

## Mini-conference on angular momentum transport in laboratory and nature<sup>a)</sup>

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This paper provides a concise summary of the current status of the research and future perspectives discussed in the Mini-Conference on Angular Momentum Transport in Laboratory and Nature. This mini-conference, sponsored by the Topical Group on Plasma Astrophysics, was held as part of the American Physical Society's Division of Plasma Physics 2007 Annual Meeting (November 12–16, 2007). This mini-conference covers a wide range of phenomena happening in fluids and plasmas, either in laboratory or in nature. The purpose of this paper is not to review these phenomena comprehensively, but to provide a starting point for interested readers to refer to related research in areas other than their own. © 2008 American Institute of Physics. [DOI: 10.1063/1.2902348]

### I. INTRODUCTION

Understanding mechanisms of rapid angular momentum transport has been an important plasma physics topic for both laboratory and astrophysical plasmas. In high-temperature fusion plasmas, spontaneous spin-ups without apparent momentum inputs have been observed experimentally in many devices. Rotation and plasma flow in general are closely tied to transport of heat and particles across field lines. In astrophysical plasmas, angular momentum transport is central to accretion disk physics, such as star formation processes, mass transfer between binary stars, and active galactic nuclei. Angular momentum transport is also important to understand other astrophysical phenomena, such as the solar dynamo. Back on the Earth, angular momentum transport can also be important in phenomena such as formation and maintenance of atmospheric cyclones (hurricanes and tornados), faster spin of the inner core than the outer core, and the related geodynamo.

There has been significant progress in the past decades in all of these areas in our understanding of these important phenomena, based on observations, theory, simulation, and laboratory experiments. The mini-conference on Angular Momentum Transport in Laboratory and Nature, held as part of the American Physical Society's Division of Plasma Physics 2007 Annual Meeting, was intended to provide a platform to summarize and discuss the recent progress and future perspectives in this field from communities of plasma physics, astrophysics, and geophysics. Because of enthusiastic responses to the call, the number of sessions had to be increased from two to four. Below we summarize each session primarily by its chairperson in the following sequence: angular momentum transport in neutral and electrically conducting fluids (Session I, chaired by H. Ji), astrophysical and laboratory plasmas (Session II, chaired by D. Uzdensky), fusion plasmas (Session III, chaired by S. Prager), and earth

cores, sun, and laboratory (Session IV, chaired by P. Kronberg). We note that this paper intends to provide only brief summaries of the contributions in these sessions without attempting to be a comprehensive review of any sort.

### II. SESSION I: ANGULAR MOMENTUM TRANSPORT IN NEUTRAL AND ELECTRICALLY CONDUCTING FLUIDS

This session was devoted to angular momentum transport phenomena in both electrically insulating and conducting fluids in nature and laboratory. It began with a presentation by D. Nolan from the University of Miami on angular momentum circulation in tropical cyclones such as hurricanes. These strong atmospheric vortices are driven by the potential energy due to sufficiently large temperature differences between upper atmosphere and sea surface, as in a “heat engine.”<sup>1</sup> Hurricanes are formed due to spin-up of rapid vertical flows due to conservation of absolute angular momentum (self-angular momentum around their axes plus rotation of the atmosphere). Transport of angular momentum within a hurricane is dominated by global circulations through swirling boundary layers or Ekman layers, where the friction with sea or land surface is a main loss of angular momentum.<sup>2</sup> A typical hurricane outside its core is anticyclonic, i.e., vorticity has an opposite sign to the rotation, and more specifically, angular velocity is a decreasing function of radius while specific angular momentum increases with radius. These flows belong to a rotating flow class, dubbed “quasi-Keplerian” flows, since they include Keplerian flows typical of astrophysical accretion disks (see more later this Section and the next Section). Interestingly, intense hurricanes have a flow profile often close to the Keplerian flows, but probably due to different reasons originated in their boundaries. Some internal waves can transport angular momentum within the hurricane vortex. The vortex-Rossby waves are considered to generate the observed spiral bands,<sup>3</sup> which in turn transport angular momentum radially inwards up an angular velocity gradient, as also argued in accretion

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disks.<sup>4</sup> In contrast, gravity waves can transport angular momentum radially outwards but only very inefficiently. The absence of efficient mechanisms to disperse the concentrated angular momentum explains the prolonged lifetimes of tropical cyclones.

