A Liquid Sodium Simulation of the $\alpha\omega$ Dynamo

A Proposal to the DOE EPSCoR Program for Support of a Laboratory Simulation of the Dynamo that Powers AGN and Creates the Magnetic Energy and Flux of the Universe

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With theory in support of Accretion Disk Magnetohydrodynamics and AGN Emission Mechanisms

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ABSTRACT

The origin of the magnetic fields of extra galactic, galactic and compact objects is poorly understood. Support is requested for a liquid sodium experiment to demonstrate (1) the magneto rotational instability (2) the poloidal to toroidal gain of the ω-phase, and (3) positive gain of an $\alpha\omega$ dynamo. The $\alpha\omega$ dynamo is the likely explanation of astrophysical magnetic fields. A magnetic field is twisted in a differentially rotating conducting fluid, liquid sodium, by Couette flow. The α-helicity is produced by jet-driven plumes. Seed monies from NMIMT, NSF and LANL have allowed us to construct a meter size, 50 kW apparatus with diagnostics. Fusion magnetic confinement and the dominant magnetic free energy of the universe both require the understanding of MHD and its instabilities. The $\alpha\omega$ dynamo is one such instability that similarly depends upon reconnection.

1 GOALS AND SIGNIFICANCE TO THE FUSION PROGRAM OF THE DOE

The goal of this project is to understand the flow of the major free energy of the universe. With the colleagues listed on the title page and others in Sec. 9, we are attempting to understand how the energy of formation of each of the central massive galactic black holes is transformed into magnetic energy and distributed throughout the universe as force-free fields. Similarly, the goal of the magnetic fusion program, to whom this proposal is addressed, is to understand and make available the largest free energy accessible to humans. Both projects are concerned with the stability and transformation of magnetic fields in a conducting medium.

This proposal is directed toward the most fundamental underpinning of the astrophysics program, namely how magnetic fields are generated in the first place. Fusion does not have to concern itself with this question because an electric generator is understood at the fundamental engineering level, given our unique and available materials of insulation and conducting wire. The problem in most astrophysical circumstances is far more complex because near perfect conductivity exists throughout the electrically generating volume. Instead of insulation, astrophysical dynamo generation must depend upon a special combination of semi-coherent flows. In a gravitational field, the flows are affected by up versus down and the persistence of rotation due to conservation of angular momentum. Most importantly, a dynamo depends upon the special instability-driven reconfiguration of magnetic fields called reconnection.

Calculations using the right combination of flows and reconnection indeed show that such a "gedanken" dynamo works. That is that the electric current and magnetic fields exponentiate with time until "back reaction" sets a limit. This is where the forces due to the fields and currents alter the flows sufficiently to bring the dynamo gain back to zero, i.e. steady state fields. If we had blind faith in our simulations, there might be small reason to further test our credulity by experiments, but experience proves the necessity for a compromise. We need both calculations and experiment to be convinced in our understanding.

In the early phase of the fusion program, the 1950's, the analytical description of magnetohydrodynamics was similarly in need of confirmation for MHD stability calculations. As a consequence, early experiments with liquid sodium (Colgate 1955) demonstrated experimentally the Rayleigh-Taylor instability, the stability of minimum B, and the tearing mode, (Colgate et al. 1960). This stimulated the subsequent analysis, so fundamental to fusion plasmas. In astrophysics we are now in need of a similar confirmation. The difference is that the astrophysical community has not had a tradition of generating its own experiments. Rather instead it has depended upon the rest of physics and astronomical observation. We have therefore been only partially successful in raising support from this community.

Our first NSF proposal initiated the project with $100k as "exploratory science". But three subsequent NSF proposals have not been successful, with one additional proposal for partial support still pending (Review expected August 2002). Only through New Mexico Tech and our theory grant at Los Alamos National Lab has the small effort continued. It is now at the point of initiating the preliminary experiments to verify and measure the friction of stable differential rotation of Couette flow in the fluid volume with mineral oil. The diagnostics to measure the magneto rotational instability, MRI, and the expected linear gain of the ω-phase of the dynamo are nearing completion. The liquid sodium MHD measurements will require additional funding, at the rate of a CoPI, post doc, graduate student and an undergraduate, or $150 k per year for 3 years.

We feel that a close connection between fusion plasma physics and the plasma physics of astrophysical magnetic fields is beneficial to both. These later fields are mostly force free, evolve as Taylor states as a function of changing boundary conditions, and dissipate through as yet unknown processes. Run-away current carriers in toroidal geometry are well known in fusion tokamaks. They are just now being observed in reverse-field pinches and spheromaks. We are convinced, because of arguments of limited energy, that the origin of the cosmic rays filling inter-galactic space must be closely associated with these same processes observed in the laboratory. There are several experiments that may lay the foundation of astronomical magnetic fields. Demonstrating the mechanism for the origin of these fields is a must. An apparatus to demonstrate this mechanism is mostly built. To continue requires the support of the fusion program.

2 INTRODUCTION

The origin of the magnetic fields of intergalactic, galactic and stellar origin is only partially understood. The transport of angular momentum in accretion disks is believed by many to be caused by the magneto rotational instability (MRI). We are requesting support for a liquid sodium analog experiment, with which we expect to observe and study both of these phenomena in the laboratory. We have requested similar funding in an NSF individual investigator proposal currently under review until August 2002 (# 0206066, Experimental Astrophysical Magnetohydrodynamics: Physics of the Magneto Rotational Instability and the alpha-omega Dynamo). We request support from some combination leading to the project size listed above, \$150k/year. The equipment under construction is an experimental platform in which to investigate (1) the MRI and (2) the conversion of poloidal to toroidal field in differentially sheared flow or the ω-phase of an $\alpha\,\omega$ dynamo. The MRI was made famous by the calculations of Balbus and Hawley as the likely mechanism for the transport of angular momentum in conducting accretion disks. Similarly the $\alpha\,\omega$ dynamo was made famous by Parker as a possible explanation of the origin of stellar and galactic fields. In both cases a magnetic field is present in a Keplerian accretion disk. We propose to simulate this flow by annular rotational Couette flow using the conducting fluid, liquid sodium.

The non-linear limit of the MRI perturbed field will be chaotic unless a back-reaction at large amplitude causes the preferential growth of a single, low wave-number mode. This may allow for the dynamo generation of large scale flux. On the other hand, the $\alpha\,\omega$ dynamo has two driven coherent motions which produce a coherent magnetic flux. The scientific question is whether the MRI can produce the large scale fields of stars, galaxies and the universe, or whether a semi-coherent driven mechanism is required. The natural coherent motions invoked for astrophysical dynamos are (1) Keplerian flow and (2), large plumes driven axially by (A) large scale convection, (stars, supernovae), (B), supernovae, (galaxies) and (C), star-disk collisions in black hole accretion disks respectively. In either case, the experiment, in addition to the Couette flow, will incorporate the provision to produce by driven jets, the second coherent motion required for the $\alpha\,\omega$ dynamo. The unique aspect of the liquid sodium apparatus is that it is designed to achieve a large magnetic Reynolds number, $R_m \simeq 120$. We predict enough modes of MRI growth, $\simeq 6$, so that turbulence may be observed, and similarly for the dynamo, positive gain when and if the second phase is funded.

With seed money from NMIMT, the NSF, and LANL, the design and construction of the experiment for the differential rotation, the Couette-flow phase of the experiment, has been accomplished. Initial flow visualization experiments in a water model have demonstrated the Couette flow and the helicity generating, plume-driven, α-deformation required by the dynamo. The prediction of the rapid growth of the MRI has been supported by analysis at LANL. Similarly, positive dynamo gain in the experiment has been predicted by calculations using a kinematic dynamo code at LANL (Colgate, Beckley & Pariev, 2002). The proposed new work for the first year is to use the apparatus to demonstrate (1) the linear growth of the MRI, (2) the production of turbulence from the MRI, and (3) the multiplication and conversion of poloidal to toroidal flux for the dynamo. A second phase is proposed for two additional years to demonstrate (1) the helicity generated by driven plumes in a rotating frame and (2) positive dynamo gain. Successful liquid sodium dynamo experiments at Riga and Karlsruhe have been performed. There are on-going sodium dynamo experiments at Wisconsin, Maryland, and Swarthmore. This $\alpha\,\omega$ dynamo experiment is unique experimentally and unique for astrophysical applications because the flow field producing the α-helicity is non-axisymmetric and episodic, thereby allowing averaged, near-steady state, large scale fields (and fluxes) to grow (Cowling). A gallium based MRI experiment is proposed at Princeton with a magnetic Reynolds number ~ 5. The initial ω-phase of the liquid sodium dynamo experiment is a unique platform to observe the MRI because the magnetic Reynolds number is so much larger, $\sim \times 24$. We predict that a low level of turbulence, driven by the Ekman layer flow, will be superimposed upon the Couette flow. The MRI should add to this turbulence. Similarly we expect that the coherent enhanced toroidal field of the ω-phase should similarly be observable above this minimum level of background turbulence.

Safety is a concern and so the experiment will be conducted at the New Mexico Institute of Mining and Technology's high explosive testing facility, the Energetic Materials Research and Testing Center.

3 PROJECT DESCRIPTION

Astrophysical magnetic fields are observed with stars, within galaxies, and extragalactic "radio lobe" structures (Kronberg et al. 2001). The magnetic energies of roughly 100 giant radio lobe sources is so large, up to 10^{61} ergs per source galaxy that we interpreted that only the central galactic black hole formation energy, $\sim 10^{62}$ ergs or $10^8 M_\odot c^2$, can supply this energy. All other free energies in the universe are at least 10^3 smaller, such as the virial energies of the extragalactic baryonic mass per galaxy spacing volume or of galactic matter itself. Therefore only a coherent dynamo converting the kinetic energy of the black hole formation disk seems even remotely feasible. Hence, our emphasis upon demonstrating the feasibility of such a dynamo.

