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.
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• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	P
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Oral	X
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Title:	**Major Scientific Challenges and Opportunities in Understanding Turbulence and Angular Momentum Transport in Accretion Disks**
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**(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)**

Many important astrophysical phenomena take place in accretion disks ranging from formation of stars and planets in proto-star systems, the mass transfer and energetic activity in X-ray binary star systems, to efficient energy releases in quasars and active galactic nuclei. In fact, the most efficient energy sources known in the Universe are accretion disks around black holes, converting 5-40% of rest mass energy to radiation. A common puzzle across all these kinds of accretion disks is why accretion occurs so fast compared to the predictions based on the classical viscosity by many orders of magnitudes [1-3]. This is equivalent to the question of how angular momentum is rapidly transported radially outwards in these plasmas. Cause of this rapid transport is generally attributed to the presence of rigorous turbulence in the accretion disk. The difficulty of the problem, however, originates from the fact that there exist no known robust linear hydrodynamic instabilities in Keplerian disks. Therefore, there exist only two categories of mechanisms to generate turbulence in accretion disks: (1) nonlinear hydrodynamic instabilities and their variations, and (2) linear magnetohydrodynamic instabilities, and more specifically Magnetorotational Instability or MRI. The nonlinear hydrodynamic instabilities, suitable for cooler and poorly ionized protostellar disks (so that magnetic fields are ineffective), are intensively studied in pipe flows, but whether they exist in Keplerian flows is an open question. The pure hydrodynamic experiments with adequate boundary conditions have shown that such flows are extremely quiescent and are likely incapable in sustaining the turbulence required for astrophysical disks. This subject is still being followed on. Other proposed candidates in pure hydrodynamics still have not been tested in the laboratory. The

MRI, suitable for hot and magnetized disks, has been extensively studied theoretically and numerically, but has not been conclusively demonstrated in the laboratory or observationally, although the related instabilities such as Helical MRI and Azimuthal MRI have been studied in the lab. There are controversial debates on what turbulent viscosity that the MRI can generate to transport angular momentum at realistic Reynolds numbers of accretion disks. Comparisons between numerical results and observations, although necessarily indirect, are just beginning. Below we list the major outstanding questions for angular momentum transport in astrophysical disks:

1. The hydro problem [e.g. 4-13]: Can nonlinear hydrodynamic turbulence efficiently transport angular momentum? If can, under what conditions? If not, why Keplerian flows are so robustly stable? Although it is common that hydrodynamic flows at large shear Reynolds numbers are nonlinearly unstable despite linear stability, it is still unclear whether this is true for Keplerian flows. There are theoretical, numerical and laboratory evidence that Keplerian flows are resilient to perturbations, but conclusions are not yet conclusive, especially in terms of the underlying nonlinear physical mechanisms and the associated angular momentum transport, due to necessary assumptions in theory, limitations in both numerical simulations and laboratory experiments.

2. The saturation problem [e.g. 14-21]: Can the standard MRI be conclusively demonstrated in a real physical system, either in astrophysics or in the lab? How does the MRI saturate to generate angular momentum transport? Related instabilities, such as Helical MRI and Azimuthal MRI, have been successfully studied in the lab, but how these instabilities are relevant to the angular momentum transport in accretion disks is unclear. Although the standard MRI is difficult to isolate in the lab due to experimental complications, its positive identifications may be near. There are several proposed mechanisms to saturate MRI, but it is unclear which mechanism(s) works under what conditions, either in the lab and in the astrophysics, and how are they related.

3. The scaling problem [e.g. 22-24]: How does the angular momentum transport scale with magnetic and hydrodynamic Reynolds numbers? Both numerical simulations and laboratory experiments operate necessarily at small Reynolds numbers, and thus scaling the relevant results to the realistic accretion disks is required in order to compare with observations. So far numerical simulations have not been able to converge on the scaling properties for the MRI turbulence and its associated angular momentum transport.

