Astrophysical Dynamos

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Working Definition

- An astrophysical dynamo is a set of mechanisms which convert mechanical energy to magnetic energy and/or sustain the magnetic field against dissipation.
- Possible venues include planets, stars, galaxies, the intergalactic medium, accretion disks, jets.
- Grand challenge problem, many opportunities & links to other areas.

Plan of Presentation

- Introduction, important problems, opportunities for observations, links to other topics (Ellen, 30m)
- Experimental opportunities (Cary, 20m)
- Theoretical & numerical opportunities (Fausto, 20m)
- Impact on astrophysics (Eric, 20m)
- Discussion (moderated by Ellen, 30m)

Recommendations: Observations

- Use existing & planned observing facilities to better characterize solar & stellar magnetic fields, map the Galactic magnetic field, probe galactic magnetic fields over cosmic time, search for an intergalactic field.
- Consider proposing new instruments & facilities.

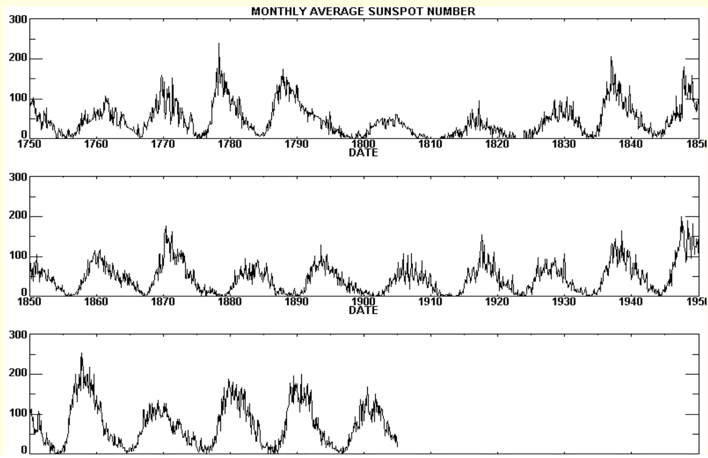
Recommendations: Experiment

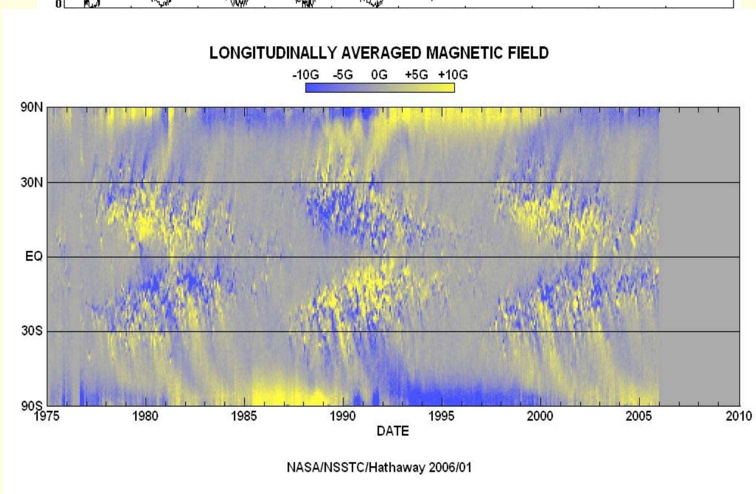
- Develop experiments on flow dominated plasma dynamos with flexible plasma parameters, flow states, & boundary conditions.
- Continue study of magnetic self-organization, field-flow coupling, role of boundary conditions, & effects beyond MHD in magnetically dominated plasmas.

Recommendations: Theory & Simulation

- Support observations & experiments to maximize their impact, validate codes, test theories.
- Use theory & simulation to extrapolate to extreme parameter regimes of astrophysical dynamos.
- Explore low order models, simple parameterizations.

