Guiding Questions

1. What are solar active regions? How do we know that sun spots are regions of strong magnetic field? How is magnetic field of the Sun measured?

2. What is the magnetic structure of a sun spot? Why are sunspots dark?

3. Can we observe magnetic field in the corona? How do we study coronal magnetic field?

4. What is a solar flare? What is the connection between solar flares and magnetic field? Where comes the energy of a solar flare?

5. What is our current understanding of the physical mechanism of solar flares? How can we be convinced that flares are driven by magnetic reconnection?

6. What is a CME? What is the connection between CMEs and the space weather? In what ways can we possibly predict the space weather?
Above the photosphere, the temperature increases with altitude!

Why are chromosphere and corona hotter? Temperature \((10^3 \text{ K})\)

Chromosphere and coronal heating has been an outstanding issue.

Standard quiet sun atmosphere model constructed from extensive spectroscopic observations by Vernazza, Avrett, & Loeser, 1981.
Looking through the Sun’s atmosphere

From the photosphere to the chromosphere and then the corona, the temperature rises from 5800 K (seen in visible light) to a few million K degree (seen in X-rays). The sun’s upper atmosphere is heated, and structured.
Opening questions:

1. Why are the chromosphere and corona hotter than the photosphere? What heats them?
2. Given the very high temperature of the corona, should hydrogen atoms escape from the corona so that the corona should be depleted?
3. How are the cool dark filaments supported? What pushes up the spicules? What powers flares, coronal mass ejections, and governs the space weather?
4. Does the Sun’s activity vary? What governs the change?
16.1 Magnetic Field and Force

Magnetic field may be viewed as being generated by electric currents. Like electric field, magnetic field applies a force on charged particles that are **moving** with a velocity perpendicular to the magnetic field.

A current applies a repulsive or attractive force on another current through the magnetic field, just like a mass applies a force to another mass through the gravitational field.

- Parallel currents attract
- Anti-parallel currents repel
Ex 1: magnetic field generated by electric currents.
(All figures from http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magcon.html#c1)

Magnetic field by a straight line current
Magnetic field by a loop current
Magnetic field by a bar magnet - where is the current?
Earth’s Magnetic field

The geographic North Pole is a magnetic south pole.

Spin axis

Magnetic field lines
Magnetic field traps charged particles by Lorentz force. Therefore, plasmas may move along magnetic field lines but not across.

Ex 2: examples of plasma – magnetic field interaction in the solar system (including the Sun).

- magnetospheres and aurorae on planets
- comet’s ion tail
- sun’s coronal loops and solar wind

On the other hand, plasmas can also push and pull magnetic field (?)
Active regions are where the atmosphere is most “active”, or hotter and more dynamic. These are regions of concentration of magnetic field. Sunspots are often found in active regions.

Active regions are bright at nearly all altitudes and wavelengths.

Active regions tend to reside in low-mid latitudes in both hemispheres.
Magnetic fields are observed/measured by **Zeeman effect**, or split and polarization of a magnetically sensitive spectral line.

Ex.3: Zeeman effect: the amount of line split is roughly proportional to the magnitude of magnetic field: $\Delta \lambda \sim B$

Magnetic field is a vector. All three components of magnetic field can be measured according to their polarization properties to produce a **vector magnetogram**.
Sun spots are cool regions of strong magnetic fields (a few hundred to a few thousand Gauss: 1 Gauss = 0.0001 Tesla) in the photosphere.

Intensity and longitudinal magnetic field maps observed by Michelson Doppler Imager. White/dark indicates field lines pointing outward/inward.
Q: why are sunspots dark?

The temperature of a sunspot is lower than the quiescent photosphere temperature.

\[ T_{\text{spot}} = 4000 \, K < 6000 \, K = T_{\text{pho}} \]

\[ F_{\text{spot}} / F_{\text{pho}} = (4000/6000)^4 = 0.2 \]

Redder and less bright!
Ex.4: around the sunspot, the force balance is maintained between gas pressure and **magnetic pressure**.

