FINAL RESEARCH REPORT FOR DE-FG02-00ER5460

PROJECT TITLE: New Approaches to the Origin and Dynamics of Magnetic Fields of Cosmic Relevance

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1. EXECUTIVE SUMMARY

The work supported by this grant focused on turbulent magnetized plasma physics motivated by, but not restricted to, processes in astrophysical plasmas. The work integrated theoretical studies of magnetic field origin and dynamics with astrophysical and laboratory environments.

A primary focus of the research was understanding non-linear magnetic dynamo theory. We have, for the first time, produced analytic models that fit fully non-linear 3-D simulations of dynamo action in turbulent plasmas extremely well. Central to the work has been understanding the role of magnetic helicity evolution. In addition to the theoretical work, we have studied dynamo models of specific astrophysical sources and laboratory systems. We have developed non-linear theories for both velocity driven and magnetically driven dynamos.

Another focus of the research has been magnetohydrodynamic plasma accretion flows and dynamo-driven outflows and jets. The direct application to astrophysical sources both in the relativistic (active galactic nuclei, gamma-ray bursts) and non-relativistic (stellar outflows) regimes was studied.

We also investigated diagnostics for general accretion plasmas around black holes based on how the geometry of the plasma accretion flow determines specific fluorescent Iron line profiles These accretion disks are sites of dynamo action and it is important to know their geometry and to test the paradigms in broad use for explaining the emission from compact accreting systems.

We also studied aspects of dynamo theory and particle acceleration in the sun.

Over 50 papers have come from this research grant.

2. COMPARISON BETWEEN OBJECTIVES AND ACCOMPLISHMENTS

The research program that resulted from this grant was a tremendous success. The objectives were exceeded and the research output went way beyond expectations.

We developed the first fully dynamically consistent non-linear magnetic dynamo theory that agrees with numerical simulations, and a new diagrammatic paradigm to understand how magnetic helicity conservations plays a fundamental role in the interpretation of the equations. We also studied a very wide range of fundamental processes in MHD turbulence, dynamo theory, and specifically applied these concepts to specific astrophysical sources and laboratory experiments. The scope of the research was very broad, while still keeping a direct connection to the intended purposes of the grant: Understanding the origin and function of magnetic fields in astrophysically relevant contexts.

This generous Faculty Development grant also served the purpose of establishing my own research program and career path: I believe that, largely as a result of the work resulting from this grant, I was given tenure in 2003 and promoted to full Professor in 2004.

Remarkably, 53 publications resulted from this grant. In what follows, I describe a sampling of each of the different topics studied and list the full set of papers associated with each section at the end of each section. Authors supported by the grant are in boldface.

3. PROJECT ACTIVITIES AND PUBLICATIONS

3.1. Magnetic Helicity and Dynamos and Turbulence: Fundamental Theory

Magnetic field amplification in astrophysical and laboratory plasmas ultimately requires an understanding of MHD turbulence. Two spectral regimes of magnetic field amplification in magnetohydrodynamic (MHD) flows can be distinguished by the scale on which fields are amplified relative to the primary forcing scale of the turbulence. For field amplification at or below the forcing scale, the amplification can be called a “small scale dynamo.” For amplification at and above the forcing scale the process can be called a “large scale dynamo.”

Kinetic helicity has long been known to be important for large-scale field growth in forced MHD turbulence and has been recently demonstrated numerically to be asymptotically consistent with slow mean field dynamo action in a periodic box. We have shown both numerically and analytically that the magnetic spectrum at, above, *and* below the forcing scale are ALL strongly influenced by kinetic helicity. We identified a critical value, $f_{h,crit}$, above which the magnetic spectrum develops maxima at a wavenumber of 1 scale and at the forcing scale. For $f < f_{h,crit}$ the field peaks only at the resistive scale. Kinetic helicity is thus important not only for generating a large-scale field, but also for establishing observed peaks in magnetic spectra at the forcing scale. We found that $Non-local$ (in wave number) effects play a key role in both the growth of the small scale field in non-helical turbulence and the growth of large and small scale fields in helical turbulence.

