Interface and shear-flow instabilities

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 astrophysical (e.g., binary pulsar) magnetospheres, the transitional region from solar wind to interstellar medium, photoevaporated molecular clouds, supernova explosions, blast waves in supernova remnants, and many others.

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. We have chosen instead to focus our discussion on topics directly related to our expertise; so, some omissions are possible. On the other hand, it is inevitable that some of these selected topics overlap with the areas covered by other panels, most obviously by the panels on magnetic reconnection, momentum transport, and jets and outflows. We consider this overlap as a positive factor, as the presence of different vantage points may provide deeper insights in the underlying physics.

We frame our discussion in terms of two domains of the plasma physics (as a science discipline), not in terms of specific objects of astrophysics and space physics: 1. Instabilities that can be adequately described by macroscopic (MHD-type, possibly multi-fluid) equations and, 2. Instabilities where kinetic description is necessary to catch essential features of the phenomenon. Again, there exists an overlap between kinetic and macroscopic phenomena (e.g., in the situations where collective collisionless effects determine macroscopic transport processes), but we are not particularly concerned with that.

Each of these two high-level domains consists of lower-level sub-domains. For each of them we formulate a compelling question that has to be answered in order to reach a qualitatively higher level of understanding. We then present several examples of connections to real objects of space physics and astrophysics.

1. Macroscopic (hydrodynamic) instabilities

1a. Instabilities induced by shear

How do shear-flow instabilities transport energy, mass and momentum across plasma boundaries?

This question is particularly relevant to understanding of the processes active at the magnetopause of the Earth’s magnetosphere and at the magnetopause of other magnetized planets and astrophysical bodies. For example, the Kelvin-Helmholtz instability may play a key role in energy transport into the magnetospheres of these bodies. Recent theoretical and multi-satellite observational studies at the Earth, for example 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. However the details remain poorly understood. 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. In relation to the Earth’s magnetosphere, future multi-point missions such as ESA Cross Scale and JAXA-CSA SCOPE may reveal some of the detailed physics. Another important example where shear flow instability may be important is the stability of the heliopause and heliosheath, and more information about this system may become available from Voyagers 1 and 2 soon, leading to a much better understanding of the structure of this region. Shear flow instabilities may also be important for energy transport in the solar corona especially due to the development of surface waves. 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 (see section 1b below).

On much larger scales, from a fraction of a parsec to megaparsecs, this question arises in conjunction with hydrodynamic properties of astrophysical jets, their collimation, stability and the length. Magnetic fields are thought to be responsible for the launching and downstream behavior of astrophysical jets. 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 specific 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.

The interactions of astrophysical jets with background gases also have some unresolved questions that could possibly be addressed in laboratory experiments and numerical simulations. Specifically, questions related to the formation of “knots” and bow shocks in jets could be addressed. Possible formation mechanisms for knots include instabilities and source modulation. Energy transfer mechanisms in bow shocks can also be investigated. Here multi-epoch observations that provide "time-lapse" views of jets and Herbig-Haro objects are important, such as those made with the Hubble Space Telescope of HH47.

Another manifestation of shear-flow instabilities is momentum transfer in the accretion discs of various kinds – the process that determines the accretion rate to the central object. It is now widely accepted that the magneto-rotational instability is principally responsible for angular momentum transfer in the inner regions of discs around compact objects. While the MRI has been reproduced in laboratory fluid experiments, it is more difficult to experimentally reproduce this instability in scaled laboratory plasma experiments. Some preliminary ideas are related to the use of an array of properly oriented, merging plasma jets with embedded magnetic field. Also required is development of an observation strategy to identify the most salient features of the accretion related to the momentum transfer with the goal of differentiating models. Laboratory experiments may provide insight into such a strategy.

1b. Gravity (acceleration) driven instability (in particular, the Rayleigh-Taylor instability)

How do acceleration-driven interfacial instabilities lead to development of complex dynamical structures and/or mix process?

It is well-recognized that 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. 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.

From very early in the explosion, deformed shocks drive the 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.

As the instabilities continue to evolve during the explosion, 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.

Finally, there are additional physical aspects of SNe that have to date typically been neglected in astrophysical simulations as well as laboratory experiments. For example, the star's magnetic field might have an effect on the character of the SN explosion. 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 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.

