Non-linear acceleration at supernova remnant shocks and the hardening in the cosmic ray spectrum.

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Abstract

In the last few years several experiments have shown that the cosmic ray spectrum below the knee is not a perfect power-law. In particular, the proton and helium spectra show a spectral hardening by $\sim 0.1 - 0.2$ in spectral index at particle energies of $\sim 200 - 300$ GeV/nucleon. Moreover, the helium spectrum is found to be harder than that of protons by $\sim 0.1$ and some evidence for a similar hardening was also found in the spectra of heavier elements. Here we consider the possibility that the hardening may be the result of a dispersion in the slope of the spectrum of cosmic rays accelerated at supernova remnant shocks. Such a dispersion is indeed expected within the framework of non-linear theories of diffusive shock acceleration, which predict steeper (harder) particle spectra for larger (smaller) cosmic ray acceleration efficiencies.

Key words: Cosmic rays – supernova remnants – acceleration of particles

1 INTRODUCTION

In the standard picture of the origin of cosmic rays (CR) the observed flux, at least below the energy of the "knee" $E_{\text{knee}} \approx 3$ PeV; see e.g. Hörandel 2006, is thought to be produced in the Galactic disc at supernova remnant (SNR) shocks through diffusive shock acceleration (DSA) (Drury (1983)). After leaving their sources, CRs are believed to propagate diffusively through the interstellar medium (ISM), and eventually escape from the Galaxy (see e.g. Berezhanskii et al. 1990). The observed CR spectrum below the knee resembles a power law in energy $\sim E^{-2.7}$ and can be roughly accounted for if one assumes that both the slope of the injection spectrum and the CR diffusion coefficient are power laws in energy, with slopes $-\gamma$ and $\delta$ respectively. Various observational constraints provide $\gamma + \delta \approx 2.7$ and $\delta \approx 0.3 - 0.6$ (see e.g. Strong & Moskalenko 1998; Evoli et al. 2008; Blasi & Amato 2012).

However, in the last few years numerous evidences have been collected which point to a more complex scenario: most notably several experiments such as ATIC-2 (Panov et al. 2009), PAMELA (Adriani et al. 2011), CREAM (Yoon et al. 2011) and AMS-02 (Aguilar et al. 2015) found a spectral hardening in the proton and helium spectra at particle energies $200 - 300$ GeV/nucleon. Moreover, the helium spectrum is found to be harder than that of protons by $\sim 0.1$ in spectral index. Some evidence for a similar hardening was also found in the spectra of heavier elements (Maestro et al. 2010). The PAMELA data (Adriani et al. 2011) suggest that the slope of protons changes from $\gamma_1 \approx 2.85$ (below $\sim 230$ GeV) to $\gamma_2 \approx 2.67$ (above $\sim 230$ GeV), with a slope change of $\sim 0.18$. Instead, the AMS-02 data found the break at $\sim 335$ GeV and a slope change of $\sim 0.13$.

This spectral feature is still not understood and several explanations have been put forward in which the spectral hardening is interpreted as: the result of a break in the CR diffusion coefficient (Tomassetti 2012; Genolini et al. 2017); a consequence of the transition from the scattering of CRs on self-generated waves to scattering on pre-existing waves (Aloisio & Blasi 2013); the effect of a nearby source (Thoudam & Hörandel 2012); the consequence of a dispersion in spectral index at the sources (Yuan et al. 2011); the result of non linear effects in DSA at SNRs (Ptuskin et al. 2013); the possibility of distinct populations of CR sources (Zatsepin & Sokolskaya 2006); the consequence of a break in the energy loss rate (Kraakau & Schlickeiser 2015).

In the present paper we suggest that the spectral hardening may be a natural prediction of the non-linear theory of diffusive shock acceleration. It would result from the interplay of the efficient magnetic field amplification at SNR shocks and of the CR Alfvénic drift in the upstream region. Following Caprioli (2012), we will show that these two effects may result in a dispersion in the CR spectral slope at the sources which may lead (see also Yuan et al. 2011) to the observed hardening. The reasons for considering such scenario are manifold: first of all, the presence of efficient magnetic field amplification has been detected in...
several SNRs (see e.g. Ballet 2006; Vink 2012) and is widely considered as a crucial ingredient for the acceleration of CRs to the energy of the knee (see e.g. Bell (2004)). Second, recent observations of $\gamma$-rays in SNRs both in the GeV (see e.g. Abdo et al. 2011) and in the TeV band (see e.g. Acciari et al. 2011) show that there may be a quite large dispersion in the slope of the CR spectrum at SNRs. In fact, in the cases in which the observed $\gamma$-ray emission is likely of hadronic origin (see e.g. Morlino & Caprioli 2012), the inferred CR spectrum shows a quite large dispersion in the spectral index, $\propto E^{-2.1} - E^{-2.5}$ (see e.g Caprioli 2011; Yuan et al. 2011 and references therein).

