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Computational Studies of Cosmic Ray Electron Injection

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Abstract. Observations of synchrotron radiation across a wide range of wavelengths provide clear evidence that cosmic ray electrons are accelerated to relativistic energies in supernova remnants (SNRs). It is widely accepted that these observations can be interpreted in terms of diffusive shock acceleration. However, the search for a viable mechanism for pre–acceleration to mildly relativistic energies (the injection problem) remains an active field of research. Here we present computational studies which show acceleration of electrons from background energies to tens of keV. We use an electromagnetic particle–in–cell (PIC) code, with parameters appropriate for quasi–perpendicular collisionless shocks in SNRs. Free energy for electron energization is provided by ions reflected from the shock front, with speeds perpendicular to the magnetic field greater than the upstream electron thermal speed. Large amplitude electrostatic waves, excited initially via a two–stream instability at a single wave number, saturate when a large fraction of the electron population is trapped by them: a power law wavenumber spectrum eventually results. During this process electrons are accelerated to speeds greatly exceeding those of the shock–reflected ions producing the initial instability. Electron energization takes place through various resonant and non–resonant processes, of which the strongest involves stochastic wave–particle interactions. In SNRs the diffusive shock process would then supply the final step required for the production of fully relativistic cosmic ray electrons.

1 Introduction

The detection of radio synchrotron emission from shell–type supernova remnants (SNRs) is a clear indication that electrons of GeV energy are being accelerated in such objects. There is now convincing evidence that synchrotron emission from some remnants extends to X–ray wavelengths (Pohl and Esposito, 1998), implying the presence of electrons with energies of order 10^{14}eV. A prime example is SN 1006, observations of which using the ASCA (Koyama et al., 1995) and ROSAT (Willingale et al., 1996) spacecraft show that X–ray emission from the bright rim has a hard, approximately power–law spectrum. In contrast, emission from the centre is softer, with a strong atomic line component. The sharp edges and strong limb brightening observed at both X–ray and radio wavelengths indicate that: the acceleration site is the strong outer shock bounding the remnant; the acceleration is continuous; and the local diffusion coefficient of electrons near the shock front is substantially reduced relative to that in the general interstellar medium (Achterberg et al., 1994). There is thus extensive observational evidence that the strong collisionless shocks bounding shell–type SNRs accelerate electrons to relativistic energies.

While diffusive shock acceleration (Bell, 1978) provides an efficient means of generating highly energetic electrons from an already mildly relativistic threshold, the "injection" or "pre–acceleration" question remains open: by what mechanisms can electrons be accelerated from background energies to mildly relativistic ones (Levinson, 1996)? In what follows, we describe a possible answer (Dieckmann et al., 2000a,b; McClements et al., 2001) which has attractive "bootstrap" characteristics. Specifically, we suggest that waves are excited by collective instability of ions reflected from a perpendicular shock, and that these waves damp on thermal electrons, thereby accelerating them. Such a process was proposed as a candidate acceleration mechanism for cosmic ray electrons by Galeev (1984) and McClements et al. (1997). Instabilities driven by shock–reflected ions at SNR shocks have also been invoked by Papadopoulos (1988) and Cargill and Papadopoulos (1988) as mechanisms for electron heating, rather than electron acceleration. On the basis of a simple analytical calculation, Papadopoulos predicted that strong electron heating would occur at quasi–perpendicular shocks with fast magnetoacoustic Mach numbers $M_F > 30$–40 through the combined effects of Buneman (two–stream) and ion acoustic instabilities. In this model the Buneman instability, driven by the relative streaming of shock–reflected ions and upstream electrons, heats the electrons to a temperature T_e much greater than the ion temperature T_i. The ion acoustic instability is then driven unstable if there is a supersonic streaming between the electrons and either reflected

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or non–reflected ("background") ions. Using a hybrid code, in which ions were treated as particles and electrons as a massless fluid, Cargill and Papadopoulos (1988) found that the electron heating predicted by Papadopoulos (1988) could occur in a self–consistently computed shock structure. However, as Cargill and Papadopoulos point out in the last paragraph of their 1988 paper, the fact that hybrid codes adopt a fluid model for the electrons means that they cannot be used to investigate electron acceleration.

