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Magnetic turbulence production by streaming cosmic rays upstream of SNR shocks

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Abstract: We present preliminary results of Particle-In-Cell simulations of magnetic turbulence production by isotropic cosmic-ray ions streaming upstream of supernova remnant shocks. The studies aim at testing the MHD predictions by Bell [1, 2] of a strong amplification of short-wavelength nonresonant wave modes and at studying the subsequent evolution of the magnetic turbulence and its backreaction on cosmic ray trajectories. The detailed knowledge of the upstream turbulence properties is crucial to ascertain all aspects of the shock acceleration process - the transport properties of cosmic rays, the shock structure, thermal particle injection and heating processes. An amplification of magnetic field would also facilitate the acceleration of particles beyond the "knee" in the cosmic-ray spectrum. Our kinetic approach is particularly suited to address the backreaction on the cosmic rays, and it allows us to test Bell's prediction of the eventual formation of extended filamentary structure in the cosmic-ray distribution and also to arrive at a reliable estimate of the total saturation magnetic-field level. The parameters chosen for the simulations are favorable for the rapid excitation of purely growing modes. We confirm the generation of the turbulent magnetic field due to the drift of cosmic-ray ions in the upstream plasma, but show that the growth rate of the field perturbations is much slower than estimated using the MHD approach and the amplitude of the turbulence saturates at about $\delta B/B \sim 1$. The magnetic field also remains below equipartition with the upstream plasma.

Introduction

Supernova remnant shock waves are prime candidates for the acceleration sites of Galactic cosmic rays. However, no firm evidence has been found so far for hadron production in SNRs, which challenges our understanding of these sources. Particle confinement near the shock is supported by self-generated magnetic turbulence and thus the detailed knowledge of the properties of the turbulence is crucial to ascertain all aspects of the acceleration process – transport properties of cosmic rays, the shock structure, thermal particle injection and heating processes. Of particular interest is the question of how efficiently and with what properties electromagnetic turbulence is produced by energetic particles at some distance upstream of the forward shocks. As the flow convects that turbulence toward and through the shock, the turbulent magnetic field structure at and behind the shock is shaped by the plasma interactions ahead of it.

We investigate the properties of magnetic turbulence upstream of the shocks of young SNRs. Cosmic rays accelerated at these shocks stream relative to the upstream plasma with the shock velocity, with the highest energy particles propagating the farthest from the shock and forming a nearly monoenergetic quasi-isotropic population at some distance upstream. Such a system has been recently studied by Bell [1] with a quasilinear MHD approach. Bell noted that the current carried by drifting cosmic rays excites non-resonant, nearly purely growing modes more efficiently than resonant Alfvén waves, which he verified with MHD simulations. Later studies suggested that regions of low density and low magnetic field strength would be formed, thus resembling a filamentation instability [2]. Here we use Particle-In-Cell simulations to verify the existence of the non-resonant modes in the presence of kinetic particle effects and explore its properties such as nonlinear evolution, saturation, and particle heating.