Mean field dynamo (MFD) theory represents a simple semi-analytic way to get a handle on large scale field amplification in MHD turbulence. Helicity has long been known to be important for large scale, flux generating, externally forced MFDs. The extent to which such MFDs operate "slow" or "fast" (dependent or independent on magnetic Reynolds number) has been controversial, but we have made progress. Simulations of α^2 dynamos in a periodic box dynamo and their quenching can now be largely understood within a simplified dynamical non-linear paradigm in which the MFD growth equation is supplemented by the total magnetic helicity evolution equation. For α^2 dynamos, the large scale field growth is directly related to the large scale magnetic helicity growth. Magnetic helicity conservation then implies that growth of the large scale magnetic helicity induces growth of small scale magnetic (and current) helicity of the opposite sign, which eventually suppresses the α effect driving the MFD growth. Although the α^2 MFD then becomes slow in the long time limit, substantial large scale field growth proceeds in a kinematic, "fast" phase before non-linear asymptotic quenching of the "slow" phase applies. Ultimately, the MFD emerges as a process that transfers magnetic helicity between small and large scales. We have now demonstrated all of this with a fully dynamic non-linear theory. How these concepts apply to more general dynamos with shear, and open boundary dynamos is a topic of ongoing research.

We have also generalized this theory to the magnetically dominated case, appropriate for both astrophysical coronae and magnetic fusion confinement configurations. Here the magnetic energy is not amplified, but but transferred from small scales to large scales via relaxation. This has led us to converge on a new paradigm for understanding the origin of the jet-mediating magnetic fields of in astrophysical rotators: Our paradigm is that a velocity driven dynamo generates magnetic fields inside the rotator but a magnetically dominated dynamo relaxes the fields further to even larger scales. Magnetic helicity conservation plays a central role in both processes. The time-dependent dynamical theory of the relaxation process in the magnetically dominated coronae also has application to the dynamical relaxation in laboratory devices, particularly RFP and Spheromaks.

Overall, the following poem summarizes our nonlinear mean-field dynamo theory of both the velocity dominated dynamo and magnetically dominated dynamical relaxation process:

For a closed turbulent flow,

the non-linear mean field dynamo,

is first fast and kinematic,

then slow and dynamic,

and magnetic helicity transfer makes it so.

For the magnetically dominated case,

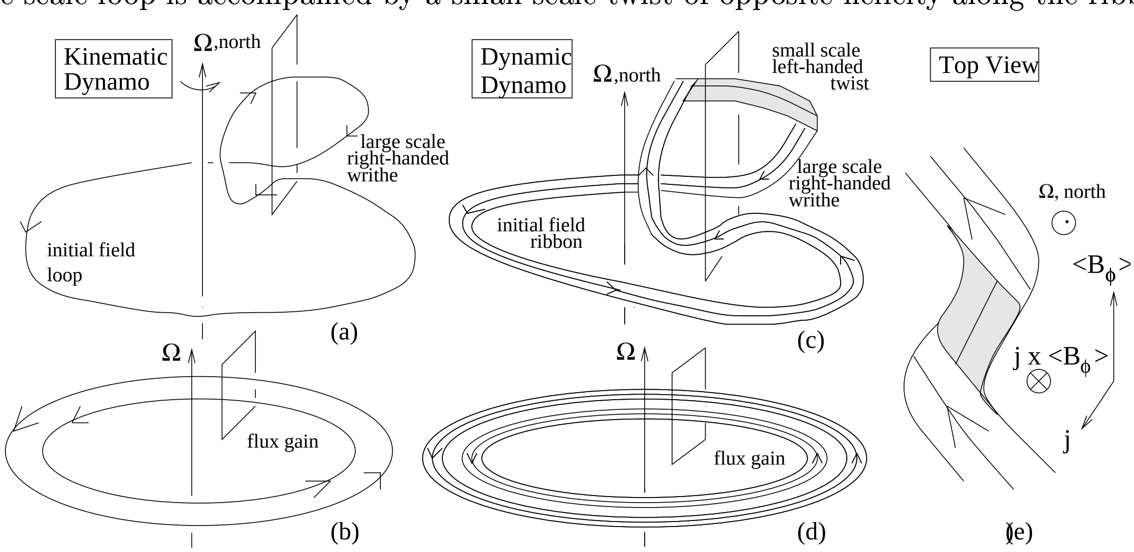
it's dynamical relaxation we face;

this starts kinematically,

but it too slows dynamically;

here kinetic helicity growth damps the pace.

