Topic 6: Interface and Shear-Flow Instabilities

6.1 Introduction and current status

Interface and shear-flow instabilities are ubiquitous in space physics and astrophysics. Examples of the systems where they play a critical role include: the solar and stellar wind flow around the planetary and pulsar magnetospheres, the transitional region from solar wind to interstellar medium, photoevaporated molecular clouds, supernova explosions, blast waves in supernova remnants, and many others.

Although a linear stage of any instability is important in defining the characteristic modes, a full effect of instabilities cannot be understood without getting to their non-linear and often turbulent stage. This is where the key questions, challenges and opportunities lie.

It is impossible in this short summary to provide a comprehensive assessment of the status of the research area of interface and shear-flow instabilities and to identify all the possible points of future rapid growth in observations, simulations and theory. We present here just a few examples for the processes occurring at a broad range of scales and astrophysical objects, as well as their laboratory counterparts.

For example, the Kelvin-Helmholtz instability may play a key role in energy transport into the magnetospheres of magnetized planets and other astrophysical bodies. Recent theoretical and multi-satellite observational studies at the Earth, especially with the Cluster constellation, have suggested that vortex merging, and secondary reconnection triggered within shear flow vortices, may critically modulate the efficiency of these transport processes. Shear flow instabilities may also be important for energy transport in the solar corona especially due to the development of surface waves.

On much larger scales, from a fraction of a parsec to megaparsecs, interface and shear-flow instabilities determine properties of astrophysical jets, their collimation, intermittent behavior and the length. The electric current flowing along the jet may cause intense kink instabilities, and the shear-flow may play an important role in stabilizing them. Several laboratories (e.g. Imperial College, University of Nevada-Reno, University of Washington) have designed experiments to investigate the effect of axial flows on the stability of magnetically confined plasma columns. These experiments produce large aspect-ratio plasma jets that have a significant axial flow that in some cases is sheared. More detailed investigations could provide insight into the possible stabilizing effect, and with proper scaling would allow comparisons to astrophysical jets.

A broad class of astrophysical phenomena is determined by instabilities driven by the normal acceleration of interfaces (primarily, the Rayleigh-Taylor and Richtmyer-Meshkov instabilities). In particular, they play a very important role in Type-II supernova explosions. A number of questions remain about details of the explosion process, and an improved understanding of several might be required to form a reasonably complete picture.

6.2 Key Scientific Challenges

Challenge 6-1: How does the magnetic field affect instabilities and further non-linear *behavior of astrophysical systems (Accretion disks, Supernovae, Supernova Remnants, Jets and outflows, Dense Molecular Clouds)?*

Existing Research Capabilities.

The critically important role of the magnetic field in the behavior of astrophysical systems has been long recognized and in some cases supported by direct observations with radio interferometers (CARMA, VLA, SMA), singledish radiotelescopes (GBT) and optical telescopes with polarimeters (CFHT) [1, 2]

Techniques have been developed for introducing dynamically-significant magnetic fields to HED experiments [3] and directly measuring them (proton deflectometry). There exist laboratory facilities with magnetized plasma jets (measured velocity profiles, plasma structure [4,5]) and unmagnetized plasma jets (measured plasma structure and global velocity, including interactions with plastic).

The magneto-rotational instability is principally responsible for angular momentum transfer in the inner regions of discs around compact objects, which determines the accretion rate. In the last decade or so, most of our understanding of accretion disk MHD has come from advances in theory and numerical simulations [6] Astronomical observations are only now catching up.

Gaps.

Direct observations of the magnetic fields in astrophysics are rare: we lack sufficient collecting area to do large survey work; existing facilities could do a few objects in each category as a typical PI experiment. There is a need for detailed model predictions at the level of synthetic observations. In HED experiments, only few attempts have been made to imitate effect of magnetic fields in astrophysics.

Laboratory experiments with jets conducted thus far do not have some of important ingredients of astrophysical objects, like the presence of an axial magnetic field and significant external density. Paradoxically resilient jets have not been explained by theory and simulations; this may be an indication of incomplete physics included. Anisotropy of transport coefficients not included in numerical modeling. In many cases, diagnostics are inadequate to make detailed comparisons with models.

