Angular Momentum Transport in Astrophysical Plasmas

The redistribution of angular momentum plays a critical role in most astrophysical systems. It is responsible for shaping much of the structure we see around us in the universe and for powering the brightest known sources of electromagnetic radiation. Disk galaxies like our own Milky Way form as plasma flows towards the center of gravitational potential wells established by dark matter, eventually settling into a disk when rotational support becomes important. Stars form inside galaxies even today as gas clouds collapse, shed angular momentum, and eventually reach temperatures at which nuclear fusion begins. And planets – including the Earth -- form as gas and rocks coalesce in the rotationally supported disk of debris surrounding a new star.

Rotation also plays a critical role in the death of stars and in the properties of the resulting compact objects (white dwarfs, neutron stars, and black holes). How massive stars explode as luminous ‘supernovae’ after fusion ceases depends critically on the rotation of the star. The redistribution of angular momentum is also the power source for the brightest sources of electromagnetic radiation in the universe: accretion of plasma onto black holes can produce energy up to 50 times more efficiently than nuclear fusion.

Magnetic fields are one of the key ways of transporting momentum in astrophysical plasmas, because they can transmit forces over relatively long distances (gravity is important for the same reason on galactic scales). As a result, understanding angular momentum transport in astrophysical plasmas requires understanding the origin, destruction, and coherence of magnetic fields. It is thus intimately connected to the problems of astrophysical dynamos, magnetized turbulence, and magnetic reconnection.

Key Scientific Challenges

To highlight several key scientific questions related to angular momentum transport in astrophysical plasmas, we focus on some of the outstanding problems in the areas of stellar astrophysics and accretion disks. These areas were identified because of their broad astrophysical importance and because the importance of momentum transport by magnetic fields in ionized plasma has been well established.

Stellar Astrophysics:

The surface of the Sun rotates differentially, with a fast equator and slow poles. Measurements of millions of solar acoustic oscillations reveal that this rotation profile largely imprints through the convective envelope, but that there is a transition to nearly solid-body rotation in the stably stratified region below. The narrow boundary layer of shear between these two regions, called the tachocline, figures prominently in most models of the global solar dynamo. Although the differential rotation within the convective envelope is widely thought to arise at least partially from momentum transport by the turbulent flows, a basic understanding of how this occurs (and how such transport depends upon parameters like the rotation rate) remains elusive. The transition to solid-body rotation in the radiative region is likewise poorly understood, though momentum transport by magnetic fields and/or internal gravity waves is thought to be crucial.

Recent observations have revealed differential rotation in other stars as well. These observations, which typically involve either examining spot patterns at the stellar surface or subtle analyses of rotational line broadening effects, have generally only been possible in the last few years, but will continue to grow in number with the advent of space-borne photometers like Kepler and COROT. Such differential rotation must figure prominently in the evolution of these stars -- through its role in magnetic dynamo action, for instance -- and so demands detailed theoretical modeling.

The mean rotation rates of stars are not constant, but typically decrease in time as stellar winds and magnetic fields remove angular momentum, spinning down the star. How this affects the interior rotation is, however, uncertain, and depends on how well magnetic fields couple the interior and exterior of the star. This uncertainty translates into significant uncertainty in how stars end their lives and in the "birth" rotation and magnetic fields of white dwarfs, neutron stars, and black holes. For example, it is now observationally well-established that the most relativistic explosions in the universe – long-duration gamma-ray bursts – are associated with the collapse and explosion of massive stars at the end of their lives; but the rate of such gamma-ray bursts is only ~ 0.1% of the core-collapse supernova rate. This diversity in stellar death is almost certainly tied to diversity in the rotation and magnetic fields of massive stars, but this is not even qualitatively understood, either theoretically or observationally.

Accretion Disks:

Accretion is the inflow of matter towards a central gravitating object. In general, the inward accretion of matter requires an outward transport of angular momentum. Collisional viscosity is incapable of producing the level of angular momentum transport needed in astrophysical disks, and thus turbulent transport is required for accretion to proceed. In 1991, Balbus and Hawley showed that the magnetorotational instability (MRI) is important in many astrophysical accretion flows. The MRI is an instability of a differentially rotating magnetized plasma in which the magnetic field is amplified on a timescale comparable to the rotation period of the disk and magnetic tension exchanges angular momentum between fluid elements, allowing some of the plasma to flow inwards. Nonlinear simulations have shown that turbulence driven by the MRI can be an effective angular momentum transport mechanism. However, many outstanding questions remain. Broadly speaking, one of the key challenges is to increase the realism of the physics in disk simulations and to use such calculations to make predictions that can be quantitatively compared to observations. Comparisons between simulations and laboratory experiments may also provide a useful testing ground for models of turbulence in astrophysical disks.