**Gas pressure**: \( P_g = nkT \)

- \( P_g \): gas pressure in N/m\(^2\)
- \( n \): particle number density in m\(^{-3}\)
- \( k \): Boltzmann constant = \( 1.38 \times 10^{-23} \) J/K
- \( T \): temperature in K degree

**Magnetic pressure**: \( P_m = \frac{B^2}{2\mu_0} \)

- \( P_m \): magnetic pressure in N/m\(^2\)
- \( B \): magnetic field in Tesla: 1 Tesla = \( 10^4 \) Gauss
- \( \mu_0 \): permeability of vacuum = \( 4\pi \times 10^{-7} \) N A\(^{-2}\)
The ratio of gas (plasma) pressure to magnetic pressure is defined as the plasma $\beta$.

$$\beta = \frac{P_g}{P_m} = \frac{nkT}{B^2 / 2\mu_0}$$

Ex 5: the magnetic field at Earth’s surface is about 0.5 Gauss (or $5 \times 10^{-5}$ Tesla). How does the magnetic pressure at Earth’s surface compare with the air pressure (eg. at the sea level)? What is the $\beta$ value?

The Sun’s photosphere is of high $\beta$, and the corona is of low $\beta$ (find this out in your homework). Therefore, in and below the photosphere, gas pushes magnetic field (e.g., dynamo); and in the corona, magnetic field pushes gas.
16.3 Magnetized atmosphere

Magnetic field rooted from below the photosphere expands upward and governs the upper atmosphere properties, such as coronal heating.

In solar corona, where the magnetic pressure dominates the gas pressure, magnetic fields are in control.
The sun’s atmosphere is highly structured and dynamic, and is filled with magnetized plasmas.

Examples:

- coronal loops: confinement and heating
- Filaments: magnetic support
- Spicules: dynamics
- flares and CMEs: energetics
- solar winds: geometry and particle acceleration
- sunspots
- solar cycle

"If the Sun did not have a magnetic field, it would be as uninteresting a star as most astronomers believe it to be." R. Leighton.
It is very difficult to directly observe and measure magnetic field in other than the photosphere, because the field becomes very weak upward, producing little Zeeman splitting.

The coronal magnetic field is reconstructed by extrapolation from photospheric magnetograms.

solarmuri.ssl.berkeley.edu
16.4 Solar flares and magnetic reconnection

The fire and the storm: explosive energy release from the Sun.

EUV image of the Sun’s corona by SDO.
A grand solar flare in progress
Most flares occur in **active regions** where magnetic fields concentrate and are complex.

They are located at where the polarity of magnetic fields reverses.
Flares are **magnetic reconnection** events.

**a.** Solar magnetic-field lines, anchored in the turbulent convective zone beneath the surface, become tangled and braided, building up magnetic stress and energy. (Tom Moore)

**b.** Reconnection between tangled field lines releases the stress and energy, forming “closed-field”, or flare loops. (Tom Moore)
magnetic reconnection is considered to release energy at observed rate.

- Magnetic field has a special property: it does not have a source or sink. Therefore, magnetic field lines cannot break.

- Anti-parallel magnetic field lines, when pushed close, exchange connectivities. This is magnetic reconnection.

- Magnetic reconnection so occurs that the magnetic configuration after reconnection has less energy than before reconnection.
As taller flare loops form in the corona, their feet (flare ribbons) expand on the surface.

(Forbes)
Reconnection may also produce the upper bundle of twisted fields, called “flux ropes”, and release them to interplanetary space.
16.5 Coronal Mass Ejections and Space Weather

CMEs often go with flares and erupting filaments. They are all driven magnetically.

The most violent solar activity is reflected in events called Coronal Mass Ejections, or CMEs.
Coronal mass ejections may carry magnetized plasmas to the Earth and be measured as a complicated magnetic structure, a “magnetic cloud”, by satellites crossing the cloud.

A complicated magnetic structure forms on the Sun and is ejected out of the Sun.

The most energetic flares are often associated with coronal mass ejections,
Q: what drive Coronal Mass Ejections? What are in a Coronal Mass Ejection?

CMEs are driven magnetically, turning magnetic energy into other forms of energies.

