Astrophysical Implications/Directions/ Challenges

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Cultural Challenges

- Astrophysical scenarios vs. physics: level of "understanding" means different things for different people. Understand who cares about what, and why.
- Fractalization of science: "Dynamo" means different things to different people. Has led to confusion and inhibits fruitful cross disciplinary discussion on even basic issues. People retreat to their comfort zone. Immersion is helpful.
- Life is short: some wonder why the same open questions persist for 60 years. Is it worth studying? Broader community loses patience. A consequence of long standing difficulties in dealing with nonlinear problems.
- Patience is required: Progress has emerged by increasing interplay between numerical simulation and theory.
- Some long standing questions will persist. Balance between targeting principles vs. phenomenological application.

General Goals

- **Identify principles that predict strength, shape, and evolution of magnetic spectra**. Predict growth rates, and saturation using "idealized" nonlinear simulations, analytic studies, experiments.
- **Model field growth in more realistic systems** using principles gained to approximate nonlinearities while also incorporating astrophysical ingredients.
- **Understand dynamical role of dynamos within broader phenomena** (accretion, jets, coronal relaxation, angular momentum transport, particle acceleration, flux accretion vs. diffusion, magnetic mixing)
- **"End game" not just massive simulations** if aim is understanding and 'practical' tools.
- **Ask not whether mean field theory is correct but whether we have the correct mean field theory.**
- Measure magnetic spectra in real objects: galaxy, coronae
- Use experiments to prove principles and benchmark codes

Types of Dynamos:

(Growth or sustenance of magnetic field against decay)

- **Small scale:** (below driving scale, no $\overline{\mathcal{E}} \cdot \overline{B}$ needed; "direct" transfer)
- **Large scale**: (above driving scale $\overline{\mathcal{E}} \cdot \overline{B}$ needed; "inverse" transfer)
  - flow/mechanically driven (FDHD)
  - magnetically driven ('magnetic relaxation') (MDHD)
  - *kinetic helicity is NOT the "deal breaker"*
  - *global reflection asymmetry vs. quasi-local reflection asymmetry*
- Both involve local and non-local (spectral) processes

Notes on Specific Systems:

- **Galaxy**: only source where we can see interior directly. Prioritize in situ over primordial; SN driving standard but consider shear and AGN/star disk collisions also
- **Sun**: detailed coronal observations. Proves existence of large scale dynamo and system of magnetic relaxation. Where is the dynamo? More needed to link interior to corona.
- **Stars**: X-ray luminosity vs. Rotation period, magnetic mixing, Ap stars, WD fields, pulsar fields, radiative zone field generation, core dynamos? Where are the dynamos? what kinds? Again: we measure only coronal fields.
- **Accretion engines, jetted systems**: dynamical consequences of field generation. Are jets and their fields self-consistently produced in disks? What is the spectrum of the magnetic stress for angular momentum transport? We measure only corona/jet fields.
- **Galaxy clusters**: isotropic forcing by galaxy streaming or AGN stirring; also large coherent field in radio sources therein--evidence of AGN core dynamo + expulsion?
- **Transient/Explosive Outflows**: SN, GRB, Planetary Nebulae: transient dynamos differ from galactic and solar dynamo paradigms.
- **Planets**: lower R_m systems.

Comments on Small scale Dynamo:

- large scale and small scale dynamo are really all part of an coupled evolution of magnetic spectrum
- Near equipartition between field and flow reached.
- But how is overall spectral shape is affected by the nature of the forcing? (helical, shear, isotropic)
- How is saturated spectrum affected by e.g. Magnetic Prandtl number? Convergence for high values?
- Spectra from simplified isotropic non-helically forced dynamos in boxes seem to disagree with observations of Galaxy and clusters.

Large scale Dynamo: 21st century Progress

- Large scale high R_M dynamo action confirmed by nonlinear simulations with dynamically strong saturated field strengths. Non-local inverse transfer.