P. Marcus from the University of California, Berkeley, presented a recent theory on transporting angular momentum by three-dimensional (3D) coherent vortices in protoplanetary disks,<sup>5,6</sup> rather than conventionally assumed turbulence.<sup>7</sup> Vertically stratified disks support stable internal gravity waves, which can be generated by noise near the disk midplane. These gravity waves propagate off midplane, then they break to form long-lived 3D vortices. Constraints on certain symmetries of these coherent vortices can lead to radial transport of angular momentum at a sizable rate. In addition to transporting angular momentum, these coherent vortices can provide homes for planetesimal formation out of dust grains. Various forces within the vortices can affect dust dynamics, but large pressure forces and vertical circulations can help trap dust. This is in contrast to turbulence, which is another candidate to transport angular momentum. But it is difficult for dust grains to settle or aggregate into planetesimals in either hydrodynamic or magnetohydrodynamic (MHD) turbulence.

E. Kim from the University of Sheffield, United Kingdom, presented a summary of a series of recent theories on turbulent transport of momentum, taking into account different combinations of effects of rotation, stratification, flow shear, and magnetic field. Quasilinear analyses were used to calculate these effects, which are dynamically coupled through the equation of motion and the induction equation. A common feature of these effects is that they introduce anisotropy into the underlying turbulence, which in turn gives anisotropic turbulent transport. Flow shear was shown to be able to strongly modify turbulence, leading to weakened, anisotropic transport of momentum.<sup>8-10</sup> In addition to the flow shear, when the fluid is strongly stratified and magnetized,<sup>11</sup> or when fast rotation is introduced,<sup>12</sup> momentum transport can become antidiffusive, or transported up the flow gradient. These offer possible mechanisms to form and sustain sheared flows, which may have some similarities with the observed solar tachocline.

E. Schartman from Princeton Plasma Physics Laboratory (PPPL) presented recent results from the Magnetorotational Instability (MRI) experiment at Princeton. There have been two main proposed mechanisms to explain angular momentum transport accompanied with fast accretion rate in astrophysical disks. When disks are hot, and thus sufficiently ionized to conduct electric current, the MRI is destabilized to efficiently transport angular momentum.<sup>7</sup> In sufficiently cold disks, however, MRI can be stable while hydrodynamic turbulence could arise due to nonlinear instabilities at extremely large Reynolds numbers.<sup>13</sup> Investigations of nonlinear hydrodynamic instability have been the first focus of the Princeton MRI experiment.<sup>14</sup> By controlling boundary effects using two pairs of separately rotatable rings at its axial ends,<sup>15</sup> no signs of hydrodynamic turbulence have been detected<sup>16</sup> up to  $Re=2 \times 10^6$ . Furthermore, by directly measuring the Reynolds stress responsible for angular momentum transport us-

ing a synchronized dual laser Doppler velocimetry system, the measured transport efficiencies are well below the required values to be consistent with astrophysical observations. Thus, the pure hydrodynamic turbulence has been effectively eliminated as a viable mechanism to transport angular momentum in accretion disks. Initial results from the MHD experiments using liquid gallium have shown that a nonaxisymmetric instability arises when a sufficiently strong, axial magnetic field is applied to hydrodynamically turbulent flows.

F. Cattaneo from the University of Chicago presented results from state-of-the-art numerical simulations of MHD turbulence driven by MRI in a cylindrical geometry similar to the Princeton MRI experiment. He pointed out that numerical experiments and laboratory experiments are often complimentary to each other in the sense that laboratory experiments can often achieve parameters beyond what can be achieved numerically, while numerical experiments have great flexibility in exploring wide ranges in parameter space. The new results presented in this talk were obtained at magnetic Reynolds numbers much higher than the experimentally achievable values, but at Reynolds numbers much below the experimental values. It was shown that MHD turbulence develops due to MRI, and the flows act as efficient dynamos because the turbulence seems to persist as long as the flow is driven, even in the absence of an externally applied magnetic field. However, the amplified magnetic fields have relatively small-scale structures, similar to what is predicted for the small-scale dynamos, rather than the structures predicted for the large-scale dynamos. Angular momentum is transported mostly by Maxwell stress, and, as a result, the background flow profiles are strongly modified.

