Lecture #17 The Solar Dynamo and Connection to Solar Activity

I. Major Problems in Solar Physics

A. Questions

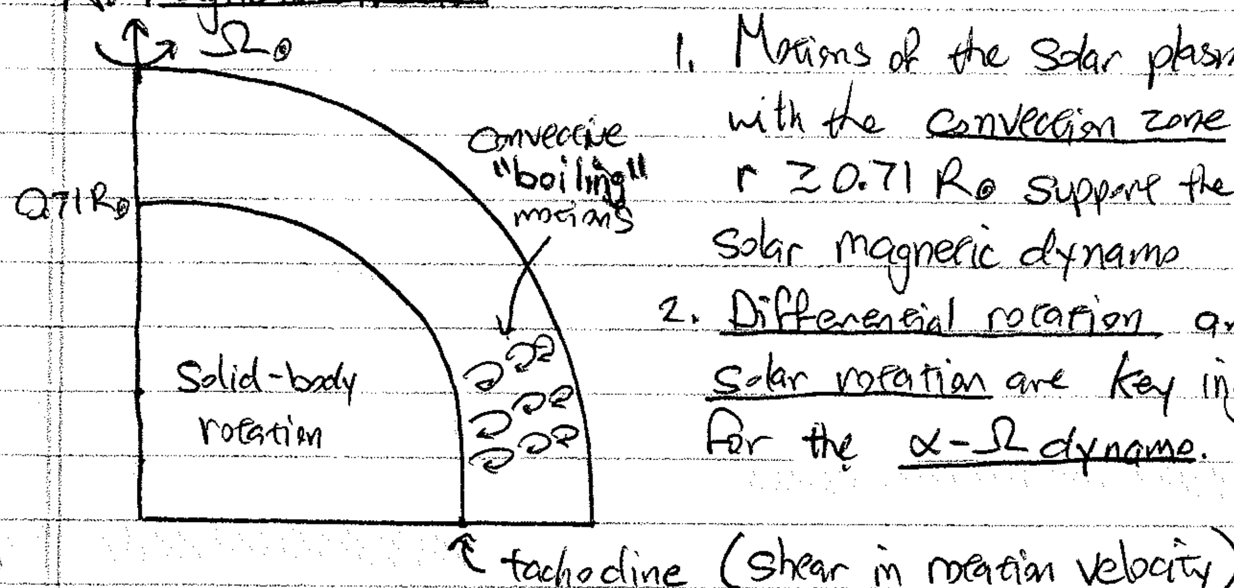
1. How is the large temperature gradient in the transition zone supported?

Related {
2. By what physical mechanisms is the solar corona heated to $\sim 10^6$ K?
3. How is the solar wind flow accelerated?
}

4. What physical processes govern the solar cycle and the solar dynamo?
5. What physical mechanism is responsible for the explosive energy release in solar flares and coronal mass ejections (CMEs)?
6. What mechanisms lead to the acceleration of energetic particles in solar events and CME-driven interplanetary shocks?

II. The Solar Dynamo

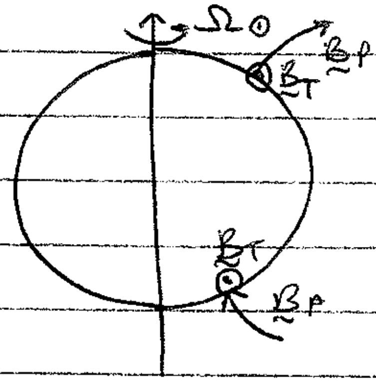
A. Magnetoconvection



1. Motions of the solar plasma with the convection zone at $r \gtrsim 0.71 R_\odot$ support the solar magnetic dynamo
2. Differential rotation and solar rotation are key ingredients for the $\alpha-\Omega$ dynamo.

