Magnetic field amplification in shock precursors

LUKE O’C. DRURY¹, TURLOUGH P. DOWNES¹,²
¹Dublin Institute for Advanced Studies, School of Cosmic Physics
²Dublin City University, School of Mathematical Sciences
ld@cp.dias.ie

Abstract: The strong cosmic ray pressure gradient expected in shock precursors can drive bulk turbulent motions through the mechanism responsible for the acoustic instability of the precursor region discussed in Drury and Falle [4]. The results of recent three-dimensional MHD simulations of this process will be presented and the implications for the shock precursor structure discussed.

Keywords: Diffusive Shock Acceleration, Magnetic field amplification

1 Introduction

The idea that magnetic fields might be substantially amplified by cosmic-ray driven processes in strong shocks, and in particular those bounding young supernova remnants (SNRs), has recently attracted considerable attention. Much of this derives from the seminal work of Bell [1, 2] who pointed out the existence of a strong current-driven instability under conditions thought to be appropriate to young remnants. It is also supported by a range of indirect, but quite compelling, observational arguments which point to substantially higher effective magnetic fields at the shocks of young remnants than would be expected just from adiabatic compression of a pre-existing interstellar field [9, 8, 10]. The idea is very attractive because it appears to fill in the missing piece in the theory of cosmic ray acceleration by SNR shocks and allow acceleration to the energies needed to explain the cosmic-ray ‘knee’ particles; if the magnetic field strength is only a few μG as expected in the interstellar medium it is very hard to get the acceleration to reach these energies [6]. Actually the idea has a long if not widely known pre-history. Hoyle [5] as far back as 1960 speculated that collisionless interstellar shocks could dissipate kinetic energy into either thermal energy, cosmic-rays or magnetic field energy and Cowsik and Sarkar [3] pointed out the need for substantially amplified fields in Cas-A on the basis of early gamma-ray observations.

The Bell mechanism, which essentially relies on the current carried by non-magnetised high-energy cosmic-ray particles driving a return current in the thermal plasma, definitely can occur in the precursor region of SNR shocks if these are strong particle accelerators. However it need not be the only process and indeed it suffers from the disadvantage that it can only generate fields on scales smaller than the gyro-radius of the driving particles. Without some inverse cascade or other process these fields are thus on scales too small to be used to accelerate the highest energy particles themselves. It is thus of interest to examine other possible mechanisms. As pointed out by Malkov and Diamond [7] one promising candidate is the instability identified by Drury and Dorfi and studied in detail in Drury and Falle [4]. This can have faster growth rates than the Bell instability and has the advantage of operating on scales large compared to the gyro-radius of the driving particles.

2 Physical basis for the instability and toy model

The instability arises very simply and generally from the fact that the cosmic ray pressure gradient in the shock precursor exerts a local ponderomotive force on the thermal plasma which will not in general be proportional to the mass density. Density fluctuations thus induce acceleration fluctuations, which lead in turn to velocity fluctuations which then induce further density fluctuations. In the case of linear perturbations of an essentially homogeneous isentropic background plasma these fluctuations are acoustic (or magneto-acoustic) modes and the process leads to the acoustic instability discussed by Drury and Falle [4], but more generally one should also consider entropy fluctuations. In one dimension the instability can be suppressed if the diffusion coefficient for the cosmic-rays is rather artificially chosen to be inversely proportional to the mass density, but it is impossible to suppress the instability in more than one dimension. If the distribution of cosmic-ray pressure is adjusted to avoid instability perpendicular to the shock front, it is unstable parallel and vice-versa.
In general the scattering experienced by the cosmic rays, and thus the effective diffusion coefficient, is a complicated function of the local magnetic field strength and power-spectrum of magnetic irregularities. It will thus change if the plasma is locally adiabatically compressed, and this will feed back into the cosmic-ray distribution and thus the cosmic-ray pressure gradients, but in a non-obvious way. Rather than try to model this we consider the simplest possible case where the cosmic-ray propagation is totally decoupled from the matter dynamics.

Motivated by Malkov’s universal asymptotic solution for strong accelerators, which has a linearly rising cosmic ray pressure in the precursor, we take a toy system consisting of a rectangular computational box extending in the $x$-direction from $-L$ to 0 within which the cosmic ray pressure $P_C$ rises linearly from zero at the inflow side to a value of order the ram pressure of the inflowing plasma at the outflow side.

$$P_C(x) = \theta \rho_0 U_0^2 (1 + \frac{x}{L}), \quad (1)$$

where $0 < \theta < 1$ is a positive parameter less than unity.

The flow is thus decelerated by a uniform body force $-\theta \rho_0 U_0^2/L$ representing the reaction of the accelerated cosmic rays (and the work done is of course the work done in accelerating them). We then seed the inflowing plasma, which is treated as an ideal MHD fluid, with small-scale density fluctuations and thereby reduce the problem to a pure computational one.

This model has the great advantage that it captures the essential physics of the instability, a bulk force acting on the plasma which is not proportional to the local density, without having to compute the cosmic ray pressure distribution and thereby reduces the problem to a pure computational MHD one.

If we assume that the incoming flow contains density irregularities of magnitude $\delta \rho$ on a length scale $\lambda$ the bulk force, operating on a time scale of order the advection time through the precursor, will generate velocity fluctuations of magnitude

$$\delta u \approx \frac{\delta \rho}{\rho_0} \frac{1}{\theta \rho_0} \frac{U_0}{L} \approx \theta \rho_0 \frac{U_0}{\rho_0}, \quad (2)$$

on the same length scale $\lambda$. If this is to drive turbulence we require the eddy turn-over time to be short compared to the outer-scale and thus

$$\frac{\lambda}{\delta u} \ll \frac{L}{U_0} \Rightarrow \lambda \ll \frac{\delta \rho}{\rho_0} L \quad (3)$$

Density fluctuations satisfying this not very restrictive condition should be capable of inducing turbulence and thus magnetic field amplification. The total amount of kinetic energy available in the turbulence can be roughly estimated as

$$\frac{1}{2} \rho_0 (\delta u)^2 \approx \frac{1}{2} \left( \frac{\delta \rho}{\rho_0} \right)^2 \theta^2 U_0^2 \quad (4)$$

and thus the maximum amplified field should be below full equipartition by a factor of order $\theta^2(\delta \rho/\rho_0)^2$. If nonlinear effects drive the density fluctuations to saturation at $\delta \rho \approx \rho$ (as is probable) then this process could be very efficient at converting flow energy into magnetic energy if $\theta \approx 1$.

3 Numerical simulations

We are running simulations of this toy model using the well-tested MHD code Hydra developed by one of us (TPD) running on the Stokes supercomputer system operated by the Irish Centre for High-End Computing, ICHEC. Results will be presented in Beijing.

References