F. Stefani from Forschungszentrum Dresden-Rossendorf, Germany, presented experimental results from the PROMISE (Potsdam ROssendorf Magnetic InStability Experiment) device in helical magnetic fields. The experiments were motivated by the theoretical prediction that MRI can be destabilized at much smaller magnetic Reynolds numbers when a helical magnetic field (with both azimuthal and vertical components) is imposed.<sup>17</sup> The predicted traveling-wave patterns, and their axial traveling direction, have been observed in the experiment by using ultrasonic diagnostics.<sup>18-20</sup> Phase speeds of the traveling waves are also comparable, although not identical, to the predictions. The effects of radial boundary conditions have also been studied. Axial boundary conditions have been further optimized in the modified experiment, PROMISE 2. Initial results indicate that Ekman circulations are reduced, and the measured phase speed of the traveling waves agrees better with the numerical predictions. He also briefly discussed whether this helical MRI can be applicable for astrophysical disks, as well as the distinction between convective and absolute instabilities when evaluating effects due to axial boundary conditions.

W. Liu from Los Alamos National Laboratory presented axisymmetric numerical and analytical studies<sup>21,22</sup> of the helical MRI in a cylindrical geometry similar to the PROMISE experiment. It was shown that helical MRI is a weakly destabilized hydrodynamic inertial oscillation propagating axially along the background Poynting flux in vertically infinite

or periodic cylinders. This mode is stable in Keplerian flow profiles regardless of axial boundary conditions. When the finite axial dimension is taken into account, the growth rates are reduced or the mode can be completely stabilized in inviscid analyses. When the actual experimental boundary conditions are accurately modeled in resistive and viscous simulations, the measured wave patterns and their amplitudes are successfully reproduced. Contrary to previous claims, the waves are shown to be transiently amplified disturbances launched by viscous boundary layers, rather than globally unstable magnetorotational modes.

### III. SESSION II: ANGULAR MOMENTUM TRANSPORT IN ASTROPHYSICAL AND LABORATORY PLASMAS

The second session of the mini-conference was mostly devoted to various astrophysical topics, including related laboratory experimental work.

E. Zweibel (University of Wisconsin–Madison) discussed the angular momentum transport problem in environments with very weak magnetic fields, relevant to various astrophysical contexts. She first addressed MRI in the weak field limit,<sup>23</sup> appropriate for seed magnetic field generated by the Biermann battery effect (with  $\omega_{ci}/\Omega \sim 1$ ). She found that collisional disks are unfavorable for the weak-field MRI, because of strong resistive damping, but collisionless disks are more favorable, due to weaker damping and rapid growth on large scales because of the pressure anisotropy. She then discussed another topic of significant astrophysical interest where weak magnetic fields may have a strong effect on momentum transport: Turbulent mixing and entrainment in magnetized shear flows, e.g., in jets. She reported the results of her ongoing numerical work with collaborators on studying the Kelvin–Helmholtz instability with a background magnetic field parallel to the flow in a resistive inviscid fluid.<sup>24</sup> Contrasting 2D hydrodynamical and 2D MHD simulations, they found that the flow structure is much more intricate and the turbulent mixing layer spreads much stronger (two to three times) in the MHD case. The flow becomes very chaotic, generating a rich magnetic structure and transiently amplifying the field (before it eventually decays due to resistivity). Momentum transport is also larger in the MHD case because of Maxwell stresses. However, tracer particle transport (chemical mixing) was similar in the two cases.

P. Sharma (University of California, Berkeley) presented his numerical work on heating and angular momentum transport in hot accretion flows onto black holes (BHs) with low accretion rate, such as Milky Way’s Galactic Center BH. These systems (called “radiatively inefficient accretion flows,” or RIAFs) have very low radiative efficiency,  $L \ll \dot{M}c^2$ , and very low density, so understanding them requires analyzing the MRI in the collisionless regime. To do this, one has to take into account the anisotropic pressure tensor, related to the anisotropic Braginskii viscosity. This requires formulating a closure prescription for the heat fluxes that control the pressure anisotropy  $\Delta P \equiv P_{\perp} - P_{\parallel}$ , e.g., as in kinetic MHD. This can be done once one incorporates small-

