Topic 2: Collisionless Shocks and Particle Acceleration

2.1 Introduction and Current Status

Shocks generally result from the collision of two flows, which occurs frequently in the Cosmos, from the interaction between the small-scale flows of the heliosphere to the interaction between large-scale flows characteristic of galactic clusters and the jets in Active Galactic Nuclei (AGN). Shocks observed in the solar wind include planetary bow shocks, the shocks driven by coronal mass ejections (CMEs), the shocks formed by the collision of fast and slow wind from adjacent regions of the Sun, and the solar wind termination shock. Shocks in the Galaxy and beyond include those driven by supernovae explosions, galactic winds, AGN jets, accretion onto compact objects, galactic motions in galaxy clusters, and Gamma Ray Bursts. These shocks span a huge domain of spatial scale, strength and plasma parameter space. Because particle densities are generally very low throughout most of the Cosmos, the mean free path due to Coulomb collisions is typically large compared with the shock spatial scales of interest. Therefore, most shocks are collisionless and the interaction between the far upstream and far downstream plasmas is mediated by electromagnetic fields. An interesting exception is charge-exchange coupling of the interacting upstream and downstream plasmas to the atoms present in partially ionized plasma. Despite their diversity, collisionless shocks share common characteristics: they are observed to accelerate nonthermal particles efficiently and to generate and amplify magnetic fields, in addition to decelerating supersonic flows.

Shocks convert a fraction of the ordered kinetic energy density of the upstream flow to the higher entropy per unit mass downstream flow by dissipative processes occurring in the shock layers. As a result of the nonlinear plasma processes involved in the shock layers, and their diversity due to the broad range of possible plasma parameters, a general understanding of the physics of shock structure is challenging. The interaction between the upstream and downstream plasmas involves (i) the ambient magnetic field and its obliquity relative to the shock normal, (ii) an electric field parallel to the shock normal associated with charge separation in an ion-electron plasma (which can contribute to reflecting inflowing ions), (iii) a rich variety of possible streaming instabilities that excite electromagnetic fluctuations, which in turn couple the flows by scattering the individual ions and/or electrons and produce an effective resistivity and viscosity in the shock layers, and (iv) particle acceleration from thermal energies up to relativistic energies. Each of these processes/instabilities, affecting the different particle species, is characterized by its own length scale parallel to the shock normal so that a particular shock will exhibit multiple length scales characteristic of the relevant processes/instabilities.

2.2 Key Scientific Challenges

A. Are Shocks in the Cosmos Well Described as Planar and Stationary?

Theoretical models of shocks are often based on the simplifying assumptions that they are stationary, and planar on the length scale of the shock structure. Although the plasma kinetic processes responsible for the dissipation are clearly not planar and stationary, the assumptions are rooted in the idea that the planar stationary “shock” resulting from an average over a large appropriately chosen ensemble of shocks provides a reasonable representation of the shock structure and physics. Community intuition about shock structure is often based on these ensemble-averaged shocks. However, observations and numerical simulations reveal interesting time dependence (sometimes periodic) and important spatial variations along a complex warped surface. Warps with a length scale similar to the turbulence correlation scale in the solar wind have been observed in interplanetary traveling shocks using multi-spacecraft measurements (Neugebauer and Giacalone, 2005). Warps change the local magnetic obliquity of the shock, which for example affects particle injection and acceleration (see Section 2.2.B). A major source of variations along the shock surface is inhomogeneity of the upstream plasma, especially density variations. The density variations create surface warps and inhomogeneous bulk flows downstream, which can drive turbulence and magnetic field amplification (Giacalone and Jokipii, 2007). An interesting temporally periodic feature of quasi-perpendicular shock structure revealed by simulations is shock re-formation (Scholer and Burgess, 2006). In general the mechanism of shock re-formation is unclear. However, for large Mach numbers it appears to result from overstable proton reflection by an unsteady shock potential that results in periodic dissipation and a periodic variation in shock speed and location. Although shock re-formation can have important consequences for particle injection, for example, it is challenging to detect with spacecraft measurements.