In addition, the flow of angular momentum outward and mass inward that can both create these objects and release the energy necessary to account for the field energy is generally thought to be caused by the magneto rotational instability, MRI. However, the MRI can not occur without a finite initial magnetic field unless it is, of itself, a dynamo. Hence investigating the MRI implies understanding whether it creates a dynamo, or whether a separate dynamo process is required. This proposal is about studying both issues.

Both the MRI and the $\alpha\,\omega$ dynamo theoretically satisfy their respective conditions for angular momentum transport and the generation of large-scale coherent flux. Neither have been proven in the laboratory. We propose to demonstrate in the laboratory that both the MRI and such a dynamo work. This is our primary objective. However, we have divided the project into two phases. The first is the differential rotation, the ω-phase, or Couette flow of the experiment where both the MRI and the generation of enhanced toroidal flux from poloidal flux should be observed. The second phase is the production of large scale helicity, or α-effect, produced by large scale driven plumes or jets. This proposal focuses on the first phase where we wish to understand the MRI and the ω-phase of the $\alpha\,\omega$ dynamo. If this proposal is funded for three years as requested, then with small additional funds from other sources, we expect to proceed to the full dynamo experiment. A shortened funding period of one year will allow the completion of the first, or ω-phase of the experiment.

We recognized in our previous proposals, but did not emphasize, that the magneto rotational instability (MRI) will be an integral part of the results of the Couette flow of the experiment. The scientific questions are as follows: (1) whether the non-linear growth of the MRI generates turbulence, (2) whether this turbulence enhances the transport of angular momentum, (3) whether this turbulence generates a dynamo, and finally (4) whether the MRI interferes with or enhances the $\alpha\,\omega$ dynamo gain. Because of the recent interest in this topic (Ji et al. 2001) and because it is an integral part of the experiment, we analyze these expected results on the MRI in some depth. In addition we will compare the results of the kinematic calculations of the dynamo of the ω-deformation, an enhanced conversion of poloidal to toroidal field, to the expected experimental results.

4 ASTROPHYSICS BACKGROUND

4.1 Accretion

The last decade has been an exciting time in the study of active galactic nuclei. We are not only realizing that most normal galaxies contain massive black holes, but also are measuring their masses. Accretion has long been thought to be the primary mechanism through which an estimated total gravitational energy of $\sim 10^{62}$ ergs is released during the formation of a common 10^8 solar mass supermassive black hole. The two important aspects controlling the evolution of accretion disks is the flow of the energy and the efficient transport of angular momentum.

It has been widely accepted that the magneto rotational instability (MRI), championed by Balbus & Hawley, is the principle mechanism responsible for angular momentum transport in ionized, or magnetically well-coupled accretion disks. The MRI was first realized by Velikhov (1959) and Chandrasekhar (1960) and has been developed in much greater detail in the context of accretion disks only during the past decade (see Balbus & Hawley 1998 for an excellent review on this subject). It is a powerful MHD instability that seems to be generic, existing in a magnetized shear flow. Furthermore, the analytic studies of MRI have been extensively validated and advanced by the powerful MHD simulations of accretion disks (see e.g. Hawley et al. 1996).

We realized that our proposed liquid sodium dynamo experiment can be ideally suited to study the MRI. This is because the required initial set-up to generate MRI is amazingly simple. In fact most numerical simulations have shown that a rotating shearing flow with $d\Omega/dr < 0$ can amplify a small seed magnetic field and render the flow unstable to MRI, producing MHD turbulence which causes angular momentum transport. A key ingredient in our previously proposed liquid sodium dynamo experiment is to establish a differentially rotating flow field (Couette flow) in a conducting medium and furthermore to demonstrate the enhanced production of toroidal field from poloidal field. This is exactly the necessary first step for MRI growth in low-shear velocity distributions. There is recent growing interest in this topic (see Ji et al. 2001) in the astrophysics community.

4.2 The Astrophysical Need for a Dynamo

Astrophysical magnetic fields are observed with stars, within galaxies, and extragalactic "radio lobe" structures. The large scale of these fields, up to Mpcs, is determined observationally by polarization, synchrotron emission, and Faraday rotation maps. The interpretation of these maps imply a large scale coherent production mechanism, particularly in cluster sources where the rotation measure maps and the emission measure maps outline magnetic structures uniquely associated with AGN and therefore with black holes. The length scale over which the rotation measure is correlated is one hundred kpc compared to the dimension in which it is generated, the black hole gravitational radius, $\sim 10^{-10}$ smaller. We need to understand how this happens. In addition the magnetic energies interpreted within giant radio lobes (Kronberg et al. 2001) imply that the generation mechanism must not self limit at low values due to back reaction (Vainshtein & Cattaneo 1992; Vainshtein et al. 1993). The $\alpha\,\omega$ dynamo satisfies these conditions theoretically. In addition it is a natural explanation of magnetic fields in stars, driven by differential rotation and diffusion truncated convection.

The origin of galactic and extragalactic magnetic fields is perhaps only slightly more puzzling than that within stars, neutron stars, and planets, if only because the magnitude of magnetic energy and flux is so much more extreme. For this reason particularly, we emphasize the extragalactic magnetic fields because the magnitudes strongly limit possible sites for their generation. The magnitude of the extragalactic magnetic energies per galaxy has become so large as to question the affect of these fields upon the structure or galaxy formation itself. Recently Kronberg et al. (2001) have compiled the magnetic and energetic properties of roughly 100 giant radio lobe sources and find energies up to 10% of the BH formation energy, especially for the extra-cluster sources and $\sim 1/30$ of this mean energy for the sources within clusters. In the past the magnitude of the energy and of the flux required has not been emphasized; yet a dynamo produces only magnetic flux and magnetic energy (see (Kulsrud 1999; Zweibel & Heiles 1997; Parker 1979; Ruzmaikin 1989; Moffatt 1978; Krause & Beck 1998; Wielebinski 1993)).

In addition, flux and energy are modestly emphasized in the observations (see reviews by (Miley 1980; Bridle & Perley 1984; Kronberg 1994)) and the observers themselves (Perley et al. 1984; Taylor et al. 1990; Taylor & Perley 1993; Taylor et al. 1994; Eilek et al. 1984; Kronberg 1994). A review in progress changes this partial neglect with major emphasis on magnetic energies in clusters (Carilli & Taylor 2001). However, the magnitude of the implied fluxes and energies, $\sim 10^{60}$ erg in galactic cluster sources as well as $\sim 10^{61}$ erg in field AGN outside clusters in the radio lobes, are so large, $\times 10^{4}$ and $\times 10^{6}$ respectively compared to these quantities within standard galaxies, that their origin requires a different dynamo than the galaxy dynamo. The difficulties associated with a primordial origin of the field is recently augmented and reviewed by the analysis of Blasi et al. (1999), leaving only an $\alpha\,\omega$ dynamo in a BH accretion disk dynamo as the plausible explanation.

These energies are much larger than the binding energy of galaxies $\times 10^{2}$ (including the dark matter) and the fluxes are $\times 10^{3}$ greater than the magnetic flux of the galaxy times the winding number of the galaxy in a Hubble time, ~ 50 turns. However, the free energy of formation of the black hole, $\sim 10^{62}$ erg, and the winding number of the disk forming the BH of nearly every galaxy is the feasible source of both this flux and energy.

The winding number or number of turns of the inner most orbits of the accretion disk is so large in the lifetime of the disk, $\sim 10^{11}$ turns in 10^{8} years, that the smallest dynamo gain per turn, e^{g}, and thus a small fraction of the exponential to the power $e^{10^{11}}$, leads to saturation in a short time. This high, near infinite gain avoids the question of the origin of the seed field. This view of the dominant role of magnetic energy in the universe is presented in Colgate et al. 2002, Colgate et al. 2001a, Colgate & Li 2001b, Colgate & Li 1998, Colgate & Li 1997.

The likely largest free energy of the universe possibly resides in force-free magnetic fields produced from the energy released in the formation of the massive central black holes of most galaxies via accretion. Our proposed experiments provide a unique pathway to investigate some of the most likely mechanisms proposed so far by which this might happen. Other branches of astrophysics support their analogous liquid metal experiments: the planetary dynamo of Lathrop at the University of Maryland as modeled by Glatzmaier & Roberts (1995), and the Dudley & James (1989) type dynamo in the turbulence of stellar convection at the University of Wisconsin, developed by Forest. Here we would like to say the $\alpha\,\omega$ dynamo of Parker (1955) in the BH accretion disk is supported by extragalactic astronomy. We feel that the MRI is applicable to all astrophysics. It is a natural first measurement with, and directly accessible to the apparatus designed for the first stage, the ω-phase, of an $\alpha\,\omega$ dynamo experiment.

5 RESULTS FROM PRIOR SUPPORT AND CURRENT STATUS OF THE EXPERIMENT

The dynamo apparatus has "seen first light". It has rotated using its primary power source in May 2002.

5.1 The Fluid Flow Simulation of the Experiment

With substantial support from NMIMT and seed money from LANL, we have simulated the α and ω flow fields in water (Beckley & Colgate 1998; Beckley et al. 2001). Figure 1(a) is the schematic showing the two differentially rotating cylinders and the pulsed plumes. Figure 1(b) shows a side view of the pulsed, rising and expanding plume outlined by a line of bubbles (like an entrained line of force). Figure 1(c) is a plot of plume rotation angle vs frame rotation angle from solid-body and differential frame rotation data and plume rotation theory. Figures 1(d, e) are a time sequence of the top view of a rising plume in a rotating frame showing the progressive rotation of the plume angle as needed for the generation of the coherent helicity.