Numerical studies of transport in disks were initially based on the equations of ideal MHD, which are appropriate for a fully ionized collisional plasma. However, in cold and dense flows (e.g., planet-forming disks around young stars) the plasma may be mostly neutral, and the ideal MHD approximation does not apply. Instead, non-ideal processes such as the Hall effect and ambipolar diffusion are crucial. At the other extreme, the inflowing plasma near a black hole is sometimes so hot and rarified that it is effectively collisionless. Fully kinetic calculations of angular momentum transport are required to understand such systems, for example the ~ 3.6 million solar mass black hole at the center of our galaxy; these have yet to be carried out. Simplified fluid models suggest that angular momentum transport in collisionless disks can be quite different from that predicted by MHD. A related question is whether turbulence (or reconnection) in these accretion disks can accelerate some of the particles to suprathermal energies. If so, this could significantly modify the spectrum of radiation from such systems.

For the most luminous accreting systems, the energy density in the radiation field close to the central black hole or neutron star greatly exceeds that internal energy density of the plasma. In such cases, the radiation field is thus dynamically important and must be self-consistently included in the dynamics. There has been significant progress in studies of the MHD of radiation-dominated flows using the flux limited diffusion approximation and gray (frequency independent) transport. However, flux limited diffusion breaks down right where it matters most: near the photosphere, where the photons we see originate. Moreover, frequency dependent transport (or at least, the inclusion of the effects of spectral lines) might be important for understanding radiation-driven outflows from disks, and relativistic effects will be important in the very inner-most regions of disks around black holes. There remains an enormous amount of work to be done to study radiation-dominated flows, and experiments may provide crucial insights into the dynamics in this regime, as well as allowing validation of the numerical methods.

Techniques and Opportunities

Astrophysical systems typically encompass an enormous range of spatial and temporal scales, with momentum transport likely involving many disparate scales. The physical processes that are relevant at one scale may not apply at others -- for instance, some systems may be collisional in some places and collisionless elsewhere. No one computation or experiment is likely to model the physics of all these scales correctly in the foreseeable future. Analytic theory is thus critical for determining the important physical processes and the important length and time-scales that must be resolved. By then combining results from numerical modeling, ever-more-detailed astronomical observations, and laboratory experiments -- each of which probe largely distinct parameter regimes -- we hope to arrive at a comprehensive understanding of transport in astrophysical environments.

On the computational front, continued progress is likely to be afforded by the ongoing increase in processor performance. That increase will ultimately allow simulations that model higher-resolution domains with greater and greater fidelity. The resolution requirements for conceptual progress vary depending on the problem. In the Sun and other stars, for example, the largest scales of motion relevant for momentum transport are likely of order the depth of the convection zone (about 200 Mm); estimates of the smallest relevant lengthscales vary, but a plausible upper limit is the width of the solar tachocline region, thought to be a few percent of the solar radius (or about 2 Mm). In the

MHD context, transport may depend on growing or parasitic modes on much smaller lengthscales. Together, these imply that the latest generation of simulations of stellar convection – with resolutions of roughly 1000^3 -- are only beginning to capture much of the relevant physics. For accretion disks, the range of length scales may be even wider, varying over 10 or more orders of magnitude. In such cases, resolving all scales is not possible; but it may also not be needed. Calculations that have sufficient scale-separation (at least a factor ~ 10-100) between relevant but disparate scales may provide the needed insights into the dynamics. Within the next few years, peta-scale machines will enable modeling at even higher resolution and correspondingly greater realism. Such machines require extremely high levels of parallelism in the numerical algorithms, and it will be challenging for researchers to exploit these new computer architectures, and the enormous volumes of data that will be produced.

