Magnetic Fields in Cosmic Particle Acceleration Sources

Andrei M. Bykov · Donald C. Ellison · Matthieu Renaud

Abstract We review here some magnetic phenomena in astrophysical particle accelerators associated with collisionless shocks in supernova remnants, radio galaxies and clusters of galaxies. A specific feature is that the accelerated particles can play an important role in magnetic field evolution in the objects. In particular, we discuss a number of cosmic-ray (CR) driven, magnetic field amplification processes that are likely to operate when diffusive shock acceleration (DSA) becomes efficient and nonlinear. The turbulent magnetic fields produced by these processes determine the maximum energies of accelerated particles and result in specific features in the observed photon radiation of the sources. Equally important, magnetic field amplification by the CR currents and pressure anisotropies may affect the shocked gas temperatures and compression, both in the shock precursor and in the downstream flow, if the shock is an efficient CR accelerator. Strong fluctuations of the magnetic field on scales above the radiation formation length in the shock vicinity result in intermittent structures observable in synchrotron emission images. The finite size twinkling, intermittent structures—dots, clumps, and filaments—are most apparent in the cut-off region of the synchrotron spectrum. Even though these X-ray synchrotron structures result from turbulent magnetic fields, they could still be highly polarized providing an important diagnostic of the spectrum of the turbulence. We discuss both the thermal and non-thermal observational consequences of magnetic field amplification in supernova remnants and radio-galaxies. Resonant and non-resonant CR streaming instabilities in the shock precursor can generate mesoscale magnetic fields with scale-sizes comparable to supernova remnants and

A.M. Bykov (✉)
Ioffe Institute for Physics and Technology, 194021 St. Petersburg, Russia
e-mail: byk@astro.ioffe.ru

D.C. Ellison
Physics Department, North Carolina State University, Box 8202, Raleigh, NC 27695, USA
e-mail: don_ellison@ncsu.edu

M. Renaud
Laboratoire de Physique Theorique et Astroparticules (LPTA), Universite Montpellier II, Montpellier, France
e-mail: mrenaud@lpta.in2p3.fr
even superbubbles. This opens the possibility that magnetic fields in the earliest galaxies were produced by the first generation Population III supernova remnants and by clustered supernovae in star forming regions.

**Keywords** Radiation mechanisms: non-thermal · X-rays: ISM · (ISM:) supernova remnants · Clusters of galaxies · Shock waves · Magnetic fields

### 1 Introduction

Particle acceleration takes place in many active astrophysical objects of very different nature and scales. Magnetic fields play the central role in charged particle acceleration either as an intermediary between the plasma flows and energetic particles, as is the case for Fermi acceleration (e.g., in collisionless shocks), or as a source of free energy to be converted into energetic particles (i.e., magnetic field reconnection processes).

The existence of the highly amplified magnetic fields in the range of 0.1–1 mG in the shells of young supernova remnants (SNRs) was established assuming equipartition between relativistic particles and magnetic fields in the synchrotron radio emitting shells (see e.g., Ginzburg and Syrovatskii 1964, and the references therein). The topology of the magnetic field in SNRs inferred from the observations of synchrotron emission differ strongly between young and old SNRs. Radio polarization studies reveal super-adiabatic magnetic field amplification and a net radial orientation of the magnetic fields in young SNRs, while it is often just shocked interstellar field, mainly tangential, in old SNRs (e.g., Milne 1990). Milne has also pointed out that as the resolution increases, the polarization structure becomes more complex.

A pixel-by-pixel map of Faraday rotation has been produced applying rotation measure (RM) synthesis to the data observed with the *Australia Telescope Compact Array*, for the entire supernova remnant G296.5 + 10.0 by Harvey-Smith et al. (2010). A highly ordered rotation measure structure, with an anti-symmetric rotation measure pattern, was observed. The authors propose that the observed rotation measures are the imprint of an azimuthal magnetic field in the stellar wind of the progenitor star. A swept-up magnetized wind from a red supergiant can produce an azimuthal pattern of the magnetic field at large distances from the star and can naturally produce the observed anti-symmetric RM pattern. Supernova expansion into such a wind could account for the apparent bilateral structure of the SNR’s radio and X-ray morphologies. In the case of SN1006, a comparison between observed and synthesized radio maps, making different assumptions about the dependence of electron injection efficiency on the shock obliquity, allowed Petruk et al. (2009) to constrain possible nonthermal electron injection models.

A number of possible amplification mechanisms were considered. Rayleigh-Taylor instabilities in the shell have been considered for many years as a potential source of the turbulent magnetic fields. The Rayleigh-Taylor instability at the interface of the ejecta and the shocked ambient medium was proposed to explain these observations. Jun and Norman (1996) performed multi-dimensional MHD simulations of the instability in the shell and its effect on the local magnetic field. They found that the evolution of the instability is very sensitive to the deceleration of the ejecta and the evolutionary stage of the remnant. The Rayleigh-Taylor and Kelvin-Helmholtz instabilities amplify ambient magnetic fields in the simulations locally by as much as a factor of 60 around dense fingers due to stretching, winding, and compression. Globally, the amount of magnetic-field amplification was nevertheless low and the magnetic energy density reaches only about 0.3% of the turbulent energy density at the end of simulation. Strong magnetic field lines draped around the fingers produce...