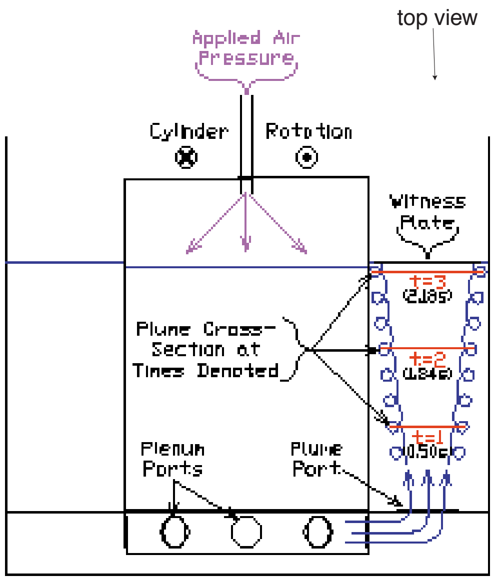

Fig. a. is a schematic of the flow simulation experiment. A plume is injected into the rotating annulus of water. It entrains a line of bubbles and is viewed from the sides and top.

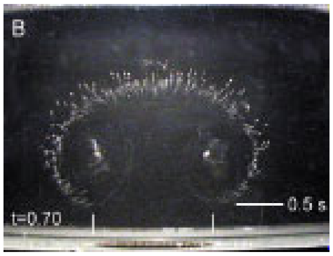

Fig. b side view, shows the r plume in a stationary frame with the port outlined.

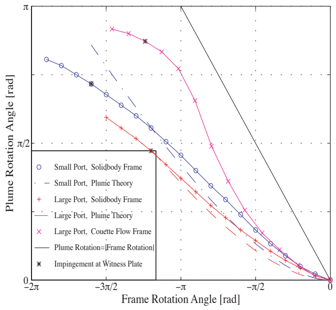

Fig.c Plume rotation vs. frame rotation, data, theory, and differential frame rot.

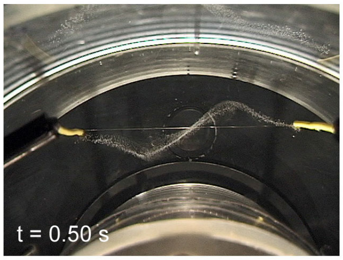

Fig. d. Top view: The plume rotates +30 degrees in -90 degrees of cylinder rotation.

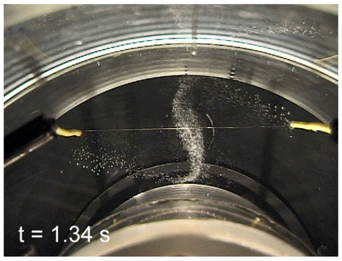

Fig. e. Top view: The plume rotates +90 degrees in -240 degrees of cylinder rotation.

Figure 1: A composite of the flow visualization experiment where a rising plume in a rotating frame, Fig. 1(a), is viewed from the side, Fig. 1(b), and top, Figs. 1(d, e). The resulting angle of differential plume rotation is measured and plotted as a function of frame rotation, Fig. 1(c). (see *http://physics.nmt.edu/∼dynamo/*)

5.2 Current Design and Completion of the Apparatus

With \$100k initial seed money from NSF in 1999 and \$65k from LANL, and substantial support from NMIMT a design of the experiment has been completed. Figure 2 shows the design of the two phases of the dynamo apparatus. Figure 3 shows the constructed experiment including subsystems and the instrumentation electronics. The radial probe housing for internal magnetic sensors is nearly complete as well. This system, designated the ω-Phase, is designed to produce $R_{m,\omega} \simeq 120$ in limiting Couette flow in liquid sodium. The apparatus was designed to fulfill the ω-Phase operation while accommodating an expansion to the second, or α-Phase of the experiment with a minimum of components being made redundant.

Figure 2(A) shows the ω-Phase design of the experiment. Figure 2(B) shows the addition of the drive mechanism for the plumes, but is otherwise the same as Fig. 2(A). The oscillating hydraulic drive mechanism for the jet-plume production, Phase II, is not yet constructed. The centrifugal stress in the vessel walls is designed to be 1/5 to 1/3 of the yield strength of the outer rotating cylinder. We envision that the total running time of the apparatus at modest speed should be no more than several hours and at extreme high speed only tens of minutes. The 50 kW electric motor, belt-drives, bearings and bearing mounts and the

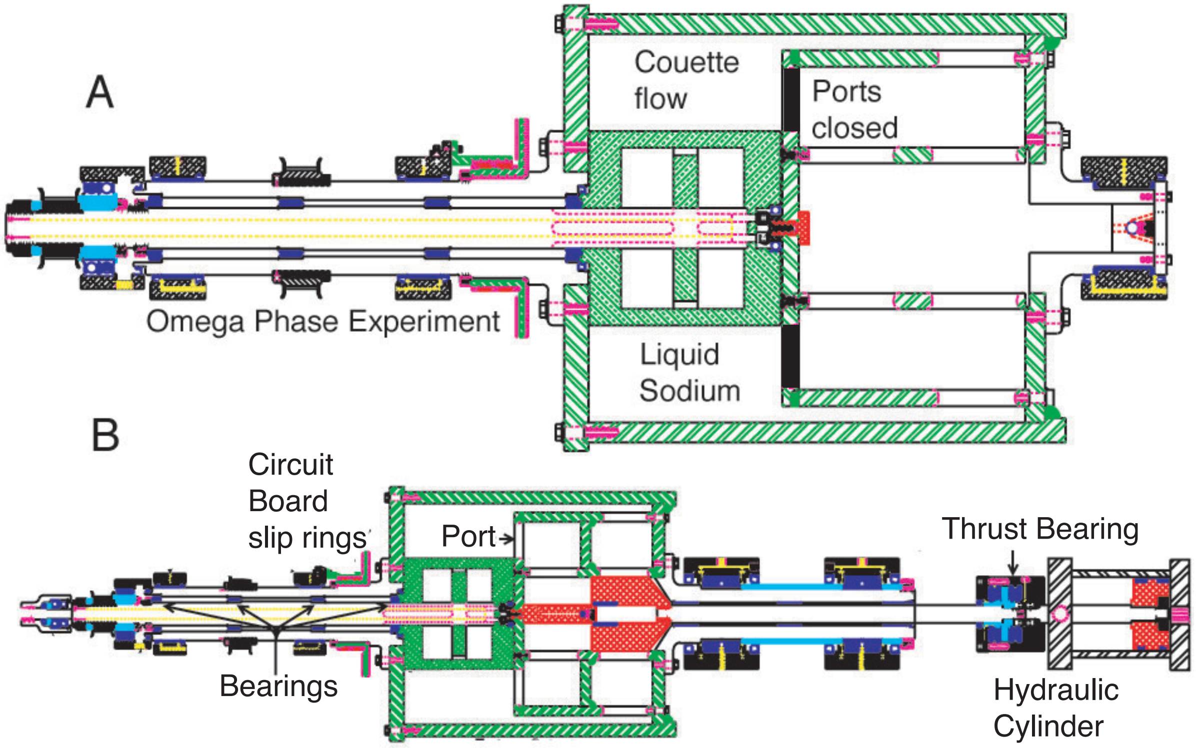

Figure 2: Figure 2(A) shows a drawing of the rotating components of the ω-Phase of the experiment. The inner cylinder is rotated at $4\,\omega$ of the outer or main cylinder of radius, $R_0 = 30.5$ cm. In the ω-Phase no plume piston, or hydraulic drive is shown, even though the constructed aluminum parts of Fig. 2(A) show the port plate and two ported reservoir plenum cylinders. The closed ports define the plume end of the Couette flow annular space. Figure 2(B) includes the plume drive mechanism. The external magnetic field coils are not shown but are designed and will be added later.

high-speed drive shaft are assembled and shown in Fig. 3(A). The massive bearing supports and base plate, $\sim$ two tons, are designed to reduce vibration. The recirculating heating (cooling)-oil system used to liquefy the sodium and the oil lubrication system are built and shown hooked up to the apparatus. The principle components of the hydraulic system necessary to produce the plumes have been designed and are reserved from surplus.

Due in part to in-kind contributions from the Research Division of NMIMT, a new laboratory space with several computers has been set up. Los Alamos National Laboratory has contributed funding to complete the construction of the ω-Phase. A project web site has been established: *http://physics.nmt.edu/∼dynamo/*.

