FROM THE SUN TO THE EARTH: MUCH MORE THAN LIGHT AND HEAT

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SEEMS THE SAME EVERY DAY
• What makes the Sun such a dynamic and fascinating object is largely its magnetic field.

• Magnetic energy is stored mainly in the magnetic field’s shape.

• Magnetic variability is the main driver behind space weather and space climate.

• Space weather is driven mainly by sudden reconfigurations of the magnetic field.

• Space climate is driven by the solar cycle and long-term changes in the solar cycle.
400 YEARS OF SOLAR PHYSICS IN 4 MINUTES
The Sun and its magnetic field (interactive visualization):

http://solardynamo.org/visualizations/AIA_HMI/index.html
Sunspots are the visible signature of regions with very strong magnetic field (Hale 1908)
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Fields generally appear at the surface in the form of bipolar structures called active regions
Sunspots are the visible signature of regions with very strong magnetic field (Hale 1908)
Hot plasma that expands in all directions from the solar corona.
The solar wind expands radially away from the rotating Sun forming a spiral.
It interacts with the planetary magnetospheres and atmospheres
Active regions are a critical manifestation of the solar cycle.

Movie by David Hathaway
The large-scale solar magnetic field is like a scuba diver...
... in murky water, so all you see is her bubbles ...
... you can learn much about the diver by studying her bubbles ...
Migration is beautifully captured by the butterfly diagram
Where does the magnetic field get its energy?

The sun's atmosphere is a superhot plasma governed by magneto hydrodynamic forces...

Ah, yes, of course.

Whenever I hear the word "magneto hydrodynamic" my brain just replaces it with "magic."
The HD equations

Mass Continuity

Conservation of Momentum
  \( F = ma \)

Conservation of Energy

Equation of State
The MHD equations

Mass Continuity

Conservation of Momentum
\( F = ma \)

Conservation of Energy

Equation of State

Magnetic Induction (E&M)
The MHD equations

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + \rho g_x
\]

\[
\rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) + \rho g_y
\]

\[
\rho \left( \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) + \rho g_z
\]

\[
r : \quad \rho \left( \frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} + \frac{u_\phi}{r} \frac{\partial u_r}{\partial \phi} + u_z \frac{\partial u_r}{\partial z} - \frac{u_\phi^2}{r} \right) = -\frac{\partial p}{\partial r} + \mu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{\partial u_r}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 u_r}{\partial \phi^2} + \frac{\partial^2 u_r}{\partial z^2} - \frac{u_r}{r^2} - \frac{2}{r^2} \frac{\partial u_\phi}{\partial \phi} \right] + \rho g_r
\]

\[
\phi : \quad \rho \left( \frac{\partial u_\phi}{\partial t} + u_r \frac{\partial u_\phi}{\partial r} + \frac{u_\phi}{r} \frac{\partial u_\phi}{\partial \phi} + u_z \frac{\partial u_\phi}{\partial z} + \frac{u_r u_\phi}{r} \right) = -\frac{\partial p}{\partial \phi} + \mu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{\partial u_\phi}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 u_\phi}{\partial \phi^2} + \frac{\partial^2 u_\phi}{\partial z^2} + \frac{2}{r^2} \frac{\partial u_r}{\partial \phi} - \frac{u_\phi}{r^2} \right] + \rho g_\phi
\]

\[
z : \quad \rho \left( \frac{\partial u_z}{\partial t} + u_r \frac{\partial u_z}{\partial r} + \frac{u_\phi}{r} \frac{\partial u_z}{\partial \phi} + u_z \frac{\partial u_z}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{\partial u_z}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 u_z}{\partial \phi^2} + \frac{\partial^2 u_z}{\partial z^2} \right] + \rho g_z.
\]

\[
\rho \left( \frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} + u_z \frac{\partial u_r}{\partial z} \right) = -\frac{\partial p}{\partial r} + \mu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{\partial u_r}{\partial r} \right) + \frac{\partial^2 u_r}{\partial z^2} - \frac{u_r}{r^2} \right] + \rho g_r \quad \frac{1}{r} \frac{\partial}{\partial r} (ru_r) + \frac{\partial u_z}{\partial z} = 0.
\]

