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Cosmic ray acceleration

A.R. Bell

Clarendon Laboratory, University of Oxford, Parks Road, Oxford, OX1 3PU, UK

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ABSTRACT

This review describes the basic theory of cosmic ray acceleration by shocks including the plasma instabilities confining cosmic rays near the shock, the effect of the magnetic field orientation, the maximum cosmic ray energy and the shape of the cosmic ray spectrum. Attention is directed mainly towards Galactic cosmic rays accelerated by supernova remnants.

1. Introduction

Until the later part of the twentieth century, cosmic ray (CR) physics was a subject with its own distinct nature that separated it from much of astrophysics. It appeared that the greater part of astrophysics could be understood without reference to cosmic rays. Cosmic rays first became important to mainstream astrophysics with the development of radio telescopes since synchrotron radiation requires energetic electrons, which have to be accelerated, and magnetic field, which is often in close energy equipartition with the energetic electrons. With the expansion of observational techniques into the whole range of the electromagnetic expansion, high energy astrophysics embraced cosmic rays as an essential part of astrophysics since a substantial fraction of the available energy is often channelled into cosmic rays. Cosmic rays are also diagnostically important as a source of radiation. Cosmic ray electrons are responsible for synchrotron and inverse Compton emission in many parts of the electromagnetic spectrum, and it appears likely, although not yet completely certain, that gamma-rays generated through pion decay provide a direct window into in situ acceleration of TeV-PeV protons.

CR arriving at the Earth with energies up to and beyond 10^{20} eV have a Larmor radius greater than the size of the Galaxy and must have their origin in extreme conditions beyond our Galaxy. Arrival directions measured by the Auger array suggest an origin correlated with AGN for the highest energy CR [7], but this is far from certain and more data are needed [8]. Cosmic rays contribute a large fraction of the energy content of explosive environments from stellar to galactic scales, and they appear to play an important role in the generation of magnetic field. Since cosmic rays are important both dynamically and diagnostically it is essential that we understand their acceleration, transport, radiative emissions, and interaction with other components of astrophysical environments.

Cosmic rays arriving at the Earth consist mainly of high energy protons with smaller numbers of electrons and other nuclei. A century of detector development since their discovery has defined the shape and extent of the CR energy spectrum. The differential energy spectrum in the Galaxy extends as a E^{-s} power law from GeV energies to a few PeV with a spectral index $s = 2.6 - 2.7$ [55]. The spectrum steepens slightly at a few PeV before flattening at about an EeV and then turning over and terminating at a few 100 EeV [77]. This is usually referred to as a knee-ankle structure with the ‘knee’ at a few PeV and the ‘ankle’ at the less well defined energy of a few EeV. The Larmor radius of a proton with energy E_{PeV} in PeV gyrating in a magnetic field $B_{\mu G}$ in μG is $r_g = E_{PeV}/B_{\mu G}$ parsec. It is mostly assumed with good reason that CR with energies above the ‘ankle’ must be extragalactic in origin since their Larmor radius is much larger than the Galaxy, and conversely that CR with energies below the knee must originate within the Galaxy. Although much debated, the common picture is that the transition from a Galactic to an extragalactic origin occurs somewhere between the knee and the ankle. A heavy nucleus with charge Z has a Larmor radius Z times smaller than a proton with the same energy, so if protons can be accelerated within the Galaxy to a few PeV then it is reasonable to suppose that a heavy nucleus can be accelerated to a few times ZPeV within the Galaxy. Composition studies support this, but heavy nuclei cannot easily account for all CR in the energy range 1–100 PeV, and a further population of protons accelerated in the Galaxy beyond the knee may be needed [56,57]. Proton acceleration to the knee pushes shock acceleration theory to its limits when applied to shell-type supernova remnants (SNR) of the kind observed in our Galaxy, so CR between the knee and the ankle pose a severe challenge to our understanding.

The arrival directions of CR at all except the highest energies are scrambled by deflection in the interstellar or intergalactic magnetic field and give no information on their source, but the

E-mail address: t.bell1@physics.ox.ac.uk

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large total CR energy in the Galaxy places severe limitations on possible sources. Supernova remnants (SNR) provide the largest energy input into the interstellar medium and, as discussed below, their associated shocks are natural particle accelerators, so it is usually assumed that Galactic CR are accelerated by SNR. To account for the Galactic CR energy budget, at least a few percent of the total SN energy has to be given to CR [10,2].

The development of Cherenkov telescopes sensitive to gamma-rays with energies approaching 100 TeV has dramatically expanded our knowledge of CR origins. Since gamma-rays are undeflected as they propagate from the source, Cherenkov telescopes point directly to the CR producing the gamma-rays. Observations by the HESS Cherenkov telescope of the supernova remnant RX J1713.7–3946 detect gamma-rays up to nearly 100 TeV with an angular resolution of 0.06 degrees [3,4]. A quantitative analysis of radiation from SNR at TeV energies can be found in Drury et al. [33]. This provides direct evidence that at least some SNR accelerate cosmic rays to within an order of magnitude of the energy of the knee since gamma-rays are generated by cosmic rays of about 7 times the gamma-ray energy, depending on the emission process [3]. It is not completely decided whether gamma-rays from SNR are emitted by ions as well as electrons, but discrimination between electron and ion sources is within reach through the measurement of the gamma-ray spectrum over a range of photon energies. When Cherenkov measurements are united with lower energy gamma-ray detections by the FERMI satellite it is becoming possible to distinguish between gamma-ray spectra characteristic of inverse-Compton and pion processes. Latest results indicate that pion processes dominate in at least one SNR [52]. CR electrons are also detectable through their synchrotron emission from radio to X-ray energies. X-ray synchrotron emission is mapped in great detail in some supernova remnants, giving direct evidence of in situ acceleration of TeV electrons.