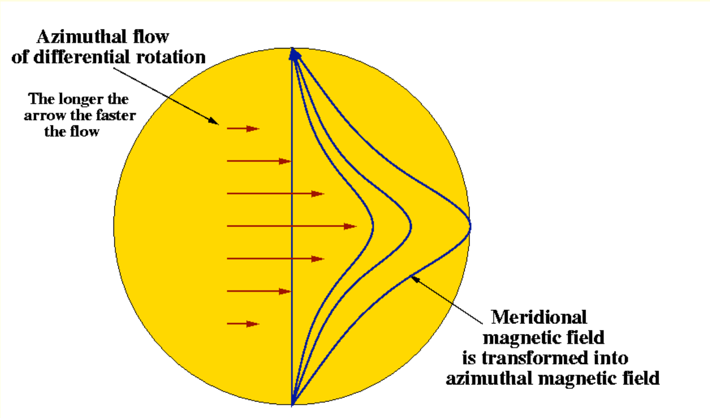
Solar Magnetic Activity Cycle

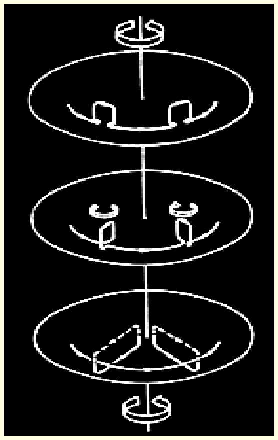




- Maximum in sunspot number every 11 yrs.
- Bipolar sunspot pairs indicate a toroidal field.
- Flux appears at progressively lower latitudes as cycle progresses.
- Toroidal field reverses every 11 yrs.
- Rotation period is 1 mo, Ohmic decay time is 10^{10} yr.

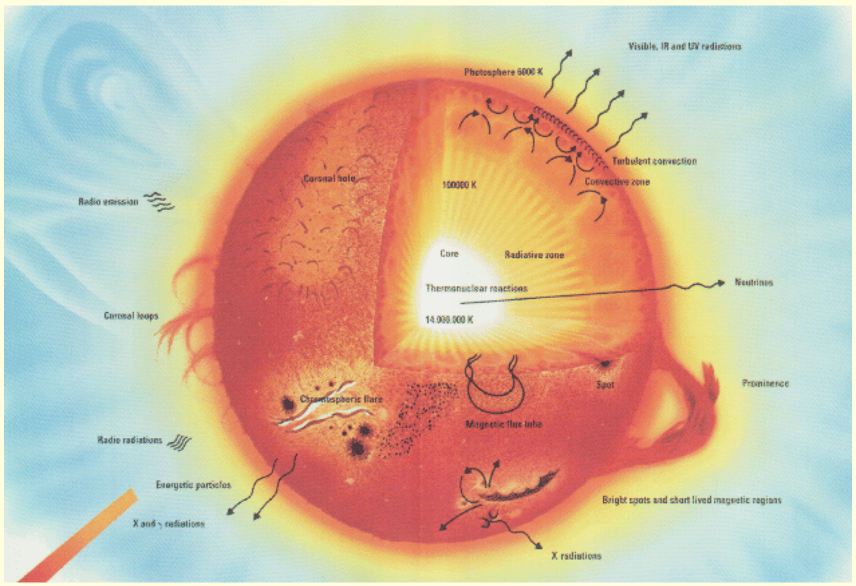
Dynamos in Differentially Rotating Systems with Thermal Convection: Parker





- Differential rotation converts poloidal to toroidal field: ω effect.
- Small scale helical motion converts toroidal to poloidal field: α effect.
- Turbulent diffusion of large scale field: β effect.

In Context of Solar Structure



- Cutaway view of the solar interior showing radiative core, convective envelope, & complex magnetic outer boundary condition.

Mean Field Electrodynamics

- Assume scale separation for **v** and **B.**
- Make quasilinear approximation.
- In the simple case of isotropic turbulence,

- Equation for mean field $\langle \mathrm{B} \rangle$

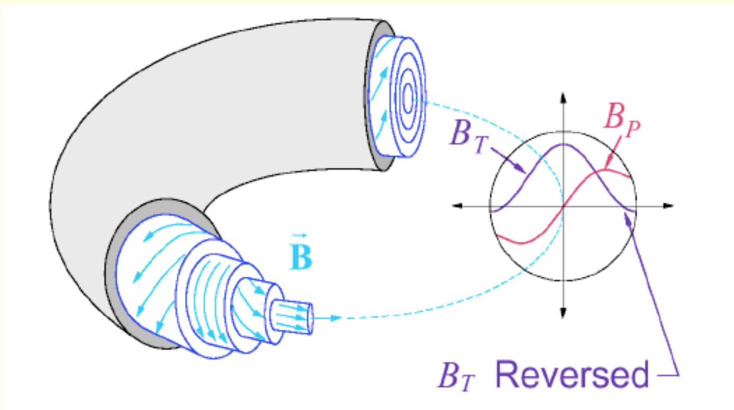
$$\partial \langle \mathrm{B} \rangle \partial t = -c\nabla \times \langle \mathrm{E} \rangle,$$

