Perspectives on Laboratory Astrophysics using plasmas and liquid metals

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Laboratory Astrophysics from the Spitzer tradition

- What it is:
  - Plasma physics experiments (Astrophysical bodies are plasma) which have applications to understanding phenomena in space and beyond (examples follow)
  - model building to build intuition
- What it isn't:
  - experiments do not directly simulate astrophysical objects
    - gravity is impossible
    - dimensionless parameters are very difficult to match

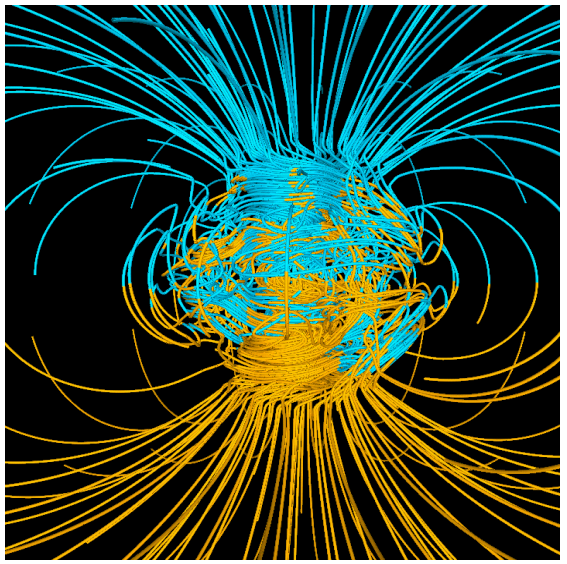
Why do experiments?

- Experiments can go places that numerical simulation cannot
  - there are always approximations, many of which are probably not correct
- Fusion perspective: even with the best minds working on explaining plasma phenomena in fusion device, we rarely get it right the first time: experiments clarify the physics
  - lack of particle acceleration at solar wind bow shock looks like a similar fiasco in astrophysics
  - similar story for internal rotation profile of sun
- Experiments are necessary and complementary
  - connect theory through parameter and geometry variations
  - measure quantities in the lab which will never be measured by observers

Dynamos: Current state of theory is to solve the non-linear MHD equations numerically

- Induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{V} \times \mathbf{B} + \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}$$



- Equation of Motion

$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = -\nabla p + \mathbf{J} \times \mathbf{B} + \mu \nabla^2 \mathbf{V} + F_{prop}$$