4. The multi-fluid problem [e.g. 25-31]: How do the Hall effects and ambipolar diffusion influence the saturated state of MRI turbulence? It is clear that non-ideal effects are important in cool disks such as protoplanetary disks where plasmas are extremely poorly ionized so that each fluid (electron, ion, neutral and even dust particles) behave quite differently while magnetic field is closely coupled only to electrons. In such plasmas, MRI manifests in significantly different forms and sometimes is even ineffective (forming the so-called "dead zone"), so that disk might be highly structured involving both turbulent and laminar domains. It is unclear how steady state accretion can be maintained in such disks.

5. The kinetic problem [e.g. 32-36]: How do kinetic effects significantly modify angular momentum transport? In accretion disks around compact objects such as in X-ray binaries and in Active Galactic Nuclei, plasmas are hot and nearly collisionless. Fluid models become their poor approximations and kinetic effects can play an important role. In such plasmas, pressure anisotropy arises naturally, and it may lead to firehose and mirror instabilities which in turn can significantly affect the MRI and the resultant angular momentum transport.

6. The extreme condition problem [e.g. 37-39]: How do radiation and relativity affect the MRI and its saturation? In plasmas near black holes, effects such as general relativity and intense radiation must be taken into account and it has been a challenge to study MRI turbulence and angular momentum transport in such plasmas.

Near-term opportunities are identified in answering these outstanding questions by the means of laboratory experiments, theory, computation, and observation. Table below summarizes the capabilities to

address these outstanding questions by each of these approaches. Green indicates the required capabilities are already in place or can be available by adequate investments from corresponding funding agencies; yellow indicates difficult or impossible to achieve in the near future.

Questions	**Theory & Simulation**	**Observations**	**Laboratory Experiments**		
			Neutral fluid or gas	Liquid metal	Plasma
Hydro					
Saturation					
Scaling					
Multi-fluid					
Kinetic					
Extreme					

1. Theory and numerical simulation. All major outstanding questions can be studied by theory and simulations using fluid, kinetic and hybrid approximations. Although simulations are limited by necessary simplifications and finite computational resources, ever-growing computational power provides major opportunities to explore and understand angular momentum transport under various conditions.

2. Observations. The remote sensing satellites provide all observational evidence on fast angular momentum transport in accretion disks, often providing only global constraints. Nonetheless, observations provide the ground truth of the angular momentum transport in nature.

3. Laboratory experiments. Laboratory efforts on this subject are relatively new and small but important results have been already obtained especially on the hydro problem. With adequate diagnostics and modeling, laboratory experiments can contribute significantly to solving this important plasma astrophysics problem. This area of research deserves strong and sustained support.

In summary, angular momentum transport in accretion disks is a fundamental plasma astrophysics problem important for understanding a wide range of phenomena from formation of stars and planets, to energetic activity from X-ray binaries, and to efficient energy release in active galactic nuclei. Major outstanding scientific challenges have been identified and most of them can be attacked by a combination of approaches based on theory/simulations, observations, and laboratory experiments, with adequate support by corresponding funding agencies through some forms of partnership.

Lastly, this topic is closely related to other plasma frontier problems including

- Magnetic field generation or dynamo problem since MRI can act a dynamo which in turn can saturate MRI (see the white paper on plasma dynamos by C. Forest et al.)
- Magnetic reconnection problem as reconnection is a saturation mechanism for MRI
- Plasma turbulence problem as MRI is a specific mechanism to generate turbulence in magnetized rotating flows

Furthermore, scientific progress on this topic will broadly impact other areas beyond plasma frontier research and plasma astrophysics research, such as

- Effects of magnetic field on momentum transport in magnetic fusion plasmas
- Shear flow (zonal flow) effects on turbulence and transport in fusion plasmas
- Interactions between turbulence and zonal flow in rotating flows in geophysics
- Nonlinear dynamics on turbulence at high Reynolds numbers

And the multi fluid problem of this topic is important for protoplanetary disk dynamics and the formation of exoplanets, which is a topic with interests to broader scientific community and general public.

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