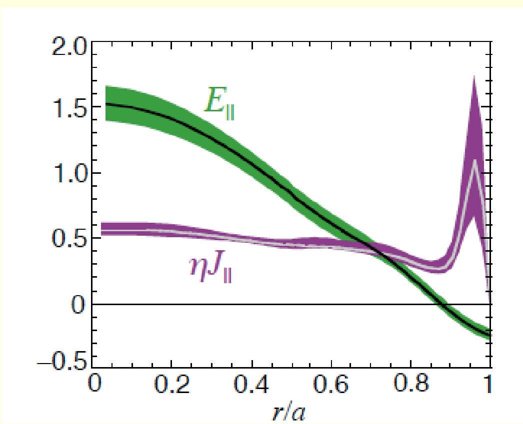
$$-c\langle \mathrm{E} \rangle = \langle \mathbf{v} \rangle \times \langle \mathrm{B} \rangle + \langle \mathbf{v}^{'} \times \mathrm{b}^{'} \rangle + (\beta + \eta)\nabla \times \langle \mathrm{B} \rangle.$$

and

$$\langle \mathbf{v}^{'} \times \mathrm{b}^{'} \rangle = \alpha \langle \mathrm{B} \rangle.$$

α effect identified in RFP





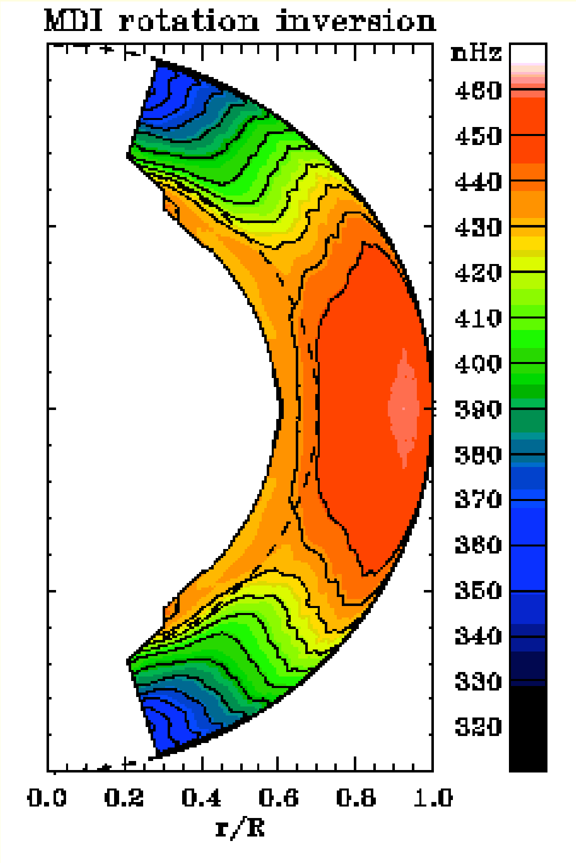
- Poloidal field is converted to toroidal field, producing the field reversal. Additional terms in Ohm's Law include MHD fluctuations, Hall terms, diamagnetic terms.

Theoretical Problems with MFED

- Predicts small scale field grows much faster than large scale field when S is large (*consequence of fieldline stretching in a fixed volume*).
- Large scale field may saturate at very low levels due to feedback on α and β.
- Scale separation not achieved in astrophysical systems.

Empirical Problems with MFED

- Not a good descriptor of numerical simulations.
- Helioseismically determined ω gives equator to pole flux migration.



Some Current Directions

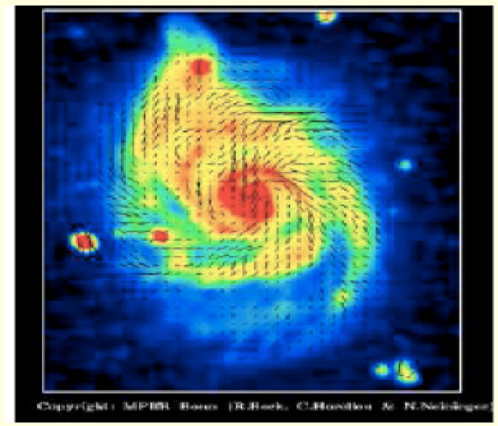
- Follow flow of magnetic helicity, including effect of ejection through the boundaries.
- Characterize essentially nonlinear dynamos as models of saturated states.
- Explore statistical properties of small scale kinematic dynamos for a wide range of spectra & parameters.
- Explore non-turbulent dynamos w. induction by coherent flow.
- Direct numerical simulation of astrophysical systems, especially stars & disks.