It is interesting to note that such spectra are significantly steeper than the universal spectrum $\propto E^{-2.0}$ predicted by the linear (test-particle) theory of DSA at SNR shocks. At first sight, the disagreement seems to be even larger if one considers non-linear theories of DSA (NLDSA), which account for the reaction of CRs on the shock dynamics (see e.g. Drury 1983; Blandford & Eichler 1987; Jones & Ellison 1991; Blasi 2002). In this context, the pressure exerted by CRs onto the upstream fluid induces the formation of a shock precursor, which in turn makes the CR spectrum at the shock concave, namely, steeper than $\propto E^{-2.0}$ at low energies and harder at high energies. Moreover, the more efficient the CR acceleration the more evident becomes the concavity and for large efficiencies the spectrum above few GeV becomes as flat as $\propto E^{-1.5}$, clearly at odd with the gamma-ray observations of SNRs reported above.

For this reason, in the last few years a number of works have been devoted to the study of possible ways to reconcile the predictions of NLDSA theories with observations. In particular it has been proposed that taking into account the velocity of the CR scattering centers (Alfvén waves propagate faster for larger values of the Alfvén speed and the proton spectral slope; (i) the magnetic field amplification acts as a self-regulating mechanism of the acceleration process. The pressure of the amplified magnetic field makes the shock compression factor smaller than 4 (which is the strong shocks limit of the test particle regime of DSA, where the field is not amplified). As a consequence of that, the maximum acceleration efficiency for strong shocks turns out to be $\sim 30\%$ and the shock modification induced by the CR pressure is quite modest. This is quite at odd with earlier formulations of NLDSA, in which the CR acceleration efficiency can reach values well above $\sim 30\%$ and the compression factor can be well above 4 (see e.g. Blasi et al. 2005)

(ii) the spectrum at energies above few GeV resembles quite well a power law whose spectral slope remains virtually constant, together with the acceleration efficiency, for a large part of the SNR lifetime (up to $\sim 20000-30000$ yr);

(iii) the combined effect of the magnetic field amplification and of the Alfvénic drift in the upstream region makes the spectrum steeper than $E^{-2.0}$, with slopes in the range 2.1 $- 2.6$ in agreement with the $\gamma$-ray observations of SNRs. In addition to that, the more efficient is the CR acceleration the steeper is the spectrum, contrary to the standard predictions of NLDSA, in which an efficient acceleration leads to harder spectra.

For a more extended discussion on this approach and its limits of validity, the reader is referred to Caprioli (2012).

Based on the results summarized above, in the following we treat the acceleration efficiency at SNR shocks as a free parameter in the range $\xi_{CR} \approx 0.03 - 0.3$, and we assume that the CR spectrum at SNR shock is a power law of slope $\gamma_{CR}$. We then compute the spectral slope as a function of the acceleration efficiency $\gamma_{CR}(\xi_{CR})$ by taking into account the magnetic field amplification by CR streaming instability and the effect of the velocity of the self-generated Alfvén waves, which act as scattering centers. In agreement with Caprioli (2012), we find that the dispersion in the acceleration efficiency induces a dispersion in the spectral slope, with steeper (softer) spectra corresponding to larger (lower) acceleration efficiencies. Finally, taking into account the dispersion in the spectral slope and the relation between acceleration efficiency and slope, the observed proton and helium spectral hardening at 200 $- 300$ GeV can be accounted for in a quite natural way.

The paper is organized as follows: in Section 2 we illustrate the calculation of the compression factor felt by CRs as a function of the CR acceleration efficiency and we show the resulting dispersion in slope. In Section 3 we use these results to estimate the observed proton and helium spectrum with the additional assumption that CRs propagate diffusively in the Galaxy with a power law diffusion coefficient (whose slope and normalization is chosen in order to fit the data) and we compare the obtained spectrum with the data. Finally, we conclude in Section 4.