In addition, we have found that the textbook diagrams of large scale dynamos involving magnetic fields should be replaced with a new type of diagram because the traditional pictures do not conserve magnetic helicity. Normally the pictures treat the magnetic fields as lines, but we have shown that the the lines should be replaced by ribbons in order to properly include magnetic helicity conservation. The figure on the left below is the traditional picture, and the middle figure is the same with the field lines replaced by a ribbon. The large scale loop is accompanied by a small scale twist of opposite helicity along the ribbon!:



Our work on MHD turbulence has also led to papers on thermal conduction, as well as a new closure approach for turbulent transport of a scalar. For the latter, we have found that, in contrast to the standard textbooks, the correct equation for turbulent transport should be a second order equation rather than a first order equation. This has been confirmed numerically by other authors.

Blackman, E. G. 2004, Plasma Physics and Controlled Fusion, 46, 423, How spectral shapes of magnetic energy and magnetic helicity influence their respective decay time scales

Blackman, E. G., & Field, G. B. 2004, Physics of Plasmas, 11, 3264, Dynamical magnetic relaxation: A nonlinear magnetically driven dynamo

Blackman, E. G., & Field, G. B. 2003, Physics of Fluids, 15, L73, A new approach to turbulent transport of a mean scalar

Blackman, E. G. 2003, MNRAS, 344, 707, Understanding helical magnetic dynamo spectra with a non-linear four-scale theory

Blackman, E. G., & Field, G. B. 2002, Physical Review Letters, 89, 265007, New Dynamical Mean-Field Dynamo Theory and Closure Approach

Blackman, E. G. 2003, (Springer) Lecture Notes in Physics, Vol. 614: Turbulence and Magnetic Fields in Astrophysics, 614, 432 *Recent Developments in Magnetic Dynamo Theory*

Blackman, E.G.& Brandenburg, A. 2002, Dynamic nonlinearity in large scale dynamos with shear, ApJ, 579, 359

Field G.B. & **Blackman, E.G.** 2002, Dynamical Quenching of the α^2 Dynamo, ApJ 572, 685.

Maron J. & **Blackman, E.G.** 2002, *Effect of Fractional Kinetic Helicity on Turbulent Magnetic Dynamo Spectra* ApJ, 566, L41

Schekochihin, A. A., **Maron, J. L.**, Cowley, S. C., & McWilliams, J. C. 2002, ApJ, 576, 806, The Small-Scale Structure of Magnetohydrodynamic Turbulence with Large Magnetic Prandtl Numbers

Schekochihin, A. A., Cowley, S. C., Hammett, G. W., **Maron, J. L.**, & McWilliams, J. C. 2002, New Journal of Physics, 4, 84, A model of nonlinear evolution and saturation of the turbulent MHD dynamo

Colgate, S. A., Li, H., & **Pariev, V. I.** 2001, Physics of Plasmas, 8, 2425, The origin of the magnetic fields of the universe: The plasma astrophysics of the free energy of the universe

Blackman, E.G.& Field, G. B. 2001, *How astrophysical mean field dynamos can circumvent existing quenching constraints*, Phys. of Plasmas, 8, 2407

Maron, J. L. , & Howes, G. G. 2003, ApJ, 595, 564, Gradient Particle Magnetohydrodynamics: A Lagrangian Particle Code for Astrophysical Magnetohydrodynamics

Schekochihin, A. A., Cowley, S. C., Taylor, S. F., **Maron, J. L.**, & McWilliams, J. C. 2004, Ap&SS, 292, 141, From Small-Scale Dynamo to Isotropic MHD Turbulence

Schekochihin, A. A., Cowley, S. C., **Maron, J. L.**, & McWilliams, J. C. 2004, Physical Review Letters, 92, 054502, Critical Magnetic Prandtl Number for Small-Scale Dynamo

Schekochihin, A. A., Cowley, S. C., **Maron, J. L.**, & McWilliams, J. C. 2004, Physical Review Letters, 92, 064501, Self-Similar Turbulent Dynamo