scale instabilities that limit the growth of  $\Delta P$ , such as the ion-cyclotron and mirror instabilities for ions and electron-whistler for electrons for  $\Delta P > 0$ , and the firehose instability for  $\Delta P < 0$ . The resulting prescriptions allow one to perform a linear stability analysis for the collisionless MRI and do shearing box simulations.<sup>25</sup> A large  $\Delta P$  could, in principle, suppress MRI, but it is itself suppressed by these small-scale instabilities to  $|\Delta P|/P \sim 1/\beta \ll 1$ . Then, MRI is not strongly affected and proceeds essentially as in the MHD regime. Sharma also reported a significant (a few percent of the total energy) electron heating by the electron-whistler instability, which is important because it ultimately determines the radiative efficiency of the plasma.<sup>26</sup>

P. Kronberg (Los Alamos National Laboratory and University of Toronto) discussed observational evidence for magnetized accretion in supermassive BHs in active galactic nuclei (AGN), based on studies of giant radio jets and lobes. Simple estimates suggest that a significant (20%) fraction of the BH gravitational infall energy feeds into these structures, which magnetizes the intergalactic medium (IGM) and has important effects on its evolution.<sup>27</sup> He then discussed observational evidence for ongoing cosmic ray (CR) acceleration in the lobes of megaparsec-size radio sources. The evidence comes from the relatively short inferred synchrotron lifetime of CR electrons compared with their travel time across these structures. It suggests a gradual ( $10^8 - 10^9$  years) dissipation of magnetic energy, presumably by reconnection. Kronberg suggested that substantial, although still undetected, magnetic energy may be present in the IGM, and that it may be detected in the future as faint diffuse synchrotron radiation. He discussed difficulties in observational jet plasma diagnostics, and some ways to address them, e.g., using Faraday rotation and the total synchrotron luminosity measurements in knots. He presented the first preliminary measurement of an electric current in an extragalactic kpc-scale jet ( $\sim 7 \times 10^{17}$  amperes), and its sign directed *away* from the AGN BH.

E. Liang (Rice University) discussed a topic related to Sharma’s: MRI-induced turbulent heating in low-luminosity BH systems and the resulting nonthermal emission, including very hard  $\gamma$ -ray spectrum. This ongoing collaborative project attempts to reach across the huge dynamic range of this complicated problem and to connect global 2D general relativistic (GR) MHD simulations of MRI with studies of small-scale turbulent dissipation and finally with radiative transport. The overall physical picture is the following: MRI produces fully developed MHD turbulence; the energy cascades down to small (unresolved) scales, leading to plasma heating and nonthermal particle acceleration. Nonthermal electrons produce soft (IR) synchrotron emission which is then Compton-scattered by the same nonthermal electrons to yield the hard  $\gamma$ -ray emission. Finally, nonthermal ions produce very hard  $\gamma$ -ray emission via pion production and decay. Liang and his collaborators plan to employ a set of theoretical and numerical tools. On the largest scales, they use GR MHD simulations of MRI turbulence. Then, to study the dissipation of the turbulent cascade and particle energization at small scales, they plan to solve the Fokker–Planck equation and/or use PIC codes. The goal of this stage is to

derive a subgrid model for both thermal heating and nonthermal electron and ion spectra, to be used locally at each grid zone in the large-scale simulation. Once this is done, the computation will be coupled to a 2D Monte Carlo radiation transfer code that includes all the important photon production and scattering processes.<sup>28</sup> As a result, one will be able to predict the spectra and even build images of the accretion flow for different viewing angles.