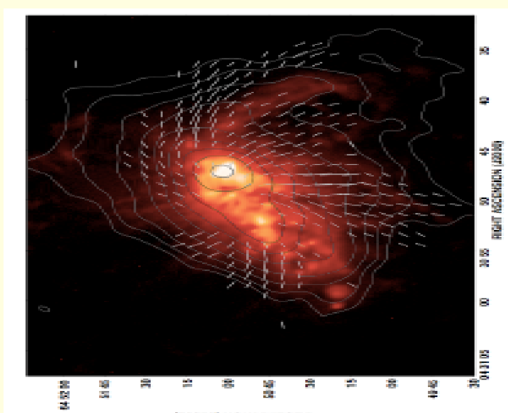
Basic Questions about Solar/Stellar Dynamos

- What controls the cycle period?
- What sets the magnetic fieldstrength?
- How does the field affect convective transport, differential rotation, & meridional flow?
- How are the interior and escaping fields related?
- Can solar activity be predicted on short timescales?

Plus *dynamos in protostars, massive stars, collapsing stars…*

Galactic Magnetic Fields





Magnetic fields of M51, a normal spiral (top), and NGC1569, a dwarf starburst (bottom), revealed by synchrotron emission. Both random and organized orientations are present, energy is comparable to turbulent energy.

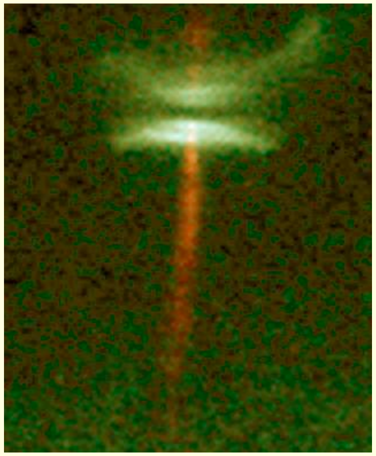
Is There a Galactic Dynamo?

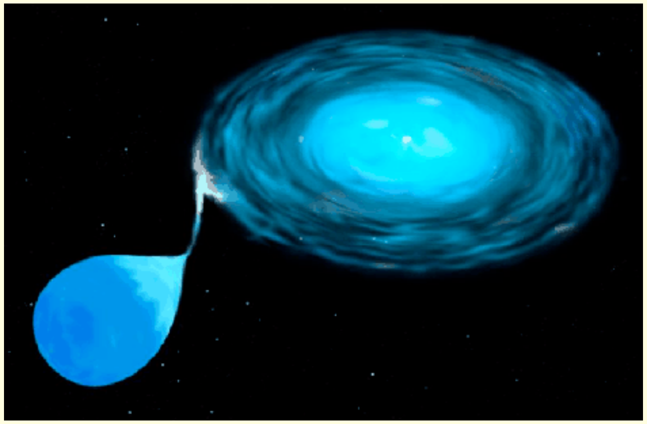
- No evidence for cycles.
- Strong argument based on 10^9 year replacement time of the interstellar medium.
- Elements of a galactic dynamo: *shearing*, *efficient diffusion into undermagnetized gas*, *assimilation of new field*, *generation of large scale field from small scale sources*.

Basic Questions about Galactic Dynamos

- How is a coherent field generated & maintained?
- What determines the overall fieldstrength & magnetic power spectrum?
- What are the consequences of nonstandard features such as cosmic rays & partial ionization?
- Is disk-halo interaction a vital part of the dynamo?
- What is the history of magnetic fields in galaxies?

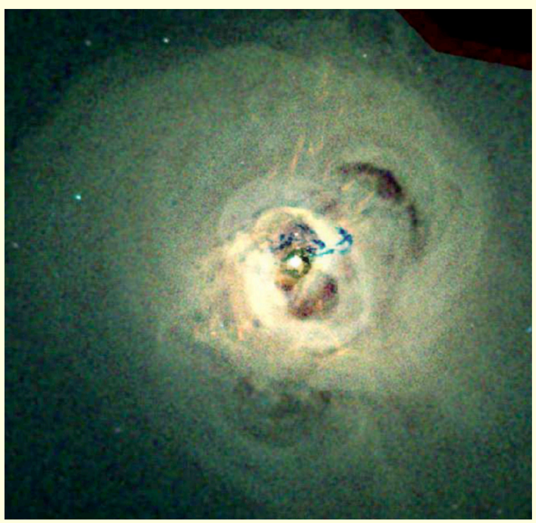
Accretion Disks





- Top: protoplanetary disk & jet. Bottom: artist's rendering of accretion disk formed by Roche lobe overflow onto a compact object. In many disks, accretion is thought to be mediated by magnetic turbulence. Does this turbulence generate a large scale field?

Galaxy Clusters



- Top: optical image of the Perseus galaxy cluster core. Bottom: x-ray image. Galaxy clusters are pervaded by hot, magnetized plasma. Can the magnetic field be explained by merging galactic fields?