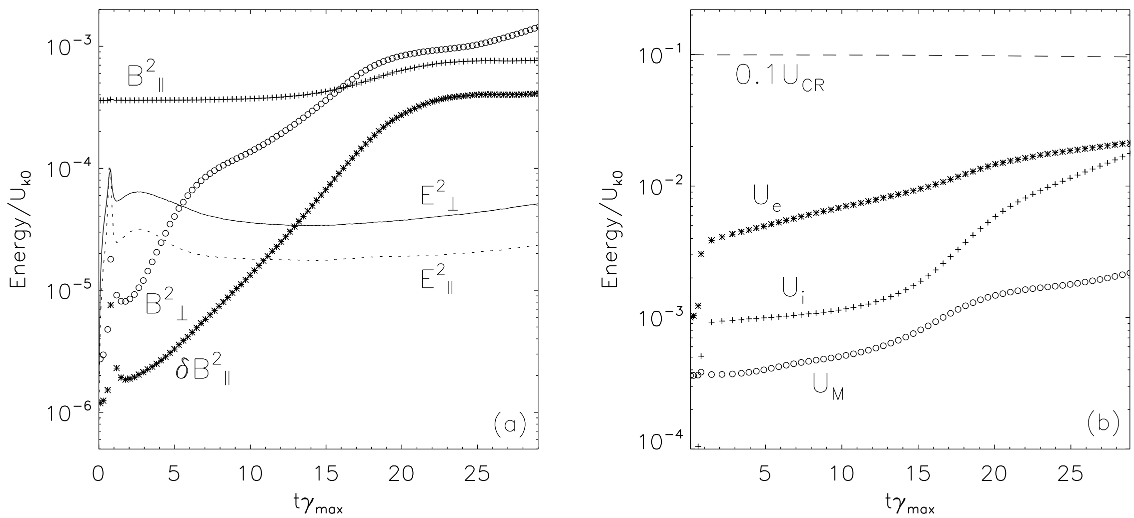

Figure 1: Temporal evolution of the total energy density in fields (a) and particles (U_{CR}, U_i, U_e) and the magnetic field U_M (b) normalized to the initial total kinetic energy in the system U_{k0}. Time is in units of the growth rate γ_{max} for the most unstable mode with wavelength λ_{max}. $B_\perp^2$ and $E_\perp^2$ indicate the magnetic and electric field energy densities in the components perpendicular to the cosmic-ray ion drift direction. The total kinetic energy in cosmic-ray ions U_{CR} is rescaled by a factor of 10.

Particle-in-cell experiment and results

We use a modified version of the relativistic 3D code TRISTAN. In the simulations, an isotropic population of relativistic, monoenergetic cosmic-ray ions with Lorentz factor $\gamma_{CR} = 2$ and number density N_{CR} drifts with $v_{sh} = 0.3c$ relative to the upstream electron-ion plasma and along the homogeneous magnetic field $B_{\parallel 0}$, carrying a current density $j_{CR} = eN_{CR}v_{sh}$. The ions of the upstream medium have a thermal distribution with number density N_i, in thermal equilibrium with the electrons. The electron population with density $N_e = N_i + N_{CR}$ contains the excess electrons to provide charge-neutrality and also drifts with $v_d = v_{sh}N_{CR}/N_e$ with respect to the upstream ions providing a return current $j_{ret} = -eN_e v_d$ to balance the current in cosmic rays. The density ratio assumed in this study is N_{CR}/N_i=1/3. The simulations have been performed using a 992×304×304 computational grid with periodic boundary conditions and with a total of 1.5 billion particles. Cosmic-ray ions drift in the $-x$-direction. The electron skindepth $\lambda_{se} = c/\omega_{pe} = 7\Delta$, where ω_{pe} is the electron plasma frequency and Δ is the grid cell size, and the ion-electron mass ratio assumed $m_i/m_e = 10$. The above parameter combination was chosen to resemble physical conditions in young SNRs and, according to quasilinear calculations [1], is favorable for the rapid excitation of purely growing, short-wavelength (as compared with cosmic-ray ion gyroradii r_{CRg}) wave modes. In the unstable wavevector regime $1 < k_\parallel r_{CRg} < \zeta v_{sh}^2/v_A^2$, the dispersion relation for the purely growing mode

$$\omega^2 - v_A^2 k_\parallel^2 + \zeta v_{sh}^2 k_\parallel / r_{CRg} = 0 \qquad (1)$$

gives the maximum growth rate γ_{max} at wavenumber $k_{\parallel max} = \zeta v_{sh}^2/2v_A^2 r_{CRg}$, where $k_\parallel$ is wavevector parallel to $B_{\parallel 0}$, v_A is the Alfvén velocity, and $\zeta = N_{CR}c\gamma_{CR}/N_i v_{sh}$. Our parameters give $\zeta v_{sh}^2/v_A^2 \simeq 826$ and the most unstable mode with wavelength $\lambda_{max} = 50\Delta$ is in the middle of the unstable wavevector range.

Figure 1 shows the temporal evolution of the magnetic and electric field and particle kinetic energy densities. An initial (up to $t \sim \gamma_{max}^{-1}$) fast growth of the turbulent fields is caused by a Buneman-type beam instability between slowly drifting electrons and the ambient ions, which leads to plasma heating until the electron thermal velocities become comparable to the electron drift speed v_d. In real