B. Coppi (Massachusetts Institute of Technology) presented his work on “thermorotational instability,” a vertically localized MHD ballooning mode driven by vertical gradients of plasma density and temperature in stratified differentially rotating accretion disks.<sup>29</sup> Quasilinearly, the main effect of this instability is to drive the vertical profiles of the plasma density and temperature toward the adiabatic condition  $\eta_T \equiv (d \log T / dz) / (d \log \rho / dz) = 2/3$ , as has been shown previously.<sup>30</sup> In addition, Coppi suggested that the nonlinear development of the thermorotational mode can result in a breakup of the accretion disk into a sequence of counterstreaming toroidal current channels—axisymmetric plasma rings.<sup>31</sup>

D. Homan (Denison University) described the MOJAVE project, a systematic study of extragalactic jets using Very Long Baseline Array. He addressed the question of what these radio observations can tell us about the helical magnetic field structure in AGN radio jets on parsec scales (e.g., Cyg. A). Thus, gradients of Faraday rotation measured across the jet represent evidence for toroidal magnetic fields,<sup>32</sup> while the observed sign-consistency of circular polarization (on time scales of up to 20 years) suggests a persistent ordered net magnetic flux along the jet axis.<sup>33</sup>

S. Prager (University of Wisconsin–Madison) talked about momentum transport by current-driven instabilities (in contrast to the MRI flow-driven transport). He first described the ongoing experimental work on Madison Symmetric Torus (MST), a reversed-field pinch.<sup>34</sup> The plasma is observed to rotate differentially in MST, with periods of steady differential rotation being disrupted by very rapid (compared to classical) momentum transfer events, showing a sawtooth-like evolution of the plasma core toroidal velocity. The rotation profile flattens and angular momentum is transported outward. Simultaneous magnetic measurements indicate that these events coincide with fast magnetic reconnection (both at the core and at the edge). The leading explanation is current-driven tearing instability that involves the reconnection of the reversing toroidal field. This produces islands with both radial and toroidal field, and since these islands are immersed in a background shear flow, angular momentum is transported via Maxwell (and Reynolds) stresses. Even a single tearing mode transports toroidal momentum radially. But with multiple modes, the transport is amplified by nonlinear coupling. Prager presented a comparison of the properties of tearing and MRI mechanisms in relation to momentum transport. To understand the roles of tearing mode in momentum transport, the MST group employs a combination of theoretical and experimental work. On the theoretical side, a quasilinear calculation was done,<sup>35</sup> as well as 3D resistive MHD simulations (with an artificial force driving the shear flow), including the studies of multimode nonlinear coupling.

Prager also discussed astrophysical implications of current-driven instability for momentum transport, e.g., for thick disks in the strong-field case, which is more relevant for jets than for disks.

C. Forest (University of Wisconsin–Madison) proposed a new type of unmagnetized plasma experiment aimed at studying MHD dynamo and the MRI. He pointed out that the existing liquid metal experiments are limited to small magnetic Prandtl numbers due to material properties and small magnetic Reynolds numbers due to the limited stirring power. In addition, liquid metals are not transparent and thus are difficult to diagnose. Plasma experiments can provide more flexibility in terms of accessible magnetic Prandtl number, do not require as much power, enable one to study non-MHD plasma effects, and are easier to diagnose. However, such laboratory plasma studies are actually difficult because strong magnetic fields are usually required to insulate the hot plasma from the cold walls of the vacuum vessel. This makes traditional plasma devices unsuitable for studies of MHD dynamo and MRI. In his talk, Forest proposed an unconventional experimental setup involving a large number of axisymmetric ring cusps made of strong permanent magnets lining the inner wall of a spherical chamber. The magnetic field is then very strong only close to the wall, providing magnetic insulation while leaving the bulk of the interior volume relatively unmagnetized. Forest then outlined possible ways to drive the plasma flow and presented estimates demonstrating the viability of this concept. He discussed several possible experimental studies that could be performed with this device, including spherical von Karman flow, small-scale dynamo at large Prandtl number, and a study of the MRI. He also described a small pilot experiment to study a plasma Couette flow now under construction in Madison.

The last talk of the session was given by T. Islam (École Normale Supérieure, France, and University of Virginia). He talked about the magnetothermal and magnetoviscous instabilities (MTI and MVI, respectively) and their role in hot, dilute, nearly collisionless plasmas in low-luminosity accretion flows on supermassive black holes in the centers of most inactive galaxies, including the Milky Way (Sag. A\*). He first explained the basic physical mechanisms of these instabilities and the key role played by even a weak magnetic field in making both the heat conduction and the viscous stress tensor highly anisotropic.<sup>36–38</sup> He then compared the linear dispersion relations and the quadratic quasilinear heat and momentum fluxes for collisional MTI and collisionless MTI, and underscored the need for improved Landau fluid closures, similar to the collisionless MHD closures.<sup>39</sup> He also discussed the existing numerical studies of the effect of MTI turbulence on angular momentum transport in accretion flows.

