Particle Acceleration in Astrophysical Plasmas

Proposal for a 10 week KITP program starting 27 July 2009

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Executive Summary: Recent theories and observations of young supernova remnants (SNRs), suggest that the efficient particle acceleration process in collisionless shocks can amplify existing turbulent magnetic fields by large factors. Since collisionless plasmas and shocks exist throughout the universe on scales ranging from the Earth bow shock to shocks in galaxy clusters, the strongly coupled plasma physics of shocks, superthermal particles, and magnetic fields may have application in a wide variety of sources beyond SNRs. These include γ-ray bursts (GRBs), active galactic nuclei (AGNs), pulsar wind nebulae (PWNe), and possibly cosmic structure formation shocks in the outskirts of galaxy clusters. It is also widely believed that this physics is directly related to the origin of cosmic rays at all energies including ultra-high-energy cosmic rays (UHECRs) above $\sim 10^{19}$ eV. The rapid advance of both ground- and space-based telescopes, with widely varying energy bands, makes it imperative that coherent theories of particle acceleration be developed now to address the expected implications of this new wealth of data for both astrophysics and particle physics. We propose a program to investigate the complex, nonlinear processes associated with particle acceleration in astrophysical plasmas with emphasis on the study of Magnetic Field Amplification (MFA) in shocks undergoing efficient Fermi particle acceleration. To accomplish this goal, we will bring together shock theorists, plasma simulators, and observers to advance the theory and to use our results to interpret important sources such as SNRs, AGNs, GRBs, and pulsars.

Collisionless shocks are known to produce relativistic particles efficiently in some sources, such as heliospheric shocks and supernova remnants (SNRs), and there is indirect evidence that the acceleration process may work efficiently in other sites, such as GRBs and AGNs. The high efficiency of the Diffusive Shock Acceleration (DSA) mechanism implies that the coupling between the accelerated particles and the accelerator plays an important role providing an instance of a system with a strong nonlinear reaction between all components (e.g., Jones & Ellison 1991; Kulsrud 2005). Of all nonlinear effects possible in this system, none is more important than the self-generation, and possible strong amplification, of magnetic fields by the shock accelerated particles.

A revolutionary recent discovery involving X-ray synchrotron filaments is that turbulent magnetic fields in SNR shocks may reach milli-Gauss levels (e.g., Vink & Laming 2003; Völk et al. 2005; Uchiyama & Aharonian 2008). These fields are a 100 times larger than generally believed possible a decade or so ago and are convincing evidence that magnetic field amplification is an intrinsic part of nonlinear DSA (Bell & Lucek 2001; Amato & Blasi 2006; Vladimirov, Ellison & Bykov 2006). The importance of large magnetic fields goes beyond controlling the physics of shocks and particle acceleration since magnetic fields also determine synchrotron radiation, the main emission process for many sources.[1] Rapid progress unraveling the nonlinear nature of shock acceleration needs to be made to make full benefit of a host of recent or planned ground- and space-based telescopes (e.g., Chandra, Suzaku, GLAST, Agile, NuStar, HESS, MAGIC, Veritas, Milagro, HAWC), and cosmic ray and neutrino experiments (e.g. Auger, HiRes, Kaskade, IceCube and Nestor). Furthermore, advances in understanding the connection and contrast between non-relativistic shocks (e.g., SNRs, stellar winds) and relativistic shocks (e.g., GRBs, AGNs, pulsars) are needed.

The amplification of magnetic fields in nonlinear diffusive shock acceleration may be the "missing link" for understanding the origin of galactic cosmic rays (CRs). If the magnetic field increases, so does the maximum proton energy a given shock can produce. Preliminary models suggest that nonlinear DSA in SNRs may be able to explain the CR "knee" at $\sim 10^{15\text{-}16}$ eV (Blasi, Amato & Caprioli 2007) and when nuclei heavier than protons are considered, energies up to $10^{17\text{-}18}$ eV can be obtained. These findings, besides representing a breakthrough in the understanding of galactic CRs, are also expected to play an important role in explaining the transition to extragalactic CRs, in the region $10^{17\text{-}19}$ eV (e.g., Aloisio et al. 2007).

The shock acceleration problem is challenging because of the multi-scale nature of the strongly coupled, self-regulated system of MHD turbulent magnetic fields and highly non-thermal energetic particles. The microscopic structure of a collisionless subshock determines the fraction of incoming particles injected into the Fermi acceleration process. This fraction in turn regulates the structure and evolution of a turbulent cosmic-ray modified shock precursor on a scale that may be 10^{10} times larger than the subshock thickness. Not surprisingly, the exact treatment of such a strongly coupled nonlinear system has not yet been achieved, but approximate calculations are making progress and have successfully modeled shocks in the heliosphere and SNR blast waves (e.g., Ellison & Cassam-Chenai 2005). Further progress requires joint efforts from people working in plasma physics and particle-in-cell (PIC) simulations, semi-analytic theory, and observations.

Perhaps the most exciting aspect of this work is that two of the outstanding problems in astrophysics – the origin of CRs and the origin of magnetic fields (at least magnetic turbulence) – may be far more intimately connected than previously believed. The rapid advance in computation power and algorithms is making it possible, for the first time, to realistically model this connection.

