White Paper for *Frontiers of Plasma Science Panel*

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Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	S
• Turbulence and transport	P
• Interactions of plasmas and waves	S
• Plasma self-organization	
• Statistical mechanics of plasmas	S

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Either Oral or Poster	
Will not attend	X

Title:	Structure and Dynamics of Shocks in Inhomogeneous Space Plasmas
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- ***Describe the research frontier*** **and importance of the scientific challenge.**

The propagation of a shock wave through a medium of non-uniform density, sometimes referred to as shock-accelerated inhomogeneous flow (SAIF), occurs in a wide variety of physical situations covering broad ranges of spatial, temporal, and energy scales.

SAIFs are an integral component of understanding laser-driven high-energy experiments, play an important role in sonoluminescence and nautical cavitation. Beyond the terrestrial context, SAIFs are of fundamental importance to understanding the dynamics and transport processes of space plasmas on virtually all cosmic scales. We will focus here on the astrophysical relevance of SAIFs such as those shown in the figure.

Because of the existence of several stable thermodynamic branches of density, temperature, and ionization state at a given pressure, interstellar plasma generally occupies spatially distinct, inter-mixed regions of different density phases, some of which may be neutral or partially ionized, while most of the volume will be occupied by hot, fully ionized plasma [Cox].

The dynamics of interstellar turbulence is driven largely by large-scale shocks from supernova explosions. Shocks in space plasmas are also generated by gamma ray burst explosions, large-scale bulk flows (accretion of matter onto galaxies and galaxy clusters and by mergers of galaxies and clusters of galaxies), the expulsive release of relativistic plasma from accreting black holes both on stellar and

galactic scales, as well as supersonic turbulence, which itself may be the result of one of the above mechanisms.

Given that separate states of well defined densities co-exist in the ISM and IGM and that shocks are prevalent in almost all astrophysical plasmas and responsible for energizing large parts of the interstellar plasma, it is *unavoidable* that SAIFs play an important role in the dynamical evolution of diffuse interstellar gas. Understanding SAIF from a laboratory and computational perspective is therefore crucial for understanding the structure and evolution of interstellar plasmas and gases.

SAIF also carries significance for the process of particle acceleration in shocks. For example, it was recently shown that SAIF could significantly increase the efficiency with which relativistic particles are accelerated at shocks propagating into inhomogeneous media [Klein, Hwang, Phillips, Beresnyak, Marcowith].

Supernova explosions deviate significantly from spherical symmetry (as evidenced, for example, by the large kick velocities of pulsars), likely a result of intrinsic inhomogeneities of the progenitors and the non-linear nature of the explosion in both nuclear fusion type I supernova detonations and core-collapse type II supernova explosions [Hillebrandt, Brouillette, Maier], where SAIF-driven turbulent mixing may affect the yields of heavy element production.

The complexity of SAIFs poses a number of challenges that must be addressed to understand the propagation of shocks in realistic multi-phase/inhomogenous media. Fundamental questions (challenges) include

C1: What is the structure of collisionless SAIFs? How is the structure of MHD shocks altered in the presence of inhomogeneities? How does turbulence and vorticity generation in SAIFs affect the generation of magnetic fields in interstellar gas?

C2: How much vorticity is generated in SAIFs in media more complicated than the simple geometric realizations studied so far? Studies should focus in particular on the propagation of shocks through fully turbulent of highly filamentary media.

C3: How does the presence of SAIFs alter the thermodynamics of interstellar and intergalactic gas?

C4: How is particle acceleration by First Order Fermi and other diffusive acceleration processes affected in SAIFs?

C5: What is the effect of shock propagation on ignition in reactive inhomogeneous media, such as in supernovae?

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

The study of SAIFs requires developments on four fronts:

- **Laboratory fluid experiments**: Basic, macroscopic properties of SAIFs are best studied in laboratory fluid experiments. Mach numbers and Atwood numbers of laboratory fluid experiments are comparable to those of most astrophysical instances of SAIFs. This requires ongoing investigation of SAIFs in shock tube experiments. Fluid studies will address challenges [**C2**], [**C3**], and [**C5**]. Although high energy density (HED) shock tubes have been studied in large laser facility experiments [Drake], they are limited to integral measurements (line of sight) and cannot achieve the high spatial resolution density and velocity fields obtainable in a conventional shock tube. Hydrodynamic similarity is the key to making shock tube studies relevant to SAIFs in astrophysical plasma. The three fundamental parameters necessary for hydrodynamic similarity are Mach number, Reynolds number and Atwood number. Shock tube experiments on the order of M~2 provide similarity for shock wave speeds found in galaxy clusters [Merloni]. Reynolds number scaling is achievable for low-density astrophysical plasmas

where Reynolds number behind a shockwave is $Re \sim 10^4$. The Atwood number, or relative density ratio, approaches unity in the ISM or IGM due to the large density difference with clouds or clumps; while this can be achieved easily in computer simulations, shock tube experiments are typically limited to $A \leq 0.95$. Similar scaling arguments can be made for fluid shock tube experiments and HED laser-driven experiments [Hansen, Ranjan].

