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Non-linear diffusive acceleration of heavy nuclei in supernova remnant shocks

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ABSTRACT

We describe a semi-analytical approach to non-linear diffusive shock acceleration in the case in which nuclei other than protons are also accelerated. The structure of the shock is determined by the complex interplay of all nuclei, and in turn this shock structure determines the spectra of all components. The magnetic field amplification upstream is described as due to streaming instability of all nuclear species. The amplified magnetic field is then taken into account for its dynamical feedback on the shock structure as well as in terms of the induced modification of the velocity of the scattering centers that enters the particle transport equation. The spectra of accelerated particles are steep enough to be compared with observed cosmic ray spectra only if the magnetic field is sufficiently amplified and the scattering centers have high speed in the frame of the background plasma. We discuss the implications of this generalized approach on the structure of the knee in the all-particle cosmic ray spectrum, which we interpret as due to an increasingly heavier chemical composition above 10^{15} eV. The effects of a non trivial chemical composition at the sources on the gamma ray emission from a supernova remnant when gamma rays are of hadronic origin are also discussed.

1. Introduction

A satisfactory understanding of the origin of cosmic rays (CRs) must deal with the issue of chemical composition. Probably the most striking instance of the role played by the different chemicals is the origin of the knee in the all-particle CR spectrum. In a scenario in which the maximum energy of accelerated particles scales with the charge of the particles involved, a knee arises naturally as a superposition of spectra of chemicals with different charges Ze. Even more important, the change of spectral slope on the two sides of the knee is determined by the relative abundance of different chemicals as a function of Z, convolved with the effects of rigidity dependent propagation in the Galaxy.

While there has been much work on the propagation of nuclei in the Galaxy (mainly because of the importance it has for the prediction of travel time of CRs in the Galaxy and ratios of secondary to primary fluxes), not much attention has been devoted to the acceleration of nuclei in the sources. CR acceleration in SNRs is believed to take place through the mechanism of diffusive shock acceleration, in its non-linear version that allows one to take into account the reaction of accelerated particles on the plasma and on local magnetic fields. Several versions of the non-linear theory of diffusive acceleration at shocks have been developed (see [34] for a review), but most of them include only protons as accelerated particles. Two noticeable exceptions are represented by the work of [10] and that of [38]. In both papers the calculations consist of a numerical solution of the coupled equations of CR transport and conservation of mass, momentum and energy flux of the overall CR plus background plasma. In the paper by Berezhko and Völk [10] the calculations were not illustrated in detail, and it is difficult for us to appreciate the assumptions that were adopted there. The spectra from individual sources was found to be very flat (flatter than E^{-2} at high energies), so that the observed CR spectrum could be recovered only by assuming a Galactic diffusion coefficient as steep as $D(E) \propto E^{0.75}$, which however is not consistent with measurements of the CR anisotropy at the Earth. In the paper by Ptuskin et al. [38], some more details were provided, and the authors discussed the important role of the velocity of the scattering centers on the shape of the spectrum of accelerated particles, which, as a consequence, is here much steeper than that found by Berezhko and Völk [10].

A fully non-linear theory which includes nuclei is made rather complex by at least two issues: (1) nuclei change the structure of the shock, making the problem harder to tackle and (2) the injection of nuclei in the accelerator is more challenging to be modelled than it is for protons, especially because nuclei can be produced as a result of dust sputtering. In a non-linear theory, the second point clearly feeds back onto the first one.

It is important to recall that the injection and the non-linear acceleration of nuclei in the Earth's Bow Shock (EBS) has been successfully described using a Monte Carlo simulation in the pioneering paper in Ref. [25]. These calculations showed how the case of

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the EBS is and remains, 20 years later, the most clear cut instance of occurrence of Non-Linear Diffusive Shock Acceleration (NLDSA) in collisionless shocks. However some caution should be adopted in extending these results to the case of SNRs, in that the physical conditions at the EBS might be somewhat different: the lack of electron injection, the fact that magnetic field amplification in the EBS appears to remain in the quasi-linear regime and the crucial role played by dust sputtering for ion injection in SNRs might be considered as possible evidences of such differences.

The last point is particularly relevant to our problem in that, in order to account for the observed discrepancy between the chemical composition of typical interstellar medium and CRs in our Galaxy, refractory elements (such as Mg, Al, Si and Fe) have to be injected in a preferential way in the acceleration process with respect to volatile elements [35,36]. Refractory elements are usually trapped in dust grains, and their preferential injection has been interpreted as a consequence of the sputtering of the grains when they are swept up by the SNR shock. In particular, the processes which lead to the injection of suprathermal iron nuclei as a consequence of the sputtering of accelerated dust grains have been put forward quantitatively for the first time in [23].

Nevertheless, a self-consistent description of this process would require both a detailed knowledge of the dust chemistry close to a SNR shock and an accurate physical description of the grain sputtering, along with a time-dependent treatment of the ionization of dust and atoms during their acceleration. The intrinsic complexity of such a phenomenon led us (as well as the authors of the previous work mentioned above [10,38]) to a simplified treatment of the nuclei injection: the measured spectra of relativistic particles at Earth are reproduced without explicitly taking into account the microphysics either of the nuclei ionization or of the dust sputtering (see Section 3).