- Robust for variety forcings: isotropic, shear, convection and happens regardless of growth of small scale field.

- **21st century nonlinear mean field theory now correctly predicts nonlinear saturation seen in simple numerical experiments** by coupling magnetic helicity density evolution into theory. Combination of iterative work of theory and numerical experiment. Progress on which to build.

- Global kinetic helicity NOT the necessary condition for LSD action. $\overline{\mathcal{E}} \cdot \overline{B}$ is required but can be sustained by flux of magnetic helicity density, or even magnetic instability.

- Question of "fast or slow" in realistic applications and the overall magnetic reynolds number remains.

- What the key ingredients that conspire for a given astrophysical setting is not yet clear. **Interplay between interior, boundary and corona** important

Simulations vs. Theory vs. Experiment

- simulations essential: but pitfalls from lack of understanding of the limitations: boundary conditions, dynamic range, limitations on choice of explicit dimensionless constants, stratification, box size etc..
- simulations/numerical experiments offer opportunity for analytic studies rather than a replacement of such.
- practical models needed for application
- Experiments may be even more limited in parameter range than simulations but can test basic principles AND benchmark codes
- instructive to compare accretion disk theory with large scale dynamo theory...

Accretion disk theory vs. MFD theory

- Textbook accretion disk theory invokes turbulence + axisymmetry and is thus a mean field theory (often poorly emphasized.)
- It ignores magnetic field dynamics (complement to MFD)
- Widely used by modelers to compare with observations (often unaware they are using a mean field theory)
- Simulations have not yet resulted in an improved practical mean field accretion model that goes beyond theory a single parameter closure, though this is an important goal
- The theory that predicts saturation seen in local accretion disk simulations is unlikely to be a one parameter closure.
- MFD theory more scrutinized in part because 20th dynamo textbooks (though incomplete) are more explicit in presenting assumptions
- 21st century nonlinear MFD theory has arguably made more progress in matching its associated simulations in a way that has yet to occur for accretion disks
- IRONICALLY: THEY ARE LIKELY BOTH PART OF A SINGLE UNIFIED THEORY FOR DISKS

Local vs. Global Transport and Connection to Large Scale Dynamos

- computational effort for discs has focused on local transport because of ‘practicality’ of SS73 and computational limitations.
- maybe transfer is more global: stratifies sims show large scale fields and cycle periods.
- large scale fields required for corona if interior is turbulent what budget of ang mom. transport do they comprise? are jet fields the result of further relaxation of coronal loops?
- solar analogy is clear: fields large enough to reach corona, relax further
- computational effort for large scale dynamos, jets, has been disjoint from accretion disk theory.
- for a real disk, mean field accretion disk theory should include MFDT (ultimately coupled equations) and jet launch, and both local and large scale angular momentum transport. (disc, corona, jets)

Connecting Dynamos with Coronae: Cross-cutting, high-priority theme

- Most work focuses on interior of rotators
- most observations are of corona
- interior is not magnetically dominated
- corona is magnetically dominated
- role of transport and boundaries
- would like to see even a toy model that solves ‘complete’ picture: interior-boundary-corona for star and disk

Disc to Corona to Jet

- consensus: astrophysical jets are result of magnetically mediated launch at unresolved scales less than 50 R_{engine}
- ironically: less consensus on relative strength of magnetic fields on resolvable scales > 50 R_{launch}
- Suggest jet launch is the end state of coupled dynamos: FDHD fields from disk escape to corona where they open up to even larger scales via MDHD; **provides direct analogue to lab plasmas in corona: Fusion plasma magnetic relaxation/dynamos directly relevant to coronae**
- "large" scale with respect to disk is "small scale" with respect to corona
- Maybe MRI driven large scale dynamo is supported by helicity flux in stratified media

Finally: Unconventional but Interesting..

- Star disk collision driven dynamos in AGN (note also jet composition)
- Dust driven dynamos around protostars
- Analogue to PR effect by radiation on electrons in AGN: competitive with Biermann battery seed field?

END