\[
\rho \left( \frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} + \frac{u_\phi}{r} \frac{\partial u_r}{\partial \phi} + \frac{u_\theta}{r} \frac{\partial u_r}{\partial \theta} - \frac{u_\phi^2}{r} + \frac{u_\theta^2}{r} \right) = -\frac{\partial p}{\partial r} + \rho g_r + \mu \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial u_r}{\partial r} \right) \right.
\]

\[
\mu \left[ \frac{1}{r^2} \frac{\partial}{\partial \phi} \left( r^2 \frac{\partial u_\phi}{\partial \phi} \right) \right. + \frac{1}{r^2} \frac{\partial^2 u_\phi}{\partial \phi^2} + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left( \sin(\theta) \frac{\partial u_\phi}{\partial \theta} \right) - 2 \frac{u_r + \frac{\partial u_\phi}{\partial \phi} + u_\theta \cot(\theta)}{r^2} = \frac{u_\phi}{r^2} \frac{\partial^2 u_\phi}{\partial \phi^2} - \frac{u_\phi}{r^2} \frac{\partial^2 u_\phi}{\partial \phi^2}
\]

\[
\mu \left[ \frac{1}{r^2} \frac{\partial}{\partial \phi} \left( r^2 \frac{\partial u_\phi}{\partial \phi} \right) \right. + \frac{1}{r^2} \frac{\partial^2 u_\phi}{\partial \phi^2} + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left( \sin(\theta) \frac{\partial u_\phi}{\partial \theta} \right) + \frac{2 \sin(\theta) \frac{\partial u_r}{\partial \phi} + 2 \cos(\theta) \frac{\partial u_\phi}{\partial \phi} - u_\phi}{r^2} \frac{\partial u_\phi}{\partial \phi}
\]

\[
\rho \left( \frac{\partial u_\theta}{\partial t} + u_r \frac{\partial u_\theta}{\partial r} + \frac{u_\phi}{r} \frac{\partial u_\theta}{\partial \phi} + \frac{u_\theta}{r} \frac{\partial u_\theta}{\partial \theta} + \frac{u_r u_\theta - u_\phi^2 \cot(\theta)}{r} \right) = -\frac{\partial p}{r} \frac{\partial \theta} + \rho g_\theta +
\]
Basic steps for building up energy in MHD plasmas
STRETCH!
0→8

TWIST!
FOLD!
STRETCH!  TWIST!  FOLD!
What stretches, twists and folds the solar magnetic field?
In the Sun this process is performed by plasma motions.
THE LARGE SCALE SOLAR DYNAMO
Poloidal and Toroidal Fields

Poloidal
\[ r - \theta \]
Poloidal and Toroidal Fields

Poloidal $r - \theta$

Toroidal $\phi$
The cycle is a process that alternates between these fields:

Poloidal: \( r - \theta \)

Toroidal: \( \phi \)
Get ready for some more MHD action!
RECONNECT!

FOLD!
THE ORIGIN OF SPACE WEATHER:
RELEASE OF MAGNETIC ENERGY
Where do you think these points connect to?
Where do you think these points connect to?
Where do you think these points connect to?
And after the flare?
And after the flare?
And after the flare?
And after the flare?
Violent release of energy due to changes in the connectivity of the magnetic field (reconnection).

Reconnecting electric fields accelerate the plasma to relativistic speeds.
Coronal Mass Ejections (CMEs)

• Violent release of energy due to topological instabilities.

• Magnetic pressure and tension act as drivers behind these events.
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EVERYTHING CHANGES WITH THE SOLAR CYCLE
The amount of flares

Aschwanden & Freeland 2012
The amount of CMEs
The solar corona
The solar wind

SWOOPS
Speed [km s\(^{-1}\)]

Solar Minimum  Solar Maximum
The solar corona

Miloslav Druckmüller
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