Magnetic field into interplanetary space:
~1 - 100 nT (1 T = 10^4 G)

Mass: 1-10 billion tons of plasmas at the speed of a few thousand km/s, or a few million mph.

Charged particles accelerated on the Sun as well as in interplanetary space.
Why study the Sun?
Streams of charged particles from the Sun lead to adverse space weather and pose threat to our ambition to explore the outer space and solar system.

We may predict space weather by a good understanding of the Sun’s magnetic field and its evolution.
16.7 Solar activity cycle
Sunspots are produced by a 22-year cycle in the Sun’s magnetic field.

The number of sunspots is largest at the solar maximum, and the smallest at the solar minimum, so vary the solar activities.
The Sun’s surface features vary in an 11-year cycle. This is related to a 22-year cycle in which the surface magnetic field increases, decreases, and then increases again with the opposite polarity. The average number of sunspots increases and decreases in a regular cycle of approximately 11 years, with reversed magnetic polarities from one 11-year cycle to the next. Two such cycles make up the 22-year solar cycle.

**Butterfly diagram**: variation in the average latitude of sunspots.
Ex.6: when the sun spot cycle reaches the maximum, what do you think is the phase of the radiation cycle? Maximum? Minimum? Or else?
The solar magnetism and its activity are generated by differential rotation (Ω effect) and convection (α effect) - solar dynamo.

As the result, the initial polar fields are turned into magnetic “kinks” in the rising cycle.

The Ω effect converts poloidal field to toroidal field by differential rotation. The α effect refers to twisting of the toroidal field by Coriolis as it rises with convection cells.
After the solar maximum, flux transfer by meridional flow and flux cancellation eventually change the toroidal field back to poloidal field with reversed polarity.
Magnetism critically depends on interior flow.

rotation of electrically conductive fluid $\rightarrow$ poloidal global field

differential rotation $\rightarrow$ toroidal field

convection + rotation $\rightarrow$ merging kinked field close to equator

meridional convection flow $\rightarrow$ polar field

flux cancellation $\rightarrow$ polarity reversal

Helioseismology determines the flow patterns beneath the surface. Helioseismology studies sound waves generated by the convective turbulence, reflected at the surface, and refracted inside the Sun, to find the temperature and density structure of the interior. It also reveals the motion patterns inside.
predicted solar cycle 24 in 2006, as comparable to cycle 23.

observed solar cycle 24 in 2014, with a totally unexpected deep minimum at the end of cycle 23, and a very weak cycle 24 – more to learn!
Key Words

- active regions
- coronal heating
- coronal mass ejection
- filament eruption
- flares
- free magnetic energy
- gas pressure
- magnetic field
- magnetic pressure
- magnetic potential field
- magnetic reconnection
- magnetogram
- non-thermal radiation
- particle acceleration
- plasma
- sunspot umbra
- sunspot penumbra
- space weather
- Zeeman effect
• 22-year solar cycle
• butterfly diagram
• convection
• differential rotation
• flux transport model
• magnetic dynamo model
• meridional flow
• solar maximum
• solar minimum
summary

- Solar **active regions** have strong **magnetic fields**, which produce enhanced heating and dynamics in the atmosphere. The solar atmosphere is magnetized.
- Magnetic field in the photosphere is studied by measuring the split and polarization of magnetically sensitive spectral lines, or the **Zeeman effect**.
- Magnetic field governs activities on the Sun. Violent energy release events like flares and CMEs are fueled by **free magnetic energy**.
- **Magnetic reconnection** is thought to be the driver of solar flares. Free magnetic energy is release by reconnection to heat plasmas and accelerate charged particles, which lead to impulsively enhanced radiation at nearly all altitudes and wavelengths.
- Streams of charged particles from the Sun lead to adverse **space weather**. Understanding the Sun’s magnetic field is critical to space weather forecast.
Solar activities, such as sunspot number, area, and distribution, and solar radiation in various wavelength, exhibit a 22-year cycle, which reflects the magnetic cycle.

The solar magnetism and its cycle are generated by magnetic dynamo through differential rotation, convection, and meridional flows.

Latest progress in numerical simulations using flux transport models and observed flow patterns inside the Sun may improve our understanding and prediction of solar cycle.