The physics of charged particle interactions with large amplitude waves has been studied extensively in the context of controlled fusion experiments (e.g. Berk, 1996): the physical understanding and techniques developed in these studies can help to shed light on the SNR electron injection problem. Improved theoretical understanding of electron acceleration at shocks will enable observations of synchrotron and inverse Compton emission to be related quantitatively to shock parameters. However, most work on particle acceleration has concentrated on ions, primarily because upstream momentum and energy fluxes are dominated by ions, so that the shock structure problem reduces essentially to that of isotropizing the ion distribution. However, the very fact that electron dynamics do not appear to be important for shock structure allows us to separate the two problems: having prescribed the parameters of the ion population using the results of hybrid code simulations, we can examine in detail the physical processes that occur on electron timescales. This is the approach followed in the fully nonlinear investigation of Dieckmann et al. (2000), involving large scale numerical simulation using a particle–in–cell (PIC) code backed up by analytical and numerical studies of the underlying plasma physics mechanisms. The primary goal is to find a mechanism capable of producing mildly relativistic electrons: once they have attained rigidities comparable to those of shock–heated protons, they can undergo resonant scattering, and subsequent acceleration to relativistic energies can then proceed via the diffusive shock mechanism. Elsewhere in these proceedings, Schmitz et al. (2001) report on PIC studies of SNR shock structure.

2 Simulations

Reflected protons are known to exist in a "foot" region upstream of perpendicular shocks, with thickness of the order of the upstream ion Larmor radius. The reflected protons form two beams, propagating towards and away from the shock, perpendicular to $\boldsymbol{B}$ (McClements et al., 1997). We use a particle–in–cell (PIC) code to simulate instabilities driven by such beams, with bulk protons and electrons having zero net drift in the simulation frame: time evolution in the simulation can then be interpreted as spatial variation in the shock foot. The proton beams are initially Maxwellian with thermal speed $\delta u_\perp = 3 \times 10^5\,\mathrm{ms}^{-1}$ (defined such that the temperature is $m_p \delta u_\perp^2$, where m_p is proton mass), and drift speeds $u_{b\perp} = 5v_{e0}$, $6v_{e0}$, where $v_{e0} = 3.75 \times 10^6\,\mathrm{ms}^{-1}$ is initial electron thermal speed. The total beam density is one third of the electron density: this is consistent with hybrid simulations of shocks with Alvénic Mach numbers ranging up to 60. The electron plasma frequency $\omega_{pe}/2\pi$ and gyrofrequency $\Omega_e/2\pi$ are 10^5Hz and 10^4Hz respectively. Normalized variables $\tilde{t} = \Omega_e t/2\pi$ and $\tilde{k} = kv_{e0}/\Omega_e$ are used to measure time t and wavenumber k. The simulations have one space dimension (x), orthogonal to $\boldsymbol{B}$.

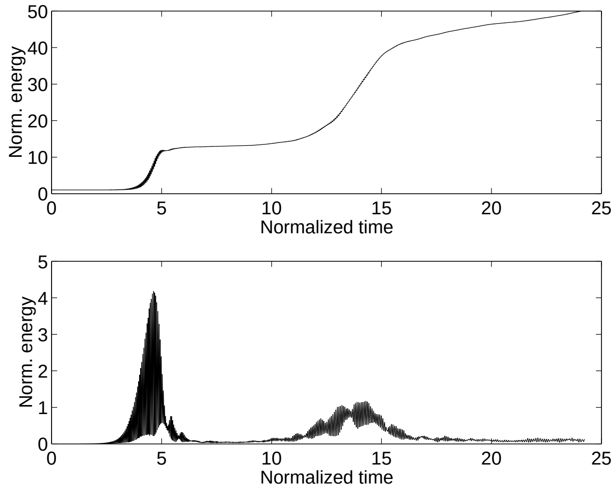

Fig. 1. Electron perpendicular kinetic energy (upper) and electrostatic field energy (lower) versus $\tilde{t}$ for $\omega_{pe}/\Omega_e = 10$, $u_{b\perp} = 6v_{e0}$.