II. A. (Continued)

3. Cylindrical coordinate system: (r, ϕ, z)



a. Poloidal Field: r & z components

b. Toroidal Field: $\hat{\phi}$ component (into page)

c. Rotation: $\Omega_\odot \hat{z}$

4. Magnetic Induction Equation: $\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B}) + \frac{\eta}{\mu_0} \nabla^2 \mathbf{B}$

- $\nabla \times (\mathbf{U} \times \mathbf{B})$: Flow $\mathbf{U}$ leads to generation of $\mathbf{B}$ to prevent decay.
- $\frac{\eta}{\mu_0} \nabla^2 \mathbf{B}$: resistive term leads to diffusion of magnetic field

a. Can one determine a simple flow of the plasma that indefinitely sustain magnetic field? → magnetic dynamo.

B. Cowling's Anti-Dynamo Theorem:
No axisymmetric ($\partial/\partial\phi = 0$) pattern of motion can indefinitely maintain either a poloidal or a toroidal magnetic field against Ohmic dissipation.
(for proof, see Shu 1992, Chap 26.)

1. Thus, flow pattern must be three-dimensional!
2. Although the details of the solar dynamo are not fully understood, it appears to involve: a) Turbulent Magnetoconvection
b) Rotating Frame of Reference
c) Differential Rotation

Lecture #17 (Continued)

II. (Continued)

C. Mean Field Dynamo Theory:

1. Turbulent magnetoconvection occurs in the convection zone, and we can attempt to model the evolution of the mean magnetic field due to the net effect of turbulent motions.
2. Separation of large (mean) and small (turbulent) scales:
   a. $\underset{\sim}{B} = \underset{\sim}{\bar{B}} + \underset{\sim}{b}$ b. $\underset{\sim}{U} = \underset{\sim}{\bar{U}} + \underset{\sim}{u}$
   c. $\langle \underset{\sim}{b} \rangle = 0$ d. $\langle \underset{\sim}{u} \rangle = 0$
   e. $\langle \rangle$ signifies an average over the small scales
3. a. $$\frac{\partial \bar{B}}{\partial t} = \nabla \times (\underset{\sim}{\bar{U}} \times \underset{\sim}{\bar{B}}) + \underbrace{\nabla \times \langle \underset{\sim}{u} \times \underset{\sim}{b} \rangle} + \frac{\eta}{\mu_0} \nabla^2 \underset{\sim}{\bar{B}}$$ ← Averaged induction equation.

   Nonlinear term that represent the net effect of turbulent $\underset{\sim}{u}$ & $\underset{\sim}{b}$ fluctuations

   b. (incompressible) $$\frac{\partial \underset{\sim}{\bar{B}}}{\partial t} + \underset{\sim}{\bar{U}} \cdot \nabla \underset{\sim}{\bar{B}} = -\underset{\sim}{\bar{B}} (\nabla \cdot \underset{\sim}{\bar{U}}) + (\underset{\sim}{\bar{B}} \cdot \nabla) \underset{\sim}{\bar{U}} + \nabla \times \langle \underset{\sim}{u} \times \underset{\sim}{b} \rangle + \frac{\eta}{\mu_0} \nabla^2 \underset{\sim}{\bar{B}}$$

   c. $$\frac{\partial \underset{\sim}{\bar{B}}}{\partial t} + \underbrace{(\underset{\sim}{\bar{U}} \cdot \nabla) \underset{\sim}{\bar{B}}}_{\text{advection of field by flow}} = \underbrace{(\underset{\sim}{\bar{B}} \cdot \nabla) \underset{\sim}{\bar{U}}}_{\text{stretching of field lines}} + \underbrace{\nabla \times \langle \underset{\sim}{u} \times \underset{\sim}{b} \rangle}_{\text{turbulent "}\alpha\text{ effect"}} + \underbrace{\frac{\eta}{\mu_0} \nabla^2 \underset{\sim}{\bar{B}}}_{\text{magnetic diffusion}}$$

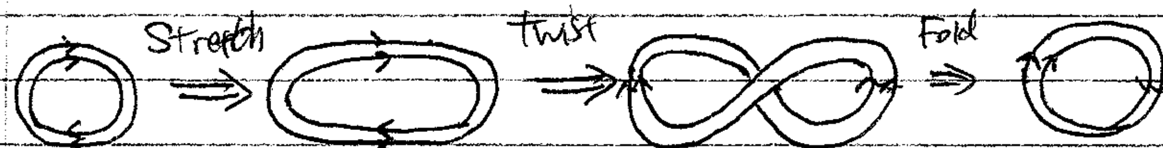
   Stretching of field lines + turbulent "α effect": Necessary components for the solar dynamo

