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The Magnetic Bootstrap

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Abstract: Recent observations with TeV telescopes strongly indicate that young supernova remnants are capable of accelerating cosmic ray protons almost to PeV energies. On quite general grounds, this, in turn, suggests that the magnetic field strength must be enhanced above the standard interstellar value by about two orders of magnitude. It is suggested that protons and electrons are accelerated through diffusive shock acceleration, with the highest energy protons streaming furthest ahead of the shock front. It is then shown that the pressure of the ~ 300TeV protons dominates that of the ambient thermal particles and magnetic field and is likely to be sufficiently anisotropic to render the pre-shock fluid unstable to resonant and non-resonant instability. A new theory of the non-resonant instabilities is outlined. The nonlinear evolution of these instabilities requires careful numerical simulation but it is conjectured that the magnetic field is amplified in this location and provides the means for efficient acceleration of progressively lower energy particles as it is convected towards the subshock in the thermal plasma. Further possible implications of these ideas are sketched.

INTRODUCTION

It has long been conjectured that most Galactic cosmic rays are accelerated at the strong shock fronts formed by young supernova remnants (SNRs) [1]. In the test particle limit, a first order Fermi process transmits a downstream cosmic ray distribution function

$$f_+(p) = qp^{-q} \int_0^p dp' \, p'^{q-1} \, f_-(p'); \quad q = 3r/(r-1),$$

where the subscript – refers to distribution function far upstream and r is the shock compression ratio. The transmitted pressure (~0.1 momentum flux, Π) and spectral slope (q~4.2) is plausibly close to the values generically observed (Drury, these proceedings and references therein). Recent observations of prominent SNR show *prima facie* evidence for electron and proton shock acceleration extending to energies of ~0.3PeV [2,3]. The scale height of the most energetic cosmic rays must exceed c/u~100 Larmor radii and be smaller than the shock radius which in turn implies that the magnetic field in the acceleration region be larger than ~ 100 μG, thirty times the nominal interstellar value.

A more detailed theory posits that the scattering is affected by nonlinear resonant hydromagnetic waves that are self-generated by the streaming cosmic rays and that the cosmic pressure moderates the acceleration by decelerating the inflow ahead of the shock. For the inflowing gas, the first portent of the shock is therefore an increase in the density of ~0.3PeV cosmic ray protons whose anisotropic partial pressure will quickly rise to a value ~0.01Π ~ 100 times the ambient thermal and magnetic pressure. The combined plasma is likely to be unstable.

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INSTABILITY

In order to study the propagation of linear, hydromagnetic waves it is general supposed that the fluid is perfectly conducting so that magnetic field is frozen to the moving fluid and that the plasma pressure tensor is and remains isotropic with $\delta P \propto s^2 \delta\rho$, where s is the adiabatic sound speed. Both assumptions are likely to be untrue in a collisionless plasma. Instead, for waves with angular frequency less than the Larmor frequency of the particles contributing to the pressure, the pressure will have perpendicular and parallel components which will vary. One simple prescription for these components uses the “double adiabatic” scaling laws, $P_{\perp,\|} \propto \rho^{\gamma_{\perp,\|}} B^{\delta_{\perp,\|}}$, where B is the strength of the field. For non-relativistic plasma, $\gamma_{\perp,\|} = 1, 3; \delta_{\perp,\|} = 1, -2.$ However, for a general anisotropic distribution function, the parallel momenta will vary as $p_\perp \propto B^{1/2}, p_\| \propto \rho B^{-1}.$ And the exponents depend upon the distribution function. For the special case of an extreme relativistic, isotropic distribution function, $\gamma_{\perp,\|} = 4/5, 12/5; \delta_{\perp,\|} = 4/5, -8/5.$ For the general case of a relativistic contribution to the pressure tensor, the exponents depend upon the distribution function though not, in practice, very sensitively. Note that an isotropic pressure becomes anisotropic when perturbed, in contrast to the collisional case which is usually erroneously assumed.

The magnetosonic normal modes can now be calculated, taking care to allow for the rotation of the magnetic field direction. A calculation leads to a dispersion relation, to which the pressure of the cosmic rays contributes, and a condition for firehose instability, $P_\| > P_\perp + B^2$. In addition, there is a mirror instability which is possible if $P_\perp > Max[B^2, 7P_\|]$, very roughly. These instabilities operate at low frequency and are non-resonant.

The use of a double adiabatic approach is somewhat controversial because when one derives fluid equations by taking moments of the Vlasov equation a closure relation must be invoked. In the standard treatment this amounts to ignoring the heat flux vector which could be very large. However, if the adiabatic invariants are treated as actions in a Hamiltonian system, then the individual particle momenta at a given position can be related to their values in a simple distribution function before the wave grows and the pressures can be computed directly by integration over momentum space, without invoking the Vlasov equation. This fluid-based approach to the description of collisionless plasma has wider application to the treatment of wave propagation, thermal subshocks and weak MHD turbulence. It may also be tested *in situ* through direct spacecraft measurement of the interplanetary medium.