Schekochihin, A. A., Cowley, S. C., Taylor, S. F., Hammett, G. W., **Maron, J. L.**, & McWilliams, J. C. 2004, Physical Review Letters, 92, 084504, Saturated State of the Nonlinear Small-Scale Dynamo

Maron, J. L., Cowley, S., & McWilliams, J. 2004, ApJ, 603, 569, The Nonlinear Magnetic Cascade

Schekochihin, A. A., Cowley, S. C., Taylor, S. F., **Maron, J.L.** , & McWilliams, J. C. 2004, ApJ, 612, 276, Simulations of the Small-Scale Turbulent Dynamo

Chandran, B. D. G., & **Maron, J.L.**, 2004, ApJ, 603, 23, Acceleration of Energetic Particles by Large-Scale Compressible Magnetohydrodynamic Turbulence

Chandran, B. D. G., & **Maron, J.L.**, 2004, ApJ, 602, 170, Thermal Conduction and Particle Transport in Strong Magnetohydrodynamic Turbulence, with Application to Galaxy Cluster Plasmas

Maron, J.L., Chandran, B. D., & **Blackman, E.** 2004, Physical Review Letters, 92, 045001, Divergence of Neighboring Magnetic-Field Lines and Fast-Particle Diffusion in Strong Magnetohydrodynamic Turbulence, with Application to Thermal Conduction in Galaxy Clusters

3.2. Dynamos: Applications

3.2.1. Planetary Nebulae

Planetary nebulae are thought to be formed when a slow wind from a progenitor giant star is overtaken by a subsequent fast wind generated as the star enters its white dwarf stage. A shock forms near the boundary between the winds, creating the relatively dense shell characteristic of a planetary nebula. A spherically symmetric wind will produce a spherically symmetric shell, yet over half of known planetary nebulae are not spherical; rather, they are elliptical or bipolar in shape. We have argued that a magnetic field could launch and collimate a bipolar outflow, and we have shown that an asymptotic-giant-branch (AGB) star can generate a strong magnetic field, having as its origin a dynamo at the interface between the rapidly rotating core and the more slowly rotating envelope of the star. The fields are strong enough to shape the bipolar outflows that produce the observed bipolar planetary nebulae. This dynamo model is similar to that of the sun.

Blackman, E.G., Frank, A., Markiel, J. A., Thomas, J. H., & Van Horn, H. M. 2001, Nature, 409, 485, Dynamos in asymptotic-giant-branch stars as the origin of magnetic fields shaping planetary nebula

Van Horn, H. M., Thomas, J. H., Frank, A., & **Blackman, E. G.** 2003, ApJ, 585, 983, Fuel-Supply-limited Stellar Relaxation Oscillations: Application to Multiple Rings around Asymptotic Giant Branch Stars and Planetary Nebulae

Matt, S., Frank, A., & **Blackman, E. G.** 2004, ASP Conf. Ser. 313: Asymmetrical Planetary Nebulae III: Winds, Structure and the Thunderbird, p449, The Last Hurrah: PPN Formation by a Magnetic Explosion

Kastner, J. H., Balick, B., **Blackman, E. G.**, Frank, A., Soker, N., Vrtílek, S. D., & Li, J. 2003, ApJ, 591, L37, A Compact X-Ray Source and Possible X-Ray Jets within the Planetary Nebula Menzel 3

Blackman, E. G. 2004, ASP Conf. Ser. 313, Asymmetrical Planetary Nebulae III: Winds, Structure and the Thunderbird, p401, Dynamo-Driven Outflows in Pre-Planetary Nebulae

3.3. Laboratory Applications

Pariev (postdoc) worked on a project that identified a new kind of dynamo utilizing flowing laboratory plasmas. Conversion of plasma kinetic energy to magnetic energy is verified numerically by kinematic dynamo simulations for magnetic Reynolds numbers above 210. As opposed to intrinsically-turbulent liquid-sodium dynamos, these dynamos correspond to laminar flow topology. Modest plasma parameters, 1-20 eV temperatures, $10^{19} - 10^{20} m^{-3}$ densities in 0.3-1.0 m scale-lengths driven by velocities on the order of the Alfven Critical Ionization Velocity (CIV), self-consistently satisfy the conditions needed for the magnetic field amplification. Growth rates for the plasma dynamos were obtained numerically with different geometry and magnetic Reynolds numbers. Magnetic-field-free coaxial plasma guns can be used to sustain the plasma flow and the dynamo.

