Highlights of Astronomy, Volume 14
IAU XXVI General Assembly, 14-25 August 2006
Karel A. van der Hucht, ed.

doi:10.1017/S1743921307010009

Particle acceleration theory

Roger D. Blandford

Kavli Institute for Particle Astrophysics and Cosmology,
Stanford University, Menlo Park, CA 94025, USA
email: rdb3@stanford.edu

Abstract. Astrophysical particle acceleration involves the efficient conversion of bulk energy to individual charge particle energy through work done by electric field. The ways in which this happens are quite varied but when considered from a physics perspective, commonalities can found between acceleration in quite different sites.

---

1. Direct acceleration

The energy gained by a high energy particle is $-q\int d\vec{r}\cdot\vec{E}$. Sometimes,these fields are created through a charge deficiency which is neutralized through breakdown of a unionized region or pair production from the vacuum, where there is a large scale electrostatic field as in a pulsar 'gap' or a double layer in an aurora. The potential difference is then given by that required for breakdown. This can be as large as $\sim 1\,\mathrm{TV}$ in pulsars. Some forms of magnetic reconnection create large current density which induce a large local 'anomalous' resistance and consequently a large potential difference in the background thermal plasma which can be traversed, collisionlessly, by high energy particles.

One generic way to create a potential difference is through unipolar induction. Here a rotating magnetized conductor creates an induced EMF, V, of order the product of the magnetic flux and the angular frequency. In the case of the Crab pulsar, $V \simeq 30\,\mathrm{PV}$ and the associated power is of order $V^2/Z_0 \simeq 10^{31}\,\mathrm{W}$, where Z_0 is the impedance of free space. The induced currents may close near the neutron star and drive a pair dominated wind. Alternatively, they may close within the nebula so that the energy transport is primarily electromagnetic and the observed X-ray jets and equatorial emission can be interpreted as ohmic dissipation. Massive spinning black holes in active galactic nuclei also act as conductors and induce ZV potentials adequate to accelerate UHE cosmic rays provided that the currents close well outside the galactic nucleus. (The jets are also interpreted as ohmic dissipation.)

In source where the electromagnetic energy dominates, it is instructive to use relativistic force-free electrodynamics which is the limit of relativistic MHD when the inertia of the plasma can be ignored. Maxwell's equations are supplemented by the constitutive relation, $\rho\vec{E}+\vec{j}\times\vec{B}=0$. These lead to an evolutionary set of equations that appear to allow the Lorentz invariant E^2-B^2 to become positive. The conditions that are necessary for this to happen are not understood. However, if it does happen, the inertia of the plasma particles must be included. and there should be a catastrophic acceleration of electrons and positrons at a rate probably limited by radiation reaction. The end result is likely to be a prodigious burst of gamma rays. Another way in which this can happen less abruptly is if there is a cascade of electromagnetic energy down to smaller length scales so that the spectral energy density of shear Alfvén modes $\mathcal{E}_k$ falls off with k slower than k^{-3}. A microscale will then develop where there is insufficient plasma to compensate the divergence of the electric field and there will volumetric dissipation of the electromagnetic energy. These mechanisms may be relevant to pulsars, gamma ray bursts and blazars.

2. Stochastic acceleration

There are many circumstances where particle acceleration is likely to be stochastic and independent of the history, as in the traditional Fermi approach. The scattering is often associated with wave modes that produce a diffusion in momentum space. The creation and evolution of the wave spectrum must be considered alongside the Fokker-Planck evolution of the particles. One example that has been discussed recently is particle acceleration by sound waves created by radio sources in clusters of galaxies. Another example may be provided by a force-free electromagnetic wave spectrum as discussed above.

3. Non-Markovian acceleration

There is a third, hybrid, possibility where the steps are small but non-Markovian. A good example is provided by diffusive shock acceleration where, in the simplest description, the energy gains in the the de Hoffmann-Teller frame is due to the electric field associated with magnetic fluctuations that scatter in pitch angle. (There is an impediment to scattering through 90°, where additional acceleration may occur.) The non-Markovian character arises because the scattering waves are likely to have been created by the diffusing particles. The simple theory of diffusive shock acceleration can account for the inferred injection spectrum of primary cosmic rays. However, it does not easily explain injection, shock mediation, the level of scattering, and the observation that cosmic ray protons appear to be accelerated up to almost PeV energies – the so-called knee in the cosmic ray spectrum. (Heavier particles are accelerated to even higher energy.) This requires that magnetic field strengths are increased to values far higher than the microgauss strengths associated with the ambient interstellar medium. Indeed, there is accumulating evidence that magnetic field is strongly amplified at shock fronts. These observations suggest a new model of diffusive shock acceleration.

Consider a shock that accelerates particles up to some maximum energy. These particles are likely to have the largest diffusion coefficient (proportional to the energy under the Bohm assumption). They will therefore stream furthest ahead of the shock front and will make the first contact with the undisturbed interstellar medium. If these particles are still being scattered at this point, then they will return to the shock for further acceleration; if they are streaming forward faster than the shock then they will escape. It is conjectured that the highest energy streaming particles have a pressure along the magnetic field in excess of the magnetic pressure and create a relativistic firehose instability which quickly grows to nonlinear strength as it is convected towards the shock front. The fluctuations in the field will be on length scales in excess of the gyro radii of these highest energy particles. As these large amplitude magnetic fluctuations approach the shock front, they encounter progressively lower energy particles which they scatter through the generation of Alfven modes in an effectively uniform local field. If this 'magnetic bootstrap' can actually occur, the maximum field strength that can actually be generated ahead of a shock will be fixed by the cosmic ray pressure, a fraction of the rhermal pressure downstream. This leads to near milligauss fields at young supernova remnants and the acceleration of near PeV protons as observed.

Overall, the prospects for developing a general physical description of particle acceleration in astrophysical and space-physical sites is good. Numerical simulations are transforming our understanding of the plasma physics and high energy density experiments are likely to have a large impact on the field. Observationally, the biggest new impact is likely to come from *GLAST*.