Lecture #17 (Continued)

I. (Continued)

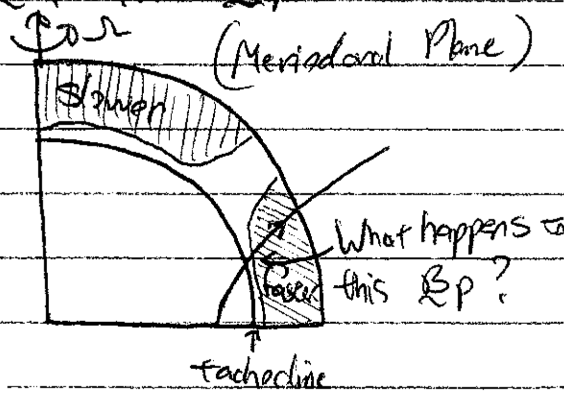
D. The Alpha-Omega ($\alpha-\Omega$) Dynamo

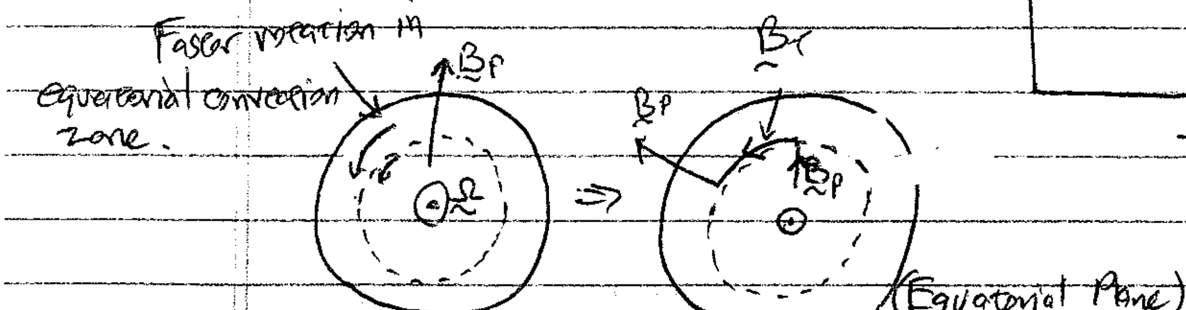
1. First, consider the general ingredients of dynamo action.
   a. Recall the stretch-twist-fold dynamo (Lect #5)



   b. This sequence of actions cannot be done in two dimensions alone (motions restricted to the plane of the page).
   c. The "twist" requires that field within the plane of the page be converted to field with a component out of the plane.

2. The Omega Effect:
   a. Ferraro, Cowling, & Walen recognized that differential rotation in the sun generates $\underset{\sim}{B}_T$ from $\underset{\sim}{B}_P$.
   b. Strong radial velocity shear at the tachocline stretches radial $\underset{\sim}{B}$ into toroidal direction.





   c. Stretching Term: $\frac{\partial \underset{\sim}{B}}{\partial t} = (\underset{\sim}{B} \cdot \nabla)\underset{\sim}{U}$

      1. Let $\underset{\sim}{\bar{B}}_P = \bar{B}_r \hat{\underset{\sim}{r}}$, $\underset{\sim}{\bar{U}} = \bar{U}_\phi(r)\hat{\underset{\sim}{\phi}}$ $\Rightarrow$ $\boxed{\frac{\partial \bar{B}_\phi}{\partial t} = \bar{B}_r \frac{\partial}{\partial r}\left[\bar{U}_\phi(r)\right]}$ Omega Effect
         $\underset{\sim}{\bar{B}}_T = \bar{B}_\phi \hat{\underset{\sim}{\phi}}$