One might argue that the relatively low abundances of nuclei in the cosmic radiation observed at Earth might make their influence on the shock structure negligible, so that in describing the acceleration process, the shock structure could be treated as determined by protons alone, with nuclei behaving as test particles. However, after correcting for propagation effects, it is easy to show that the nuclear contribution to the total pressure and magnetic field amplification in the vicinity of a typical supernova remnant shock may be as important as that of protons.

In this paper we describe the generalization of the non-linear theory of DSA developed by Amato and Blasi [7,8] and Caprioli et al. [21] to include nuclei of different charges. We calculate the spectrum of all species as accelerated at the shock and the structure of the shock (including magnetic effects) induced by them. We also comment on the implications of acceleration of nuclei on the spectra of secondary products of particle interactions, especially gamma rays. Finally we show the all-particle CR spectrum at Earth resulting from this calculation.

The calculations discussed here are semi-analytical, and from the computational point of view very inexpensive. This allows us to explore a wide region in parameter space, which is particularly important when dealing with the goal of explaining the CR spectra and chemical abundances observed at Earth. For simplicity we consider here only supernovae exploding in a homogeneous interstellar medium (ISM). While more complex situations can be treated in the context of our formalism, they introduce a wide range of new and hardly accessible parameters, which overshadow the main physical results. We will comment further on this point whenever we deem it necessary.

The paper is organized as follows: in Section 2 we illustrate the generalization of the equations and solution techniques following the non-linear theory of [7,8,21]. In Section 3 we comment on the abundance of nuclei in CRs and at the sources, and how it relates to the injection of the nuclear component at the shock. In Section 4 we illustrate our results for the spectra of accelerated particles and the structure of the shock. In Section 5 we discuss the implications of the presence of accelerated nuclei at the shock for the prediction of a gamma ray flux, as due to production and decay of neutral pions. In Section 6 we compare our findings with the CR flux detected at Earth, discussing the spectra of individual chemicals and the appearance of the knee at $E \sim 10^6$ GeV. We discuss our general results and we compare them with previous findings in Section 7.

2. Equations and solution techniques

In this section we generalize the semi-analytical formalism developed in [7,8,21] to the case in which nuclei heavier than Hydrogen (hereafter simply Heavy Nuclei, HN) are also injected and accelerated at a stationary, plane, parallel (background magnetic field parallel to the shock normal), newtonian shock wave. We label with a subscript i quantities referring to different chemical elements, so that the convection–diffusion equation for the isotropic part of the distribution function, $f_i(x,p)$, reads, for each species [see e.g. 39]:

$$\tilde{u}(x)\frac{\partial f_i(x,p)}{\partial x} = \frac{\partial}{\partial x}\left[D_i(x,p)\frac{\partial f_i(x,p)}{\partial x}\right] + \frac{p}{3}\frac{d\tilde{u}(x)}{dx}\frac{\partial f_i(x,p)}{\partial p} + Q_i(x,p). \tag{1}$$

Here $D_i(x,p)$ is the parallel diffusion coefficient, which may depend both on space and momentum, $\tilde{u}(x) = u(x) + v_W$ is the total velocity of the scattering centers in the shock frame, given by the sum of the fluid velocity $u(x)$ and wave velocity v_W, and $Q_i(x,p)$ is the injection term. The shock is at $x = 0$ and subscripts 0, 1 and 2 label quantities taken, respectively, at the upstream free-escape boundary $x = x_0$, immediately upstream and downstream of the subshock.

An especially important issue, when taking into account nuclei, is that of particle injection, as stated in the introduction and as should become clear below. Unfortunately, the microphysics of this process is not yet fully understood even for the case of protons alone, and much more so for nuclei. In the following we simply assume that protons are injected from downstream via thermal leakage as described in [14], while the injection of HN is tuned in such a way as to reproduce the relative abundances observed in the CRs. We do not account for the details of the HN injection, likely related to the complex physics of the dust sputtering process. Indeed, the required preferential injection of HN is likely related to the fact that partially ionized heavy particles (i.e., thermalized particles with large mass/charge ratios) have large Larmor radii and are hence preferentially injected in a thermal leakage scenario (see [24]), and/or in the fact that refractory nuclei can be efficiently injected via dust grain sputtering [23] (we will discuss these points in Section 3).

More precisely, we assume that all protons with momentum $p > p_{inj,\mathrm{H}}$ have a large enough Larmor radius to cross the shock (subshock) from downstream and start being accelerated. Since the shock thickness is expected to be of the order of the Larmor radius of particles with thermal momentum $p_{th} = \sqrt{2m_\mathrm{H}k_BT_{\mathrm{H},2}}$ (where $T_{\mathrm{H},2}$ is the downstream proton temperature and k_B is the Boltzmann constant), we take $p_{inj,\mathrm{H}} = \xi_\mathrm{H}p_{th,\mathrm{H}}$, with $\xi \sim 3$–4. Furthermore, at a given momentum p the Larmor radius of a HN with charge Z_ie is a factor Z_i smaller than that of a proton. Hence, in this scheme, it is very natural to assume that $p_{inj,i} = Z_i\, p_{inj,\mathrm{H}}$.

Clearly, if nuclei are not completely ionized or if they are injected via dust sputtering this simple recipe may fail to describe the low-energy tail of the CR distribution. Nevertheless, since the spectra of the relativistic particles observed at Earth are consistent with power-laws extending from a few GeV/nucleon up to the knee, it seems reasonable to assume that injection always occurs