B. Understanding Particle Injection and Diffusive Acceleration at Shocks

An important channel of shock dissipation is particle acceleration by a combination of first-order Fermi acceleration and shock drift acceleration known as diffusive shock acceleration (DSA) (Axford et al., 1978; Bell, 1978; Blandford and Ostriker, 1978; Krymsky, 1977). This mechanism is responsible for most of the energetic particle populations in the heliosphere, the majority of galactic cosmic rays, and presumably many of the other energetic particle populations in the Cosmos. At higher energies the mechanism is conceptually straightforward, although the nature and excitation of electromagnetic fluctuations and their impact on particle scattering and transport is not well understood (see Section 2.2.C). The major uncertainty in application of the mechanism to specific shocks and their associated energetic particles is the rate at which upstream thermal particles are injected into the process. This uncertainty undermines the predictive power of diffusive shock acceleration and is presumably in part responsible for the huge variation in observed ion intensities in solar energetic particle events (Kahler, 2001). The injection rate is certainly dependent on the detailed electromagnetic structure of the shock, which determines the rate at which incoming particles are reflected or scattered back upstream, and it appears to be very sensitive to the local magnetic obliquity. For quasi-perpendicular shocks, particles with energies comparable with the normal component of the upstream plasma velocity relative to the shock are not able to scatter sufficiently to initiate diffusive shock acceleration before being swept through the shock by the magnetic field. Determining the injection mechanism is nontrivial. Even after years of investigations at Earth’s bow shock based on ISEE and Cluster data, the origin of the field-aligned beams that initiate the ion acceleration process is unknown.

Finally, the lower injection rate of electrons when compared with ions, in spite of the higher speed of electrons, is not well understood.

C. Understanding Magnetic Field Amplification at Shocks

The ambient magnetic field fluctuations in the solar wind and interstellar space are generally not sufficient to yield efficient diffusive shock acceleration. However, the accelerating particles are a high-energy manifestation of the interpenetrating upstream and downstream plasmas. The streaming of these particles relative to the upstream flow excites the cyclotron-resonant hydromagnetic streaming instability at lower proton intensities, the non-resonant current-driven instability at higher proton intensities, or variations of these instabilities. The hydromagnetic instability, which maximizes for wave propagation parallel to the ambient magnetic field, is generally evident as an enhancement in the upstream hydromagnetic fluctuation power at quasi-parallel shocks in interplanetary space, which are able to inject solar wind ions into the acceleration process (Lee, 1983; Kennel et al., 1986). The waves often grow to large amplitude, are compressed at the shock, modify the shock structure, and provide effective particle scattering downstream. They also modify the compression ratio sensed by the accelerating particles. Upstream of Earth’s bow shock, where wave magnetic amplitudes are comparable with the ambient field strength, the compressive front of a magnetosonic wave is often observed to grow to a Short Large Amplitude Magnetic Structure (SLAMS), which presumably is excited by the free energy released by the ions which it scatters in enhanced numbers back toward the shock (Lucek et al., 2008). Other compressive wave fronts form “shocklets” (Hoppe et al., 1981), which generate whistler precursors. The details of many of these processes including their initiation are not well understood, particularly the nonlinear evolution of the excited hydromagnetic waves. They need to be pursued by analytical and numerical investigations.

At quasi-perpendicular shocks the streaming instability is not as effective. Particle transport across the average field is primarily by random walk of field lines, which leads to small scattering mean free paths parallel to the shock normal and steep spatial gradients. This configuration is unstable to a version of the Rayleigh-Taylor instability as the upstream plasma is decelerated by the ion pressure gradient (Drury and Falle, 1986; Zank et al., 1990). The resulting warped field lines in the shock precursor presumably reduce the magnetic obliquity, increase the field strength, and increase injection rates and acceleration efficiency. This scenario is speculative and requires further calculations and simulations.