Magnetized shocks in the SN remnants do accelerate cosmic rays, but the cosmic rays must have a back effect on the structure and stability of these shocks. Little is known regarding, in particular, ripple instabilities of the shock front in such a setting. Getting a clear answer to the stability problem may help in explaining the complex structures observed in SN remnants. It is unknown to what extent will the ripple instability of the collisionless shock front depend on the orientation of the shock with respect to the up-stream magnetic field. It would be very interesting if some observational signatures of shock stability/instability could be found. The presence of the ripple instability may introduce additional, mesoscopic-scale features in the structure of the shock front. These processes could be assessed in properly designed laboratory experiments with collisionless plasmas. However, to our knowledge, there is no organized and supported activity in this direction.

While the MRI has been reproduced in laboratory fluid experiments, it is more difficult to reproduce in scaled laboratory plasma experiments. Also required is development of an observation strategy to identify the most salient features of the accretion related to momentum transfer with the goal of differentiating models. Laboratory experiments may provide insight into such a strategy.

Challenge 6-2: Understand the interaction of the solar wind with geomagnetic field through the smallest scales: Characterize the role of kinetic effects and magnetic reconnection in the non-linear development of Kelvin-Helmholtz instabilities (KHI) and interchange instabilities (II), and their impact for the efficiency of plasma mixing, transport, and energy propagation.

<u>Existing Research Capabilities.</u>

Fluid scale constellation (e.g., ESA-NASA Cluster) and local single satellite missions (e.g., Geotail, THEMIS), have characterized the development of non-linear KHI at the magnetopause, including the potential importance of secondary magnetic reconnection inside non-linear KHI vortices, and of II in dipolarization fronts in the plasma sheet. 3-D non-linear simulations have examined these effects in the fluid domain in global magnetospheric simulations, or at the kinetic scale in simplified geometries and/or in limited spatial domains [7].

<u>Gaps.</u>

Observational capabilities from satellites for understanding non-linear KHI and II development are mostly limited to fluid scales and/or single point measurements, and in general exclude the kinetic regime. Extended phase mission operations often focus on science targets where closure can be gained from measurements from a single platform or mission. Science targets requiring multiple mission and hence multi-point measurements (e.g., as a "great observatory") are often de-emphasized or lacking. Kinetic 3-D simulations are not generally possible at global magnetospheric scales. Local simulations are often limited by simplifications such as periodic boundary conditions, by less realistic geometries, or by limited spatial/temporal resolution and limited domain. The coupling between the development of shear flow structure and vortices and kinetic scale processes in the intra-vortex reconnection regions is also not well-understood.

The development of coherent structures within the time-dependent behavior of shocks remains poorly understood. The formation and reformation of coherent structures appears to play a key role, especially in quasi-parallel shocks, but the details of how these structures form, their timescales, and relationship to shock processes at the fluid, electron and ion scale are not well known and observational studies are confined mostly to single point measurements. Recent observations have also suggested that coherent, wave-like, structures may form on the shock front itself which is unexpected and not understood.

Challenge 6-3: Can we apply HED physics techniques, both experiments and simulations, to NIF-based laboratory astrophysics experiments relevant to interface and shear instabilities in radiation controlled astrophysical systems?

<u>Existing research capabilities</u>

There exist numerous HEDP experiments (e.g., [8]) on the RT and KH instabilities driven by lasers. Computer capabilities include: Petaflop-scale computers;

direct numerical simulation of 3D RT with Reynolds number up to 32,000 – just above the Re~20,000 turbulent mixing transition; very high resolution 2D simulations; sub-grid scale models to capture effects of unresolved scales; and multidimensional multiphysics astrophysics codes.

Gaps

Smaller scale HEDP facilities which cannot reach the regimes of the radiation-dominated processes. While there exist many codes, they often do not meet the specific needs of specific problems. Smaller scale facilities cannot achieve a radiation pressure dominated regime. There exist limited diagnostics on NIF; and funding and facility time are both currently sparse.