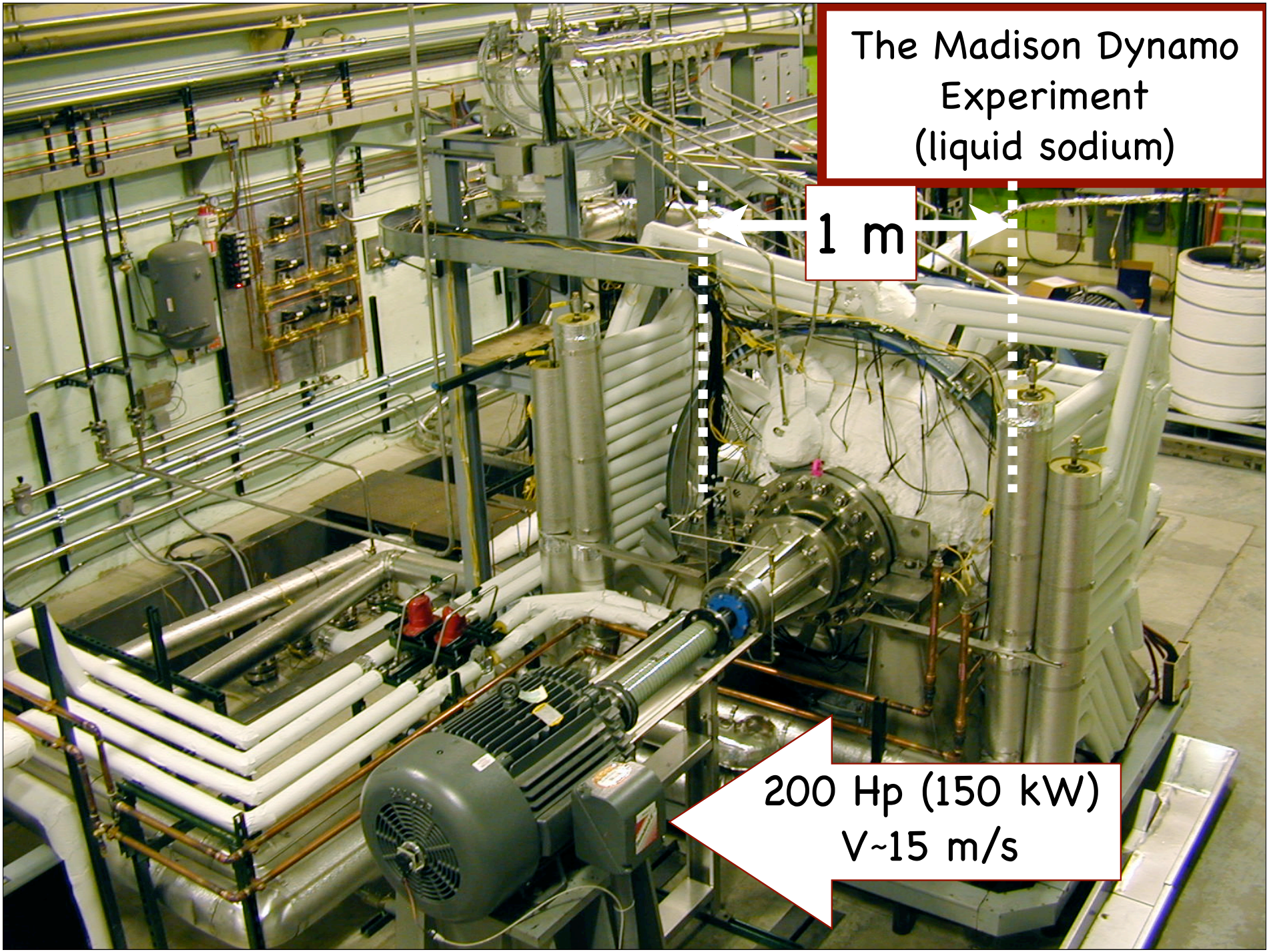
Why do Experiments?

...in magnetohydrodynamics one should not believe the product of a long and complicated piece of mathematics if it is unsupported by observation.