A Wide Range of Plasma Conditions

- Collisional (stellar interiors) to collisionless (galaxy clusters, black hole accretion disks).
- Pm (ν/η) >> 1 (interstellar gas) to << 1 (stellar interiors).
- Rm (LV/η) >> 1 (interstellar gas) to << 1 (protostellar disks).
- M << 1 (stellar interiors) to >> 1 (interstellar gas).
- Skin depths & gyroradii generally microscopic.

Current Experiments

- Liquid metal (Cadarache, Los Alamos, Maryland, Wisconsin).
- Magnetically dominated RFP plasmas (Wisconsin, Padova).
- Plasma dynamo experiment at Wisconsin recently funded.

Goals of Dynamo Studies

- Predict or explain gross features of astrophysical dynamos: field strength, parity, & temporal behavior as they relate to the underlying system.
- Develop (or rule out the possibility of) a simple low order parameterized theory of astrophysical dynamos, useful to nonspecialists.

Opportunities for Observations

Solar & Stellar Magnetic Fields

Galactic & Intergalactic Magnetic Fields

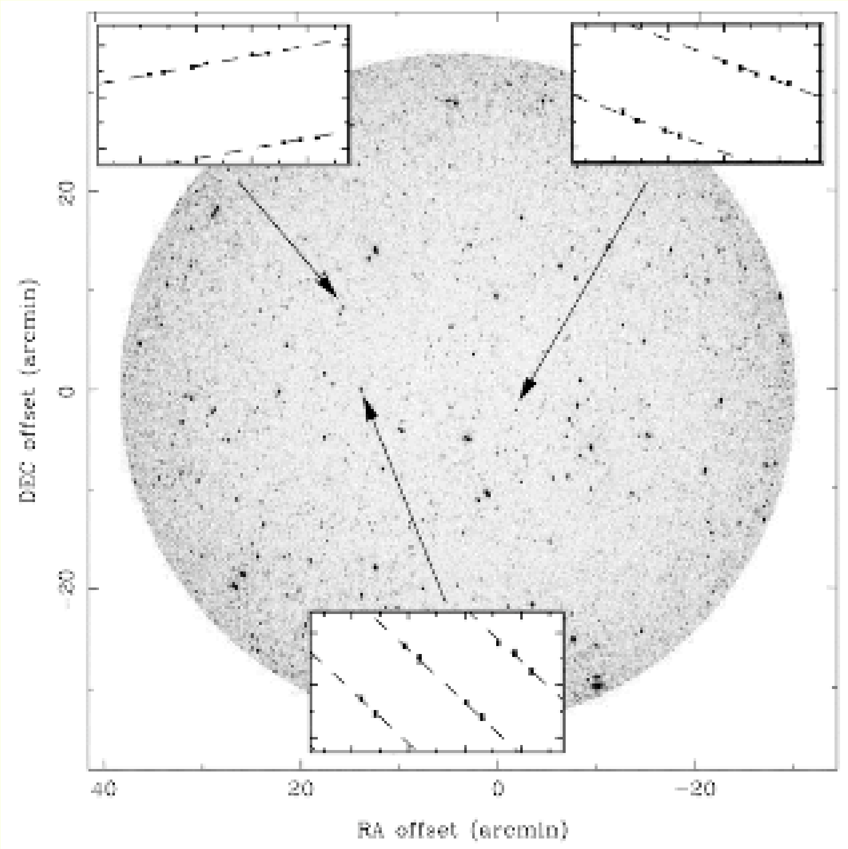
Methods of Detection

- Zeeman effect (longitudinal & transverse)
- Faraday rotation
- Synchrotron radiation
- Absorption & emission from magnetically aligned dust grains
- UV & x-ray emission known to be correlated with magnetic fields.

Some Solar/Stellar Opportunities

- Solar Dynamics Observatory (2010 launch), magnetograms at 1” resolution every 90 s.
- Advanced Technology Solar Telescope, magnetic & kinetic helicity fluxes at tiny scales.
- Statistics of stellar activity: Sloan Digital Sky Survey, Kepler.