2 MAGNETIC FIELD AMPLIFICATION, ALFVÉN SPEED AND THE PROTON SPECTRAL SLOPE

Keeping in mind the results by Caprioli (2012) on the spectrum of accelerated particles at SNRs in the presence of magnetic field amplification by CR streaming instability and of Alfvénic drift, in this section we illustrate a simple calculation which allows to quickly estimate the slope of the CR spectral slope under the following assumptions:

(i) the CR acceleration efficiency $\xi_{CR}$ is an input parameter of the problem, and is in the range $\xi_{CR} \sim 0.03 - 0.3$. Thus the shock modification is modest and the CR spectrum is nearly a perfect power law, as found by Caprioli (2012);

(ii) the magnetic field is amplified by the CR streaming instability and is assumed to be the same in the whole upstream region;

(iii) the Alfvén waves excited in the upstream propagate against the fluid at velocity $v_{A1}$, which is computed in the amplified magnetic filed, while they are assumed to
we show the dependence of the effective compression factor $\xi_{CR}$ on the CR acceleration efficiency: $\xi_{CR} = 0.1$, $0.2$ and $0.3$.

be isotropized in the downstream region, giving $v_{A2} \sim 0$ (the subscripts 1 and 2 refer to quantities calculated in the upstream and downstream region, respectively).

The slope of the CR spectrum depends on the effective compression factor felt by CRs, which in turn depends on the CR acceleration efficiency $\xi_{CR} \equiv P_{CR}/\rho_1 u_1^2$, on the fluid and Alfvénic Mach numbers upstream ($M_f^2 \equiv \rho_1 u_1^2/\gamma P_1$ and $M_A^2 \equiv \rho_1 u_1^2/(2\rho_1$, respectively) and on the jump conditions at the shock, where $\rho_1$, $u_1$, and $P_1$ are the upstream gas density, velocity, and pressure. $P_{CR}$ is the CR pressure at the shock and $P_o$ is the pressure of the amplified (upstream) magnetic field. Here, we neglect the modest shock modification induced by the CR pressure in the upstream fluid, which implies that all the relevant physical quantities characterising the fluid do not depend on the location upstream. Finally, we assume that the gas can be described by an adiabatic equation of state.

Following the calculations presented in Caprioli (2012), one can evaluate the effect of the magnetic field amplification due to CR streaming instability, and estimate the shock Alfvénic Mach number as a function of the CR acceleration efficiency (Equation 2.22 in Caprioli 2012):

$$M_f^2 = \frac{4}{25} \left[ 1 - \left(1 - 1/\xi_{CR}\right)^2 \right]. \tag{1}$$

Another crucial parameter is the fluid compression factor $R = u_1/u_2$, which can be computed after taking into account the pressure of the amplified magnetic field. Following a procedure similar to that presented in Vainio & Schlickeiser (1999) and Caprioli 2012 we get:

$$M_f^2 \frac{1}{2} - \frac{\gamma - 1}{1 + \Lambda_B} \approx 1, \quad \text{where} \quad \Lambda_B = W \left[ 1 + R \left( \frac{2}{\gamma} - 1 \right) \right] \quad \text{and} \quad W = \frac{\gamma M_f^2}{2 M_A^2} \tag{2}$$

The effective compression factor felt by CRs differs from $R$, because in the upstream region the Alfvén waves generated by the CR streaming instability propagate in the direction opposite to the fluid. Since CRs are coupled to waves through scattering, the effective advection velocity they experience in the upstream region is not $u_1$, but rather $u_1 - v_{A1}$. Thus, the effective compression factor felt by CRs is:

$$R_{eff} = \frac{u_1 - v_{A1}}{u_2} = R \left( 1 - \frac{1}{M_A} \right). \tag{3}$$

The CR spectral slope can then be estimated as (see e.g. Blandford & Eichler 1987; Berezinskii et al. 1990)

$$\gamma_{CR} \sim \frac{3 R_{eff}}{R_{eff} - 1}. \tag{4}$$

It is important to stress that only two physical parameters regulate the system: the fluid upstream Mach number $M_1$ and the CR acceleration efficiency $\xi_{CR}$.

In Figure 1 we show the dependence of the effective compression ratio $R_{eff}$ on the Mach number $M_1$ for three different values of $\xi_{CR}$. For $M_1 \gtrsim 10$ the effective compression ratio (the same result also holds for the fluid compression ratio and for the spectral slope) is virtually independent on $M_1$. This implies that the slope of the spectrum of accelerated particles does not change for most of the SNR lifetime. This is in agreement with the findings of Caprioli (2012).

