Topic 9: Relativistic, pair-dominated and strongly magnetized plasmas

1. Introduction

Relativistic, pair-dominated and strongly magnetized plasmas are ubiquitous in the high energy universe. Their properties, behaviors and observable manifestations often differ drastically from those of ordinary plasmas. While some theoretical progress has been made in the past decades, such plasmas have rarely been studied experimentally in the laboratory. This landscape is rapidly changing due to the advance in ultra-intense lasers and accelerator beams that makes the laboratory creation and controlled studies of such plasmas a reality.

2. Key Scientific Challenges

Here we discuss challenges and opportunities in relativistic plasmas, focusing on four main topics: (1) dissipation of relativistic beams and collisionless shocks; (2) creation of pair-plasmas and ultrastrong magnetic fields; (3) relativistic jets; (4) relativistic turbulence and reconnection.

2.1 Beam Dissipation and Collisionless Shocks

Violent astrophysical phenomena often produce relativistic directed outflows such as pulsar winds (PW), gamma-ray bursts (GRB), jets in active galactic nuclei (AGN) and microquasars. Such outflows are observed because they produce intense radiation throughout the electromagnetic spectrum. For this to happen, bulk flow energy must be efficiently converted into the internal energy of the radiating electrons and magnetic fields. Theory and computer modeling indicate that Weibel-like current instability likely play an important role when relativistic beams/outflows interact with an unmagnetized plasma. Although Weibel (1959) instability has been well studied theoretically, there has been few dedicated experiments to test it in relativistic beams. Weibel instability also plays a critical role in relativistic collisionless shocks. Shocks are believed to be responsible for the observed radiation of pulsar wind nebula (PWN), Gamma Ray Bursts (GRB), some AGN jets, and the production of high-energy cosmic rays. Besides dissipating the bulk flow energy, shocks accelerate nonthermal particles and generate/amplify magnetic fields. However, the physics of relativistic collisionless shocks and the resultant particle acceleration and magnetic field generation are not fully understood.

Major scientific questions on relativistic beams and shocks include: (1) how do the growth and saturation of Weibel-like instability depend on the beam size, density, composition, temperature and Lorentz factor? (2) when is Weibel stabilized or suppressed? in that case can beams still dissipate efficiently via 2-stream electrostatic instability? (3) how does Weibel-generated magnetic turbulence form shocks and accelerate nonthermal particles? (4) what is the radiation output from current-unstable electron beams? (5) how does the shock structure depend on upstream magnetization, composition (pair vs. e-ion), and field geometry? (6) how do relativistic and strongly magnetized shocks differ from nonrelativistic and unmagnetized shocks?

2.2 Pair plasmas and ultra-strong magnetic fields

Relativistic electron-positron (e+e-) pair plasmas are ubiquitous in the high energy universe, from the first few seconds of the Big Bang, to pulsar winds, blazars jets, and GRBs. Transient thermal pair-equilibrium plasmas may also be present around stellar-mass black holes during gamma-ray flares. Because of the unity mass ratio, pair plasmas behave differently from electron-ion plasmas in many respects. Hence it is extremely desirable to study pair plasmas in the laboratory, both for the fundamental physics and for astrophysical applications. Neutron star magnetic fields can exceed 100TG, while white dwarf fields may reach 100MG. Ultra-intense lasers are now capable of generating transient fields approaching 10^9G, which overlaps with magnetic white dwarfs and millisecond pulsars. The study of laboratory plasmas with strong fields may demonstrate for the first time that the conditions appropriate to the atmospheres of these neutron stars and magnetic white dwarfs can be reproduced in a terrestrial laboratory. Measurements of such plasmas may enable the study of highly dynamical phenomena such as the "photon bubble" instability. They may also permit probes of non-linear regimes of the Zeeman effect in hydrogenic atoms, as well as "guiding center drift atoms" where the strong field changes electron orbits into ExB drift orbits. Laboratory insights hence may spawn new observational diagnostic of neutron stars and magnetic white dwarfs. Theories of anisotropic radiation and particle transport in strong fields may be meaningfully tested in the laboratory. For example, lasers coupled with gigagauss magnetic fields will allow us to probe the Landau levels using resonant scattering, and explore laser cooling of magnetically trap electrons. Since pairs and strong magnetic fields are both present in neutron star magnetospheres, the simultaneous creation of pairs and strong fields using ultra-intense lasers will provide a unique platform to study neutron star physics.