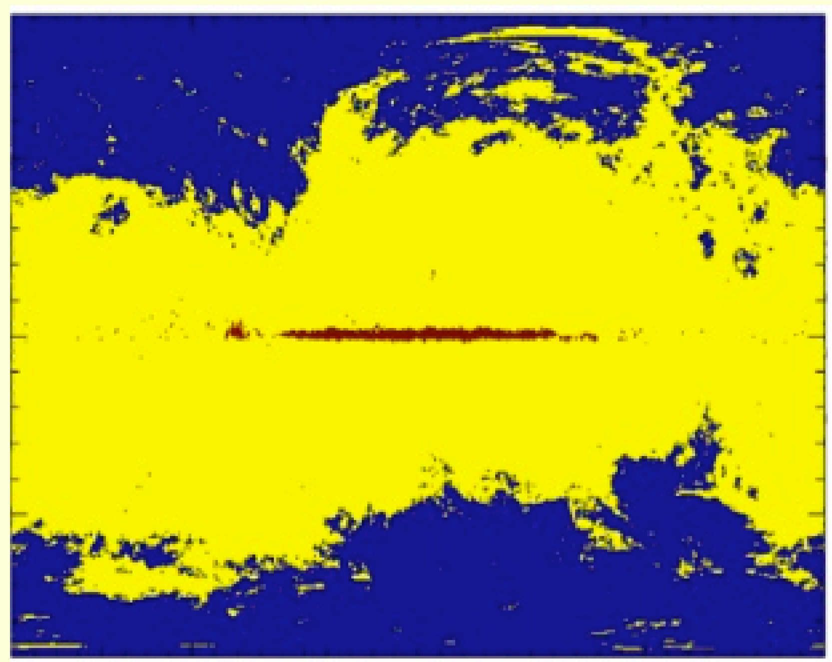
Some Galactic/Extragalactic Opportunities



- full-hemisphere survey with SKA will provide 10,000-fold increase in number of sources to probe Galactic Faraday rotation (simulated ~1 deg region shown)

Some Galactic/Extragalactic Opportunities (continued)

- NASA's planned CMBpol mission is aimed at inflation-era gravity waves, but will also deliver polarized dust emission
- Areas of sensitive dust polarimetry maps from Planck (red) and EPIC-IM CMBpol mission (yellow)

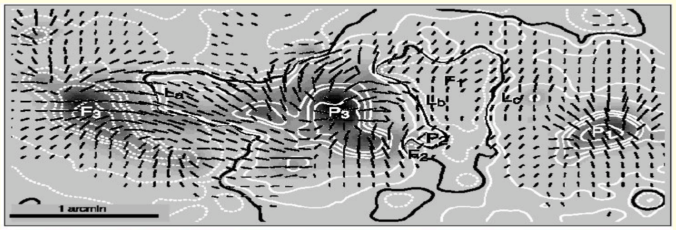


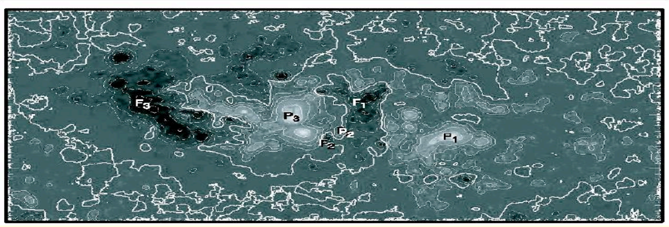
Links to Other Topics

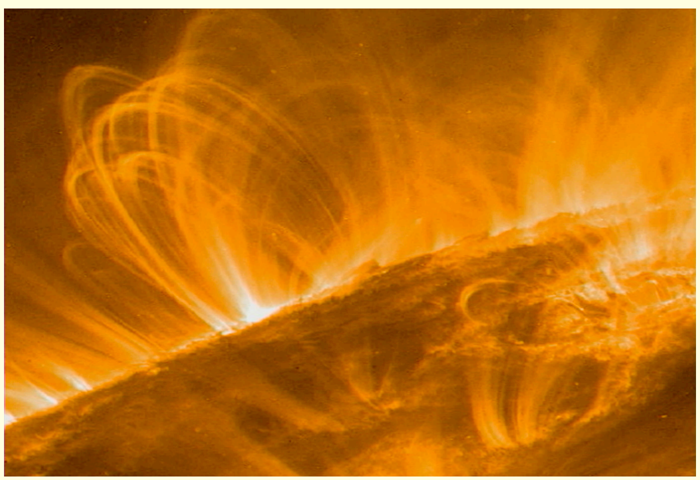
- Turbulence *(traditionally key, role disputed*)
- Reconnection *(no dynamo without topological change*)
- Momentum transport (*field reacts back on flow)*
- Large scale instabilities (*may play a role in generation of large scale field, relaxation, saturation)*