The magnetic field amplification by the non-resonant current-driven instability is now well established theoretically (Lucek and Bell, 2000; Bell, 2004) and observationally, through the analysis of X-ray images of supernova remnants. This result is crucial to the theory for the origin of galactic cosmic rays up to the “knee” at SNR shocks (see Section 2.3.A).

2.3 Major Opportunities

A. A Major Initiative to Understand the Acceleration of Cosmic Rays

The discovery of cosmic rays a century ago marked the beginning of space science, led to the discovery of many new subatomic particles, and ushered in the Space Age. Incredibly we still do not fully understand the origins of these particles. The most promising source of the bulk of cosmic rays up to the "knee" appears to be diffusive shock acceleration at the shocks driven by supernovae remnants. Shocks can produce power-law energy spectra, recent X-ray and γ-ray observations show that electrons and/or protons are accelerated to TeV energies in supernovae remnants, and theory has shown that magnetic fields are amplified at strong shocks to magnitudes that enable them to accelerate protons to the "knee." However, many questions remain including the injection rates of electrons and protons at the shock, why cosmic ray electrons and ions have different power-law spectral indices, why cosmic ray anisotropies are so small, what is the source of the cosmic rays beyond the "knee," and which nearby sources accelerate the highest energy electrons. With key observations available from HESS, FERMI, AUGER, PAMELA and many other spacecraft, balloon and ground-based experiments, and the development of powerful numerical simulations (Spitkovsky, 2008), the time is ripe to concentrate on the remaining pieces of the puzzle. Understanding the origin of cosmic rays requires an interdisciplinary approach focused on the structure of supernovae remnants and their shock, the process of diffusive shock acceleration, and the galactic propagation of cosmic rays.

B. Renewed Investigation of Shock Structure and Formation in the Laboratory

With relatively primitive plasma machines and diagnostics, shocks were identified in laboratory devices in the 1960s and 1970s, a period described as the First Golden Age of shock studies. However, the slow response time of the ions, the influence of the walls of the chambers on the particle distributions and the primitive diagnostics made it difficult to establish whether the "shock" was fully formed. Between this period and the present shock studies suffered as funding decreased for magnetic-pinch fusion, the configuration in which most of the shocks had been formed. However, with the advent of new High Energy Density facilities and other facilities designed to study basic plasma physics, there are new opportunities to revive laboratory simulations of collisionless shocks. These new facilities include the Nevada Terawatt Laser Facility, the LANL-FRC and "plasma gun method" facilities, the UCLA LArge Plasma Device, UCLA's Enormous Toroidal Plasma Device and the National Ignition Facility. For example, the LAPD anticipates in about a year being able to produce a perpendicular collisionless shock with Alfven Mach number ~4 and with spatial and temporal scales large enough to include ~4 shocked proton Larmor radii/gyrations (Constantin et al., 2009). These limitations will certainly improve, and also allow for the study of quasi-parallel shocks. In collaboration with numerical simulations, such shock experiments will enable quantitative studies of shock formation timescales, proton and electron (and possibly a minor ion) dissipation processes, and electron acceleration. Such studies will improve our understanding of shocks observed in space.

