Why bother with stellar magnetic fields?

- Sun is evidently a (mildly) magnetic star, with (major) impacts on our technological society
- Stars are primary builders of magnetism, by dynamo action in their convection zones
- Stellar magnetic fields likely influence winds and mass loss during evolution (recycling)
- Thus end states of stars can hinge on how much mass is left (WD vs NS vs BH vs nothing)
- But studying dynamo processes is tough, since stellar convection is highly turbulent

Solar & Stellar Magnetism

- Discuss solar magnetism: its interior origins and photospheric properties. Consider magnetic activity on other stars. Focus on interplay between observations and modeling.
- Examine helioseismic measurements of solar interior and constraints on dynamo models.
- Evaluate 3-D MHD models of global-scale convection coupled to rotation, and building magnetic fields through dynamo action.
- Consider flux transport from the base of solar CZ into surface layers. Look at thin flux tube models and rising flux bundles.
- Study turbulent dynamo processes and spectro-polarimetric measurements of small-scale photospheric fields.
- Assess capabilities and limitations of current instrumentation and modeling efforts. Consider promise of ATST and terascale computing.

Course Resources and Structure

- Major review articles: Living Reviews in Solar Physics (on web) selected reviews
- Heliophysics summer school: three volumes: selected articles
- Lectures will be recorded for later review, powerpoint/keynote slides available as pdf’s
- Course primarily lectures and discussions, some problem sets and group projects

STARS come in very many sizes and colors

Evolution path and color/brightness depends on mass

Magnetism in STELLAR Birth and Life
Magnetism in STAR DEATH: white dwarfs; supernovae: neutron stars and black holes

Basic truths: gravity pull = pressure gradient push

1. SPHERICAL nature of gravity: ROUND star
2. High PRESSURE needed at CENTER, achieved with high TEMPERATURE
3. NUCLEAR BURNING maintains hot center: reactions HIGH powers of TEMPERATURE
4. LUMINOSITY very sensitive to MASS

What is role of rotation or magnetism in stars?
- Either rotation or magnetism can break radial (1-D) symmetry of star assumed in stellar structure and evolution.
- Rapid rotation can flatten, even leading to disk, with new preferred direction (rotation axis).
- Rotation can yield Coriolis forces, as one goes into rotating (non-inertial) coordinate system.
- Magnetism can provide spatial linkages over broad range of scales, and introduce new time scales.
- Lorentz forces serve to couple flows and magnetism.

Brief stellar review: why OBAFGKM ?!
- Spectral (color) classification
  - O = bluest, hottest
  - G = yellow (Sun)
  - M = reddest, coolest
A bit of history: **Classifying Stars**

**World War I, Harvard College observatory**

Women were hired by Pickering as "calculators" to help with a new survey of the Milky Way.

Most had studied astronomy, but were not allowed to work as scientists.

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Devising the odd spectral (temperature) code

- **Original classification of spectra (1890)** was:
  - A = strongest hydrogen feature
  - B = less strong hydrogen
  - C, D, etc.

- Annie Jump Cannon realized that a different sequence made more sense (~1910)

→ **OBAFGKM!!**

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**Which absorption (dark) lines are strongest?**

![Image of spectral classification]

- **Spectral Classification: O B A F G K M**
  - **O** hottest stars: ionized helium only
  - **B** hot stars: A F helium, hydrogen
  - **A** cooler stars: G hydrogen, heavier atoms
  - **F** coolest stars: M molecules, (complex absorption bands)

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**Why stellar spectra are so different:**

**TEMPERATURE**

- Cecelia P-G showed that surface temperature is the big factor (not composition)
- She used newly-derived **SAHA EQUATION (1920)**, estimating how many electrons remain attached to atoms as temperature (avg KE of atoms in collisions) is changed (for the level of ionization)

Cecelia Payne-Gaposchkin (Harvard PhD thesis 1925)

→ **OBAFGKM → decreasing temperature**

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**SAHA predicts spectral line strengths with temperature**

![Image of SAHA diagram]
Further refinements:

DECIMAL SUBDIVISION

LUMINOSITY CLASSES

Sun is: G2 V

COLOR CLASS

Further refinements:

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Proton-Proton (P-P) Chain  
(From Hans Bethe 1937)

Sun burns 600 million tons of H every sec, making 596 million tons of He and 4 million tons goes into ENERGY*.