Extra Slides

Solar Active Regions

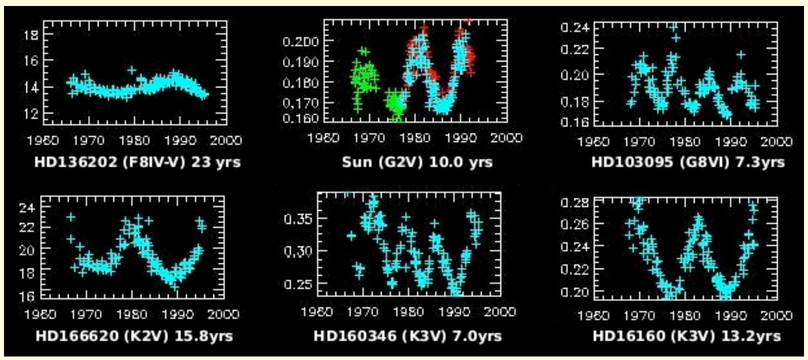


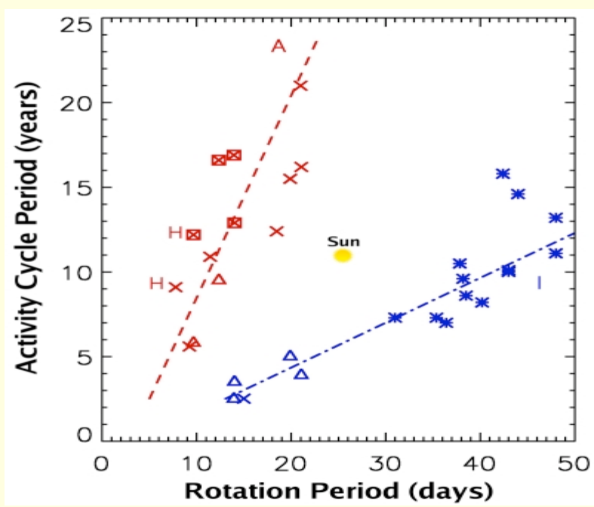




- Vector magnetogram (top) and EUV image (bottom) indicate multiplicity of scales and complex outer boundary condition of the solar magnetic field.

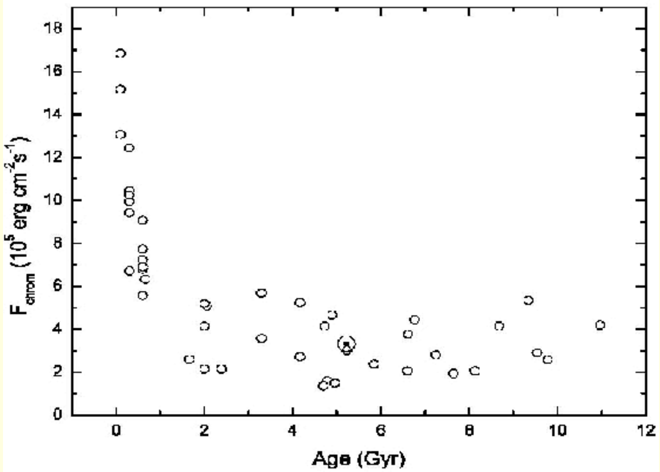
Stellar Cycles

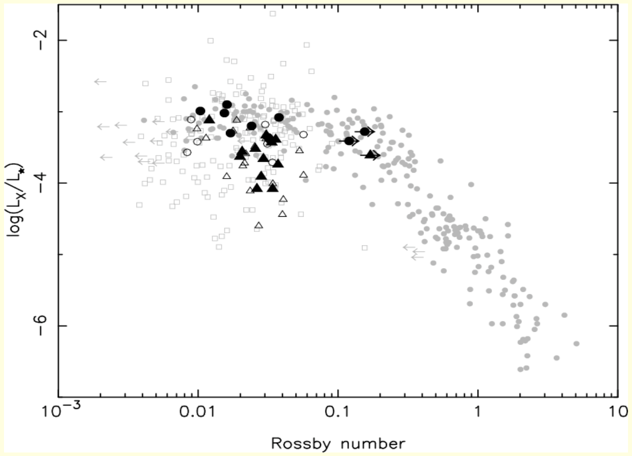




- Stars with envelope thermal convection, like the Sun, have activity cycles.
- Cycle period tends to increase with rotation period, and with age.