#### IV. SESSION III: ANGULAR MOMENTUM TRANSPORT IN FUSION PLASMAS

Momentum transport and momentum generation are important physics issues for tokamak plasmas. Momentum transport is observed to be more rapid than the classical value. In addition, tokamak plasmas rotate even in the ab-

sence of an applied torque. The cause of the transport and the spontaneous, or intrinsic, rotation are yet undetermined. The presence and structure of plasma rotation are of substantial consequence. Sheared flow can reduce turbulence, influence the transition to the H mode, form internal transport barriers, and stabilize resistive wall instabilities. A session during the mini-conference was dedicated to laboratory observations of momentum transport and intrinsic rotation, as well as theoretical studies.

J. Rice (MIT) inferred general properties of rotation in tokamaks by comparing observations from many tokamaks in plasmas in the high confinement (H) mode.<sup>40</sup> The intrinsic rotation appears to propagate inward from the edge, with rotation being larger in H mode plasmas [relative to low (L) mode]. Rotation increases with stored plasma energy (normalized to the plasma current). Both the thermal and Alfvén Mach numbers increase with the normalized beta, possibly implying a connection to MHD. In ITER (International Thermonuclear Experimental Reactor), the normalized beta is expected to be about 2.6, so that the thermal and Alfvén Mach numbers would be expected to be about 0.3 and 0.02, respectively, with rotation speeds about 250 km/s. This value of rotation might be large enough for stabilization of resistive wall instabilities. Rotation is roughly independent of the normalized gyroradius and normalized collisionality, possibly suggesting independence from electrostatic turbulence.

Experimental studies in the DIII-D tokamak have also revealed how momentum transport (or the momentum confinement time) varies with key plasma parameters. W. Solomon (PPPL) presented such information for DIII-D plasmas with only a weak torque provided by neutral beams.<sup>41</sup> The torque in H mode plasmas with the presence of an edge-localized mode (ELM) was scanned, holding beta constant. The intrinsic rotation profile is deduced from the scan. The intrinsic rotation, of interest for its own sake, must also be taken into account in evaluation of the momentum confinement time. It is found that the confinement time decreases as the applied torque increases. A cautionary note to the above conclusions is that they can be influenced by anomalous diffusion of fast ions (possibly implied by neutron emission measurements).

In the NSTX (National Spherical Torus Experiment), a small aspect ratio tokamak, strong shear flows are observed<sup>42,43</sup> that are 510 times larger than the growth rate for ion temperature gradient instabilities, as reported in a paper by S. Kaye *et al.* (and delivered at the mini-conference by W. Solomon). The momentum diffusivity behaves quite differently from the ion particle diffusivity. The momentum diffusivity is larger than the neoclassical value in plasmas for which the ion particle diffusivity is approximately neoclassical. Moreover, the momentum diffusivity scales differently from particle diffusivity (unlike the case of normal aspect ratio tokamaks). For example, the momentum diffusivity scales more strongly with the toroidal magnetic field than with the plasma current, unlike the particle diffusivity. Momentum perturbation experiments were performed by imposing rotation damping by magnetic perturbations (with toroidal mode number=3). The rotation damping is consistent

with neoclassical toroidal viscosity. Transport analysis indicates the presence of an inward momentum pinch.

G. Tynan from University of California, San Diego (UCSD) presented experimental results from a linear plasma device on the development of an azimuthally symmetric, radially sheared plasma flow in the absence of an external source of momentum. The measured radial flux of azimuthal momentum (i.e., the Reynolds stress) is consistent with such a sheared flow, which is damped by ion-neutral drag and ion-ion collisional viscosity.<sup>44,45</sup> This indicates that turbulent momentum transport appears to be the mechanism that sustains the shear flow. Two-field turbulence simulations of the experiment also show the natural emergence of such a shear layer from nonlinearly interacting collisional drift waves, providing further support to this interpretation. It is also found that the shearing rate varies on a very slow frequency scale (i.e.,  $\sim 1\%$  of the diamagnetic drift frequency), and is linked to a similar slow variation in the turbulent Reynolds stress and the turbulence amplitude. In addition, radially outgoing bursts of plasma are occasionally born in the region of the shear layer, and then propagate convectively outwards, away from the main plasma.<sup>46</sup> These recent observations suggest that shear layer modulation, turbulence and turbulent Reynolds stress modulation, and generation of bursts of outward going plasma events (referred to as blobs, fingers, and avaloids in the literature) are linked, and form a complex dynamical system.