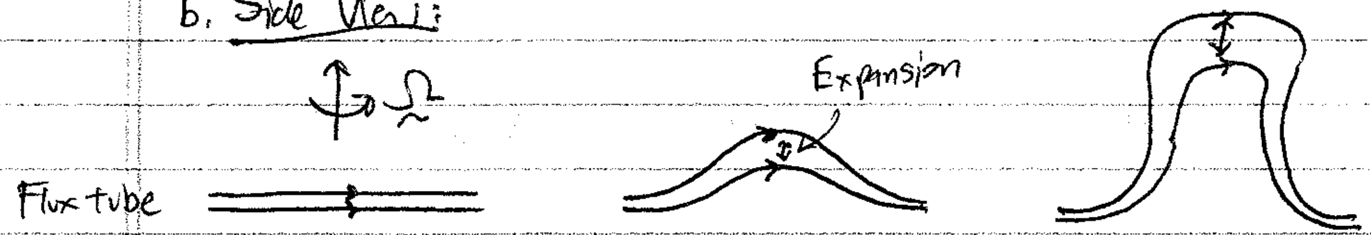
         Field line stretching by shear flow.

II. D. (Continued)

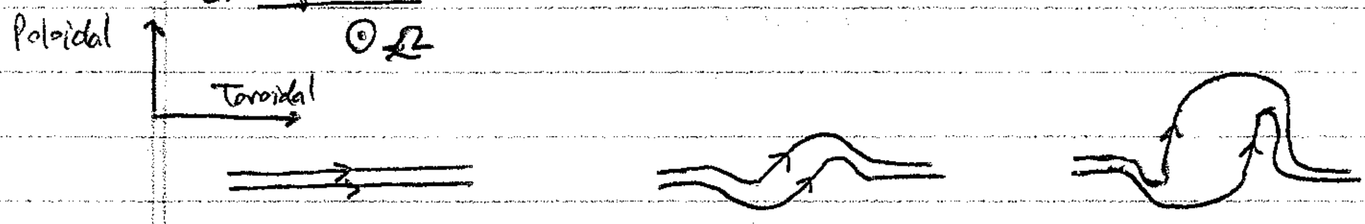
3. The Alpha Effect:

a. Parker recognized that, as blobs of plasma rise in the convection zone, they expand and twist due to the Coriolis force in the rotating frame of reference.
  $\Rightarrow$ This regenerates $\underset{\sim}{B}_P$ from $\underset{\sim}{B}_T$.

b. Side View:



c. Top View:



d. Quantitative Treatment: $\nabla \times \langle \underset{\sim}{u} \times \underset{\sim}{b} \rangle \approx \alpha \overline{\underset{\sim}{B}}$