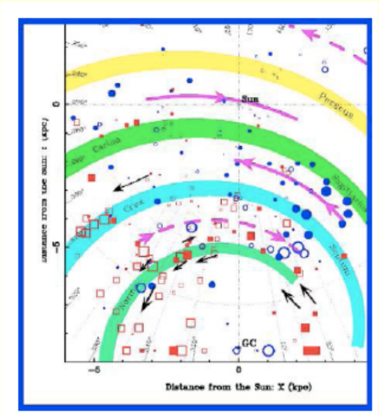
Trends in Stellar Magnetic Activity

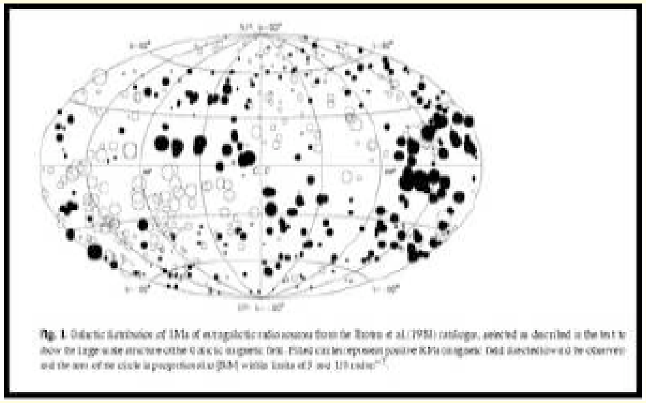




- Activity decreases with age.
- Activity decreases with Rossby number Ro (the ratio of flow time to convective turnover time).

Milky Way Magnetic Field

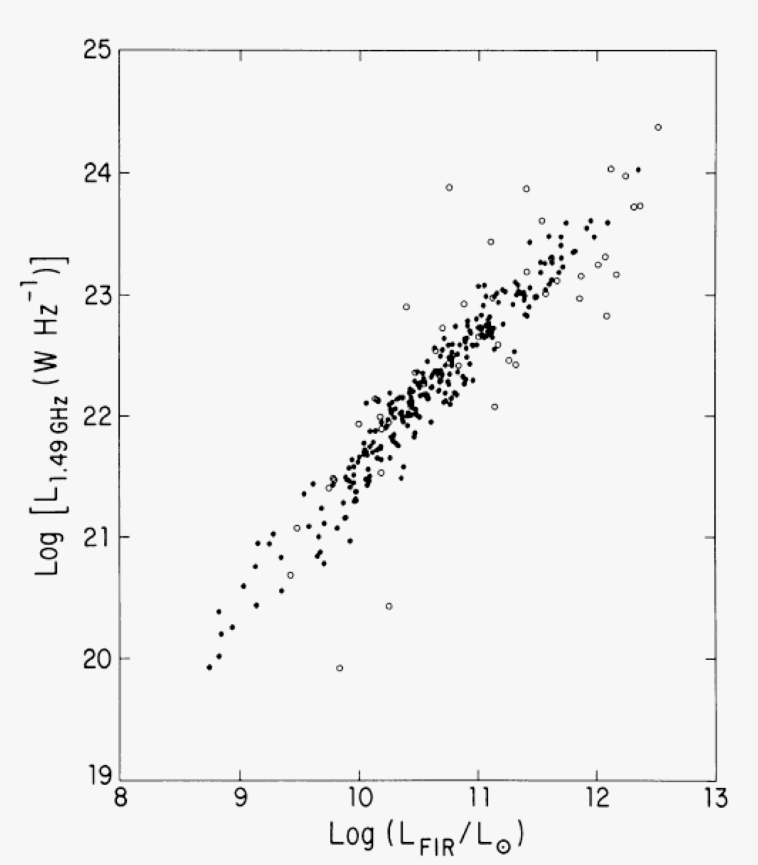




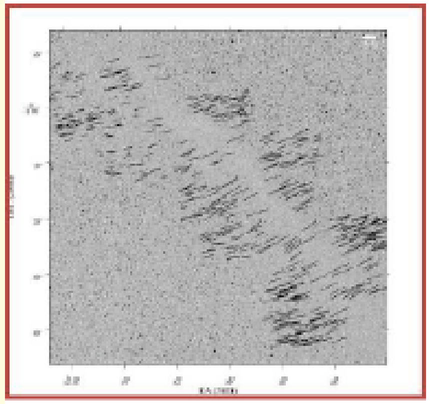
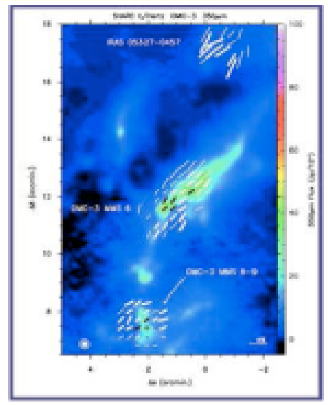
- Faraday rotation of pulsars & extragalactic sources reveals a uniformly directed field nearly aligned with galactic rotation as well as a random component 2-3 times larger.

Synchrotron - Star Formation Correlation

- There is a tight correlation between far infrared luminosity, a measure of the star formation rate, and synchrotron luminosity, a measure of the magnetic & cosmic ray energy densities.



Diagnostics From Aligned Dust Grains

- Left: Orientation of magnetic field outside a dense interstellar cloud. Right: Orientation of magnetic field in a star forming region revealed by far-IR emission.