C. A Study of the Connection Between Astrophysical and Heliospheric Shocks?

The plasma-β of the solar wind, including the important contribution to the pressure of interstellar pickup protons beyond about 10 AU, increases from values β << 1 near the Sun, through values β ~ 1 near Earth orbit, to values β >> 1 in the outer heliosphere. Voyagers 1 and 2 recently crossed the nearly perpendicular (at the locations of the Voyager traversals) solar wind termination shock, whose downstream pressure was inferred to be dominated by shock heated interstellar pickup protons (Richardson et al., 2008). The NASA IBEX Mission is currently measuring energetic neutral atoms to probe the global morphology of the termination shock and the other heliospheric boundaries (McComas et al., 2009). In several years the ESA spacecraft Solar Orbiter and NASA's Solar Probe Plus will explore for the first time the inner heliosphere inside 0.3 AU. Solar Probe Plus will reach a distance of 0.05 AU from the Sun. With these missions we shall have a complete heliospheric shock laboratory featuring observed shocks with a very wide range of plasma-β and magnetic obliquity, and a reasonable range of Mach number. This diverse collection of shocks allows us to investigate several outstanding questions in shock physics including the magnitudes of ion and electron injection rates, the influence of upstream fluctuations on shock warps and magnetic field amplification, the structure of nearly perpendicular shocks and their efficacy for particle acceleration, the degree of distinction between quasi-parallel and quasi-perpendicular shocks for high intensities of upstream turbulence, and the huge observed variation in the intensities of energetic particles accelerated by apparently similar shocks (Kahler, 2001). These shocks will provide a broad variety of cases to compare with numerical simulations. Furthermore, they will provide scalings for injection rates, upstream turbulence and other quantities as functions of Mach number, which should allow us to learn much about astrophysical shocks at higher Mach numbers.

2.4 Impacts and Major Outcomes

Cosmic rays have a pressure comparable with the interstellar gas and magnetic field in our Galaxy and presumably other galaxies. Establishing their origin would be a tremendously exciting accomplishment, which would highlight the interconnected roles of energetic particles, shocks and supernovae in determining the structure of galaxies and other astrophysical objects. A major unknown aspect of the acceleration of thermal plasma at a collisionless shock is the injection rate as a function of plasma parameters. The injection rate, which is not predicted by the theory of diffusive shock acceleration, is clearly dependent on the electromagnetic structure of the plasma shock transition. The opportunity to investigate shock structure and possibly injection rates as a function of magnetic obliquity in several current and planned laboratory plasma experiments, with supporting numerical simulations, is sure to advance significantly our understanding of shock structure and particle acceleration. Finally, the ongoing in situ observational and theoretical studies of shocks in the heliosphere and their associated energetic particle populations will provide insights into their structure and specific shock processes such as injection. The solar wind termination shock, recently encountered by Voyagers 1 and 2 and currently viewed remotely by IBEX, is challenging our ideas about shocks; in a few years Solar Orbiter and Solar Probe Plus will encounter shocks close to the Sun in a domain with small plasma-β unlike any we have observed previously. These observations of heliospheric shocks, with the support of numerical simulations, will provide scalings and insights into the nature of astrophysical shocks.

2.5 Connections to Other Topics

Much of the material in Sections 2.1 – 2.4 has described the unstable growth of magnetic fluctuations at a shock (and their associated velocity fluctuations, density fluctuations and plasma heating) into large amplitude structures as an intrinsic feature of collisionless shocks. Since a shock can generally be viewed as a large-amplitude magnetosonic wave, this is perhaps not surprising. Although the growth of the magnetic fluctuations may be couched in terms of wave growth and quasilinear theory, the importance of nonlinear wave-particle and wave-wave interactions is apparent, particularly for the strong shocks expected in interstellar space. The question arises whether these fluctuations evolve to a turbulent state in which the initial quasilinear associations between velocities and wavevectors are lost to the characteristics of the turbulence. This must certainly be the case for sufficiently strong shocks. It also raises the question whether the distinction between quasi-perpendicular and quasi-parallel shocks has any meaning in a turbulent shock. Would a turbulent shock perhaps be amenable to a simpler theoretical description? This topic, at least for strong shocks, is clearly connected to Waves and Turbulence. As is evident in Section 2.2.C, the amplification of magnetic field upstream of strong collisionless shocks also connects this topic to the Magnetic Dynamo. Finally, the common association of shocks with jets and outflows (e.g. the solar wind termination shock), in particular relativistic outflows (e.g. the shocks occurring in relativistic jets from AGNs), connects this topic to Jets and Outflows Including Structure Formation and to Relativistic, Ultra-strongly Magnetized, and Pair Plasmas.

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