Major scientific questions on pairs and strongly magnetized plasmas include: (1) How does pair plasma kinetics, such as plasma instabilities, wave-particle interactions, particle acceleration mechanisms and radiative processes, differ from e-ion plasmas? (2) Can thermal pair-equilibrium plasmas be created in the laboratory? (3) What are the observable manifestations of pair plasmas besides their annihilation radiation? (4) How do strong magnetic fields alter the atomic structure, ionization, collision and radiative properties? (5) Can novel astrophysical phenomena such as the "photon-bubble" instability in accreting neutron stars be tested in the laboratory? (6) Can we model the magnetospheres of strongly magnetized white dwarfs and neutron stars using laboratory experiments?

2.3 Relativistic jets

Relativistic jets are long narrow dynamic structures that emanate from compact objects such as stellar mass black holes, neutron stars, and active galactic nuclei. Despite their widespread occurrence, many aspects of astrophysical jets are not well understood, e.g. how jets are launched and accelerated, why jets are so narrowly collimated, why jets appear to be extremely stable and straight. Moreover, the relative abundances of ions, pairs and Poynting flux are not known, and their roles in the jet dynamics, dissipation and radiation remain to be understood. Only a few jet parameters can be determined through observations so models of jets are still in a primitive stage. However, new observations from Fermi and other observatories will shed important new light on jets.

Major scientific questions on relativistic jets include: (1) how are relativistic jets launched and accelerated? (2) why are relativistic jets so well collimated? (3) why are they so stable? (4) do relativistic jets behavor differently from non-relativistic jets? (5) what are the differences between Poynting flux and hydrodynamic jets? (6) how do the multi-scale jet regions interact with each other (e.g. via internal shocks, shear layers and/or reconnection)? (7) how do e+e-pair jets behave differently from e-ion jets? (8) which kinetic dissipation and radiation mechanisms are important in jets?

2.4 Turbulence and Reconnection in Relativistic Plasmas

Many astrophysical plasmas exist in a strongly turbulent state, where the local properties such as density and electromagnetic fields experience quasi-random fluctuations driven by large scale forces, due to motion of macroscopic bodies or plasma elements. Dissipation of turbulent motion leads to plasma heating, generation of magnetic field and acceleration of particles to super-thermal energies. Thus the interpretation of many astrophysical observations, from solar flares to black hole accretion disks, requires understanding of turbulent processes. Though these environments are very different in terms of plasma parameters, the turbulent processes can be generally grouped into several categories: MHD (collisional) turbulence; Whistler/Hall turbulence; Shock-and-reconnection-generated turbulence; Turbulence in collisionless plasmas; Turbulence in strongly magnetized plasmas (sigma >1). The new features we are adding to this list are relativistic plasma temperatures, and/or flow speeds and pairs. As turbulence cascades down to the kinetic level, eventually it forms large numbers of thin current sheets. Hence the dissipation of turbulence at the kinetic level is inseparable from that of reconnection and current sheet instabilities.