Previous reviews of cosmic ray acceleration include Drury [32], Blandford and Eichler [24], Jones and Ellison [62] and Malkov and Drury [74]. Only a small fraction of the extensive literature on diffusive shock acceleration and related astrophysics can be covered in a review of the present length which considers mainly the plasma physics of CR acceleration by SNR. This review does not cover heliospheric shocks (e.g. [118]) which are generally weaker and more dependent on the local context due to their smaller spatial extent. Injection of initially thermal particles into the acceleration process and their subsequent acceleration to non-relativistic energies (e.g. [92]) are important aspects of heliospheric shocks not discussed here. Also, this review does not consider CR acceleration at shocks with relativistic velocities (e.g. [64,1,103,82,83]). A comprehensive review of observational signatures of cosmic ray acceleration can be found in Helder et al. [54].

2. Diffusive shock acceleration

More than 60 years ago Fermi [46] suggested that CR gain their energy from large scale fluid motions in the interstellar medium. In the second order Fermi process, CR are reflected elastically by moving magnetic field structures that might be anchored in interstellar clouds. A 'head-on' encounter between a CR and a cloud leads to the CR gaining energy. A 'tail-on' encounter leads to an energy loss, but the CR gains energy on average because head-on encounters are more frequent than tail-on encounters. If the typical cloud velocity is $\mathbf{u}$ and CR move at the speed of light c, the average fractional energy exchange on each encounter is of order u/c, and the excess of head-on over tail-on encounters is also u/c, making the mean energy gain on each encounter of order $(u/c)^2$, which makes the process second order. The second order Fermi process may play a role in CR acceleration in older SNR [80], but attention has moved to a faster first order Fermi process that operates in the environment of shocks. In the rest frame of a shock, the upstream plasma moves into the shock at the shock velocity u_s and exits downstream at a lower velocity u_s/r where r is the density compression ratio at the shock. $r = 4$ for a non-relativistic shock with a high Mach number. If a CR reflects back and forth between magnetic structures upstream and downstream of the shock, when viewed in an appropriate frame every encounter is head-on with a mean fractional increase in energy of order u_s/c producing relatively rapid acceleration. The key to the operation of first order Fermi shock acceleration is that CR trajectories are scattered by fluctuations in the magnetic field. If the local magnetic field were uniform, CR would easily escape the shock environment by streaming along magnetic field lines. It was shown around 1970 [66,117,99–101] that CR streaming excites fluctuations in the magnetic field in the form of Alfven waves propagating along the field lines with wavelengths on the scale of a CR Larmor radius. The resonance between the Larmor radius and the wavelength of the fluctuation produces a strong interaction that scatters CR so they propagate diffusively along the field lines [94]. CR perform a random walk along field lines which can lead to a particular CR crossing and recrossing the shock many times, gaining energy on each crossing.

The resulting CR spectrum can be derived either from solution of the Boltzmann equation for a CR distribution near a shock [65,9,25] or equivalently from the statistics of a random walk by a single particle [14,15]. These equivalent derivations were proposed independently, and they can be outlined as follows.

The derivation from single particle [14] can be separated into two steps:

(i) The first step is to derive an expression for the probability of a CR crossing and recrossing the shock m times before escaping downstream. From simple kinetic theory the rate at which CR cross from upstream to downstream is $n_s c/4$ where n_s is the CR number density at the shock. The rate at which CR are carried away downstream at velocity u_s/r by background fluid motions is $n_\infty (u_s/r)$ where n_∞ is the CR number density far downstream. In the diffusion approximation, valid for $u_s \ll c,\ n_s = n_\infty$. The ratio of the two rates prescribes that on average a CR crosses and recrosses the shock $rc/4u_s$ times. Since the CR has equal probability of being carried away downstream on each adventure into the downstream plasma, the probability of escape during one excursion into the downstream plasma is $4u_s/rc$. The probability of making at least m shock crossings is therefore $(1 - 4u_s/rc)^m$. Assuming a strong shock, $r = 4$ and the number of CR still present at the shock after m crossings is

$$N_m = (1 - u_s/c)^m N_0$$

where N_0 is the number of CR initially encountering the shock.

(ii) The second step in the derivation is to find an expression for the average energy gained after m shock crossings. By averaging over the various angles at which relativistic CR cross and re-cross a strong non-relativistic shock we find that the average energy gain ΔE on one cycle of crossing from upstream to downstream and back to upstream is $\Delta E = (u_s/c)E$, and the average energy after m such cycles is

$$E_m = (1 + u_s/c)^m E_0$$

where E_0 is the initial CR energy. Since (u_s/c) is small, $(1 + u_s/c)^m \approx 1/(1 - u_s/c)^m$, $(N_m/N_0) = (E_m/E_0)^{-1}$ and $N(E) \approx (E/E_0)^{-1} N_0$. $N(E) \propto E^{-1}$ is the integral energy spectrum of CR reaching at least energy E, so the differential energy spectrum $n(E) = -dN/dE$ is

$$n(E) \propto E^{-2}.$$

It can be shown by a similar argument that the equivalent p^{-2} momentum spectrum applies to non-relativistic as well as relativis-