties of a classical fluid follows from the solution of the Navier-Stokes equations, coupled to the induction equation for the time evolution of the background magnetic field $\mathbf{B_0}$. In order to simulate a shock discontinuity expanding in the presence of a clump, a numerical approach has been adopted, through a three dimensional simulation in cartesian coordinates within the PLUTO code [2]. A magnetic field of intensity $B_0^{\rm up} = 5\mu$G is set in the region upstream of the shock, inclined by 45° with respect to the shock normal, with $\mathbf{B_0} = (B_{0x}, 0, B_{0z})$ and $B_{0x} = B_{0z}$. In order to investigate a situation as much similar as that of high-mass star SN explosion, like RX J1713.7-3946, the upstream region is simulated as a low density medium with $\rm n_{up} = 10^{-2}$ cm^{-3}, which gets compressed by the shock in the downstream region up to $\rm n_{down} = 4 \times 10^{-2}$ cm^{-3}. A strong shock is moving in the direction of the z-axis, with a sonic Mach number $M = v_s/c_s \simeq 37$, as expected for this remnant, given its measured shock speed of $v_s = 4.4 \times 10^8$ cm s^{-1} and an upstream temperature of $T = 10^6$ K, which is typical for bubbles inflated by stellar winds. As initial condition, the clump is set in the upstream with a density as high as $\rm n_c = 10^3$ cm^{-3}. Therefore, a density contrast $\chi = n_c/n_{\rm up} = 10^5$ is assumed: if the shock speed is $\mathbf{v} = v_s\widehat{z}$, it propagates inside the clump with a velocity $\mathbf{v_{s,c}} = v_{s,c}\widehat{z}$ equal to $v_{s,c} = v_s/\sqrt{\chi} = 1.4 \times 10^6$ cm s^{-1} [1]. The interesting time interval for the evolution of the background plasma is about 300 years from the first shock-clump interaction, as for larger times clumps will have been crossed by the contact discontinuity and thus they will soon be emptied of CRs. Within this time interval, results from MHD simulations can be summarized as follows: i) the shock slows down inside the clump; ii) the clump maintains its density contrast, although the density distribution tends to smoothens; iii) the regular magnetic field is wrapped around the clump surface in a region with a typical size of $R_c/2$: it results compressed in the clump skin, such that the magnetic energy density is ~ 100 times larger than outside; iv) in the region immediately behind the clump, a long tail develops where the plasma becomes turbulent: as a consequence, the vorticity amplifies the magnetic field in a turbulent dynamo-like process, by a factor up to 10. Note that the fact that the magnetic field around the clump is mainly directed along the tangential direction implies that it is difficult for accelerated particles to diffuse orthogonally to the clump surface.

2.2 Particle transport

The propagation of accelerated particles into a magnetized ISM is described by the transport equation, which regulates the temporal and spatial evolution of the CR density function in the phase space $f(\mathbf{x}, \mathbf{p}, t)$. In in the shock reference frame, this equation reads as

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f = \nabla \cdot [D \nabla f] + \frac{1}{3} p \frac{\partial f}{\partial p} \nabla \cdot \mathbf{v} + Q_{\rm CR} \tag{1}$$

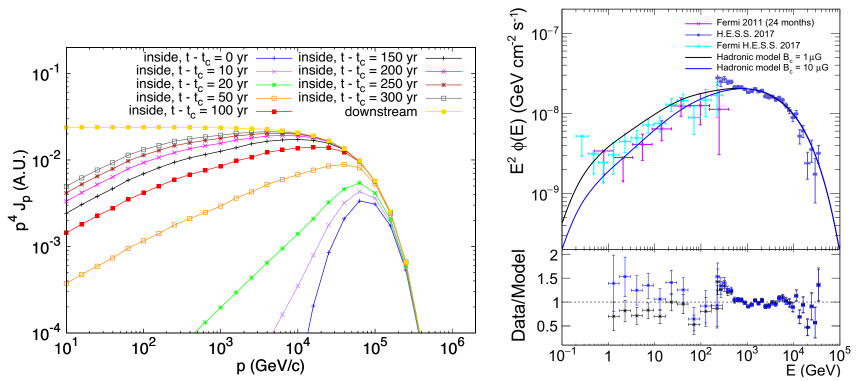
Here $D(\mathbf{x})$ is the particle diffusion coefficient, $\mathbf{v}$ is the plasma velocity field, p is the particle momentum and $Q_{\rm CR} = f_{\rm inj} v_s \delta(z - z_s)$ is the injection flux acting at the shock position $z = z_s$. Given the system symmetry, Eq. (1) will be solved in cylindrical coordinates, through a finite difference method (see [3] for further details). The initial condition of the simulation includes the presence of a shock precursor in the upstream region. A stationary isotropic Bohm diffusion is assumed through all the space: its space dependency is dictated by a magnetic field $B_0(\mathbf{x})$, which defined four regions in the space: i) the unshocked CSM, in the far upstream, ii) the shocked CSM, where $B_0 \equiv B_{\rm CSM} = 10\,\mu$G, iii) the clump interior, with a size of $R_{\rm c} = 0.1$ pc, where diffusion is expected to be not efficient because of ion-neutral damping, such that $B_0 \equiv B_c = 1\,\mu$G, and iv) the clump skin, with a size of $R_{\rm s} = 0.5 R_{\rm c}$ around the clump itself, where the amplification of the magnetic field is realized such that $B_0 \equiv B_s = 100\,\mu$G. Following the test-particle approach of DSA, a p^{-4} power-law spectrum is set at the shock position: an exponential cut-off in momentum $p_{\rm cut}$ is introduced in order to take into account the maximum attainable energy. Results are shown in Fig. 1(a), where $p_{\rm cut} = 70$ TeV/c was set in order to reproduce the very-high-energy gamma-ray data of RX J1713.7-3946. The spectrum of particles from younger clumps appears much harder than the one accelerated at the shock: in fact, low-energy CRs are prevented from penetrating into the clump, due to both the amplified magnetic field at the skin and the linear dependency of the diffusion coefficient with the particle momentum. Thus, the entrance of low-energy CRs into the clump is delayed, while high-energy particles can freely propagate in it.