Sample scientific questions on relativistic turbulence and reconnection include: (1) Alfven/whistler/Hall turbulence. As the turbulent cascade propagates to smaller scales, the typical frequencies of fluctuating electromagnetic field may become high enough so that ions stop responding to them. What are the properties of the turbulence in this case? (2) Turbulence in collisionless high beta plasmas. In most relativistic regimes, coulomb collision times are much longer than the cyclotrons and plasma oscillations periods. How does dissipation proceed on kinetic scales? (3) Turbulence in strongly magnetized plasmas (e.g. corona of magnetars, AGN and GRB jets), where energy density of magnetic field exceeds plasma energy density, including rest mass. In all of these turbulence types the key questions are: what are the spectra and anisotropic properties of the fluctuating quantities on different scales, and what are the spectra of particles accelerated by Fermi-type diffusion mechanism and DC-electric field generated in current sheets and reconnection sites. This is an especially promising route in a magnetic-dominated plasma, where most of the energy is stored in the magnetic field. (4) How do current sheet dissipation and reconnection proceed in relativistic/pair/strongly magnetized plasmas?

3. Major Opportunities

In addition to advances in theory and computer simulation, the study of relativistic plasmas will benefit from new experiments using lasers and particle beams. Below we highlight some emerging experimental opportunities.

3.1 The ability to perform relativistic beam dissipation and shock experiments in the laboratory will provide critical new information on the complex shock physics and cosmic particle acceleration, and allow the calibration of the computer codes. Intense lasers and accelerators are ideal tools for generating relativistic beams and collisionless shocks in the laboratory. A collisionless ambient plasma may be first created using the Z-machine at SNL, or long pulse lasers at Omega and NIF, to heat a sufficiently large volume of hydrogen plasma to multi-keV temperatures so that it becomes collisionless. Then a short pulse laser of intensity $>10^{20}$W.cm^{-2} can be used to deliver a strong shock in this overdense plasma. While the shocks generated by such collisions will only be mildly relativistic ($\leq 0.1c$), it can propagate through a large volume of plasma so that it can be studied in detail. Such mildly relativistic shocks are relevant to the afterglows of GRBs and blazar jets and microquasars. Alternatively, multiple short pulse lasers, such as the Omega-EP or NIF-ARC system, can create colliding multi-MeV electron-positron jets. Provided that these jets can be generated with sufficient density and column density, so that the interaction region is larger than the plasma skin depth, they may be able to form ultra-relativistic shocks with Lorentz factors > 50, which are relevant to the emissions of AGN, GRB and PWN. Particle beams produced by conventional accelerators may also be able to drive relativistic shocks after undergoing current filamentation instability. Current filamentation experiments are underway at the Brookhaven Natioanl Laboratory and are planed at the SLAC FACET facility.

A critical need for studying relativistic Weibel instability is diagnostic development. Weibel instability may be probed indirectly using the jitter radiation emitted by the hot electrons passing through the self-generated turbulent magnetic field. A more direct approach is to image the transition radiation emitted when the electron/positron filaments emerge from a target. The magnetic fields created by Weibel may be probed using deflection of proton beams created by another intense laser. Computationally, 3D PIC simulations of Weibel need to be extended to much larger domains in space and time to replicate realistic laboratory conditions, not to mention astrophysical settings. This will require larger supercomputers (100000 CPUs, terascale to exascale memory system), faster, memory-efficient algorithms, as well as smarter graphics/visualization software to handle the corresponding large amount of data generated in the simulations. In addition to lasers with intensities $>10^{20}$W.cm^{-2}, magnetized shock experiments will require >10MG pulse magnets. Relativistic shocks also need to be diagnosed on picosecond time scales to measure in-situ temperature, density, magnetic field, pair fraction, particle spectra, and radiation output with high spatial resolution. Computationally, we need to link and merge various multi-physics codes to perform end-to-end simulations of realistic shock experiments, including 3D MHD, PIC, and hybrid codes, plus post-processing codes to model the radiation. DOE supercomputers such as the Roadrunner should be made available to academic groups working on Weibel and shocks. An international team of leading academic groups and experimentalists at the laser facilities should be formed to integrate astrophysical observation, theory, simulation and laboratory experiments. **We strongly recommend a 5-year dedicated pilot program to study this topic**.