The electronic instrumentation has been designed and constructed by graduate student Rocky Ginanni with the help of undergraduate students, Clint Ayler, Manuel Jaramillo, Ian Bentley, and Robert Koegler. It has been designed to measure the pressures at 6 radii at the end plate, temperatures (at 5 locations) and magnetic fields at various locations. The primary measurement of either the turbulent fields from the MRI, the toroidal gain due to the shear or possible dynamo gain will all depend primarily upon 6 (3-D) Hall detectors (18 single-axis, 0.2 G to $\sim$ 10 kG detectors) mounted within a radial probe. In Phase II,

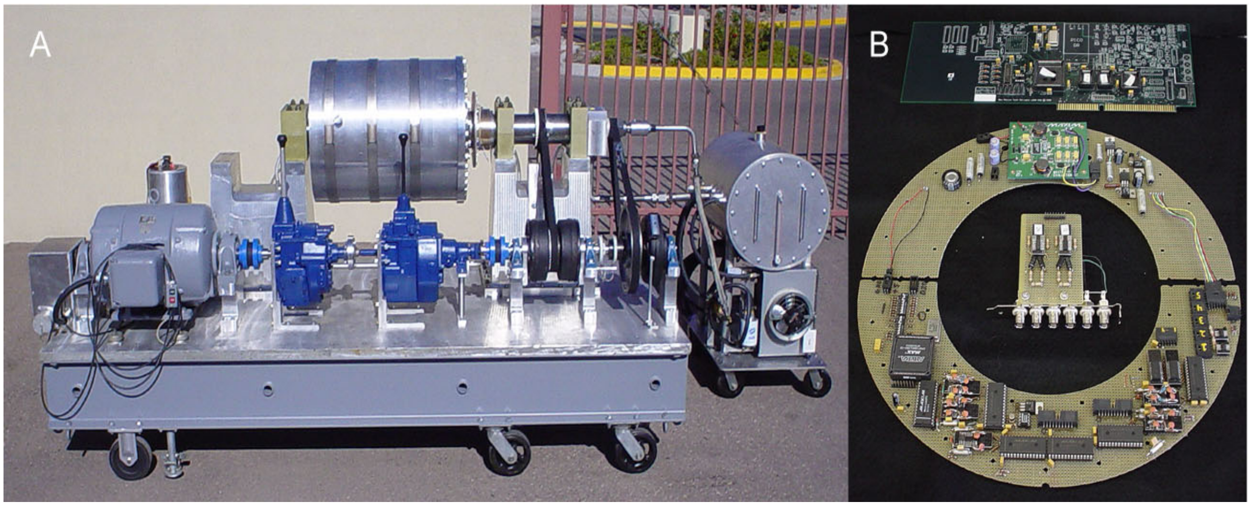

Figure 3: Figure 3(A) shows a photograph of the completed mechanical construction of the ω-phase of the experiment. The inner and outer cylinders are rotated by the 50 kW drive motor, shown on the left. The belt drives are driven from an intermediate shaft through two transmissions for variable speed. The outer cylinder is driven by a 1:1 belt drive from the intermediate shaft. The inner cylinder is rotated at $4\,\omega$ by the electro-clutch and belt drive on the right. The recirculating thermal oil system is visible to the right. The lubricating oil reservoir is visible in the background to the left. The electronic circuit boards for data acquisition, control, conversion and transmission of the rotating digital data are shown in Fig. 3(B). The two halves of the annular circuit board are mounted on the apparatus as denoted in Fig. 2(A). The annular circuit board assembly utilizes real-time digital control of the power to and signals from the analog magnetic field, conductivity, pressure and temperature sensors. The small circuit board in the center is one of two used for the long-line transmission of bi-directional digital data from the remote operations van to the apparatus ($\sim$ 100 m). The printed circuit board at the top of Fig. 3(B) is the computer interface board used for real-time control, acquisition and storage of the digitized analog sensor signals.

the α-phase, there will be an additional array of 30 (3D) Hall detectors on the outside of the end plate to measure the fields induced by the plumes for the α-helicity generation. A property of the plume-generated, α-helicity is that the resulting poloidal flux appears external to the vessel and so can be diagnosed externally. A fraction of the magnetic signal induced by MRI turbulence will also be observable from outside the vessel, but not in Phase I. The detector signals are converted for digital transmission to the computer. In total, 128 sensors (fields, conductivity, pressures and temperatures) are designed to be monitored at $\sim$ 10 MHz data rate from a rotating system with a centrifugal acceleration of $\sim$ 1000 g at the sensors and $\sim$ 300 g at the electronics. The sensors for the first phase have been tested and mounted. The data acquisition, transmission, and interconnection electronics with the computer are nearly completed with some of the electronic boards shown in Fig. 3(B). In the stationary frame there are provisions to monitor $\sim$20 additional detectors.

5.3 Engineering, Safety and Operation of the Experiment

In our NSF proposal of 2000 the engineering section was more detailed than would be of general interest. This was because our prior NSF proposal was firmly criticized for lack of detailed engineering calculations of the strength of the vessel and the power to drive it to the necessary magnetic Reynolds number. Our NSF proposal of 2000 is now posted on our web site and a detailed engineering design is given. This passed review in our previous proposal review.

Similarly an extensive safety planning and analysis was presented in a previous proposal. This passed review and is given on our web site. However, we wish to emphasize that these tests will be performed remotely at a special facility, the Energetic Material Research and Testing Center (EMRTC) at New Mexico Institute of Mining and Technology. This facility has had a 60 year history of tens of thousands of accident free high explosive tests. Sodium is a less dangerous material compared to HE because it cannot detonate. Finally one of us (Colgate 1955) has had extensive hands-on use of liquid sodium in laboratory experiments for determining MHD stability. The experiment will be performed in compliance with Federal, State, Industry and Institutional safety practices and procedures involving the receipt, storage, handling, disposition and use of sodium metal. Because of length, the *Safety Practices, Procedures and Compliance* are presented at the project's web-site *http://physics.nmt.edu/∼dynamo/*.

A removable, electrically heated, safety shield will surround the cylindrical vessel and will be used whenever the apparatus is rotated and filled with either oil or sodium. This will confine any dynamic sodium loss and absorb the kinetic energy and containment of disrupted parts should a mechanical failure occur.

Operating procedures include: safety training, balancing, hydrostatic pressure testing with oil, pressure deflection checks, calibration of pressure sensors, relief-valve testing and setting, and thermal controls. Because of length, these *Operating Procedures* are also presented in our web-site for the project: *http://physics.nmt.edu/∼dynamo/*. Initial safety training has taken place. Dynamic balancing, hydrostatic pressure testing and deflection checks have already been performed.

Associated with the three proposals submitted to the NSF, the reviews have produced many questions that are never answered explicitly because of the nature of the NSF review process. We have taken the time to study and reply to and discuss most of these questions. They are now posted on our web site.

5.4 Publications and Talks

The following papers have been submitted for publication:

Beckley, H.F., Colgate, S.A., Romero, V.D., and Ferrel, R., “Rotation of a Pulsed Jet in a Rotating Annulus: A Source of Helicity for an $\alpha\,\omega$ Dynamo”, Phys. of Fluids, Submitted, 2001.

Colgate, S.A., Pariev, V., Beckley, H.F., Ferrel R., Romero V.D., and Weatherall, J. C., "The New Mexico $\alpha\,\omega$ Dynamo Experiment: Modeling Astrophysical Dynamos", Magnitnaya Gidrodinamika, vol. 38, pp. 122-135, 2002.

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

The following talks have been given:

S.A. Colgate, Invited talk, "The Origin of the Magnetic Fields of the Universe: The Plasma Astrophysics of the Free Energy of the Universe", APS, Quebec 10/23/00.

Beckley, H.F. & Colgate, S.A., "Fluid Flow for an Experimental $\alpha\,\omega$ Dynamo: Plume Rotation", 1998, APS, DFD., Abst. 5253.

Colgate, S.A. & Beckley, H.F., "Flow Field for an Experimental $\alpha\,\omega$ Dynamo: Plume Rotation", 1998, APS, DFD., Abst. 5252.

Additional talks or posters have been given at: NMIMT colloquium, 11/1998; The New Mexico Symposium, NRAO, 10/99; NMIMT colloquium, 12/1999; Aspen Center For Physics, winter workshop 1/31/2000; Cornell Univ. colloquium, 3/10/2000; SLAC colloquium, 4/18/2000; APS Meeting, Long Beach, 4/29/2000;

Aspen Center For Physics, summer workshop, 6/2000; HEAD, Honolulu, 4/10/00; LANL, NM, 12/4/00; Texas Symp., Austin 12/10/00; Coral Gables, FL, 12/14/00; Santa Fe, NM, 4/1/01; APS, Washington, 4/23/01; Aspen Center For Physics, summer workshop, 6/28/01; NRAO, NM, 9/28/01; SLAC, CA, 10/11/01; AAS-HEAD, Alb., NM, 4/2002; NMIMT colloquium, 5/2/02; AAS, Alb., 6/2002.

5.5 Additional Results in Theory

The theory and astrophysical motivation for the experiment has been substantially advanced, supported by Los Alamos National Lab. We, (S. Colgate, H. Li, J. Finn, V. Pariev, K. Noguchi of LANL, P. Kronberg of Toronto and R. Lovelace of Cornell) believe we have developed an understanding of several problems that when linked, create a picture of the flow of the magnetic, we believe the major, free energy in the universe. This endeavor has recently been recognized by LANL with major support for the theoretical and computational understanding of cosmic magnetic fields and their influence on structure formation and upon the development of galaxies. The $\alpha\,\omega$ dynamo is only one, but crucial link in this sequence. But without this mechanism being investigated by laboratory measurements, as Roberts & Jensen (1993) and Roberts & Soward (1992) have pointed out, "it will forever be a sterile theory". Additional laboratory experiments need to be performed to understand the evolution of force-free fields in our universe such as reconnection and acceleration. But until the starting point of the origin of magnetic fields is firm, subsequent theories will be less constrained.

6 PROPOSED RESEARCH

We propose to demonstrate in the laboratory how MRI works and how an $\alpha\,\omega$ dynamo operates. We have divided the project into two main Phases. We term **Phase I** as the **ω-phase**, during which we will focus on the physics associated with a differentially rotating, magnetized flow (Couette flow), especially the physics of MRI. We term **Phase II** as the **α-phase**, during which we will investigate the production of the large scale helicity, or α-effect, produced by large scale driven plumes or jets. Then this will be combined with the differential rotation to study the physics of the $\alpha\,\omega$ dynamo. We will show how these two fundamental astrophysics problems can be naturally integrated into one experimental program with a common experiment setup using liquid sodium. We will also discuss our proposed theoretical work associated with these experiments. In the following, we will give a brief introduction to the topic of interest, discuss our previous relevant research and describe the proposed work. If this proposal is funded for three years as requested, then with additional funds from other sources, we expect to proceed to complete both phases. A shortened funding period will still allow the completion of the first or ω-phase of the experiment.