Experimental studies of rotation have also been reported in a simple torus, the TORPEX experiment. TORPEX contains a dominant toroidal magnetic field and a much weaker ( $\sim 100$  times) vertical field. Thus, the field lines are open. The plasma is produced by microwaves, and the resulting plasma exhibits both vertical and toroidal flows. The 2D flow pattern (reported by B. Labit) has been measured with an insertable Mach probe. The flow pattern agrees with that expected from  $E \times B$  drift in the measured radial electric field. However, the toroidal flow is about 100 times larger than expected from the  $E \times B$  drift (and comparable in magnitude to the vertical flow). Local increases in toroidal flow are observed simultaneously with density blobs. These features are thought to be associated with interchange modes.<sup>47</sup> The excess flow and the density blob are both expelled radially and simultaneously, suggesting a conservation of momentum.

Substantial theoretical effort is underway to explain both the intrinsic rotation and the transport of momentum. Three theoretical studies were presented at the mini-conference, spanning effects from turbulent transport to neoclassical momentum generation. Ö. D. Gürçan from UCSD (delivering a paper by P. H. Diamond *et al.*<sup>48</sup>) presented a theory of turbulent equipartition of angular momentum.<sup>49,50</sup> The theory is motivated, in part, by experimental observations that the rotation profile is centrally peaked in some cases, and that the Reynolds stress and rotation are correlated (implying an anomalous mechanism). From conservation of angular momentum density, a model is derived in which turbulent mixing leads to conservation of a local quantity  $L_\Phi/\lambda$ , where  $L_\Phi$  is the toroidal angular momentum, and  $\lambda=B$  for a slab with inhomogeneous magnetic field, or  $\lambda=B^2$  for a low  $\beta$  torus.

The mixing stops at “equipartition,” which occurs when the angular momenta in two adjacent toroidal shells are equal. This process leads to an inward pinch of angular momentum density. A general model including both the effects of  $E \times B$  shear driven residual stress<sup>51</sup> and the turbulent equipartition pinch is introduced. Intrinsic rotation and centrally peaked profiles are possible consequences of this model.

A. Aydemir presented a neoclassical theory for edge flows and intrinsic momentum.<sup>52,53</sup> The model is motivated by three experimental observations: all tokamaks have mass flow at the plasma edge, all tokamaks have toroidal rotation in the core, and the L-H transition requires more power if the  $\nabla B$  drift points away from the  $x$  point in the magnetic field. The neoclassical model might be able to explain all three observations. In the presence of collisions, neoclassical theory predicts that a dipolar flow pattern develops in which a major radial flow arises directed from the low-field side to the high-field side, leading to a return flow in the scrape-off layer. This constitutes a dipole pattern of counter-rotating vortices, or transport-driven flows. The interaction of these flows with a poloidally asymmetric field geometry (e.g., due to a divertor null in the poloidal field) can provide a net toroidal momentum input from the edge, a possible source of intrinsic rotation. The flows have the correct symmetry properties and dependence on field direction to account for the  $\nabla B$  drift dependence of the L-H power threshold.