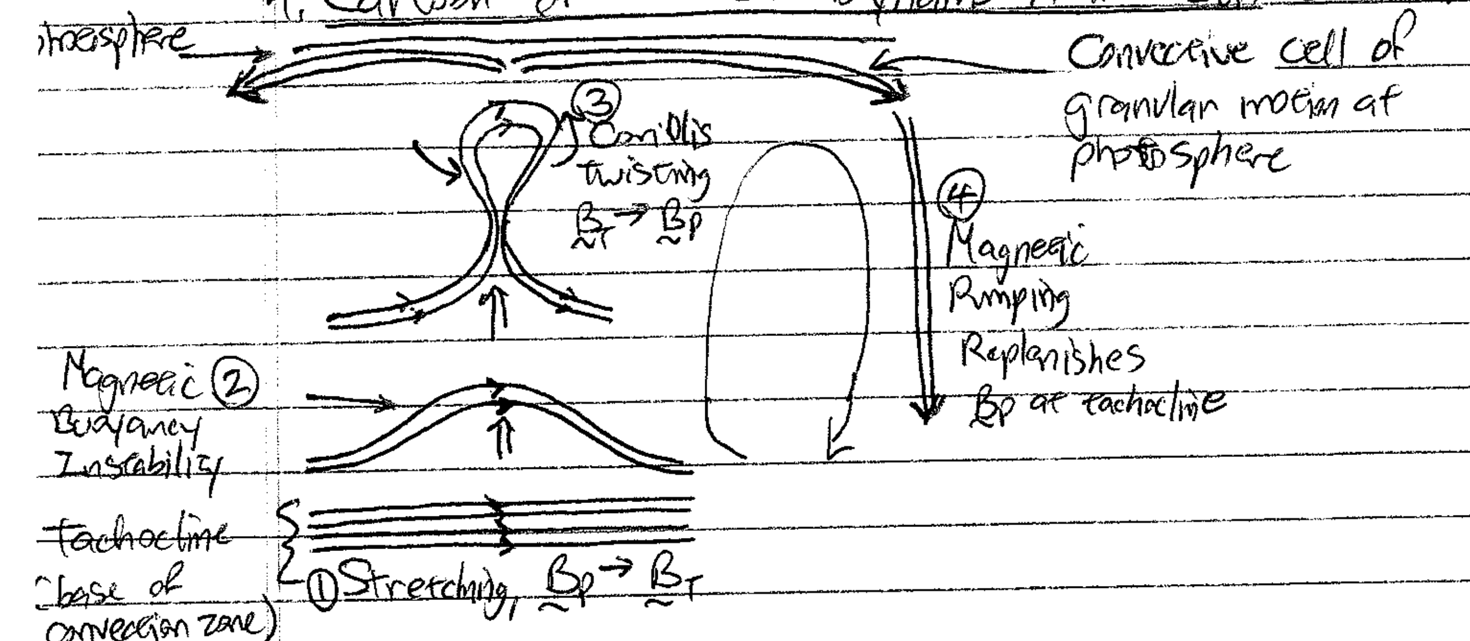
1. Thus, the alpha effect regenerates the field,

$$\frac{\partial \overline{\underset{\sim}{B}}}{\partial t} \approx \alpha \overline{\underset{\sim}{B}}$$

Lecture #17 (Continued)

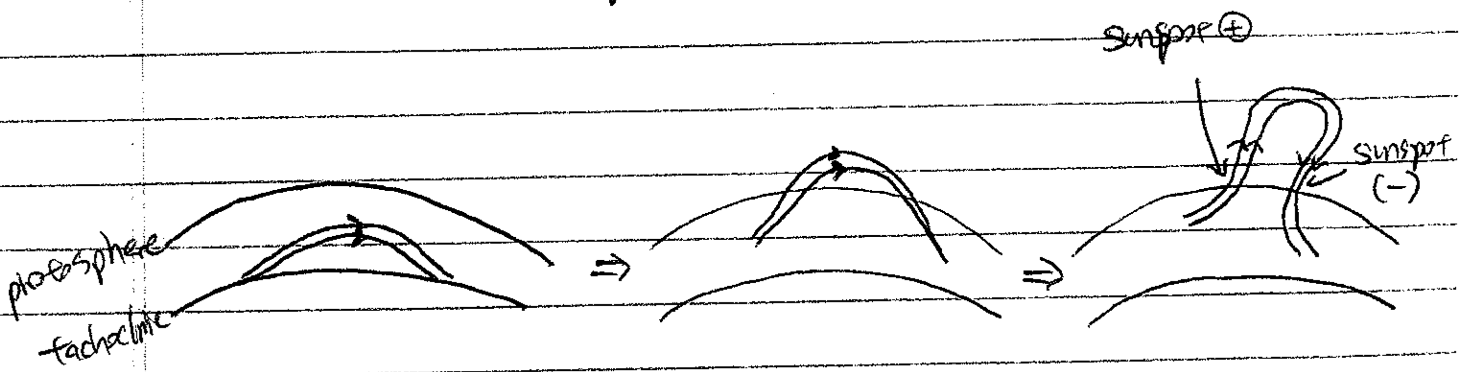
II. D. (Continued)