In both simulations energy was rapidly transferred from beam protons to electrons, with the power flux between the two species increasing when $u_{b\perp}$ was raised from $5v_{e0}$ to $6v_{e0}$. Fig. 1 shows the time evolution of perpendicular kinetic energy and electric field energy for $u_{b\perp} = 6v_{e0}$. The distributions in perpendicular speed $v_\perp$ at $\tilde{t} = 70$ in the simulations with $u_{b\perp} = 5v_{e0}$ and $u_{b\perp} = 6v_{e0}$ (Fig. 2) can both be approximated by single Maxwellians, respectively with $v_e \simeq 8v_{e0}$ and $v_e \simeq 12v_{e0}$: the perpendicular thermal speeds thus exceed the velocities of the proton beams which produced them. In the case of $u_{b\perp} = 6v_{e0}$, the final electron temperature (11.5 keV) is easily sufficient to account for thermal X–ray emission observed from SNRs such as Cas A (Papadopoulos, 1988). Individual electron energies of up to several tens of keV were observed in this simulation.

Fig. 3 shows the time evolution of wave amplitude versus $\tilde{k}$ when $u_{b\perp} = 6v_{e0}$. Waves with $\tilde{k} \simeq 1.8$ rise sharply in magnitude at $\tilde{t} \simeq 3$, reaching a peak electric field amplitude $E = 35\,\mathrm{Vm}^{-1}$ and generating a harmonic at $\tilde{k} \simeq 3.6$. The most unstable waves have $\omega \simeq \omega_{pe}$, and are unaffected by the magnetic field: the growth rate does not depend on the proximity of ω to cyclotron harmonics. After $\tilde{t} \simeq 8$, when the initial wave activity has ceased, a more broadband perturbation is generated at $\tilde{k} \simeq 1.3$, the mean $\tilde{k}$ decreasing with time.

The linear growth of waves in the simulations is described

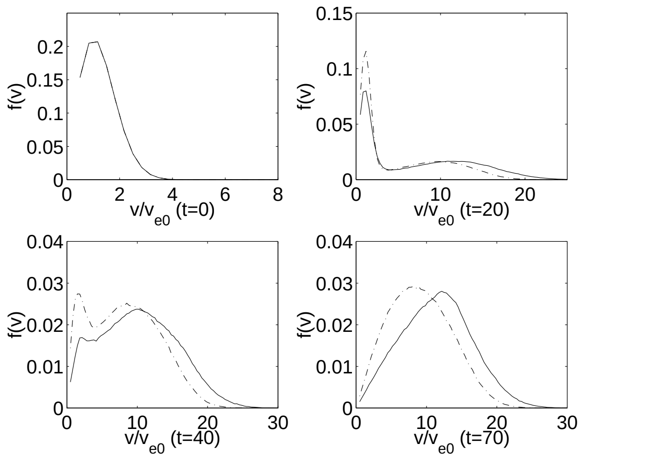

Fig. 2. Electron perpendicular speed distributions for $\omega_{pe}/\Omega_e = 10$ and $u_{b\perp} = 5v_{e0}$ (dashed), $u_{b\perp} = 6v_{e0}$ (solid).