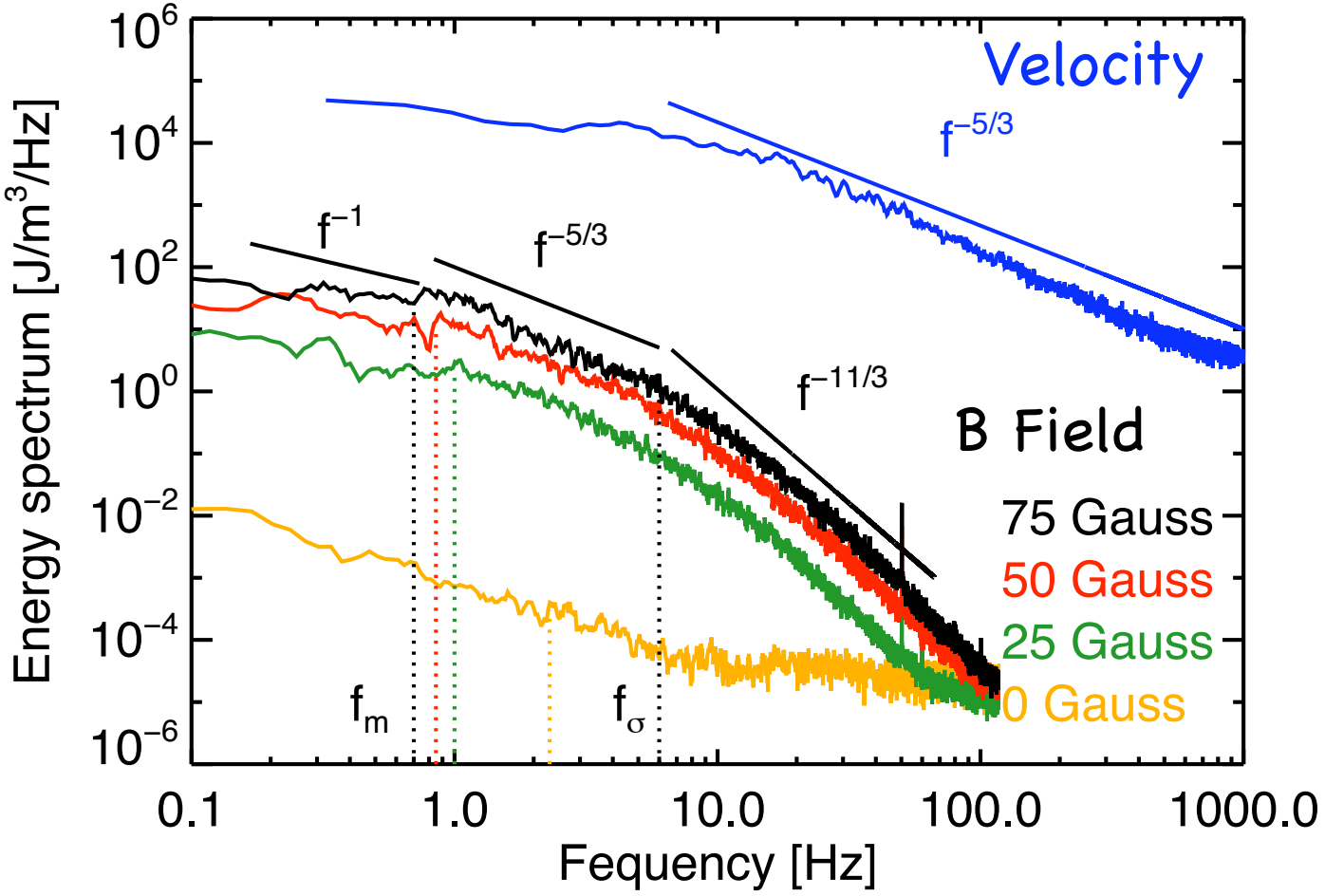
Enrico Fermi

Why do experiments when we can simulate self-exciting dynamos?

- Simulations are limited in resolution and speed
- To resolve resistive dissipation scale requires a 3D grid of Rm^3
  - easy for Earth where Rm=300-600
  - hard for Sun where $Rm=10^7$
- To resolve viscous dissipation scale requires a 3D grid of Re^3
  - Pm = Rm/Re is a property of the medium
  - for liquid metals and solar plasma $Pm=10^{-5}$
- $Re>10^7$ in Earth and Liquid metal experiment
  - Flows are very turbulent
  - Can't be simulated accurately


The Madison Dynamo Experiment (liquid sodium)
1 m
200 Hp (150 kW)
V~15 m/s

Naturally models all of the scale-lengths of a high Re flow



Nornberg, Spence, Bayliss, Kendrick, and Forest, *Measurements of the magnetic field induced by a turbulent flow of liquid metal*, Phys. Plasmas **13** 055901 (2006).

Examples of Laboratory Plasma Astrophysics

- devices which exhibit analogous phenomena
  - RFP
    - momentum transport, current generation, ion heating
  - Tokamak
    - sawteeth and solar flares
- devices which are geometrically similar for intuition development
  - dipole confinement
  - terrella experiments
  - solar flare experiments
  - reconnection experiments
- Experiments designed to test concepts (any relation to astrophysical geometry is purely coincidental)
  - characterization of high beta, high Rm turbulent plasmas
  - dusty plasmas
  - magnetic field generation by flows of liquid metal or plasmas

Biggest Challenges for the Field

- recognition by Astrophysics Agencies that astronomical observations, numerics, and theory is not sufficient: experiment, even if it has a different set of dimensionless parameters, is essential for discovery
  - NRC could help build this scientific argument
- Well diagnosed plasma experiments require facilities, teams, and diagnostics similar to small fusion experiment
  - a broader spectrum of plasma astrophysics experiments are possible and needed
- Proposal: 0.5% of NASA mission budget go to laboratory modeling of mission--broaden scope