Pariev (postdoc) and Nordhaus (undergrad) also worked on analysis of a separate magnetic dynamo experiment is under construction at the New Mexico Institute of Mining and Technology. The experiment is designed to demonstrate in the laboratory the $\alpha - \omega$ magnetic dynamo, which is believed to operate in many rotating and conducting astrophysical objects. The experiment uses the Couette flow of liquid sodium between two cylinders rotating with different angular velocities to model the ω (shear) effect. The α (helicity) effect is created by the rising and expanding jets of liquid sodium driven through a pair of orifices in the end plates of the cylindrical vessel, presumably simulating plumes driven by buoyancy in astrophysical objects. The water analog of the dynamo device has been constructed and the flow necessary for the dynamo has been demonstrated. Results of the numerical simulations of the kinematic dynamo were studied by Pariev (postdoc).

Colgate, S. A., **Pariev, V.I.**, Beckley, H. F., Ferrel, R., Romero, V. D., & Weatherall, J. C. 2002, *The New Mexico alpha-omega Dynamo Experiment: Modeling Astrophysical Dynamos* Magnetohydrodynamics, 38, 129-142,

Noguchi, K., **Pariev, V. I.** , Colgate, S. A., Beckley, H. F., & Nordhaus, J. 2002, ApJ, 575, 1151

Wang, Z., **Pariev, V.I.**, Barnes, C. W., & Barnes, D. C. 2002, *Laminar Plasma Dynamos*, Physics of Plasmas, 9, 1491

Pariev, V. I., & Delzanno, G. L. 2003, Physics of Plasmas, 10, 1262, Stability analysis of hollow electron columns including compressional and thermal effects: Initial value treatment

Delzanno, G. L., **Pariev, V. I.**, Finn, J. M., & Lapenta, G. 2002, Physics of Plasmas, 9, 4863, Stability analysis of hollow electron columns including compressional and thermal effects: Integrability condition and numerical simulations

4. Plasma Outflows and Jets

4.1. Magnetically Driven Outflows

In astrophysics, MHD winds can emanate from both stars and surrounding plasma disks. When the two systems are coupled by accretion, it is of interest to know how much wind power is available and which (if either) of the two rotators dominates that power. We investigated this in the context of multi-polar planetary nebulae (PNs) and protoplanetary nebulae (PPNs), for which recent observations have revealed the need for a wind power source in excess of that available from radiation driving and a possible need for magnetic shaping. We calculated the MHD wind power from a coupled disk and star, where the former results from binary disruption. The resulting wind powers depend only on the accretion rate and stellar properties. We found that if the stellar envelope were initially slowly rotating, the disk plasma wind would dominate. If the star were rapidly rotating, the stellar wind could initially be of comparable power to the disk wind until the stellar wind carries away the star's angular momentum. Since an initially rapidly rotating star can have its spin and magnetic axes misaligned to the disk, multipolar outflows can result from this disk wind system. Magnetized plasma activity such as X-ray flares from magnetic reconnection may be associated with both the central star and the disk and would be a valuable diagnostic for the dynamical role of MHD processes.

With Tan, we have also considered dynamos and dynamo driven outflows in the first generation of stars formed in the metal free plasma of the early universe. We showed that magnetic fields can in fact be produced and produce outflows that affect the rate at which the gas accumulates to form stars. The star formation process in the early universe is one of the fundamental observational constraints in the study of the cosmological evolution of galaxies, and depends on the plasma physics of the interstellar medium.

We have also studied aspects of jet physics in highly relativistic sources. Pariev considered the stability, particle acceleration and emission from relatvistic magnetically dominated jets at the cores of active galaxy centers. These jets emanate from within a few Schwarzchild radii of the central black holes. The jets observed out to parsec scales from the engines of these active galaxies are thought to be so magnetically dominated that $B^2 >> \rho c^2$, where B is the field and ρ is the density.