A new generation of astrophysical techniques and telescopes will provide a qualitative advance in our understanding of stellar rotation and accreting systems in the next ~ 5-10 years. The Solar Dynamics Observatory will dramatically increase our understanding of solar convection, interior rotation, and magnetism. High precision photometry on new satellites such as COROT and Kepler is providing extremely precise stellar light-curves and, in some cases, measurements of many different modes of stellar oscillation. Over the next ~ 5 years this should provide a breakthrough in our understanding of stellar (differential) rotation as a function of mass and age; in principle the rotational diagnostics can also be correlated with surface magnetic activity to understand better the relationship between rotation and magnetic field. These observational results will provide a wealth of data for comparison to models of stellar dynamos, differential rotation, and stellar death. This data will complement the much more detailed information available for the sun.

Observations of accreting compact objects have traditionally been spatially unresolved. Our inferences are largely based on interpreting the spectrum of emitted radiation and its variation with time. In many contexts (e.g., the observed time variability), theory lags behind observations and improvements in numerical models are likely required for significant progress. Qualitatively new observational insights will be provided, however, on several fronts. Using advances in interferometry at mm and infrared wavelengths, spatially resolved images of plasma in the vicinity of a black hole will be obtained for a few of the nearest massive black holes in galactic nuclei. Higher spectral resolution observations of X-ray lines from accreting neutron stars and black holes will provide direct constraints on the rotational structure of the underlying disk.

Experiments using rapidly rotating conducting fluids such as plasmas and liquid metals can be used to study the instabilities that give rise to angular momentum transport in accretion disks and stars. Instabilities arise from various free energy sources in astrophysical systems, including flow shear, pressure gradients, and current gradients. For each free energy source, there can in principle be hydrodynamic, magnetohydrodynamic, or small-scale plasma instabilities. Although there has been extensive theoretical work assessing which instabilities dominate under different astrophysical conditions (e.g., the MRI), there is much to be gained from a range of experiments that can produce these instabilities in a laboratory setting. They may also be used as a platform for validating numerical codes used in simulating astrophysical systems. Taken together, experiments and simulations span a broader parameter space than either individually; both will be required for constructing scaling laws that extrapolate to astrophysically significant regimes. Both hydrodynamic and magnetohydrodynamic experiments have been performed in Taylor-Couette flow established between differentially rotating cylinders. This simple device provides a standardized platform for studying shear flow instabilities that give rise to turbulence in rapidly rotating fluids. Spherical Couette devices with differentially rotating spheres have also been employed to study geometries closer to that of planetary and stellar dynamics. Most current experiments use either water (for hydrodynamic experiments) or a liquid metal, in particular Gallium or Sodium (for MHD experiments). Proposed experiments in weakly collisional plasmas will significantly increase the range of astrophysically relevant conditions that can be studied experimentally.

A recent breakthrough on the experimental side was in the study of the hydrodynamic stability of differentially rotating Taylor-Couette flow. A purely hydrodynamic transition to turbulence would be a compelling model for cooler collisional accretion disks such as protoplanetary disks, which may be too resistive to sustain transport by magnetic fields. Initial experiments using water seemed to support such a transition to hydrodynamic turbulence but careful measurements of the momentum transport in follow-up experiments demonstrated that quasi-Keplerian flows up to $Re \sim 10^6$ can be achieved with transport comparable to that due to microscopic viscosity (i.e., little turbulence). This difference in experimental results is attributed to differences in boundary layer control. At such high Reynolds numbers sharp boundary layers form along the container walls resulting in a bulk circulation called Ekman flow. The large-scale radial flows are typically unstable and result in turbulence that enhances angular momentum transport. Disrupting or suppressing the boundary layers is required to create conditions in which the effects of bulk flow are not masked by instabilities in this secondary flow. Further use of boundary layer control in experiments may be critical for experimental studies of angular momentum transport.

Challenges For The Next Five Years

We expect that progress will continue to come from the interaction between theory, simulation, and experiments. Focused experiments have the potential to directly study important astrophysical processes in a controlled setting. The plasma physics community has developed advanced numerical algorithms for the study of weakly collisional plasmas; the application of such tools to astrophysics problems could help advance the field substantially. Collaborative use of advanced computing systems such as those provided at DOE's National Center for Computational Science could also be of considerable use. In conclusion, we provide a summary of key opportunities over the next ~ 5 years for the study of angular momentum transport in (1) laboratory experiments, (2) stars, and (3) accretion disks.