On the other hand, both the fluid and effective compression ratios, and thus also the spectral slope, strongly depend on the CR acceleration efficiency. This is evident from Figure 2, where one can see that, for $\xi_{CR}$ ranging in $\sim 0.03-0.3$, the slope ranges from $\sim 4.1$ to $\sim 4.6$. This result shows that the inclusion of the magnetic field amplification and of the Alfvénic drift in the calculation of the compression factor leads to quite steep source spectra, with larger $\xi_{CR}$ corresponding to steeper spectra. Note that within the present setup the fluid compression factor always remains $\lesssim 4$, while in the standard NLDSA theories compression ratios much larger than 4 are usually found and the CR acceleration efficiency can be well above $\sim 30\%$ (see e.g. Blandford & Eichler 1987; Blasi 2002).

**Figure 1.** Effective compression factor felt by CRs at the shock as a function of the upstream fluid Mach number $M_1$ and for three different values of the CR acceleration efficiency: $\xi_{CR} = 0.1$, $0.2$ and $0.3$.

**Figure 2.** Fluid compression factor $R$, effective compression factor $R_{eff}$ and CR spectral slope $\gamma_{CR}$ as a function of the CR acceleration efficiency $\xi_{CR}$. The value of the fluid Mach number is $M_1 = 100$. 

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3 COMPARING THE PREDICTED PROTON AND HELIUM SPECTRA WITH DATA

Here we assume that SNR shocks accelerate CRs with an efficiency uniformly distributed in the range $\xi_{CR} \sim 0.03 - 0.3$, which implies, as shown in Section 2, a dispersion in the CR spectral slope, $\gamma_{CR}$, in the range $\sim 4.1 - 4.6$. Formally, this is the slope of the CR spectrum at the shock, and not that of the spectrum of particles escaping the SNR and injected in the ISM. However, under reasonable assumptions these two spectra are identical (see e.g. Gabici 2011 and references therein). After escaping SNRs, CRs are believed to propagate diffusively in the Galaxy with a diffusion coefficient $D(R) = D_0 (R/GV)^3$ ($R$ is the particle rigidity). The values of $D_0$ and $\delta$ are chosen in order to fit the observed proton spectrum in the energy range 40 GeV-10 TeV, namely around the spectral hardening at 200-300 GeV.

As for helium, we used the same injection spectral slopes and diffusion coefficient of protons, but we also took into account spallation. The proton and helium spectra below $\sim 40$ GeV/nucleon are not considered since at these energies both the solar modulation and possible advection effects are important (see e.g. Aloisio et al. 2015), which were not included in our calculation.

Under these assumptions the proton spectrum ($E$ is the particle energy) can be written as (see e.g. Berezinskiia et al. 1990, Blasi & Amato 2012)

$$f_p(E) = \int_{\xi_m}^{\xi_M} \frac{R_{SN} H}{\pi R_d^2 2D(E)} g_p(E) \frac{d\xi_{CR}}{\xi_M - \xi_m},$$

where

$$g_p(E) = \frac{\xi_{CR} E_{SN}}{I(\gamma_{CR})(m_c^2)} \left( \frac{E}{m_c^2} \right)^{-\gamma_{CR} + 2}.$$  

$$I(\gamma_{CR}) = \int_{\gamma_{CR}}^{\infty} dx x^{2-\gamma_{CR}} \left[ \sqrt{1+x^2} - 1 \right]$$

is a normalization factor chosen in such a way that $\int_{E_{min}}^{E_{max}} g_p(E) E_{kin} dE = \xi_{CR} E_{SN}$, where $x \equiv E/m_c^2$ and $E_{kin}$ is the particle kinetic energy.

The helium spectrum is given by

$$f_{He}(E) = \int_{\xi_m}^{\xi_M} \frac{R_{SN} H}{\pi R_d^2 2D(E)} g_{He}(E) \frac{1}{1 + \frac{E_{kin}}{D(E)}} \frac{d\xi_{CR}}{\xi_M - \xi_m},$$

where

$$g_{He}(E) = \eta_{He} \frac{\xi_{CR} E_{SN}}{I(\gamma_{CR})(m_c^2)} \left( \frac{E}{m_c^2} \right)^{-\gamma_{CR} + 2}.$$  