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. A promising opportunity to do so should come next year, with the installation of dual polarization receivers on the CARMA radio interferemeter. These receivers will allow determination of both the orientation and magnitude of magnetic fields in molecular clouds, through dust polarization and Zeeman effect measurements, respectively. Additional insights can come from developing an adequate laboratory platform for scaled simulation of the ablation instability both with and without the magnetic field. An advent of NIF may provide an opportunity for developing a scaled laboratory model of this phenomenon.

1c. Instabilities of shocks and detonation/deflagration waves

How do intrinsic instabilities of shocks (including ionizing shocks) and detonation/deflagration waves affect their global dynamics?

Instabilities of shock-like transitions affect as diverse phenomena as the structure of the bow shock in the Earth environment to SN type I explosions. Blast waves in the SN remnants are often unstable with respect to the ripples. An interesting issue is to link this instability to the observed complex structure of the SN remnants.

A radiative shock can become unstable and effect the structure of a SN remnant. When a supernova shock breaks out of a star it is strongly radiative. The structure of the shock consists of an optically-thin precursor region and a compressed and optically thick shocked layer. The region behind the shocked layer rapidly cools, which causes the region to collapse. This collapsed layer becomes a thin shell and is susceptible to thin-shell or Vishniac-like instabilities, which could explain the complex structure of supernova remnants.

In type IA SN explosion models with a transition from deflagration to a centrally-initiated detonation, the outgoing detonation wave is perturbed by large-scale ash bubbles created during the deflagration stage. Would such a low-mode perturbed shock drive Richtmyer-Meshkov instability growth at the outer surface of the star? If so, could a signature of this instability survive into the remnant stage?

An interesting and yet essentially unexplored problem is shock stability in a dusty partially-ionized plasma, like the one met in the interiors of the photoevaporated clouds. Instability of shock and blast waves in such an environment would have an effect both on the global behavior of dense molecular clouds and on the processes of the star formation in them. The recently launched Herschel Space Observatory has far-infrared spectrometers and cameras designed to examine the dust properties in the deep interiors of such clouds, and could be used to explore this problem. A challenge with be to create a laboratory platform for the studies of these phenomena.

2. Kinetic effects in shear-flow instabilities and interface instabilities

2a. Collective effects in the shock structure and global stability

What governs the global dynamics and structure of astrophysical bow shocks on electron, ion and fluid scales?

Can microturbulence within the collisionless shock front affect the global (in particular, ripple) stability of the shock?

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. Indeed, the role of electron and ion scale physics in controlling the macro-structure of the shock such as the foot, overshoot region etc needs further study again especially in the time-dependent reforming quasi-parallel case. Recent observations have also suggested that coherent, wave-like, structures may form on the shock front itself which is unexpected and not understood.

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.

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 proposed future Cross-Scale (ESA) and SCOPE (Jaxa-CSA) satellite missions.

2b. Shear-flow instabilities in collisionless systems.

What are most salient features that make shear-flow instabilities in collisionless systems different from their purely hydrodynamical counterparts?

Collisionless sheared-flow instabilities are often present in fusion devices and are thought to have a significant effect on their performance. A lot of effort has been and is being spent on experimental, analytical and numerical studies of this research area. Most of the results pertain to a low-beta plasma, but in some cases plasmas with beta approaching unity have also 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 time acquire a form of zonal flows, existing 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. Validation and verification of the relevant codes could be attempted.

Recent observations in the Earth's magnetotail with THEMIS have shown the Earthward flows in the plasma sheet released by tail magnetic reconnection develop structures which appear to be dominated by kinetic processes. Whilst the flows exist in fluid models, the THEMIS observations suggest the at least ion scale structures develop at the leading edge of these flow bursts, being accompanied by steepened magnetic field structures leading to plasma wave growth, and kinetic scale energy dissipation processes. Moreover, at the edge of these fast flows shear instabilities form and develop. Collisionless kinetic processes appear to be important for the energy balance and evolution of these reconnection released fast flows, and similar processes could be operating in reconnection in other planetary magnetosphere and magnetized astrophysical objects. Similarly, the plasma sheet in the tail of the Earth is populated by turbulence, interrupted by these coherent fast flows. The role of kinetic scale processes in the formation of coherent structures in such turbulent media, and for energy dissipation in the plasma turbulence are not well known. Further studies are warranted, and in the case of the Earth multi-point measurements from missions such as Magnetospheric Multi-Scale (MMS – NASA), SCOPE (JAXA-CSA), and Cross-Scale (ESA) will provide key observational data for advancing our understanding.