7 THE MAGNETO ROTATIONAL INSTABILITY

7.1 Background

Most of the numerical MHD studies on MRI have focused on the existence and early nonlinear evolution of MRI under varying conditions (Balbus & Hawley 1991b; Matsumoto & Tajima 1995; Hawley et al. 1996; Stone et al. 1996; Gammie 1996; Sano & Miyama 1999 ; Noguchi et al. 2000; Sano & Inutsuka 2001). It is shown to be a mechanism for exciting and sustaining MHD turbulence in a magnetized but Rayleigh-stable fluid.

The numerical simulations of MRI, however, have been limited in the size of the disk as well as the number of disk revolutions. Hence, our understanding of MRI at the long-time and fully nonlinear stage has been, to say the least, incomplete. Further work is also needed in understanding the on-set of MRI in a magnetized flow with a finite magnetic Reynolds number. It is believed that some disks or regions of certain types of disks do not have the required level of ionization to ensure a "perfect" coupling between plasmas and magnetic fields. Since the MRI is of fundamental importance to astrophysics, we seek to demonstrate it in the laboratory. In the following, we will first describe our recent analysis on MRI, then we delineate our research plan.

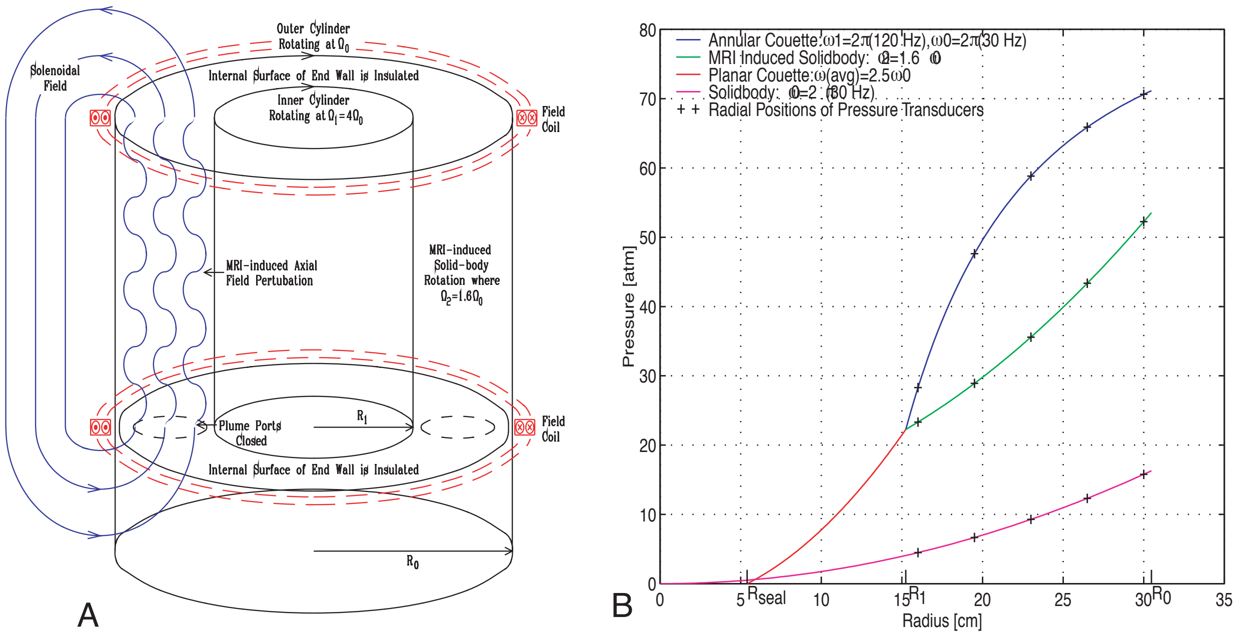

Figure 4: The view in Fig. 4(A) shows the expected radial MRI perturbations for a $1/k \simeq 4$ wave length of a purely axial magnetic field imposed by external coils. The subsequent distortion of these radial perturbations by the azimuthal shear will give rise to both radial and azimuthal magnetic perturbations, which will be observed with the 3-D Hall detectors of the radial probe. Figure 4(B) shows the expected change in the pressure distribution of the Couette flow due to the stress of the non-linear growth of the MRI. Here we assume an amplitude of $< B_{turbulent} >^2$ sufficient to lock-up or to make the Couette flow into solid body rotation with a slip condition at the inner and outer boundaries. The solid body or non-Couette flow and Couette flow pressure profiles are shown for comparison.

7.2 Our Recent Research on MRI

7.2.1 Linear Local Stability Analysis

Based on our proposed experimental parameters (see later), we have performed a local stability analysis while taking into account both the formation of an Ekman layer against the rigidly rotating cylindrical boundaries as well as the finite Reynolds number of the magneto-fluids.

Table 1: Actual and Normalized Quantities in the New Mexico (Sodium) and Princeton (Gallium) Experiments

	Actual		Normalized	
Property	*Sodium*	*Gallium*	*Sodium*	*Gallium*
Kinematic Viscosity, $\nu(cm^2 s^{-1})$	$7.1{\cdot}10^{-3}$	$3.2{\cdot}10^{-3}$	$3.6{\cdot}10^{-8}$	$2.2{\cdot}10^{-7}$
Reynolds Number, R_e	-	-	$1.3 \cdot 10^7$	$3.0 \cdot 10^6$
Magnetic Diffusivity, $\eta(cm^2 s^{-1})$	810	2000	$4.2{\cdot}10^{-3}$	$1.4{\cdot}10^{-1}$
Magnetic Reynolds Number, R_m	-	-	120	4.7
Density, ρ(g cm^{-3})	0.92	6.0	-	-
Alfvén Velocity, V_A(cm s^{-1}) (0.1 T)	$2.9 \cdot 10^2$	$1.1 \cdot 10^2$	$4.6{\cdot}10^{-2}$	$1.2{\cdot}10^{-1}$
Inner Radius, R_1(cm)	15.25	5	.5	.33
Outer Radius, R_2(cm)	30.5	15	1	1
Length, L(cm)	30.5	10.	1	0.66
Inner Angular Velocity, Ω_1(s^{-1})	829	533	4	8.2
Outer Angular Velocity, Ω_2(s^{-1})	207	65	1	1
Prandtl Number, $P_M = R_m/R_e$	-	-	$9.2 \cdot 10^{-6}$	$1.6 \cdot 10^{-6}$
High Turbulent Prandtl #, P_{MHt}	-	-	1.17	3.23
Ekman Turbulent Prandtl #, P_{MEt}	-	-	0.012	6.3×10^{-3}

Stability conditions are presented and unstable regions are identified in terms of magnetic field strength and shear flow. Unstable conditions for the sodium experiment are compared with another proposed MRI experiment using liquid gallium (Ji et al. 2001; Goodman & Ji 2001). Stable and unstable regions must be identified in terms of magnetic field strength and shear flow. In addition the number of unstable modes and the Prandtl number further define the parameter space. If the number of unstable modes is large compared to unity, then there exists the possibility of observing turbulence generated by the MRI. Finally we have investigated the instability boundary when fluid turbulence is injected and when the minimum turbulence level is produced by the Ekman layer flow. The experimental challenge will be to separate this minimum level of turbulence from that produced by the MRI. If larger field strengths are used for the MRI, for example, such that the MRI produced turbulence is larger than this minimum Ekman layer produced turbulence, then the back reaction of the additional stress in the fluid will be to produce a greater level of fluid turbulence by the unstable shear of the slip condition at the inner and outer boundaries.

It is critical to have large shear rates in order to observe the MRI. However, excessive shear will hydrodynamically destabilize the flow by the Kelvin-Helmholtz instability. In the limit of infinitely large hydrodynamic Reynolds number, R_e, the stability condition for Couette flow is given by $\Omega_1 R_1^2 < \Omega_2 R_2^2$ (Landau & Lifschitz 1959). In order to maximize the shear flow and minimize the turbulent drag, and therefore power, the limiting Couette flow condition has been chosen for the experiment. Of course lower rotation rates can be used in both experiments, but it is assumed for this analysis that the highest rates are of greatest scientific interest.

We have analyzed the stability boundaries in terms of the growth rates for axial field strength, wave number k_z, k_r, turbulence levels, expressed in terms of the Prandtl number, $P_M = \nu/\eta$, and the shearing rate or epicyclic frequency. The complex stability plane for the growth rate versus axial field with the minimum Ekman layer driven turbulence, $P_m =$ is given in Noguchi et al. (2002). The conditions for these two figures and a comparison to the gallium experiment proposed at Princeton is given in Table I (Noguchi et al. 2002). The induced turbulence will be measured in the radial probe for various values of the magnetic field. The turbulence generated by the MRI will be superimposed.

7.3 Proposed Work on MRI

Our proposed work address several key scientific questions: (1) whether the linear growth of the MRI occurs for conditions predicted in our analysis, (Noguchi et al. 2002) (2) whether the non-linear growth of the MRI generates turbulence, (3) whether this turbulence enhances the transport of angular momentum, (4) whether this turbulence generates a dynamo, and finally (5) whether the MRI interferes with or enhances the $\alpha\,\omega$ dynamo gain.

The experimental procedure for each of these questions is:

(1) An axial magnetic field, $B_z(t)$, increases with time within a Couette flow in liquid sodium. **We plan** to monitor B_z, B_r, & B_ϕ. The growing mode should be observable with a signal to noise ratio of $S/N \simeq 10^2$.

(2) A constant axial magnetic field, B_z, is established within a Couette flow in liquid sodium. **We plan** to monitor B_z, B_r, & B_ϕ. The growing mode should be observable with a signal to noise ratio of $S/N \simeq 10^2$.

(3) A constant axial magnetic field, B_z, is established within a Couette flow in liquid sodium. **We plan** to monitor the change in torque as a function of the turbulence and B_z above and the transient change in pressure distribution of Fig. 5. The change in torque and pressure should be observable with a signal to noise ratio of $S/N \simeq 10^2$.

