NUMERICAL SIMULATIONS OF TURBULENT DYNAMOS

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Many astrophysical bodies (for example the Sun or the Milky Way) consist of hot ionized gas which is electrically conducting. Such flows are also turbulent. However, a purely hydrodynamic turbulent state can become unstable to the dynamo instability, so the final state becomes magnetized. Significant amounts of energy can then be converted to and dissipated through magnetic fields. Numerical simulations show a turbulent forward cascade in which the magnetic spectral energy is always slightly larger than the kinetic spectral energy. The ratio of kinetic to magnetic energy dissipation scales with the magnetic Prandtl number approximately to the 1/2 power, so at low magnetic Prandtl numbers, most of the energy is dissipated magnetically. This leaves much less energy in the rest of the kinetic energy cascade than at unit magnetic Prandtl numbers. Consequently, at given numerical resolution the viscosity can be lower than otherwise. Simulations show that for isotropically forced turbulence, the so-called small-scale dynamo exists at magnetic Prandtl numbers down to 0.01.

Next, I will discuss two quite different examples in which turbulent hydromagnetic flows can develop spatio-temporal structures on scales much larger and longer than those of the turbulence. The first example is what is sometimes referred to as a mean-field or large-scale dynamo, which requires finite helicity of the flow. Since magnetic helicity is conserved in the limit of high electric conductivity, it is driven preferentially to larger scales. This process can be modeled quantitatively in terms of averaged equations in which the magnetic diffusivity is renormalized and other new terms (e.g. the alpha effect) appear.

The second example is about a process that is now sometimes referred to as negative effective magnetic pressure instability. In this case the magnetic pressure gets renormalized and can become negative. This process is general and exists even in isotropic non-helical turbulence. However, when it is applied to a strongly stratified gas with an applied uniform magnetic field, an instability develops that leads to magnetic flux concentrations on scales encompassing that of at least ten turbulent eddies. The physics behind this is straightforward: as the magnetic field is increased, it increases the magnetic pressure, but it also suppresses the turbulent pressure, and this effect can be stronger, rendering the total magnetic effect a negative one.

These two examples illustrate the general principle by which the consideration of averaged equations can lead to new insights with quantitative predictions that are then also borne out by direct numerical simulations. Other dramatic examples include the turbulent pumping of passive scalars and angular momentum transport even for rigid rotation. Applications to the Sun will be discussed.