When the cosmic rays stream through the background plasma faster than the Alfven speed, waves with wavelength resonant with the cosmic ray Larmor radius will also grow. Their growth rate which cannot be computed using the double adiabatic approach, is slower than that of the non-resonant waves at threshold by a factor of u/c. However, both resonant and non-resonant waves are important for determining the non-linear evolution of this instability.

MAGNETIC BOOTSTRAP

It is proposed that the magnetic field builds up to nonlinear strength from an interstellar value of order a few microGauss within a few Larmor radii far ahead of the shock front and at the expense of the ~ PeV cosmic ray energy density. The instability is driven by the energy and momentum fluxes of the cosmic rays accelerated closer to the shock front by diffusive Fermi acceleration. In round numbers, the highest energy cosmic ray pressure will be ~10^{-10} dyne cm^{-2}, a hundred times the interstellar value and perhaps ten percent of the post-shock GeV cosmic ray pressure and one percent of the post-shock gas pressure. The magnetic energy density would have to increase steadily as the shock is approached. (Note that it is not necessary for the magnetic energy density to be as large as the dynamical pressure of the ISM or the cosmic ray pressure which opposes it, in order to mediate the interaction between these two components. This is because the force density acting on the ISM (CR) is $j_{ISM(CR)}$ B which can be much larger than μ_0^{-1} BdB/dx because the gradient in the magnetic field is given by dB/dx = μ_0 (j_{ISM}+j_{CR}) which can be much smaller than $j_{ISM(CR)}$ B if and when the two currents largely cancel. The increase in the magnetic field strength is mandated by the requirement that the diffusion length be smaller that the shock radius.)

The magnetic field strength variation will be determined by linear damping processes and growth associated with the cosmic rays, as described above and transit time damping as well as nonlinear, three and four wave processes. Large dynamic range numerical simulations will be necessary to understand cosmic ray transport quantitatively. A simpler and less convincing description is possible if one makes the ansatz that the cosmic rays are subject to Bohm diffusion in an ambient background magnetic field determined by the behavior of higher energy particles. The behavior at the highest energies is determined using Monte Carlo simulation in a spherical geometry plus the growth rates of the instabilities described above. Both electrons and protons can be accelerated by this mechanism to comparable energies as long as radiative losses for the electrons are ignorable.

OBSERVATIONS OF SUPERNOVA REMANTS

Much of the recent excitement in this field is due to X-ray observations of sources like SN 1006 with Chandra and ASCA [2] and VHE gamma-ray observations of remnants like RX J1713.7-3946 with H.E.S.S. [3,4]. The former show X-ray synchrotron emission by ~ 100 TeV electrons concentrated close to the shock front and sometimes confined to filaments. This is *prima facie* evidence for diffusive shock acceleration. The TeV emission may also be leptonic, arising from the inverse Compton scattering of the cosmic microwave background. The difficulties with this explanation are that the magnetic field strength inferred to account for the strength of the X-ray emission is much lower than that required to accelerate the electrons or confine the filaments. Furthermore, the highest energy electrons may cool on timescales comparable with the ages of the remnants which could explain spectral curvature in the TeV spectra and the surprising sensitivity to detailed physical conditions in the sources. The detailed spatial association of the non-thermal X-ray and the TeV emission in RX J1713.7-3946 also makes sense if the magnetic field variations are small.

However, the TeV emission could plausibly be attributed to hadronic emission through π^0-decay. This is possible if ten percent of the SNR energy is in the form of ~ GeV protons and the ambient density is ~ 1 cm^{-3} again in RX J1713.7-3946. The puzzle here then is to explain the absence of thermal X-rays. Another question is how to account for the full Galactic cosmic ray energy density given that only a minority of remants are seen by H.E.S.S.-like instruments today.

PROSPECTS FOR GLAST

It is projected that GLAST will detect shell-type SNRs and thus establish a new class of GeV sources, several of which will have also been observed at TeV energy. These observations should enable a decision to be made between hadronic and leptonic explanations of the TeV emission. In the former case, a feature associated with the π^0 production threshold may be seen. In the latter, there is the prospect of deriving a detailed description of the evolution of high energy electrons that simultaneously emit synchrotron and inverse Compton radiation. With any luck, we will find examples of both cases. Either way we are on the threshold of determining empirically the manner in which non-relativistic shocks inject and accelerate electrons and protons. This understanding should be important for describing collisionless shock waves in a wide variety of cosmic sources where shocks are found and relativistic particles must therefore be accelerated. It will also provide a target for the increasingly sophisticated particle in cell codes that have been used to try to understand shock structure numerically.

REFERENCES

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