(4) A constant axial magnetic field, B_z, is established within a Couette flow in liquid sodium. **We plan** to monitor B_z, B_r, & B_ϕ. The averaged growing mode of any of the three components of the flux should be observable with a signal to noise ratio of $S/N \simeq 10^2$.

(5) Only in Phase II, when and if a dynamo of positive gain is established, can one compare the random fluctuating components of B_z, B_r, & B_ϕ due to a presumed MRI with the large episodic fluctuations calculated and expected from the helicity of the driven plumes. From this comparison one can infer the relative importance of each.

We plan to measure first the pressure distribution for solid body rotation and then for Couette flow in mineral oil of the ω-Phase of the experiment. These results will be compared to our understanding of Fig. 5.

We plan to test the torque and power required, transiently, for establishing the Couette flow in mineral oil of the ω-Phase of the experiment. These results will be compared to our understanding of the boundary layer theory.

We plan to measure in steady state the torque and power required to maintain Couette flow in mineral oil of the ω-Phase of the experiment. These results will be compared to our understanding of the Ekman layer torques.

We plan to measure the fluctuating component of the pressure at several radii and expect to observe the turbulence during spin up where the turbulence should be much larger and possibly observe the Ekman-induced turbulence during steady state rotation. **We plan** to measure and compare the same quantities for solid body and Couette flow in liquid sodium of the ω-Phase of the experiment. These results should be just scaled by the density ratio.

We plan to measure the magnetic fields for the conditions out lined in (1)-(5) above in liquid sodium at various values of B, ω, and $d\Omega/dr$ and compare the results to theory.

We plan to measure the ratio of the radial component of an externally established poloidal field, B_r, to the toroidal field, B_ϕ as a function of Ω and $d\Omega/dr$ and compare these results to the expected multiplication where for limiting Couette flow $B_\phi/B_r \simeq R_m/2\pi$. For the limiting rotation rate and limiting Couette flow where $R_m = 120$, we expect $B_\phi/B_r \simeq 20$.

We plan to measure the fluctuating component of the toroidal field produced by the radial bias field in order to observe the MRI in a toroidal field.

We plan to measure the number of modes, k_{min}, excited as a function of magnetic Reynolds number, $R_{mag} < 120$ and compare this to our theoretical analysis.

We plan to measure the back reaction of the turbulent stress as a function of the number of unstable modes excited by measuring the change in the torque and in the Couette flow, pressure profile, P_r, due to this stress.

8 THE $\alpha\,\omega$ DYNAMO

8.1 Why the $\alpha\,\omega$ Dynamo

The MRI as a mechanism for α-disk accretion has had wide popular appeal, and so has little need for further justification of an experimental verification. The $\alpha\,\omega$ dynamo, on the other hand, is less familiar and so perhaps requires some justification for its experimental verification supported by astrophysical funds. The $\alpha\,\omega$ dynamo is fundamental to most astrophysical dynamos because of the requirement to produce large coherent fluxes on scales large compared to the scale of the source. If the field, and hence, flux produced by the dynamo were to reverse each revolution, then flux ejected from a galactic black hole accretion disk dynamo would have up to 10^{11} reversals in the life time of the accretion disk. One would be hard pressed to make a giant radio lobe that shows the same sign of flux over several Mpc. Hence a dynamo that produces all one sign of magnetic flux is important to astrophysics.

The $\alpha\,\omega$ dynamo depends first upon the differential rotation or shear of a poloidal flux. This rotation provides the large scale coherence and the shear produces an enhanced toroidal flux. The conversion of a fraction of the enhanced toroidal flux back into poloidal flux is called helicity. Helicity can take place because of plumes produced in the rotating frame. These plumes must rise axially well above a surface and rotate a finite angle before falling back to the surface. We have chosen the accretion disk surrounding the massive black hole of every galaxy as the most likely extreme example of such an $\alpha\,\omega$ dynamo. We could have chosen a stellar dynamo as an example, but the origin of such large scale plumes is more problematical. We could have chosen a supernova dynamo as an example, but the production of large scale plumes in neutrino mediated convection is only now emerging (Herant et al. 1994). We could have chosen a galactic dynamo driven by supernovae blowing plumes out of the galactic plane, (Ferrière 1992; Ferrière 1993; Ferrière 1993b), but the number of revolutions of the galactic disk in a Hubble time, $\simeq 50$ is an arguable constraint. On the other hand the BH accretion disk dynamo has the advantage of simple geometry; the disk is thin compared to its radius. Also advantageous is the strong motivation that such a dynamo potentially can convert the black hole formation energy, the largest free energy of the universe, into a magnetic form. We believe that this dynamo is formed because of the differential rotation within the Keplerian disk and the plumes produced by star-disk collisions or turbulence. We could claim turbulence drives the necessary plumes in the disk (Chakrabarti et al. 1994), but we would have difficulty explaining sufficient turbulent intensity. Plumes lifted by star-disk collisions appear to be more plausible. When ejected to large heights above the disk, these plumes most probably give rise to some fraction of the broad emission lines (Zurek et al. 1994). Pop III stars are a small mass fraction, $\sim 10^{-2\,to\,-3}$, of the pre-galactic mass, but their predicted collisions with the disk are frequent enough to drive the necessary helicity or α-deformation of the $\alpha\,\omega$ dynamo (Pariev et al. 2001). In addition to this translation of matter and magnetic flux to large heights above the disk, we have predicted and now confirmed with a laboratory water flow visualization experiment discussed above (Beckley & Colgate 1998) how expanding plumes in a rotating frame, rotate *in the same direction every time* differentially through a finite angle, $\sim \pi/2$ radians, relative to the rotating frame. This finite, coherent, rotation angle forms the basis for the coherent α-deformation, or helicity, of the $\alpha\,\omega$ dynamo. The plumes are produced by driven pulsed jets in the experiment that in turn are meant to simulate plumes driven by any suitable natural mechanism.

8.2 Astrophysical Theory

Finally we are interested in extending the theory of the $\alpha\,\omega$ dynamo in the context of astrophysics. Already at Los Alamos, in conjunction with the initiation of this experiment, we are developing the theory of (1) the formation of the accretion disk leading to the galactic black hole, (2) the formation of the $\alpha\,\omega$ dynamo within this disk at a radius where it becomes conducting, and (3) the formation of the force-free helix that distributes the magnetic energy and flux throughout the universe. However, this experiment is hosted by NMIMT, where also the VLA and VLBA share joint faculty appointments. It is fair to say that almost half or the observations in the radio spectrum depends upon synchrotron emission from some object with a magnetic field of unknown origin (Molecular emission being the other half). One of us, Prof. Weatherall, shares a joint appointment with NRAO. This offers the opportunity for a much needed link between theory, observation, and experiment. **We plan** to pursue further calculations of the $\alpha\,\omega$ dynamo and apply these to both the experiment as well as to astrophysical objects, including disks and stars and also to supernovae during their explosion phase. The asymmetries observed in such explosions, especially in polarized light, might well be explained by this same mechanism; a dynamo, the ejection of a force-free magnetic helix and its luminosity from synchrotron emitting electrons.

8.3 Our Previous Research on the $\alpha\,\omega$ Dynamo

8.3.1 How an $\alpha\,\omega$ Dynamo Works

Figure 5(A) shows how the $\alpha\,\omega$ dynamo works in the Liquid Sodium Dynamo experiment. Figure 5(B) shows how the $\alpha\,\omega$ dynamo works in the accretion disk forming the galactic black hole. In the Liquid Sodium Dynamo, differential rotation is established between two rotating cylinders as Couette flow, $\Omega \propto 1/R^2$, by driving the inner cylinder at at a higher angular velocity than the outer or $\Omega_1 = 4\,\Omega_0$ where $R_0 = 2R_1$. In ionized accreting matter around a central mass, the black hole, the Keplerian angular velocity is $\Omega \propto 1/R^{-3/2}$. Thus the differential rotation in a conducting fluid wraps up the radial component of an initial poloidal, quadrupole field; in Fig. 5(A) $B_{Na} \sim 100$ G made with coils, or in Fig. 5(B) an infinitesimally small, $B_{seed} < 10^{-19}$ G field from density structure at decoupling. In either scenario, the resulting toroidal field is stronger than the initial poloidal field by $B_{toroidal}/B_{poloidal} = n_\Omega B_{poloidal}$, where n_Ω is the number of turns before dissipation or gain interfere. This multiplication factor becomes $n_\Omega \simeq R_{m,\Omega}/2\pi$ for dissipation alone. The magnetic Reynolds number for the sodium experiment is $R_{m,\Omega} = \Omega_0 R_0^2/\eta_{Na}$, where η_{Na} is the resistivity of liquid sodium. For the accretion disk ionized plasma, $R_{m,\Omega} = \Omega_0 H_{disk}^2/\eta_{plasma}$, where the height of the disk, $H_0 << R_0$. Then a driven pulsed jet Fig. 5(A), or a collision with the disk by a star, Fig. 5(B(c)), causes a plume to rise toward the end plate or above the disk with entrained and displaced toroidal flux forming a loop of toroidal flux. The radial expansion of the plume material causes the plane of this loop to untwist or rotate differentially about its own axis relative to the rotating frame so that the initial toroidal orientation of the loop is transformed into a poloidal one, Fig. 5(B(d)). Resistive diffusion in liquid sodium metal or reconnection in ionized plasma, allows this now poloidal loop to merge with the original poloidal field. For positive dynamo gain, the rate of addition of poloidal flux must be greater than its decay. It is only because the toroidal multiplication can be so large, or that $R_{m,\omega}$ can be so large that the helicity deformation of the $\alpha\,\omega$ dynamo can be more rare and episodic. This is different from the α^2 dynamos of the Raedler (1998) and Busse (1996) experiments and the Gailitis (2000) experiment. In these the helical flow is steady, but the dynamo-generated magnetic field either reverses periodically or is produced non-axisymmetrically. Positive dynamo gain occurs at a lower value of $R_{m,\alpha} \simeq 17$. However, despite this low R_m, this steady helical flow must be driven and maintained by rigid vanes and walls so that the turbulent friction with the walls is relatively large. The ω flow on the other hand is maintained in our experiment by Couette flow where, because of stability, the friction loss is very much less, $\sim 1/10$. As a final thought, the $\alpha\,\omega$ dynamo