Blackman, E.G., Frank, A., & Welch, C. 2001, ApJ, 546, 288 Magnetohydrodynamic Stellar and Disk Winds: Application to Planetary Nebulae

Frank, A., & **Blackman, E. G.** 2004, ApJ, 614, 737, Application of Magnetohydrodynamic Disk Wind Solutions to Planetary and Protoplanetary Nebulae

Tan, J. C., & **Blackman, E. G.** 2004, ApJ, 603, 401, Protostellar Disk Dynamos and Hydromagnetic Outflows in Primordial Star Formation

Pariev, V. I., Istomin, Y. N., & Beresnyak, A. R. 2003, A&A, 403, 805 Relativistic parsec-scale jets: II. Synchrotron emission

Beresnyak, A. R., Istomin, Y. N., & **Pariev, V. I.** 2003, A&A, 403, 793 Relativistic parsec-scale jets: I. Particle acceleration

4.2. Clumpy Flows

Many astrophysical flows occur in inhomogeneous (clumpy) media. We numerically studied steady, planar shocks interacting with a system of embedded cylindrical clouds in a two-dimensional geometry. We used an adaptive mesh refinement to simulate the interaction of embedded inhomogeneities with a shock and showed that it depends primarily on the thickness of the cloud layer and arrangement of the clouds. We identified a critical cloud separation along the direction of the flow and perpendicular to it distinguishing between the interacting and noninteracting regimes of cloud evolution. These results are also applicable/testable with laser plasma driven flows in the presence of obstacles.

We also considered the stability of an accretion disk wind to cloud formation when subject to a central radiation force. For a vertical launch velocity profile that is Keplerian or flatter and the presence of a significant radiation pressure, the wind flow streamlines cross in a conical layer. We argued that such regions are highly unstable, and are natural sites for supersonic turbulence and, consequently, density compressions. We suggest that combined with thermal instability these will all conspire to produce clouds. Such clouds can exist in dynamical equilibrium, constantly dissipating and reforming. As long as there is an inner truncation radius to the wind, our model emerges with a biconical structure similar to that inferred for the enigmatic broad line region (BLR) of active galactic nuclei (AGN). Our results may also apply to other disk-wind systems.

Poludnenko, A. Y., Frank, A., & **Blackman, E. G.** 2002, ApJ, 576, 832, Hydrodynamic Interaction of Strong Shocks with Inhomogeneous Media: Adiabatic Case

4.3. Laboratory Jet Experiments

We collaborated on presenting the first results of astrophysically relevant experiments where highly supersonic plasma jets are generated via conically convergent flows. The convergent flows are created by electrodynamic acceleration of plasma in a conical array of fine metallic wires (a modification of the wire array Z-pinch). Stagnation of plasma flow on the axis of symmetry forms a standing conical shock effectively collimating the flow in the axial direction. This scenario is essentially similar to that discussed by Cant and collaborators as a purely hydrodynamic mechanism for jet formation in astrophysical systems. Experiments using different materials (Al, Fe, and W) show that a highly supersonic (M 20), well-collimated jet is generated when the radiative cooling rate of the plasma is significant. Scaling the experiments for numerical code verification was considered. The experiments also allow direct exploration of astrophysically relevant issues such as collimation, stability, and jet-cloud interactions.

Lebedev, S. V.; Chittenden, J. P.; Beg, F. N.; Bland, S. N.; Ciardi, A.; Ampleford, D.; Hughes, S.; Haines, M. G.; Frank, A.; **Blackman, E. G.**; Gardiner, T. 2002, Laboratory Astrophysics and Collimated Stellar Outflows: The Production of Radiatively Cooled Hypersonic Plasma Jets, ApJ, 564, 113

Lebedev, S. V.; Ampleford, D.; Ciardi, A.; Bland, S. N.; Chittenden, J. P.; Haines, M. G.; Frank, A.; **Blackman, E. G.**; Cunningham, A. 2004, ApJ Letters, 616, 988, Jet Deflection via Crosswinds: Laboratory Astrophysical Studies