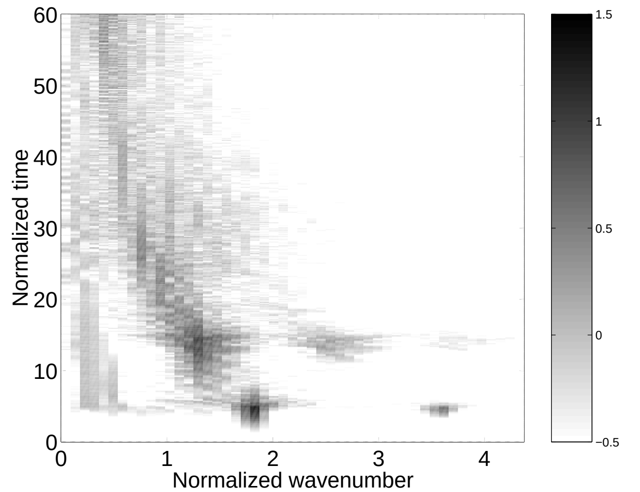

Fig. 3. Electric field amplitude versus $\tilde{k}$ and $\tilde{t}$ for $\omega_{pe}/\Omega_e = 10$ and $u_{b\perp} = 6v_{e0}$.

by the electrostatic dispersion relation

$$\frac{\omega_{pi}^2}{\omega^2} - \frac{2\omega_{pb}^2\left[1+\zeta Z(\zeta)\right]}{k^2\delta u_\perp^2} + \frac{\omega_{pe}^2}{\omega\lambda e^\lambda}\sum_{\ell=-\infty}^{\infty}\frac{\ell^2 I_\ell}{\omega-\ell\Omega_e} = 1 \qquad (1)$$

Here, ω_{pi}, ω_{pb} are background and beam proton plasma frequencies, Z is the plasma dispersion function with argument $\zeta \equiv (\omega - ku_{b\perp})/k\delta u_\perp$, and I_ℓ is the modified Bessel function of the first kind of order ℓ with argument $\lambda \equiv v_{e0}^2 k^2/\Omega_e^2$. It can be shown from Eq. (1) (Dieckmann et al., 2000a) that the mode appearing at $\tilde{k} \simeq 1.8$ in Fig. 3 arises from a Buneman instability driven by beam protons. If $\omega_{pe}/\Omega_e \gg 1$, and the instability drive is sufficiently strong, electrons are effectively unmagnetized and, in the frame used in the simulations, the mode has frequency $\omega \simeq ku_{b\perp} \simeq \omega_{pe}$ and growth rate

$$\gamma \simeq (3\sqrt{3}\omega_{pb}^2\omega_{pe}/16)^{1/3} \qquad (2)$$

(Dieckmann et al., 2000a). Beyond the linear phase, there are strong indications that the waves saturate because of electron trapping in the wave potential (Dieckmann et al., 2000b).

In both simulations wave excitation is correlated with acceleration and heating of electrons. Although particles can be energized via Landau damping, one would expect this process to be of limited effectiveness when, as in the present case, the waves are propagating perpendicular to a magnetic field. It is likely therefore that the strong acceleration observed in the simulations is due at least in part to nonlinear processes. Karney (1978) identified a critical electric field above which particle motion becomes stochastic and hence rapid acceleration is possible. The peak wave electric fields in both of the simulations discussed above were well above the critical value (Dieckmann et al., 2000a) and so it appears likely that strong electron acceleration occurred because of stochastic wave–particle interactions.