3 The case of RX J1713.7-3946

The case of RX J1713.7-3946 is of special interest to this respect. This remnant has been considered for long time the best candidate for an efficient acceleration scenario, mainly due to its high gamma-ray flux. The detection of gamma-ray emission in the energy range [1 − 300] GeV by the Fermi-LAT satellite [4] has shown an unusually hard spectrum which, at a first glance, seems to be in a better agreement with a leptonic scenario. Nevertheless, a deeper analysis shows that neither the hadronic nor the leptonic scenarios, taken in their simplest form, can unequivocally explain the observations [5–7]. To address this issue, the presence of dense inhomogeneities can be invoked: in fact, the magnetic field can result amplified all around the clump both because of field compression and because of hydrodynamical instabilities developed in the shock-clump interaction. Consequently, the gamma-ray spectrum would be harder than the parent proton spectrum accelerated at the forward shock. Results are shown in Fig. 1(b), where a uniform distributions of clumps inside the remnant shell was assumed (for a total mass in clumps equal to $45\,M_\odot$). An efficiency of the pressure conversion mechanism from bulk motion to accelerated particles equals to $\eta \simeq 2\%$ was also set. Two different models are presented, either with $B_c = 1\,\mu$G or with $B_c = B_{\rm CSM} = 10\,\mu$G: both are shown to adequately describe the hardening observed in multi-GeV gamma rays.

4 Conclusions

The presence of dense molecular clumps where a shock propagates strongly affects the plasma properties, in such a way that the large scale magnetic field around the clumps result amplified. As a



(a) (b)

Figure 1. (a) Proton spectrum inside clumps of different ages. The downstream particle energy density, which is constant in time, is also reported. (b) Gamma-ray flux from SNR RX J1713.7-3946. The points are Fermi-LAT data (pink), H.E.S.S. data (violet) and H.E.S.S. analysis of Fermi-LAT data (light blue). The hadronic models (solid lines) refer to the configuration with a magnetic field inside the clump equal to $B_c = 1\,\mu$G (black) and to $B_c = 10\,\mu$G (blue). The field in the clump skin is fixed to 100μG in both models, to mimic the amplification.

consequence, low-energy accelerated particles needs more time to penetrate the clump compared to high-energy ones, resulting into a significant hardening of the particle energy spectrum inside clumps with respect to the acceleration spectrum. The cumulative contribution of clumps embedded between the contact discontinuity and the current shock position is able to reproduce the observed GeV hardening observed in RX J1713.7-3946. Remarkably, for the gas density inside the clump assumed here ($n_c = 10^3$ cm^{-3}) the evaporation time is much longer than the SNR age: hence, the clumps crossed by the forward shock do not produce significant thermal X-ray emission, in agreement with observations. This scenario would also naturally account for the fast variability in non-thermal X-rays reported in some hot-spots inside RX J1713.7-3946: the electrons entering the regions of amplified magnetic field would rapidly lose their energy because of synchrotron emission. An independent signature on the clump origin of the gamma-ray emission could be revealed by means of morphological studies by CTA, as a large spatial fluctuation of the gamma-ray flux is expected, unlike a scenario where the SNR is expanding into a uniform medium. Finally, the detection of neutrinos would constitute an unambiguous probe of the hadronic origin of the radiation observed: for a 100% hadronic origin, a significant detection appears realistic within one decade of operation of KM3NeT.

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