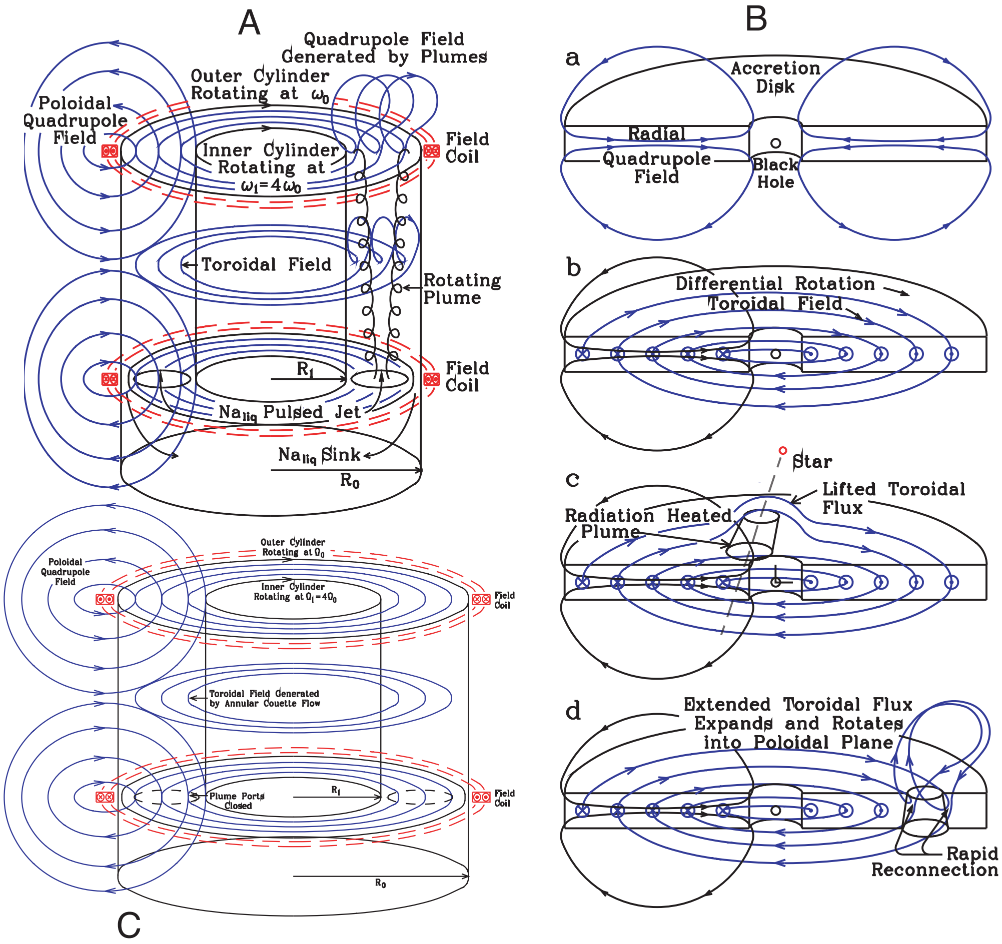

Figure 5: Figure 5(A) shows the sodium dynamo experiment in comparison to the accretion disk dynamo of Fig. 5(B). In both cases differential rotation in a conducting fluid wraps up an initial poloidal, radial field component into a much stronger toroidal field. Then either liquid sodium plumes driven by pulsed jets or star-disk collision, eject and rotate a loop of toroidal flux into the poloidal plane. Resistivity or reconnection merges this new or additional poloidal flux with the original poloidal flux leading to dynamo gain. In Fig. 5(C) we show the ω-phase of the dynamo, Phase I of this experiment. The multiplication of the poloidal field by the differential shear flow produces and enhanced the toroidal field which can be directly measured with large signal to noise ratio.

has episodic periods of turbulence, the plumes, separated by relatively long periods of laminar flow. This may be important if turbulence indeed interferes with dynamo gain (pvt. com. J. Finn, J. Lathrop).

8.3.2 The Simulation of the $\alpha\,\omega$ Dynamo

Pariev et al. (2001) and Colgate et al. (2002) have performed kinematic dynamo calculations using a 3-D vector potential code for the evolution of the magnetic field as a function of time by a time-dependent velocity flow field. By its nature the $\alpha\,\omega$ dynamo is 3-D and non axisymmetric, but the primary flow is circular, Couette or Keplerian, with occasional non-axisymmetric flows or plumes. Thus the code is written in cylindrical coordinates, analogous to both the experimental or astrophysical geometries. We use the vector potential for the calculated quantity, because then $\nabla \cdot \mathbf{B} = \mathbf{0}$ at all times and no periodic calculational "cleaning" of $\nabla \cdot \mathbf{B}$ has to be performed. The boundary condition is perfectly conducting so that the flux through the boundary must be constant in time. This allows for an initial poloidal bias field, but thereafter the flux through the boundary must remain constant. Therefore all the flux generated by a dynamo solution must remain within the box. Since this is not the case for either the experiment or the astrophysical circumstance, we must simulate problems with the walls as far removed from the region of action as possible. A non-conduction boundary condition requires the solution of the external potential field at each time step and is planned for the future.

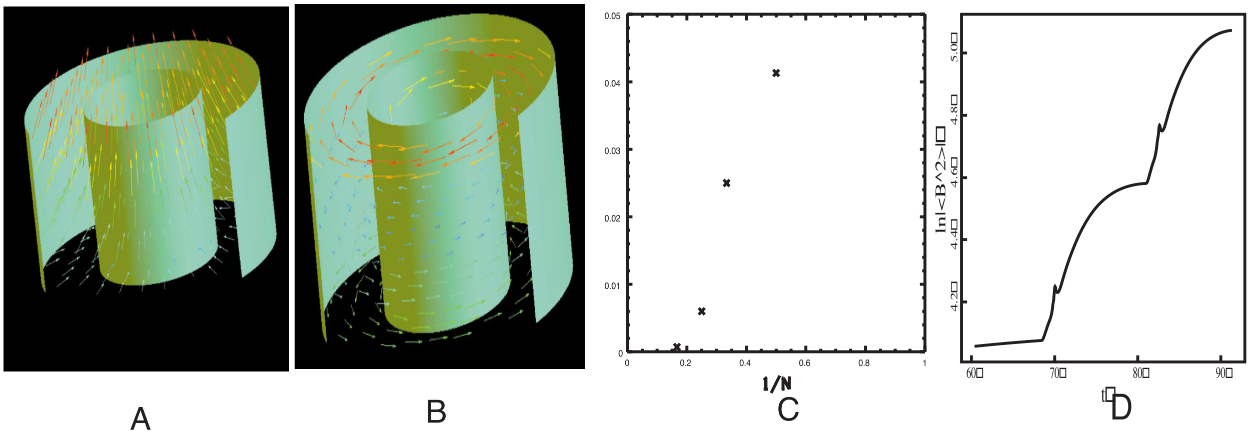

Figure 6: Figure 6(A) shows the dynamo calculations of Pariev et al. (2001) and Colgate et al. (2002) with an initial bias poloidal field with both radial and axial components. In Fig. 6(B) this field is wrapped up by the differential rotation in the liquid sodium. Figure 6(C) shows a pair of plumes every N revolutions gives rise to a gain that shows marginal gain at one pair of plumes each 6 revolutions. The exponentiating field energy is shown in Fig. 6(D) where $N = 3$ and the pulsed increase in field energy is seen for each plume cycle.

Figure 6(A) shows the cylindrical geometry with a radial initial poloidal field, a potential field as will be imposed by external coils. Differential rotation, Couette flow, $\Omega \propto 1/R^2$, is imposed with a value of resistivity such that $R_{m,\Omega} = (R_0 - R_1)v_0/\eta_{Na} = 120$. Figure 6(B) shows the poloidal field wrapped up into a toroidal field. Figure 6(C) shows the dynamo gain when a pair of symmetric, cylindrical plumes are injected vertically of initial radius, $r_{plume,0} = R_0/6$ or $2r_{plume,0} = d_{plume,0} = (2/3)(R_0 - R_1)$. For positive dynamo gain, $\simeq 0.12$ per revolution, this pair of plumes is pulsed once every 3 turns with a vertical velocity of $v_{plume,z} = 0.5v_0$. The simulated plumes are cylinders of constant radius that untwist or rotate relative to the frame such that their change in angle is $\pi/2$ radians when the background fluid at the plume radius has rotated π radians. A marginal positive dynamo gain of 0.01 per turn is observed for a pair of plumes per 5 revolutions. Figure 6(D) shows $ln(B^2)$ as a function of time, where each "bump" is the helicity injected by the plumes, or synchronous with the plume frequency. In the experiment we expect the plumes to diverge as they rise and rotate more rapidly when they strike the end wall, as observed in the fluid visualization experiment. As a consequence of both these effects, the experimental plumes should create greater helicity than in the simulations. Other (unknown) effects will surely decrease the dynamo gain. We are therefore planning the experiment to meet these conditions.