(1) A challenge for studying angular momentum transport in laboratory experiments or numerical simulations is extrapolating the results to astrophysically relevant parameters.

Neither experiments nor simulations can reach the dimensionless plasma parameters appropriate for accretion disks or stars. They do, however, provide valuable insight into the basic processes thought to be responsible for angular momentum transport. Existing liquid metal experiments operate in the regime of ideal MHD whereas in real astrophysical plasmas one may need to consider the Hall effect, ambipolar diffusion, anisotropic viscosity, or microinstabilities that limit anisotropy (depending on the problem of interest). Significant new opportunities will be provided by existing or improved liquid metal experiments, and by plasma experiments that span a wide magnetic Reynolds and Prandtl numbers, and access low-collisionality weakly magnetized plasmas. These will provide an opportunity to access a wide range of plasma conditions and study transport in astrophysical plasmas in detail.

(2) The differential rotation observed in stars, and probed in detail in the Sun, remains poorly understood. The change in stellar rotation with stellar age is even less well understood, but is a crucial for understanding stellar death (via supernovae and gamma-ray bursts) and the properties of neutron stars and black holes. Turbulent convection and large-scale magnetic fields are probably the most important transport processes in stars. Simulations of convection have made some contact with the helioseismic constraints for the sun, but have not yet been fully tested by observations of other stars or by experiment. The flood of data on stellar variability soon to come from Kepler, the near-term advent of the Solar Dynamics Observatory, and the prospect of a tunable plasma experiment all represent major opportunities for understanding the stellar angular momentum problem.

(3) In the next ~ 5-10 years, observations will for the first time directly resolve plasma near the event horizon of a black hole, in our Galactic Center and in the nearby galaxy M87. This is possible through interferometry at radio and (possibly) infrared wavelengths. These observations will constrain the temperature, density, magnetic field, and time-variability of the plasma near the black hole. Such observations can only be understood with the appropriate plasma physics models. Kinetic plasma models in General Relativity, combined with relativistic radiative transfer calculations that include the relevant high-energy radiation processes, can predict the emission from plasma accreting onto a black hole. Although some such tools exist, they do not currently include sufficient plasma physics to make reliable predictions for the observed emission. Doing so is a grand challenge for plasma astrophysics. These systems may provide the best opportunity for astronomical observations to constrain the plasma physics of accretion disks. There will also be enormous public interest in these results.

Astrophysical Impact

Angular momentum transport plays a critical role in a wide range of astrophysical systems, from stars and planets, to black holes, to the disks of galaxies. In many instances, the problem of angular momentum transport is also fundamentally a problem in plasma astrophysics. It therefore requires advances in basic plasma physics. Progress on understanding the plasma physics of momentum transport would have a major impact on a broad range of astrophysics problems, including (1) how planets form, (2) how the brightest sources of electromagnetic radiation in the universe work (accreting black holes and neutron stars), and (3) how stars form, evolve, and end their lives.

Connections to Other Problems in Plasma Astrophysics

Momentum transport in ionized plasmas is fundamentally a problem in how magnetic fields are created, organized, and destroyed. Understanding momentum transport thus requires understanding other important plasma astrophysical processes, most notably magnetic reconnection, dynamos, and turbulence. For many astrophysical applications, the transport problem also requires moving beyond ideal MHD. In accretion disks around massive stars, and for luminous disks around black holes and neutron stars, the energy in the radiation field can greatly exceed that in the plasma. Understanding transport thus requires understanding the behavior of plasmas under radiation-dominated conditions. By contrast, in disks around stars like the sun the fluid is so poorly ionized that non-ideal MHD effects are critical. In many cases, the primary charge carrier in such disks is not even the plasma itself, but rather the dust grains that are the building blocks of rocky planets like the Earth.

The connections between momentum transport and other problems in plasma astrophysics go both directions: theoretical and experimental developments in understanding magnetized rotating plasmas in accretion disks are having a significant impact on our understanding of dynamos more broadly. In addition, the large-scale magnetic fields that dominate transport in disks and stars – the origin of which is a central problem in dynamo theory – also create the initial conditions for understanding the collimated magnetized jets these systems can produce. Magnetized outflows from rotating stars and disks may even be the one of the most important sources of magnetic fields for the universe at large.