We have also carried out simulations with $\omega_{pe}/\Omega_e = 100$, $T_e = 9\,\mathrm{eV}$ and $u_{b\perp} = 0.06c$, where c is the speed of light (McClements et al., 2001). As in the two other simulations, a strong Buneman instability occurs at the electron plasma frequency. As the amplitude of this wave increases, harmonics of it appear. After a certain time, the initial wave and its harmonics are replaced with a continuum (Fig. 4): waves appear at every wavenumber permitted by the finite size L of the simulation box ($L = 4\lambda_0$ where λ_0 is the wavelength of the initial Buneman instability). This can be attributed to sideband instabilities, initially at dimensionless wavenumbers $\kappa \equiv ku_{b\perp}/\omega_{pe} = 0.75$, 1.25 and subsequently at other κ. Approximating the high wavenumber tail of the distribution by a power law, with $E_0 \propto \kappa^{-\alpha}$, we obtain $\alpha \simeq 2.3$. At $0.25 \leq \kappa \leq 1$, where the spectrum departs from a power law, there are several modes of comparable amplitude. These have $\omega \sim \omega_{pe}$, and therefore the phase speed of the longest wavelength mode ($\kappa = 0.25$) is $v_\phi \sim 4\times\omega_{pe}\lambda_0/2\pi \simeq 0.24c$. The electron (x, v_x) phase space shortly after the appearance of the continuous κ spectrum is shown in Fig. 5. The presence of many waves in the system gives rise to a complex interaction between several trapped particle islands, with the result that trapped electrons are accelerated up to about the phase speed of the fastest–propagating mode in the system. If simulations were carried out with higher L/λ_0, so that smaller wavenumbers and higher phase speeds could be represented, it appears likely that acceleration to higher energies would be observed (similar box sizes were used in the simulations with $\omega_{pe}/\Omega_e = 10$ and 100). There are also indications that strong acceleration perpendicular to both $\boldsymbol{B}$ and the wave propagation direction can occur when ω_{pe}/Ω_e is greater than 100 (McClements et al., 2001).

3 Conclusions and discussion

Using PIC simulations and analytical theory we have found that electrostatic waves, excited by protons reflected from high Mach number perpendicular shocks, can effectively heat and accelerate electrons. This process may help to account

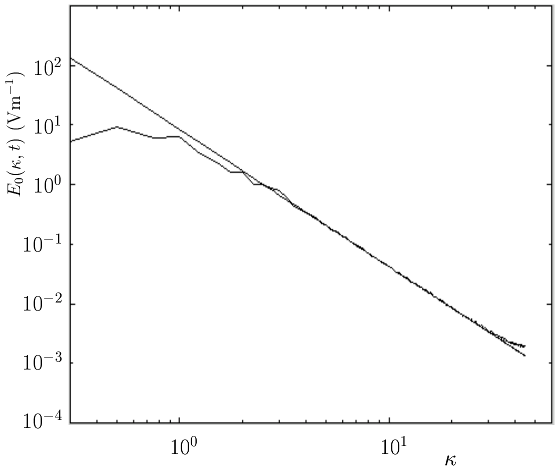

Fig. 4. Snapshot of wave spectrum in simulation with $\omega_{pe}/\Omega_e = 100$. The straight line indicates a power law fit to the high wavenumber tail of the spectrum, with index $\alpha \simeq 2.3$.

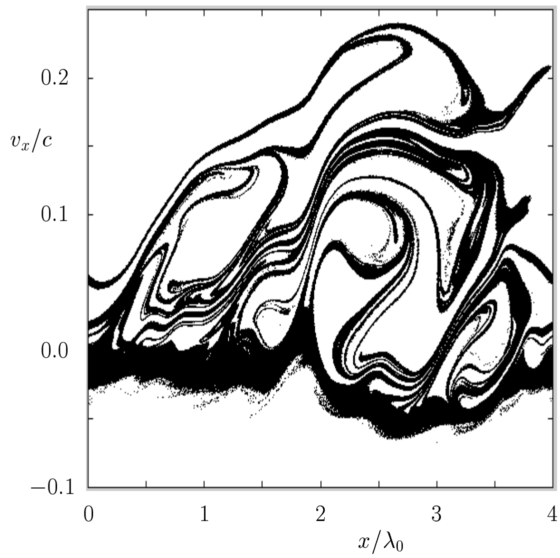

Fig. 5. Electron distribution in (x, v_x) space at $\omega_{pe}t/2\pi = 43$ in simulation with $\omega_{pe}/\Omega_e = 100$. The quantity $\lambda_0 = 2\pi u_{b\perp}/\omega_{pe}$ is the wavelength of the initial Buneman instability.