- **Laboratory plasma experiments:** HEDP experiments have been employed to study SAIFs in the context of inertial confinement and will continue to provide important insight into SAIFs in the. However, the study of space plasmas requires macroscopic low density, low energy experiments. The challenge in preparing a stable multi-fluid interface in a plasma context and driving a shock across the interface may be addressed in the context of magnetically driven flows [Bellan]. Plasma experiments will be able to address [**C1**] and [**C3**].
- **Macroscopic computational investigation of SAIFs:** Macroscopic propagation of shocks in inhomogeneous media should be studied using MHD simulations [Li]. More sophisticated treatment of transport in plasma codes will be necessary to study shock structure and the effect of magnetization on the development of Richtmyer-Meshkov instability in magnetized SAIFs. This work will address [**C1**], [**C2**], [**C3**], and [**C5**].
- **Kinetic Simulations of SAIFs:** First-principle numerical calculations by Particle-in-Cell Codes (PIC) and analytic approaches will be required to address the kinetic theory of SAIFs and the effects of SAIFs on particle acceleration [Capriole] and field generation [Huntington]. Ab initio kinetic simulations will be able to address challenges [**C1**] and [**C4**].

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

Super-critical pressure discontinuities are abundant in space plasmas. The study of SAIFs will inform our understanding of plasmas both within the solar system (as the structure of the heliosphere as the Sun traverses different phases of the interstellar medium) and on Galactic and extra-galactic scales. A detailed understanding of how supernovae energize the interstellar medium and drive large scale turbulence requires a solid understanding of SAIFs, and it is likely that SAIFs play an important role in the energetic of even the largest cosmic structures, galaxy clusters, which undergo shocks for a variety of reasons and are important probes in the study of cosmology and structure formation [Vikhlinin, Allen].

Given the wide range of terrestrial conditions in which they occur, studies of SAIFs will impact a variety of technologies and scientific fields. The most obvious terrestrial applications include inertial confinement and other forms of high-energy and explosive phenomena. Potential societal benefits may include advances in fusion research, increased efficiency in combustion engines, robustness of structures in supersonic aviation, industrial fluid applications and the development of blast-resistant materials.

Experimental and numerical techniques developed towards modeling SAIFs will have wide applicability in related studies – for example, shock tube diagnostics can be employed in a wide range of high-speed experiments, both within fluid mechanics and plasma studies as well as other fields where high-speed phenomena occur. Magneto-hydrodynamic and plasma kinetic codes similarly have wide applicability in plasma studies.

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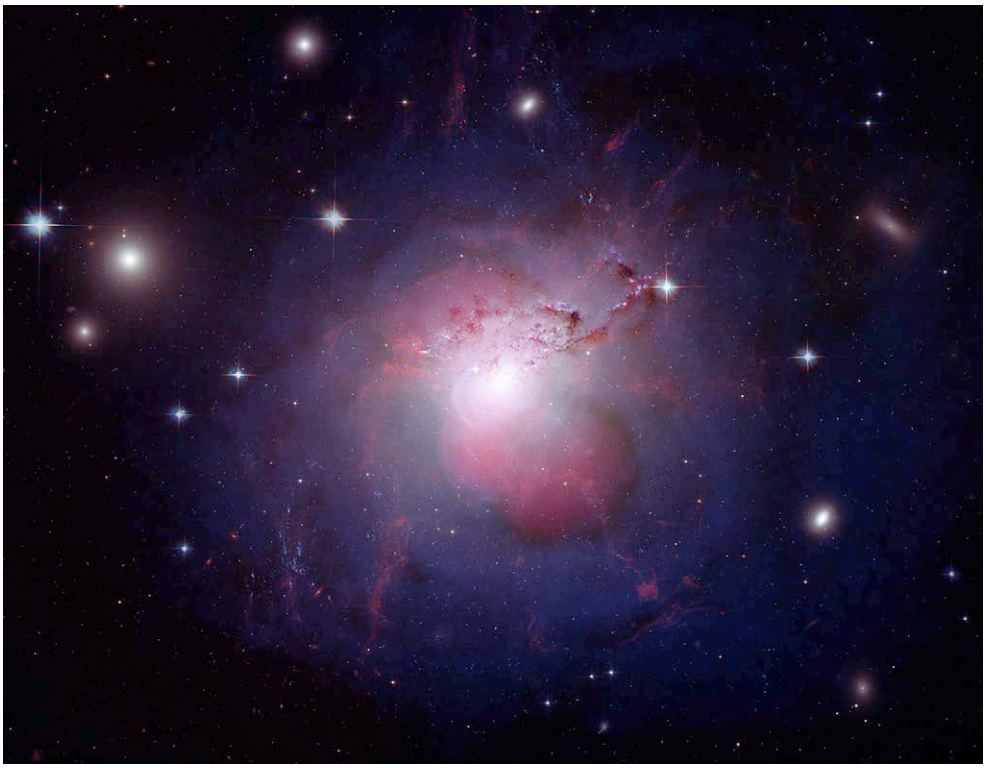
Figure



Perseus cluster (from http://chandra.harvard.edu/photo/2008/perseus/perseus_lg.jpg) showing waves, molecular gas, ionized thermal gas and relativistic plasma in a complicated filamentary mix.