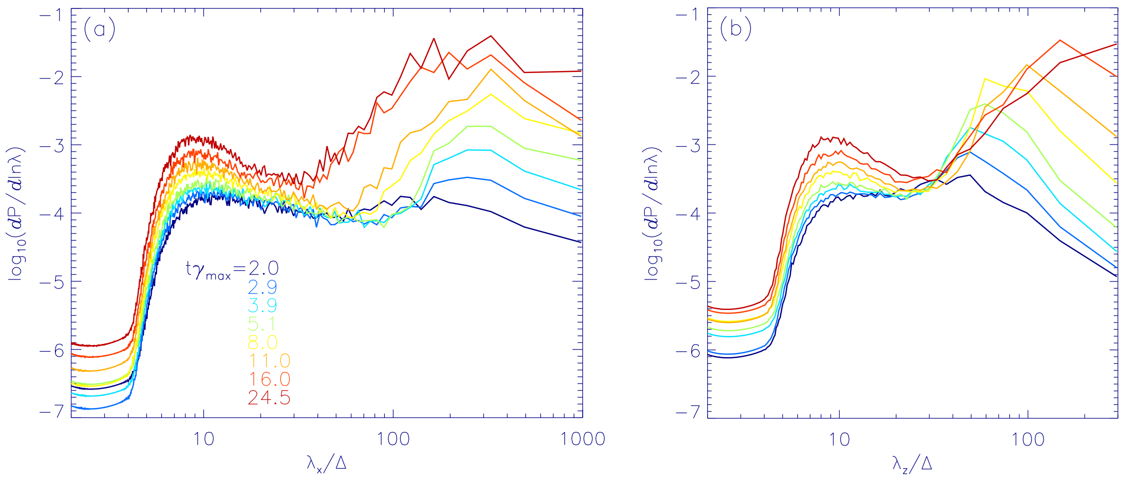

Figure 2: Power spectra of the magnetic field component B_y in the direction parallel (a) and perpendicular (b) to the cosmic-ray ions drift direction at different times as given in units of the growth rate γ_{max}. The spectra were calculated in the 2D slice in the xz-plane at $y/\Delta = 200$.

SNRs the density ratio is likely much larger than the sound Mach number, and therefore the electron drift speed is smaller than the thermal velocity. The initial instability is thus solely a consequence of the initial conditions in our simulations, in particular the initial temperature of the background medium.

The wave modes due to the instability caused by the cosmic-ray ions streaming in the upstream plasma start to emerge at $t \sim 2\gamma_{max}^{-1}$ and the magnetic field turbulence is excited mainly in the components transverse to the cosmic-ray drift direction. The dominant wave mode is oblique at an angle of about 75^o to the x-direction (Fig. 2), and has the wavelength component $\lambda_\perp \approx 50\Delta$, which is numerically similar to λ_{max}. The character of the mode is thus different than that predicted from the linear analysis by Bell [1, 2], which assumed that the most rapid growth occurs for wavenumbers parallel to $B_{\parallel 0}$ (Eq. 1). As seen in Fig. 2, the dominant scale in $\lambda_\perp$ grows as the turbulence develops, but the parallel scales ($\lambda_\parallel = \lambda_x$) remain roughly constant, so after about $20\gamma_{max}^{-1}$ the structures have similar size parallel and perpendicular to the drift. Comparison with Fig. 1 reveals that at those late times $\delta B_\perp$ is of the order of $B_{\parallel 0}$, so the system becomes magnetically nearly isotropic. The drift of the cosmic-ray particles is still kinetically dominant, which suggests an important role of the homogeneous magnetic field component for the evolution of the magnetic turbulence.

The spatial structures of the turbulent magnetic field and accompanying ambient plasma distribution are shown in Fig. 3 for $t \approx 10\gamma_{max}^{-1}$. The perpendicular field is concentrated around regions of low background plasma density. The cosmic-ray distribution is homogeneous, and therefore the magnetic field is associated with a strong net cosmic-ray current flowing inside ambient-plasma voids, and the field lines circle around the center of the cavities according to Ampere's law. The formation of the cavities in the plasma is due to the $\vec{j}_{ret} \times \vec{B}$ force, which accelerates the upstream plasma away from the center of the voids, and also causes the cavities to expand. This is visible as the evolution towards larger scales shown in Fig. 2b. The growth of the cavities and the subsequent merging of the adjacent plasma voids lead to a compression of the plasma between cavities and also to an amplification of the magnetic field. Because the magnetic field has a preferred orientation around each cavity, the magnetic field lines cancel each other in the space between the voids (Fig. 3).

