White Paper on: Experiments to Demonstrate Solar and Astrophysical Dynamos

Stirling A. Colgate, LANL, Nov. 12, 2010

Summary:
A significant fraction of solar physics depends upon the existence of magnetic fields in the sun as well in other stars, yet so far there has been no laboratory demonstration of a dynamo in unconstrained flow in a conducting fluid. A similar situation exists for the cosmos. Indeed the experiments based on the early ansatz that turbulence alone would make a dynamo have all led to the recognition that turbulence leads primarily to enhanced resistive diffusion and not, by itself, to a dynamo. Only flows, constrained by rigid walls have shown dynamo gain. It is only through experiments, not theory or modeling that this understanding has emerged. At NMIMT we have demonstrated that large scale coherent flows and natural stability, not turbulence, has led to large gain, x8, in one of the two orthogonal motions necessary for dynamo gain. At Madison the addition of a midplane rigid wall baffle to reduce unconstrained shear turbulence has had a similar, x4, positive effect in Dudley-James flow. We therefore believe that a continuing program seeking dynamo gain through laboratory experiments is vital to discovering the truth about dynamo physics.

The purpose of this recommended research is to explore whether a solar or astrophysical dynamo is created primarily by coherent motions as opposed to turbulent motions. This question needs to be addressed in many experiments, because modeling and theory have failed, so far, relative to experiment, in giving us the answer.

The laboratory $\alpha-\Omega$ dynamo at NMIMT is based upon coherent, stable fluid motions and now has a successful result of high shear gain, the Ω phase, in a stable, Couette shear flow of low turbulence in liquid sodium. One expects low turbulence in shear flow in three circumstances of astrophysics: 1) Keplerian accretion disks; (The years of theoretical and computational effort to prove a robust source of turbulence in accretion disks is proof enough that a stable gradient of angular momentum is a significant barrier to turbulence.) 2) When the fluid Reynolds number is small as in the cores of planets one expects sufficient viscosity to damp the turbulent eddies. 3) At the base of the convection zone of stars we expect a similar stabilization due to the gradient of entropy. This latter needs to be demonstrated by calculations. The ability of viscous damping, a gradient of angular momentum, and a gradient of entropy to damp eddies should be demonstrated in the laboratory.

The α-phase of an astrophysical dynamo, the source of the helicity, is conceptually the most difficult to imagine. By comparison the Ω–phase, the coherent rotational shear in an accretion disk, is almost a no-brainer. The α-phase or coherent helicity has been suggested as originating in a naturally occurring fluid deformation, i.e., plumes in a rotating frame. The helicity is the deformation of the conducting fluid that captures a fraction of the enhanced toroidal flux from the α-phase coherent winding and transforms a fraction back into orthogonal, poloidal flux of one sign and one geometry such that subsequent α-phase coherent winding amplifies it again creating more toroidal flux. Coherence in this case means the same twist of poloidal flux, a quarter turn, and a translation of the flux out of the symmetry plane every time.

This would seem to be a tall order, but surprisingly nature seems to do this to a buoyant plume of matter rising relative to the plane of symmetry in a rotating frame. One observes a typical smoke plume from a smoke stack rising in a turbulent fashion, but when a "puff" of gas or smoke is ejected from an orifice, it travels several diameters and expands transversely before mixing with the background gas. This transverse expansion causes an increase in the moment of inertia of the plume matter so that transiently it rotates slower than the frame. It is the transient conservation of angular momentum that causes the plume to rotate relative to the frame, as observed in water simulation experiments. Surprisingly the combination of transient rotation and mixing limits the effective rotation to about ¼ turn, the ideal to transform toroidal flux into poloidal flux. Meanwhile the plume has risen relative to the plane of symmetry. This is the ideal helicity deformation for a coherent dynamo. In a star or the sun, the analysis by Chandrasekar of the Rayleigh-Taylor growth in a gradient of unstable buoyancy (density) predicts the fastest growing mode is not the smallest wave length, but instead a wave length corresponding to the logarithmic gradient of the buoyancy or roughly the density scale height. This large scale is then the expected scale of the first plumes to rise at the base of the convective zone. The combination of scale and finite plume rotation make this natural deformation an ideal source of helicity to complete the solar dynamo cycle.

Finally there is one observation that suggests consistency with this coherent model. The back-reaction limit of such a dynamo would most likely be the stress of the magnetic fields altering the dynamics of the plumes. The dynamic stress of these plumes is the stress of convection or: solar luminosity = area * rho $v^3/2$. Then $B^2/ 8\pi$ = rho v^2 with rho ~ 0.1g/cm^2. Solving for B ~ 10,000 gauss. The largest sun spots show a core of order B ~ 5,000 gauss. It there has been some expansion in the rise from the convective zone, then these values are approximately consistent.

The simulation of such a stellar dynamo is still a major challenge to computational science because of the difficulty of modeling turbulence and the necessary immense range of scales. The one simulation of such a dynamo using a vector potential code approximated the plumes as right circular cylinders without the typical structure of a pulsed plume. The uncertainty of simulations of turbulence will justify experimental truth for some time to come.