5. Accretion Disk Plasmas

5.1. Theory

In addition to the scalar Shakura-Sunyaev α_{ss} turbulent viscosity transport term used in simple analytic accretion disk modeling, a pseudo-scalar transport term also arises. The essence of this term can be captured even in simple models for which vertical averaging is interpreted as integration over a half-thickness and each hemisphere is separately studied. The additional term highlights a complementarity between mean field magnetic dynamo theory and accretion disk theory treated as a mean field theory. Such pseudo-scalar terms have been studied, and can lead to large-scale magnetic field and vorticity growth. We showed that vorticity can grow even in the simplest azimuthal and half-height integrated disk model, for which mean quantities depend only on radius. The simplest vorticity growth solutions seem to have scales and vortex survival times consistent with those required for facilitating planet formation. These calculations included the magnetic back-reaction.

In a separate project, we considered a model of turbulent accretion disks supported by magnetic pressure of turbulent magnetic fields. The turbulent kinetic energy is in equipartition with the turbulent magnetic energy and exceed the thermal energy and radiation energy in the disk. Such supersonic turbulence has a dissipation time of the order of one turnover time of the largest eddy, which is limited by the disk thickness. The energy dissipated by the turbulence is radiated away from the surface of the disk. We derived the condition for the radiation loss time scale to be short enough to justify the self-consistency of a magnetically dominated thin disk. We also calculated the radial structure and emission spectra of such a disk and discussed its applications to actively accreting extragalactic sources.

Blackman, E.G., 2001, Implications of mean field accretion disk theory for vorticity and magnetic field growth, MNRAS, 323, 497

Pariev, V. I., **Blackman, E. G.**, & Boldyrev, S. A. 2003, A&A, 407, 403 Extending the Shakura-Sunyaev approach to a strongly magnetized accretion disc model

5.2. Laboratory Analysis of Shear Instabiltiy

V. Pariev (postdoc) participated in the analysis of a laboratory experiment for testing astrophysical magnetic rotational instabilities. Despite the importance of the magnetorotational instability (MRI) as a fundamental mechanism for angular momentum transport in magnetized accretion disks, it has yet to be demonstrated in the laboratory. A liquid sodium alpha-omega dynamo experiment at the New Mexico Institute of Mining and Technology provides an ideal environment to study the MRI in a rotating metal annulus (Couette flow). A local stability analysis was performed as a function of shear, magnetic field strength, magnetic Reynolds number, and turbulent Prandtl number. The later takes into account the minimum turbulence induced by the formation of an Ekman layer against the rigidly rotating end walls of a cylindrical vessel. Stability conditions were presented and unstable conditions for the sodium experiment compared with another proposed MRI experiment with liquid gallium at Princeton. Due to the relatively large magnetic Reynolds number achievable in the sodium experiment, it was shown that it is possible to observe the excitation of the MRI for a wide range of wave-numbers and further to observe the transition to turbulence.

Noguchi, K., **Pariev, V.I.**, Colgate, S. A., **Nordhaus, J.**, & Beckley, H. F. 2002, Magnetorotational Instability in Liquid Metal Couette Flow, ApJ, 575, 1151.

Noguchi, K., & **Pariev, V. I.** 2003, AIP Conf. Proc. 692: Non-Neutral Plamsa Physics V, 692, 285

6. More on Relativistic Plasmas

6.1. Gamma-ray Bursts

Poynting-flux driven outflows from magnetized rotators are a plausible explanation for powerful relativistic gamma-ray bursts, the most luminous astrophysical plasma sources located at cosmological distances. We have suggested a new possibility for how such outflows might transfer energy into radiating particles. We argued that in a region near the rotation axis of a magnetized rotator, Poynting flux drives non-linearly unstable large-amplitude electromagnetic waves (LAEMW) that 'break' radii $r_t \sim 10^{14}$cm from the plasma engine where the MHD approximation becomes inapplicable.

In the 'foaming' (relativistically reconnecting) regions formed during the wave breaks, random electric fields stochastically accelerate particles to ultra-relativistic energies which then radiate in turbulent electromagnetic fields. The emission properties are similar to synchrotron radiation, with a typical cooling time $\sim 10^{-3}$s. During the wave break, the plasma is also bulk accelerated in the outward radial direction and at larger radii can produce optical after-glows due to interactions with the external medium. The near equipartition fields required by afterglow models may be due to magnetic field regeneration in the outflowing plasma (similar to field generation by LAEMW in laser-plasma interactions) and mixing with the upstream plasma.