Compared with Bell's MHD studies, the growth of the magnetic perturbations in our kinetic modeling is much slower. The initial growth rate ($t \sim (2-6)\gamma_{max}^{-1}$) of the perpendicular field turbulence is only 1/5 of γ_{max}, and becomes smaller during

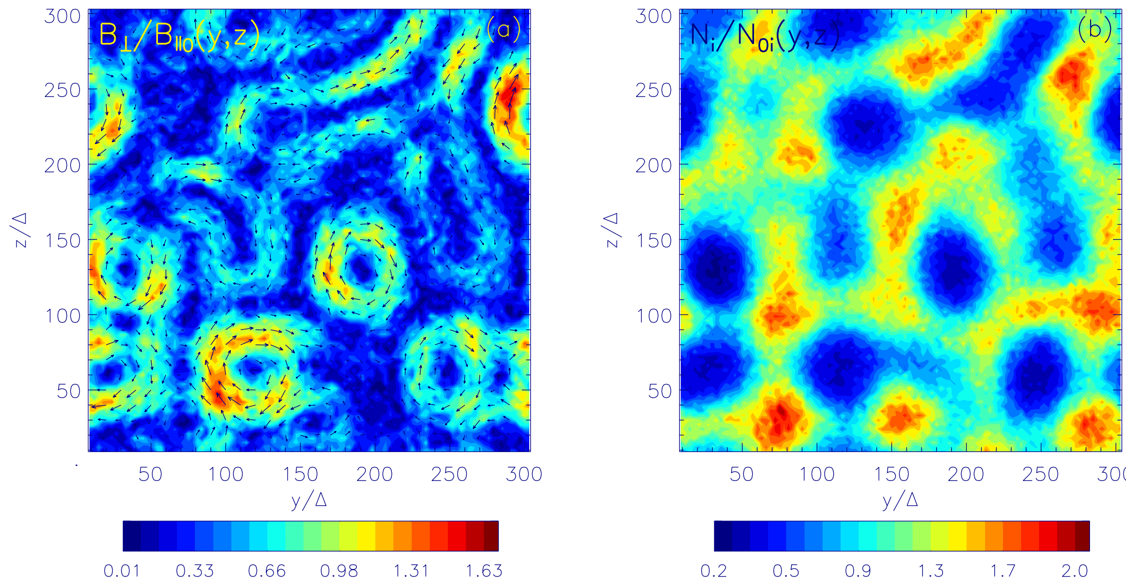

Figure 3: The magnitude and direction of the perpendicular magnetic field component $B_\perp = (B_y^2 + B_z^2)^{1/2}$ (a) and the ambient ion density N_i (b) in the plane perpendicular to the cosmic-ray ion drift direction at $x/\Delta = 500$ and $t \approx 10\gamma_{max}^{-1}$. $B_\perp$ is normalized to the amplitude of the homogeneous field $B_{\parallel 0}$, and N_i to the initial ambient ions density. The electron distribution follows that of ambient ions.

the later evolution. Moreover, the amplitude of the turbulent component never considerably exceeds the amplitude of the regular field and the field growth saturates when $\delta B_\perp/B_{\parallel 0} \approx 1$. Note, that although for $t > 25\gamma_{max}^{-1}$ the field structures become larger than the size of the simulation box, the magnetic field saturation level is not influenced by the boundary conditions, which we have confirmed using larger-box 2D simulations, that well reproduce the results of the 3D experiment. The field growth is also accompanied by heating of the ambient plasma, and the field remains below equipartition with the upstream medium. The cosmic-ray density distribution remains roughly unchanged till the end of the simulation.

Summary and conclusions

The process of the production of magnetic field turbulence by cosmic-ray ions drifting upstream of SNR shocks has been studied here using PIC simulations. Turbulent field is indeed generated in this process, but the growth of magnetic turbulence is much slower than estimated using the MHD approach, and the amplitude of the field perturbations saturates at approximately the amplitude of the homogeneous upstream field. The energy density in the turbulent field is also always much smaller than the plasma kinetic energy density. This suggests that the efficiency of magnetic field generation in this mechanism may not be sufficient to account for the high magnetic fields observed in some young SNRs and also leaves open the question of the ability of diffusive particle acceleration at SNR shocks to produce particles with energies beyond the ”knee” in the cosmic-ray spectrum.

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