Nuclear vs chemical burning

- Nuclear p-p burning:
  1 kg of H becomes 0.993 kg He
- 7 grams releases: $6.3 \times 10^{14}$ joules
- Some energy released by chemically burning ~20,000 tons of coal!! (2 unit trains)
- Sun’s luminosity: (vs 40 W lightbulb)
  $L \approx 3.8 \times 10^{26}$ joules/sec (watts)

Three pathways for “p-p chain”

P-P Chain & C-N-O Cycle

Both fusion processes occur in parallel, but C-N-O makes far more energy at higher temperatures.
Stars hotter than F3, C-N-O wins

C-N-O Fusion Cycle

Can provide vast luminosity for massive stars on MS
C-N-O Cycle (another view)

But how long does a star live there?

MASS-LUMINOSITY RELATION

Simple (bold) play with numbers

How long can stars burn H in their cores?

More massive stars have (very) short lives!

Main Sequence: range of stellar properties

L range is biggest!

The main sequence: stars burning hydrogen in core

Range of properties

More massive stars have shorter lives!

$E_{bol} = 3.5 	imes 10^{38}$ ergs/yr

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**Differences between Sun and massive stars**

- **A-type star**
  - Mass: 2.0 M
  - Luminosity: 19 L
  - Core: Convective envelope, radiative core
  - CZ: Convective zone
  - RZ: Radiative zone

- **G-type star**
  - Mass: 1.0 M (Sun)
  - Luminosity: 1.5 M
  - Core: Radiative envelope, convective core
  - CZ: Convective zone
  - RZ: Radiative zone

**Star Clusters – two varieties**

- **Globular cluster**
  - Old, millions of stars
  - M80, HST

- **Open cluster**
  - Young, thousands of stars

**Globular clusters – much older, bigger**

- Generally much older -- up to 13 BILLION years
- Made up of millions of stars, very densely packed

**Open star cluster: Pleiades**

- “Open cluster” only about 100 MY old – involves several thousand stars
- Unlike Sun’s age of 4.6 BY
- Bright B-type stars, O stars now missing

**Clusters can test lifetimes on main sequence**

- Great advantages:
  - All stars at about the same distance
  - Apparent brightness tracks luminosity
- All formed at about the same time
- Range of different mass stars
- Stars “peel off” MS as core is exhausted → red giants
Life track in H-R diagram of solar-mass star.

Many meanders, but MS phase (longest, red giant phase(s)) shorter, finally white dwarf left to cool slowly.

1: Low-Mass Star on MS
H burning in core.

Longest phase: 10,000 MY = 10 BY if solar mass

2: Subgiant to Red Giant (first visit)
H burning in shell, makes much more energy.

Vast expansion, RG phase lasts ~ 500 MY

Huge convective envelope

3: Helium Flash

He core burning — removes electron degeneracy.

He core burning now with thermostat

"Horizontal branch star"
Helium flash $\rightarrow$ He fusion to C in core (horizontal branch)

4: Horizontal branch star

He core burning, H shell burning

Short phase, lasts ~50 MY

Triple-alpha fusion: 3 He $\rightarrow$ C

H-R diagram of globular cluster

MS $\rightarrow$ Red Giant I $\rightarrow$ Horiz Branch $\rightarrow$ Red Giant II (or Supergiant)

5. Red Supergiant

Double-shell burning of H and He

Phase could be very short if He burning is errors (unstable) -- then lasts only a few MY, and blows off outer shells

Review so far, and then ...
6. Planetary Nebula

Outer shells of red supergiant "puffed off"; Great pictures; "Naked" white dwarf emerges

Step 6: Planetary Nebula

Red supergiant ejects envelope in great of "Jupiter";

Ejected hot envelope; stars vary; lasts 0.1 My

Nebula shell

Hot central star illuminates nebula

Hot "Jupiter" dwarf left behind; slowly cools down; turns "white dwarf".