3.2 Lasers with intensity$>1.4\times10^{18}$Wcm^{-2} irradiating solid high-Z (e.g. Au) targets can be used to create e+e- pairs in a high-Z target, via the Trident and Bethe-Heitler processes. Recent experiments using the LLNL Titan laser irradiating mm thick Au targets created an estimated 10^{11} pairs in a picosecond, with an estimated in-situ pair density $>10^{16}$cm^{-3}. Later experiments at OMEGA- EP produced even higher pair yields, and showed that the pairs have a quasi-thermal energy distribution. Future experiments at NIF-ARC should produce much higher pair yield and density. Conventional accelerators can also produce GeV e^+/e^- bunches with densities in the 10^{17}cm^{-3} range. To replicate radiation-dominated neutron star accretion columns in the laboratory we require radiation temperatures of the order of 1 keV at densities of order 10^{-3}g/cc and magnetic fields ~0.1-1Gigagauss, which would be required to prevent transverse expansion of photon bubbles and confine the plasma to flow in one direction. Ultra-strong fields can be generated by relativistic laser interactions ($>10^{18}$ W/cm^2) due to currents produced by supra-thermal electrons accelerated in the evanescent region of the laser plasma. This magnetic field is in the azimuthal direction about the laser axis and the peak field extends for about an anomalous skin depth into the plasma, near the critical surface during the actual time of the interaction of the picosecond laser pulse with the high density plasma. Such fields cannot be measured with conventional techniques such as Faraday rotation.

The needs of future pair plasma experiments include: (1) dedicated facilities with multiple kJ-class PW lasers, (2) diagnostic developments for measuring in-situ pair densities and temperature, and positron to ion ratio, (3) techniques for trapping and cooling dense pair plasmas, (4) techniques to accelerate and collimate pairs to form pair jets. Computationally, we need to link 3D plasma codes with particle physics codes (e.g. CERN-GEANT4) to perform self-consistent end-to-end simulations of pair creation experiments. A coordinated program to create relativistic pair plasmas and study their astrophysical and technological applications should be formulated. Such a program should involve astrophysicists, positron physicists, accelerator physicists and laser experimental teams at DOE facilities.

Experimental work is presently behind theory in the creation of superstrong magnetic fields. Precise magnetic field measurements are most critical to identify the important mechanisms and to verify predictions. To date the highest measured fields (up to 0.7 Gigagauss) have been inferred by laser plasma interactions at 10^{20}W/cm^2 using polarization measurements of scattered radiation. With intensities up to 10^{23}W/cm^2 becoming available with pending lasers, magnetic fields greater than several Gigagauss should be generated, which should allow a more systematic study of high field physics. The use of charged particle probe beams (e.g. protons) may allow the strength and dynamics of the magnetic fields to be measured with high resolution. To examine the "photon bubble" instability requires the co-location of a nanosecond high energy laser system with a PW-level short pulse laser to produce the large B-fields, plus another high power short pulse laser to generate a particle probe beam. Several facilities which are capable of such experiments are presently in operation (OMEGA-EP, HERCULES, Texas Petawatt) and others are under construction (NIF-ARC). To model pulsar magnetospheres we need the co-location of pair plasmas and superstrong fields. Such experiments may be pursued with NIF-ARC, using some of the laser beams to create the pairs while using other beams to create the superstrong magnetic fields.

3.3 Modern laboratory experiments on magnetized jets use advanced pulsed power magnetic technology and have been underway at Caltech and at Imperial College. Magnetized jet experiments are also planned at Cornell University and at the University of Nevada, Reno. Laboratory experiments on unmagnetized hydrodynamic jets using high energy density laser technology are underway at the University of Rochester and at the Rutherford Appleton Lab. However the detail characterization of most jet parameters has not yet been performed. Relativistic jets of electrons and hybrid electron-pair plasmas have been generated using ultra-intense short pulse lasers and conventional accelerators. Recent experiments at Omega-EP demonstrated that laser- created positrons can be efficiently accelerated to Lorentz factors > 20 by sheath electric fields to form a relativistic jet.