The RT instability plays a very important role in Type-II supernova explosions. Scaled laboratory experiments have already been used to explore relevant unstable flows and validate codes used to simulate SN hydrodynamics. However, there is still no consensus view that can explain the set of available data, including evidence of very fast mixing of material from the deep interior into the outer layers of the progenitor.

From very early in the explosion, deformed shocks drive Richtmyer-Meshkov instability, and it is not clear how this instability seeds and interacts with the RT growth that dominates later on. Once perturbations have grown to large amplitudes, a transition to an inherently three-dimensional turbulent mixing zone can occur, and this presents significant challenges for both computational and experimental approaches. Numerical simulations are limited in the effective Reynolds numbers they can attain, and techniques for diagnosing turbulent HED laboratory systems remain to be developed.

In the area of computations, we can't do fully developed 3D turbulence with extended inertial range; the treatment of transitional flow is incomplete; and astrophysical codes are unvalidated through routine application to relevant nonlinear-phase experiments.

6.3 Major opportunities

Challenge 6-1:

In observations, telescopes currently under construction will broaden the scope of research in these areas. ALMA, with large collecting area and very high resolution [9] will allow extensive surveys of many classes of objects. The LSST will open a new regime of time domain astronomy to potentially investigate the evolution of jets, discs, and SNRs [10]. In laboratory experiments, we can use the capabilities of HEDP facilities (NIF, Z, Omega), combined with advanced diagnostics. More important than facilities is people: efforts must be made to broaden collaboration between observers, modelers, and experimenters.

Magnetic fields have typically been neglected in astrophysical simulations of SNe as well as laboratory experiments. Introduction of a dynamically-significant magnetic field in the laser-driven experiments may be quite challenging, but the reward could be significant, providing a test-bed for validation and verification for the MHD codes used in simulating of magnetized SNe.

Additional factors can potentially be introduced by the differential rotation of the magnetized progenitor. Rotation may also be responsible for a typically high peculiar velocity of the SN type-II remnant. Reproducing low-mode-number SN instabilities in the laboratory experiments would be a great step forward. Designing experiments that would imitate the explosion of a rotating star is a challenging but not hopeless task. These experiments may also shed light on the connection between instability structure created during the rapid explosion and the structure observed much later in the remnant.

Challenge 6-2:

Current and future proposed constellation mission operations should be coordinated to cover ion, electron and fluid scales at the magnetopause and plasma sheet to target non-linear KHI development and transport, "dipolarization front" interchange instabilities, and the role of such coherent structures in plasma dissipation and turbulence. Future missions include: NASA MMS, JAXA-CSA SCOPE, ESA Cross-Scale.

Future solar missions such as Solar Probe and Solar Orbiter may be important for establishing the role of these shear instabilities for the acceleration and properties of the fast and slow solar wind, or for energy transport during large scale magnetic topology changes in solar active regions. At the heliopause, and also in rotating planetary and astrophysical magnetospheres, interchange instabilities may also be contemporaneously important with shear flow instabilities.

In the case of the magnetosphere and heliosphere, detailed structure of the shocks and other interfaces is strongly affected by collisionless effects, making this whole area of research very rich in terms of plasma physics. Unique opportunities to study important fundamental collisionless shock processes with multi-point measurements at the electron, ion and fluid scales may be provided by the Cross-Scale and SCOPE missions.

Collisionless sheared-flow instabilities are often present in fusion devices and are thought to have a significant effect on their performance. Much effort has been and is being spent on experimental, analytical and numerical studies of this. Most of the results pertain to a low-beta plasma, but in some cases plasmas with beta approaching unity have been studied, most notably in mirror devices. Shear flows in collisionless plasmas, very much like their hydrodynamic counterparts, may drive instabilities, but they may also lead to stabilization of other, more virulent instabilities. In fusion devices, shear flows often acquire a form of zonal flows, which exist also in space and astrophysical plasmas. We feel that the exchange of information between fusion scientists and astrophysicists/space physicists could be more intense, leading to helpful cross-fertilization. Perhaps, an attempt to identify a set of problems of common interest in the areas of, e.g., Earth magnetosphere, could be made.