Here $R_{SN} \approx 1/30$ yr is the SN explosion rate in the Galaxy, $R_d \approx 15$ kpc is the Galactic disc radius, $h \approx 250$ pc is the Galactic disc height, $H \approx 4$ kpc is the Galactic halo size, $n_d \approx 5$ cm$^{-3}$ is the average gas density in the disc. $\eta_{He}$ is a factor chosen in such a way to reproduce the correct normalization of the helium spectrum. Finally, $\sigma_{sp}$ is the helium spallation cross section (see e.g. Blasi & Amato 2012). The CR acceleration efficiency is in the range $\xi_m \approx 0.03$ to $\xi_M \approx 0.3$. In Fig. 3 we show the proton flux as computed from Equation 5 (red line) compared with the data by PAMELA (Adriani et al. 2011), by AMS-02 (Aguilar et al. 2015) and by CREAM (Yoon et al. 2011). The plot has been obtained with the diffusion coefficient parameters: $D_0 \sim 8 \times 10^{28}$ cm$^2$/s and $\delta \sim 0.4$. The slope found for the diffusion coefficient is well within the observational constraints, namely $\delta \sim 0.3 - 0.6$. With this diffusion coefficient, the grammage traversed by CRs, namely $X = n_d H c m_p / D(R)$, is $\approx 11 g/cm^2$ at 10 GeV/n (see e.g. Blasi 2013).

On the same Figure we also show the proton flux (green line) computed in the case of two distinct populations of CR sources, one with $\xi_{CR} \approx 0.03$ and the other with $\xi_{CR} \approx 0.3$. Also this plot has been obtained with a diffusion coefficient slope of $\delta = 0.4$, while the explosion rate of the population with the largest acceleration efficiency has been taken to be $\sim 3$ times smaller than that with the smallest efficiency. Notice that taking into account such scenario could be motivated by a different behavior of type I and II supernovae in the acceleration of CRs (see e.g. Zatsepin & Sokolskaya 2006). In Fig. 4 we show the same as in Fig. 3 for the helium flux.

Note that the dispersion in the CR acceleration efficiency, and the consequent dispersion in the CR spectral slope, naturally leads to a spectral hardening in the proton

![Proton flux compared with the PAMELA, AMS-02 and CREAM data. The plot has been obtained by assuming a spatially independent CR diffusion coefficient with spectral slope 0.4.](image1)

![Helium flux compared with the PAMELA, AMS-02 and CREAM data. The plot has been obtained with the same diffusion coefficient used for the proton flux.](image2)
spectrum at \( \lesssim \) TeV energies and, overall, to a good agreement with the data. A similar hardening is found also in the helium spectrum. Moreover, in agreement with observations, this feature is less prominent in the helium spectrum compared to the proton spectrum and the helium spectrum is found to be harder than the one of protons. This is due to spallation, which hardens the spectrum, especially at lower energies (see also Blasi & Amato 2012). In the case of two distinct populations with different acceleration efficiencies the spectral hardening is also well reproduced, both in the proton and helium spectrum. However in this case the spectral feature appears to be sharper (see e.g. Genolini et al. 2017) than in the case of uniformly distributed efficiency.

Finally, when comparing our results with data, one has to keep in mind that the AMS-02 and CREAM data for helium at \( \sim 1\) TeV/nucleon differs by \( \sim 20 – 30\%\), making it impossible to obtain an equally accurate fit to both data sets.

4 CONCLUSIONS

The magnetic field amplification at SNR shocks, which is thought to be necessary in order to accelerate CRs up to PeV energies, may also act as a feedback process which limits the maximum achievable CR acceleration efficiency to \( \sim 30\%\), thus keeping the overall shock modification modest. Moreover, together with the Alfvénic drift, the magnetic field amplification leads to quite steep CR source spectra (slopes in momentum \( \sim 4.1 – 4.6\)), in agreement with CR spectra in SNRs inferred from \( \gamma\)-ray observations (Caprioli 2012 and references therein).

In this paper we studied the acceleration of CRs at SNR shocks under the following realistic assumptions:

(i) the CR acceleration efficiency may vary within the range \( \sim 0.03 – 0.3\);
(ii) the shock modification induced by the CR pressure at the shock is modest;
(iii) the magnetic field is significantly amplified by CR streaming instability and the Alfvén speed (computed in the amplified field) upstream of the shock is enhanced accordingly.

We showed that the dispersion in the CR acceleration efficiency produces a dispersion in the shock compression factor. This in turn results in a dispersion in the CR spectral slope, with steeper spectra corresponding to larger acceleration efficiencies. This result has then been used to demonstrate that, by assuming a diffusive propagation of CRs in the Galaxy with a spatial independent diffusion coefficient, the above mentioned dispersion in the slope of the injection spectrum can account in a quite natural way for the spectral hardening found in the proton and helium spectrum in the energy range \( \sim 200 – 300\) GeV/nucleon. Moreover, in agreement with observations, because of spallation the helium spectrum is found to be harder than the proton spectrum (even if their injection spectra are identical) and the helium spectral hardening is less prominent than that of protons.

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