Pariev also worked on the polarization expected from Poynting flux dominated GRB outflows. This was shown to be consistent with observations to date, and motivated the need for further observations to test the Poynting flux GRB paradigm against hydrodynamic GRB paradigms.

Lyutikov, M. & **Blackman, E.G.** 2001, *Gamma-ray bursts from unstable Poynting-dominated outflows*, MNRAS, 321, 177

Lyutikov, M., **Pariev, V. I.**, & Blandford, R. D. 2003, ApJ, 597, 998 Polarization of Prompt Gamma-Ray Burst Emission: Evidence for Electromagnetically Dominated Outflow

6.2. Plasma disk geometry diagnostics

The central engines of active galactic nuclei (AGN) contain cold, dense material as well as hot X-ray-emitting gas. The standard paradigm for the engine geometry is a cold thin disk sandwiched between hot X-ray coronae. Strong support for this geometry in comes from the study of fluorescent iron line profiles, although the evidence is not ubiquitously airtight. The thin disk model of line profiles in AGN and in X-ray binaries should still be bench-marked against other plausible possibilities. One proposed alternative is an engine consisting of dense clouds embedded in an optically thin, geometrically thick X-ray-emitting plasma engine. This is also motivated by studies of geometrically thick two-temperature plasma engines such as advection-dominated accretion flows (ADAFs). We computed the reprocessed iron line profiles from dense clouds embedded in geometrically thick, optically thin X-ray-emitting plasma disks near a Schwarzchild black hole. We considered a range of cloud distributions and disk solutions, including ADAFs, pure radial infall and bipolar outflows. We found that such models can reproduce line profiles similar to those from geometrically thin, optically thick disks and might help alleviate some of the problems encountered from the latter. Thus, independent of thin disks, thick disk engines can also exhibit iron line profiles if embedded dense clouds can survive long enough to reprocess radiation.

We have also calculated iron line profiles from accretion disks with spiral velocity structures. We find that quasi-periodic bumps, step-like features and secondary peaks appear in the profiles. Non-axisymmetry is important for low radial mode spirals. This study was motivated by recent work showing that spiral density waves can result from magnetohydrodynamic instabilities even in non-self-gravitating disks, such as those of active galactic nuclei or X-ray binaries, and by improved spectral resolution of forthcoming X-ray missions.

Blackman, E. G., & **Hartnoll, S. A.** 2003, ASP Conf. Ser. 290: Active Galactic Nuclei: From Central Engine to Host Galaxy, 290, 79

Hartnoll, S. A. & Blackman, E.G. 2001, MNRAS, 324, 257 Reprocessed emission line profiles from dense clouds in geometrically thick accretion engines

Hartnoll, S. A. & Blackman, E. G. 2002, MNRAS, 332, L1 Iron line profiles from black hole accretion disks with spiral velocity structure

7. Solar Plasmas

We have applied the concepts learned from our nonlinear dynamo theory to the solar cycle. We showed that the solar dynamo ejects both small scale and large scale magnetic helicities into the corona. The ejection of the small scale helicity keeps the cycle period from quenching and the ejection of the large scale field limits the maximum field strength in the sun.

Solar flares represent sites of magnetic helicity loss, as well as X-ray emission. We have studied the acceleration of particles in solar flares using new models of stochastic Fermi acceleration.

Selkowitz, R., & **Blackman, E. G.** 2004, MNRAS, 354, 870, Stochastic Fermi acceleration of subrelativistic electrons and its role in impulsive solar flares

Brandenburg, A., & **Blackman, E. G.** 2002, ESA SP-506: Solar Variability: From Core to Outer Frontiers, 805, Magnetic helicity and the solar dynamo

Brandenburg, A., **Blackman, E. G.**, & Sarson, G. R. 2003, Advances in Space Research, 32, 1835, How magnetic helicity ejection helps large scale dynamos

Blackman, E. G., & Brandenburg, A. 2003, ApJ, 584, L99, Doubly Helical Coronal Ejections from Dynamos and Their Role in Sustaining the Solar Cycle