Challenge 6-3:

NIF can achieve new regimes that can be relevant to instabilities occurring in astrophysics. Larger and more complex geometries can be used on NIF. More extensive participation is needed in inter-disciplinary meetings, and collaborations with astronomers and astrophysicists in laboratory experiments from proceed from inception through execution. The field must take a long-term view in addressing the community integration and young researcher influx problems by establishing a program to involve astro students and postdocs in laboratory astrophysics efforts. Can we find more cross-fertilization in diagnostic development, etc, as well as conceptual guidance and simulation?

In SN physics, effects of spherical divergence may become important, and multiple mixing zones can begin to interact with one another. On the contrary, most SN-motivated laboratory RT experiments have focused on a single interface in planar geometry. Higher energies available on new facilities such as the NIF should allow the community to significantly broaden the scope of their experiments. It would also be novel to create an experiment with an RT unstable interface and a radiative shock. One could observe the effects of the radiation on the instability. This could be related to red supergiant supernovae, where the reverse shock is strongly radiative and interacts with the RT-unstable shocked ejecta.

In the case where the interface is accelerated by the ablation pressure, an "ablatively-driven RT" may develop. This instability is the basis for a leading model of the formation of complex structures of photo-evaporated molecular clouds. For instance, it may be responsible for the formation of pillars in the Eagle Nebula. The dynamics of photoevaporated clouds are likely strongly affected by magnetic fields, both regular and turbulent. Direct observations of the magnetic field in both the dense gas regions and in the HII regions that border them would help a lot in solving the mystery of the molecular cloud dynamics. Additional insights can come from developing an adequate laboratory platform for scaled simulation of the ablation instability both with and without the magnetic field.

Exaflop-scale computing (considered feasible this decade) would reach another factor of 10 in Reynolds number, allowing unambiguous, fully-developed, RT turbulent mixing. An integrated "Cradle to Grave" stellar modeling approach would provide better coupling of stellar modeling to explosion modeling, and explosion modeling to remnant modeling. The field could collect a "benchmark" set of instability experiments, defined and characterized in "astrophysics-code-friendly" terms, and deliver them to the astrophysics community as a tool for code validation.

6.4 Impact and Major Outcomes.

Challenge 6-1:

Obtaining detailed observational information on the magnetic field in the astrophysical objects would certainly lead to breakthroughs in our understanding of their behavior. This could be accompanied by scaled laboratory experiments on a variety of facilities, both with low-density (collisionless) and high-density (usually collisional) plasmas. Specifically, those models of SN explosions, accretion discs and photoevaporated clouds that imply an important role of the magnetic field would be either confirmed or rejected.

Challenge 6-2:

Constellation-type missions with many tens of nano-satellites would measure spatial and temporal characteristics of instabilities and turbulence in a collisionless plasma with an unprecedented level of detail, possibly exceeding the level attainable in laboratory experiments [10]. This would give rise to truly comprehensive models of collisionless turbulence, a subject of great intellectual value.

Challenge 6-3:

Broad use of new HEDP facilities (NIF, Z, and facilities to be built in other countries) for dedicated, astrophysics related experiments, would open up possibilities to reaching (in a scaled fashion) the domain where radiation pressure and the magnetic field play dynamically-significant role. This would allow experimentalists to peek into the processes occurring in such systems as supernovae and accretion discs around black holes.

6.5 Connection to Other Topics.

Interface and shear instabilities are ubiquitous in astrophysics. On the one hand, they may set the stage for the further development of nonlinear motion and turbulence, on the other hand, they are affected by the processes occurring at micro-scales, in the collisionless domain. They are directly connected to several topics in this report:

Topic # 1 (Magnetic Reconnection). Shear-flow instabilities affect reconnection physics, in particular, by shearing the magnetic field and preparing the stage for reconnection.