Our program is timely and will build on recent observational advances provided by Chandra, XMM, Agile, HESS, HiRes and Auger. We anticipate a significant amount of new data to emerge prior to the workshop, particularly from GLAST which is scheduled for launch this spring. GLAST will provide observations of unprecedented sensitivity and spectral coverage for many sources including a number of SNRs. In the GeV-TeV γ-ray band, HESS and MAGIC are being upgraded and Veritas-IV is now fully operational. In the cosmic-ray field, Auger and HiRes have firmly established the existence of the GZK cutoff, compelling the deep exploration of bottom-up models for sources of UHECRs, i.e., those models that generally invoke particle acceleration at shocks. All in all, the Fall 2009 timing of our workshop should allow us to capitalize on what promises to be an exceptionally active period of space observation.

[1] In fact, there were some early indications and speculation of large magnetic fields in SNRs, particularly Cassiopeia A, before Chandra observations gave more convincing evidence for their existence (e.g., Chevalier et al. 1978; Cowsik & Sarkar 1980; Reynolds & Ellison 1992).

Following is a list of specific questions we plan to address with this program:

1. **The nature of magnetic field amplification is still largely uncertain and a number of fundamental questions remain:**
   1.1. In nonlinear DSA, is MFA dominated by resonant or non-resonant instabilities?
   1.2. How does MFA influence the particle distribution function and maximum particle energy, $p_{\max}$, a shock produces?
   1.3. How does particle escape at $p_{\max}$ influence MFA?
   1.4. What is the best way to determine a self-consistent spatial and energy dependent diffusion coefficient with MFA, including particle escape, for semi-analytic and Monte Carlo approximations?
   1.5. How does magnetic turbulence dissipation influence the shock precursor and is the heating caused by this dissipation observable?
   1.6. How does MFA depend on shock parameters?

2. **Particle-in-cell (PIC) simulations are the only way to self-consistently determine the plasma processes responsible for particle injection and magnetic field generation in collisionless shocks. However, the extreme computational requirements of this technique have prevented applications to shocks where a wide range of particle energies are produced:**
   2.1. Must PIC simulations be fully 3-D as suggested by basic work on ignorable coordinates by Jones, Jokipii & Baring (1998)?
   2.2. What minimum set of parameters (e.g., particle mass ratio, Mach numbers, initial magnetization, box size, etc.) can be chosen that will allow a meaningful determination of the injection and acceleration of thermal particles in a non-relativistic shock?
   2.3. What is the internal structure of collisionless shocks as a function of flow parameters?
   2.4. What mass ratios can be used to adequately investigate the electron to proton injection and acceleration efficiencies in collisionless shocks?
   2.5. How do PIC simulations of non-relativistic, mildly relativistic, and fully relativistic shocks differ and is MFA an integral component of relativistic shocks?
   2.6. Can instabilities responsible for MFA be simulated with PIC methods? What is the nonlinear evolution of these instabilities and the back reaction of the field on the shock structure?
   2.7. What is the best way to merge PIC, Monte Carlo, and kinetic approaches?

3. **To be useful, models of nonlinear DSA must cover large ranges of time, length, and particle energy. We will investigate how PIC results can be combined with faster Monte Carlo and semi-analytic techniques to realistically model CR production:**
   3.1. What is the most effective way to parameterize the plasma physics determined by PIC simulations for use in semi-analytic models?
   3.2. What are the integrated CR spectra produced by SNRs of various parameters and are these consistent with CR propagation models?
   3.3. How do nonlinear effects from CR production influence thermal X-ray line emission in the region between the forward and reverse shocks in SNRs?
   3.4. Can CRs beyond the knee at ~$10^{15\text{-}16}$ eV be produced in SNRs and what elemental composition can be expected in this range?

3.5. What is the energy limit for UHECRs produced by radio jets when MFA is considered and are these jet models consistent with Auger spectral, composition, and spatial correlation measurements or limits?

4. All realistic models of nonlinear DSA with MFA have a number of poorly known parameters that must be constrained by observations. Observational issues and questions we plan to address include:

4.1. What observations are required to confirm the existence of large magnetic fields in SNRs?
4.2. What observations are required to definitively determine if the GeV-TeV γ-ray emission from SNRs is of leptonic or hadronic origin?
4.3. What is the best way to collect and interpret new observations of CRs at the knee and higher energies as they become available?
4.4. Can spatially consistent radio and X-ray observations, both thermal and nonthermal, of SNRs be coordinated to help constrain broadband emission models?

While all of these questions cannot be fully addressed in a ten-week program, we hope to foster longer-term collaborations that will continue this work and benefit future observational programs.

Conference: We plan to have a conference during the program that will bring together a larger group of researchers. We think that a 3-5 day conference of ~100 people, with a concentration of theorists and plasma simulators working mainly on the nonlinear connection between particle acceleration and magnetic field amplification in shocks, is necessary. To our knowledge, this problem has not yet been the focus of a meeting. The field is developing rapidly, often along different lines of research, and a "bringing together of experts" should be extremely beneficial. We feel that the best time for the conference is near the middle of our program and the only potential conflict we have identified is the XXVII IAU meeting in Rio de Janeiro (Aug 3-14, 2009).

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