8.4 Proposed Work on the $\alpha\,\omega$ Dynamo

With this knowledge of MRI driven turbulence and ω gain and funding permitting, **we plan** to continue with constructing the driving mechanism for the α-deformation. **We plan** to measure separately the flux of helicity from the driven jets or plumes, $\Delta B_{r,z}$. Finally with both the α and ω deformations together **we plan** to measure the dynamo gain. We expect to achieve positive gain within the design limits of the strength of the containment vessel and power available for the experiment. Should the gain prove to be significantly less, i.e. negative, than that predicted from the kinematic dynamo calculations (Colgate et al. 2002), then there are two alternate ways to measure this negative gain: (1) **we plan** to measure the change in the (negative) decay rate, of the poloidal field, dB_r/dt, with and without dynamo action, and (2) **we plan** to add a modest fraction of iron in the *external* poloidal field circuit to enhance the dynamo gain. By measuring the gain as a function of the amount of iron (reluctance of the external space) a true gain can be determined.

The prior verification of plume rotation is central to the feasibility of the experiment. The verification of the rotation of the toroidal magnetic flux entrained within the plumes is similarly crucial to the dynamo. **We plan** to measure this rotated flux in the experiment by measuring the external poloidal flux created from the enhanced toroidal flux for individual plume pulses and under conditions less extreme; i.e. lower velocity and hence lower R_m than would predict positive dynamo gain. The advantage of stable Couette flow in the laboratory is the greatly reduced friction and hence reduced power required for reaching a given velocity and hence, a high value of magnetic Reynolds number.

When all the above parameters of the experiment have been measured and sufficiently understood, **we plan** to increase the power, velocities, and R_m to a point as close to or above the predicted positive dynamo gain and measure this gain, either positive or negative.

8.5 The $\alpha\,\omega$ Dynamo Compared to Other Experimental Dynamos

Recent years have been marked by exciting developments in the field of MHD dynamos, in particular the experimental realization of homogeneous dynamos was achieved. After many years of research and preparations, an exponentially growing dynamo mode was observed in the experiment conducted in a liquid-sodium facility in Riga, Latvia (Gailitis et al. 2000; Gailitis et al. 2001). This experiment reproduces the dynamo flow proposed by Ponomarenko (1973) in the laboratory. Another successful dynamo experiment of a different type was built in Karlsruhe, Germany. This experiment verifies the potential of a regular spatial arrangement of vortices to amplify the magnetic field. The growth of the magnetic field starting from the initial seed value of $\approx 1\,$Gauss up to $\approx 70\,$Gauss was observed in Karlsruhe experiment (Stieglitz & Müller 2001). The magnetic field reached the back-reaction, saturated limit, and the excitation of the non-axisymmetric mode predicted by the theory was observed. There are a number of other dynamo experiments, which are under preparation or discussion. Each of these experiments is designed to test different flow patterns capable of dynamo action. All these experiments (except Karlsruhe experiment) are designed to use axisymmetric rotating flows, either stationary or non-stationary. We designed another kind of dynamo experiment which will use essentially non-axisymmetric, non-stationary flows.

Here, because the flow is non-stationary and non-axisymmetric, then the field, averaged over many plume ejections, will approach a near steady state of axisymmetric symmetry. The flux from such a dynamo thus may simulate the astrophysical fluxes observed on large scales. Real dynamos operate in nature on astrophysical scales, in planets, convective envelopes of stars, galactic disks, accretion disks, and, possibly, on the largest scale in the clusters of galaxies. Since Parker (1955), most astrophysical dynamo theories, especially $\alpha\,\omega$ dynamos, refer to cyclonic or anticyclonic plumes as a source of the helicity. In the case of planetary and stellar dynamos such plumes are believed to be rising and sinking convective cells (Parker 1979; Mestel 1999). Here we invoke for both the experiment and the accretion disk dynamo anticyclonic plumes because of their finite rotation angle, $\simeq \pi/2$ radians.

9 ADMINISTRATIVE JUSTIFICATIONS

1) Cooperation with Los Alamos National Lab, is assured by the principle investigator's joint appointment at both institutions. The directed funded research on active galaxies has the following list of collaborators all of whom in some way base their work on the existence of a dynamo that accesses the free energy of the galactic black hole formation. Hui Li, Josef Koller, X-1; Stirling Colgate, Nathan Currier, Mike Warren, T-6; Vladimir Pariev, T-6 & Univ. of Rochester; John Finn, Xianzhu Tang, Giovanni Lapenta T-15; Burton Wendroff, S. Li, T-7; Koichi Noguchi, T-6 & CNLS; Peter Gary, Kazumi Nishimura, NIS-1; Philipp Kronberg, IGPP & Univ Toronto; Howard Beckley, Jim Weatherall, Rocky Ginanni, Robert Koegler, Ian Bentley, NMIMT; Richard Lovelace, Cornell; Renyu Cen, Princeton; Brian McNarama, Ohio Univ.; Robert Buchler, Univ. of Florida;

2) The construction and development of the apparatus is performed at the Physics Department of NMIMT. The senior graduate student, Howard Beckley, expects to receive his PhD based upon Phase I of this experiment and to continue as a postdoc if funded. Another graduate student and undergraduate students are from the Physics Department and Electrical Engineering.

3) The sodium experiments will be performed at the Energetic Materials Research and Testing Center (EMRTC), a division of NMIMT, Socorro, NM, where explosives and armaments have been tested and developed since WWII. Many students, graduate and undergraduate, work at EMRTC, so that strong student participation has been a tradition for 58 years. Thus education, safety, and health are fundamental to the operation as well as the basic engineering and experimental expertise.

4) The VLA and VLBA operations center of NRAO is located on the NMIMT campus. Several Physics Dept. faculty positions are jointly held at NRAO (e.g. Prof. J. Weatherall, CoPI). Thus, astrophysics plays a major role in the Physics Dept. where the principal investigator is an adjunct professor.

5) The calculational simulation work has been initially performed at Los Alamos National Laboratory in the Theoretical Division. Recently three year funding has been obtained from within the lab, "LDRD" (Hui Li, PI, S.A. Colgate, CoPI at Los Alamos), that is supporting kinematic dynamo calculations, vortex accretion disk theory, calculations of the helix-jet formation of AGN resulting from the saturated dynamo, and general relativistic effects close to the black hole. This work is done in several divisions of the laboratory. The PI holds an adjunct professorship at New Mexico Tech and an associate position at Los Alamos.

6) We expect a future expansion of this computational work and theoretical support both at New Mexico Tech and at other universities. Particularly we hope the Frontier Proposal with the University of Wisconsin (Center for Liquid Metal Studies of Astrophysical and Geophysical MHD Phenomena, NSF # 0137518) will be funded in the future, in which case this experiment will be part of larger consortium of liquid metal experiments in support of astrophysics. Funding will then be adjusted by the DOE and NSF accordingly.

7) Initial financial support for the fluid flow visualization experiments has been given by both NMIMT through EMRTC, $\sim \$13k$, and the IGPP University program of Los Alamos National Lab, $\sim \$7k$ per year for three years. This support has led to the flow visualization experiments that have defined the fluid flow field for the sodium dynamo experiment. Further funding of $\sim \$35k$ this last year has been given by LANL as bridge funding to continue the experiment until this year's proposals are decided.

9.1 Project and Collaborating Personnel

Stirling Colgate is an astrophysicist and experimental physicist. He holds an associate position (retired) at LANL and is an Adjunct Professor of Physics at NMIMT. He has had extensive past experience as an experimentalist in the plasma physics of fusion and sodium MHD experiments. His experience with liquid and solid sodium include four MHD experiments (Colgate 1955; Colgate et al. 1960). He also has a reputation in theoretical astrophysics. No funding is requested in this proposal for his support or travel.

Howard Beckley is a PhD graduate student in experimental astrophysics at NMIMT. He has over 16 years experience in prototype and development machining with approximately 10 years of design engineering experience embedded within that. The Phase I development of the project and hydrodynamic operation of the experiment is his PhD dissertation. He has designed, machined and constructed virtually all the dynamo apparatus. He expects to be completed by late August 2002. His funding as a postdoc is requested for three years of the experiment.

James Weatherall is a Associate Professor of Physics at NMIMT. He specializes in theoretical astrophysics, and is a Collaborating Scientist at NRAO. One month per summer for three years funding is requested in this proposal for his support.

The following LANL staff are partially supported for theoretical work on the galactic dynamo and its consequences for AGN and quasars by the project: DR, Life Cycles of Active Galaxies, 3 y. No further DOE or NSF funding is involved, but active theoretical support of the project is important. Some of the equipment costs of the dynamo are support on the project by LANL, $35k per year.

Hui Li is a member of group X-1 who is leading the DR project "Life Cycles of Active Galaxies". He has specialized in x-ray and gamma-ray emission mechanisms and spectra. He will be instrumental in the astrophysical interpretation of the saturated dynamo and AGN. He has also led the effort on the Rossby vortex mechanism of accretion disks and thus the hydrodynamic basis of the galactic dynamo. (LANL support)

Koichi Noguchi is a postdoc in The Center for non-Linear Studies and Theoretical Plasma Physics, LANL, and is supported and directed in his research on the magneto rotational instability by the funding of the DR project "Life Cycles of Active Galaxies". (LANL support)

Vladimir Pariev previously a graduate student at Univ. of Arizona (Jokipii and Levy professor) has spent summers at LANL, published in GR of black holes, and written and tested the kinematic $\alpha\,\omega$ dynamo code. He received his PhD the summer of 2001 and is now a postdoc working on turbulent dynamo theory with Eric Blackman of the University of Rochester. We expect continuing collaboration on MHD problems associated with this work. (LANL travel support)

John Finn is a staff member in T-15, theoretical plasma physics at LANL. He has published in dynamo theory, written kinematic dynamo codes, and helped direct Vladimir Pariev in writing the kinematic dynamo code. He is a highly respected senior scientist in plasma physics and in the magnetic fusion program. (LANL support)

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