Topic # 2 (Collisionless Shocks and Particle Acceleration). Microturbulence that determines the structure of collisionless shocks (will certainly affect macroscopic (ripple) stability of such shocks.

Topic # 3 (Radiative Hydrodynamics). The presence of radiation in many cases strongly influences gravity-driven instabilities, in particular, in accretion discs. Radiative drive is of a prime importance for the stability of photoevaporated fronts.

Topic # 4 (Momentum Transport). Shear-flow instabilities make transport possible.

Topic # 8 (Waves and Turbulence). Interfacial instabilities often set the stage for the further development of turbulence.

Topic # 9 (Jets, Outflows& Structure Formation). Both Kelvin-Helmholtz and Rayleigh-Taylor instabilities are important in this general area

References

1. Crutcher, R.L., Heiles, C., and Troland, T. 2003, "Observations of Interstellar Magnetic Fields" in Turbulence and Magnetic Fields in Astrophysics, ed. E. Falgarone and T. Passot, 155
2. Donati, J-F. and Landstreet, J.D. 2009 "Magnetic Fields in Nondegenerate Stars", ARA&A, 47, 333
3. Gotchev OV, Chang PY, Knauer JP, et al. 2009, "Laser-Driven Magnetic-Flux Compression in High-Energy-Density Plasmas" Physical Review Letters, 103, 215004.
4. Suzuki-Vidal F, Lebedev SV, Ciardi A, et al. 2008, "Formation of episodic magnetically driven radiatively cooled plasma jets in the laboratory" Astrophysics And Space Science, 322, 19.
5. Shumlak U, Nelson BA, Balick B 2007, "Plasma jet studies via the flow Z-pinch", Astrophysics And Space Science, 307 41.
6. Stone, J. M., Gammie, C. F., Balbus, S.A. and Hawley, J.F. 2000 "Transport Processes in Protostellar Disks",in Protostars and Planets IV, 589
7. Review-style reference (Ian?)
8. Kuranz CC, Drake RP, Harding EC, et al. 2009, "Two-dimensional blast-wave-driven Rayleigh-Taylor instability: experiment and simulation", Astrophysical Journal, 696, 749.
9. http://science.nrao.edu/alma/index.shtml
10. http://www.lsst.org
11. Review-style (Ian?)

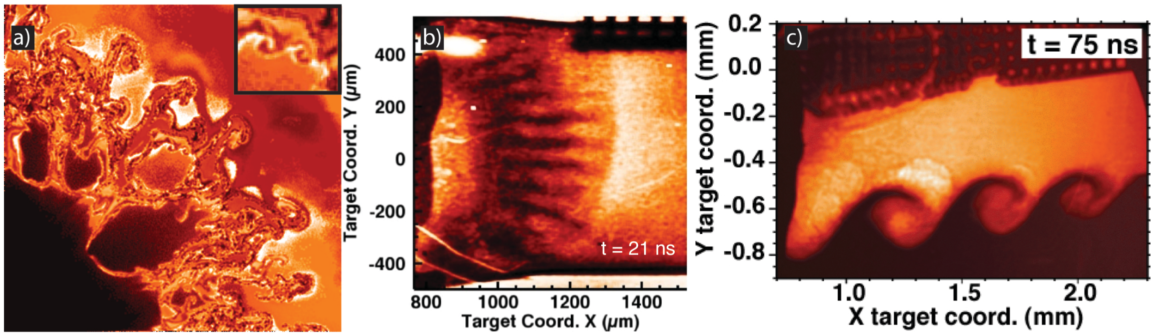

Figure 1: a) Results from a 2D calculation of SN1987A adapted from Muller et al. and showing the instability growth at the He-H interface of SN1987A. The Rayleigh-Taylor instability causes dense spikes of He to move outward and lower density bubbles of H to penetrate inward. The Kelvin-Helmholtz instability is also seen in these results (inset) caused by shear at the spike-bubble interface. Laboratory experiments allow one to study these instabilities individually. Experiments performed at the Omega Laser Facility investigate b) the Rayleigh-Taylor instability and c) the Kelvin-Helmholtz instability.