for observations of thermal bremsstrahlung from SNRs, and could also provide a seed population for diffusive shock acceleration to GeV energies. Our results confirm an earlier suggestion (Papadopoulos, 1988) that streaming between reflected protons and upstream electrons gives rise to a strong Buneman instability. The geometry used in the PIC simulations excludes the possibility of acceleration along $\boldsymbol{B}$, for example via the modified two–stream instability (McClements et al., 1997). It is likely that the Buneman instability and the modified two–stream instability both play important roles in the production of high energy electrons at SNRs.

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References

Achterberg, A., Blandford, R. D., and Reynolds, S. P., Evidence for enhanced MHD turbulence outside sharp–rimmed supernova remnants, Astron. Astrophys., 281, 220-230, 1994.

Bell, A. R., The acceleration of cosmic rays in shock fronts – I, Mon. Not. R. Astron. Soc., 182, 147-156, 1978.

Berk, H. L., Breizman, B. N., Fitzpatrick, J., Pekker, M. S., Wong, H. V., and Wong, K. L., Nonlinear response of driven systems in weak turbulence theory, Phys. Plasmas, 3, 1827-1838, 1996.

Buneman, O., Instability, turbulence, and conductivity in current-carrying plasma, Phys. Rev. Lett., 1, 8-9, 1958.

Cargill, P. J., Papadopoulos, K., A mechanism for strong shock electron heating in supernova remnants, Astrophys. J., 329, L29-L32, 1988.

Dieckmann, M. E., McClements, K. G., Chapman, S. C., Dendy, R. O., and Drury, L. O'C., Electron acceleration due to high frequency instabilities at supernova remnant shocks, Astron. Astrophys., 356, 377-388, 2000.

Dieckmann, M. E., Ljung, P., Ynnerman, A., and McClements, Large–scale numerical simulations of ion beam instabilities in unmagnetized astrophysical plasmas, Phys. Plasmas, 7, 5171-5181, 2000.

Galeev, A. A., Acceleration of electrons to ultrarelativistic energies by shock waves and synchrotron radiation of these electrons, Sov. Phys. JETP 59, 965-971, 1984.

Koyama, K., Petre, R., Gotthelf, E. V, Hwang, U., Matsuura, M., Ozaki, M., Holt, S. S., Evidence for shock acceleration of high-energy electrons in the supernova remnant SN 1006, Nature 378, 255-258, 1995.

Levinson, A., On the injection of electrons in oblique shocks, Mon. Not. R. Astron. Soc., 278, 1018-1024, 1996.

McClements, K. G., Dendy, R. O., Bingham, R., Kirk, J. G., Drury, L. O'C., Acceleration of cosmic ray electrons by ion-excited waves at quasi-perpendicular shocks, Mon. Not. R. Astron. Soc., 291, 241-249, 1997.

McClements, K. G., Dieckmann, M. E., Ynnerman, A., Chapman, S. C., and Dendy, R. O., Surfatron and stochastic acceleration of electrons at supernova remnant shocks, Phys. Rev. Lett., submitted, 2001.

Papadopoulos, K., Electron heating in superhigh Mach number shocks, Astrophysics and Space Science, 144, 535-547, 1988.

Pohl, M. and Esposito, J. A., Electron acceleration in supernova remnants and diffuse gamma rays above 1 GeV, ApJ 507, 327-338, 1998.

Schmitz, H., Chapman, S. C., and Dendy, R. O., The influence of electron temperature and magnetic field strength on cosmic ray injection in high Mach number shocks, ICRC 2001 (these proceedings).

Willingale, R., West, R. G., Pye, J. P., and Stewart, G. C., ROSAT PSPC observations of the remnant of SN 1006, Mon. Not. R. Astron. Soc., 278, 749-762, 1996.