The conjunction of new experimental facilities that can replicate essential features of astrophysical jets, new computer codes that can solve the complex systems of equations characterizing jets, and new telescopes that can observe jets with higher energy and resolution than ever before, indicates that the next decade is a time of remarkable opportunity for developing an understanding of relativistic jets which have been an enigma for many decades. To take advantage of this opportunity it is proposed that a National Center for Astrophysical Jet Studies be established. This Center would support the experimental, numerical and observational studies now underway at a number of institutions under one roof and would coordinate these efforts by holding regular workshops. The Center, by promoting a synergism of the institutions now working on jets, would greatly accelerate the rate at which the questions listed above become addressed and answered.

3.4 If we inject relativistic electron/positron or MeV proton jets generated by intense lasers into a plasma with a steep density gradient, or if we can create multiple relativistic colliding shocks using multiple laser beams, they may be able to generate sufficient plasma turbulence to address some of the questions above. Furthermore, if we can also create magnetic fields of opposite polarities in the ambient plasma prior to the jet/shock interactions, the MHD turbulence created by the jet-jet/jet-plasma interactions may induce or enhance current sheet dissipation and magnetic reconnection. This will help to address the outstanding question whether turbulence can dissipate and nonthermally heat electrons/positrons/ions by enhancing the current sheet dissipation and magnetic reconnection. The physics of current sheet dissipation and reconnection in relativistic and/or pair plasmas is important to black hole accretion, the pulsar wind "sigma problem", gamma-ray bursts and many other high energy astrophysics phenomena.

Multiple intense lasers will be needed to create the colliding shocks or particle beams capable of generating relativistic plasma turbulence. At present only NIF at LLNL may possess such capability, if the proposed short pulse ARC beams are completed. In addition to the lasers, pulsed magnets of > 10 MG fields with reversing polarities will be needed to create intense current sheets. Diagnosis of the magnetic field, particles and waves generated by the turbulence will be major challenges. New diagnostic techniques will be needed before meaningful measurements can be made. Computationally, the huge gap between MHD and PIC simulations will need to be bridged before we can confidently explore the cascade from the MHD to the kinetic scale. 3D reconnection simulations have recently reached a major threshold where electron-positron plasmas can be meaningfully studied with sufficient mode numbers for both the kink and tearing instabilities. However, realistic electron-ion simulations in 3D reconnection is still in its infancy and must await even faster and larger supercomputers. To study particle acceleration in turbulence and reconnection, we need to keep track of only the most energetic particles. Finally, since radiative cooling may be energetically important in strongly magnetized relativistic plasmas, radiative damping terms will need to be included in PIC codes for some turbulence and reconnection applications.

4. Impacts and connections to other topics

4.1 The physics of beam dissipation and collisionless shocks provides the foundation for understanding the most energetic phenomena of the universe, from gamma-ray bursts to high energy cosmic rays. This subject will benefit from close interactions with the NASA community. Results of laboratory experiments should be rapidly communicated to astrophysicists analyzing Fermi data. These plasma phenomena are also critical to future technologies such as the Fast Ignition approach to inertial fusion.

4.2 Both pair plasmas and gigagauss magnetic fields are important frontiers of high energy astrophysics. Creation of such plasmas in the laboratory will allow us to explore these most exotic regimes in astrophysics. Potential technological applications of such plasmas have not been thoroughly explored, but are clearly transformative. Study of this new regime of plasma physics should be strongly supported and encouraged by funding agencies.

4.3 Relativistic jets are only the extreme version of jets from young stellar objects to white dwarfs and neutron stars. The study of relativistic jets is therefore intimately connected to that of nonrelativistic jets. There should be considerable synergism between both kinds of jets.

4.4 Relativistic turbulence and reconnection are extensions of conventional turbulence and reconnection. Advances in their understanding will undoubtedly benefit the study of this topic.