C-S. Chang described the sources for angular momentum in the tokamak edge plasma. Full-f gyrokinetic ion-electron simulation<sup>54</sup> of quiescent edge plasmas (including the pedestal, lower single null magnetic separatrix, scrape-off, and the grounded material wall) finds three spontaneous rotation sources in the edge plasmas. (a) Ion orbit losses due to the existence of a magnetic  $x$  point<sup>55,56</sup> gives rise to cocurrent rotation in the H-mode-like pedestal top/shoulder region. In an L-mode-like pedestal, the cocurrent rotation source becomes small.<sup>57</sup> (b) A strong negative radial electric field in the vicinity of the magnetic separatrix yields a sharp valley of countercurrent rotation at the same radial location. In an H-mode pedestal, the negative radial electric field and, thus, the countercurrent rotation valley, become strong. In an L-mode pedestal, this phenomenon becomes weaker. (c) Plasma wall interaction generates positive radial electric field and cocurrent plasma rotation in the scrape-off region. The cocurrent rotation in the scrape-off plasma becomes stronger in an L-mode edge. The general trend is that in the lower single null L-mode plasma, there is a strong cocurrent rotation in the scrape-off region, without much rotation in the pedestal top. As the pedestal steepens, the cocurrent rotation moves into the pedestal top from scrape-off plasma. These findings from the gyrokinetic particle simulation are consistent with experimental observations.<sup>58</sup> It has also been shown that plasma interaction with background neutral particles can modify the toroidal rotation.<sup>59</sup> When the neutral gas is puffed from the high-magnetic-field side in NSTX, the rotation becomes stronger and the H-mode power threshold is lower than when the gas puff is from the low-magnetic-field side. Resonant magnetic perturbations are also seen to produce spontaneous cocurrent rotation.

## V. SESSION IV: ANGULAR MOMENTUM TRANSPORT IN THE EARTH'S CORE, SUN, AND LABORATORY

Session IV began with a presentation by B. Buffett (University of Chicago) on angular momentum transport and magnetic interactions between the Earth's cores and the mantle. Magnetic field is continuously generated by convection in the liquid iron core, known as the geodynamo,<sup>60,61</sup> and is believed to sustain a differential rotation between the inner and outer boundaries. The differential rotation is thought to be a consequence of large-scale fluid circulation in a region defined by the tangent cylinder (a hypothetical cylinder that is tangent to the solid inner core at the equator). Different detailed mechanisms were discussed on the interactions between gravitational and magnetic forces that regulate the deformation, rotation, and axial misalignment of the Earth's core.

D. Lathrop (University of Maryland) summarized several experiments that study flows between differentially rotating spheres and cylinders, in attempts to model geophysically relevant phenomena. In a spherical Couette flow of liquid sodium, MHD modes were observed when an axial magnetic field is imposed along the rotation axis.<sup>62</sup> He attributed the modes to the MRI because of associated torque increases and similarities in dependences on the field strength, although there were differences on the predicted mode structures and the boundary conditions, as well as the fact that the base states were already hydrodynamically turbulent before magnetic field is imposed. He went on to describe experimental results on inertial waves driven by differential rotation in another (larger) spherical Couette flow also in liquid sodium.<sup>63</sup> The magnetic field was used as a tracer measurement for the fluid motion. Despite a turbulent background, coherent oscillations were observed that agreed with linear theory of the inertial waves, in terms of frequency, wave number, and induced magnetic structure. He hypothesized that these waves are excited by the differential rotation of the inner sphere to the outer sphere, and similar phenomena may exist in the Earth as the inner core rotates faster relative to the outer core.

The tachocline layer of the solar interior is a puzzling phenomenon. It has been a focus of several efforts to model and understand it. Its importance as a plasma physics testbed is underlined by the existence of a recent book on the subject.<sup>64</sup> The tachocline is a thin ( $\leq 4\%$  of  $R_{\odot}$ ) layer at  $r \sim 0.7 R_{\odot}$ . It is very stably stratified. It separates the inner, solid body rotating radiative zone from the outer convection zone, and appears to play a major role in transporting angular momentum inward to the Sun's core. Most solar dynamo models rely on processes at or near the tachocline. The differential rotation that occurs throughout the convection zone occurs above, but not below, this remarkable, thin discontinuity. It also influences the sunspot cycle behavior. An overview talk by S. Tobias (Leeds University, UK) presented various ideas on how angular momentum could be transported through the tachocline, and summarized different competing physical models.<sup>65</sup> The tachocline has a relatively high density,  $\rho \sim 0.2 \text{ g cm}^{-3}$  and is hot ( $T \sim 2 \times 10^6 \text{ K}$ ), giving a pressure of  $\sim 6 \times 10^{12} \text{ Pa}$ . Its plasma  $\beta$  is  $\sim 10^5$  with



tions can accumulate into a groundbreaking theory, which can unify our understandings in different systems.

We hope that this mini-conference serves as a modest first step for the interplay between different systems on the problem of angular momentum transport.

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