4. Cartoon of α-Ω Dynamo in the Sun (Parker)



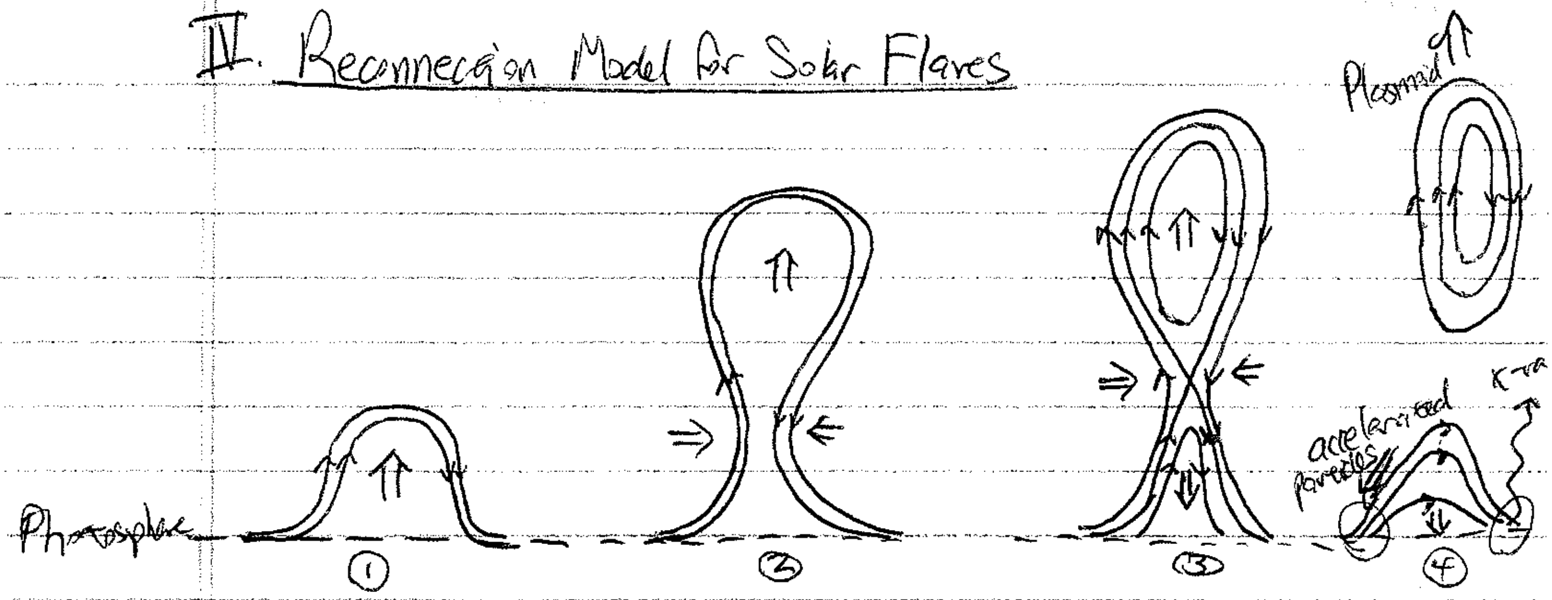
III. Connection Between Solar Activity and Solar Dynamo

A. Rise of Unstable Magnetic Flux Tubes:



1. Stretching of magnetic field at base of convection zone (in the tachocline) causes flux tube to become unstable to Parker (Magnetic Buoyancy) instability.
2. Very strong magnetic flux tubes can penetrate photosphere
3. Ultimately, flux tube penetration appears as a pair of sunspots perhaps driving vigorous solar activity (flares, prominences, CMEs).
4. Powerful mechanism for transport of magnetic energy.

IV. Reconnection Model for Solar Flares



① Unstable magnetic flux tube rises rapidly in solar atmosphere

② As flux tube continues to rise, it stretches out, and to maintain incompressibility, upgoing and downgoing field lines move together (like dripping water from a faucet)

③ Magnetic reconnection takes place, disconnecting outward moving plasmoid from field lines that return to the solar surface. A significant amount of energy is stored in the highly stretched magnetic field lines.

④ As reconnected field lines are pulled back toward the solar surface by magnetic tension, it accelerates the plasma on the field lines. Energetic particles can stream along the field line down to more dense, partially ionized chromosphere where they lead to significant bremsstrahlung X-ray emission ⇒ Flare.

1. Note the similar magnetic configuration in ③ to the Near-earth neutral line model of magnetic substorms in the geotail.