2022 12 19-II Stars

2022년 12월 18일 일요일 오후 10:22

Sun

Luminosity

$L_\odot$ = 3.828 × 10^{26} W = 3.828 × 10^{33} erg/sec

= 10^{12} g/sec burning

Radius

$R_\odot$ = 6.957 × 10^8 m = 0.6957 × 10^6 km

Mass

$M_\odot$ = 1.9885×10^{30} kg = 1.99×10^{33}g

= 0.333x10^6 $M_\oplus$

Mass parameter

$GM_\odot$ = 1.3271244 × 10^{20} m^3 s^{-2}

Temperature

$T_\odot$ = 1.57×10^7 K (Center)=1.35keV/k_B,

= 5772 K (Photosphere),

≈ 5×10^6 K (Corona)

Age

≈4.6 Billion years

출처: <https://en.wikipedia.org/wiki/Star#Temperature>

	Observation data
Mean distance from Earth	1 AU ≈ 1.496×10^8 km 8 min 19 s at light speed
Visual brightness (*V*)	−26.74[5]
Absolute magnitude	4.83[5]
Spectral classification	G2V[6]
Metallicity	*Z* = 0.0122[7]
Angular size	31.6–32.7 minutes of arc ≈0.5°
Orbital characteristics	
Mean distance from Milky Way core	≈2.7×10^{17} km ≈ 29,000 light-years
Galactic period	(2.25–2.50)×10^8 yr
Velocity	≈220 km/s (orbit around the center of the Milky Way) ≈20 km/s (relative to average velocity of other stars in stellar neighborhood) ≈370 km/s (relative to the CMB)
Physical characteristics	
Equatorial radius	695,700 km 696,342 km 109 × Earth radii
Equatorial circumference	4.379×10^6 km 109 × Earth
Flattening	9×10^{-6}
Surface area	6.09×10^{12} km^2 12,000 × Earth
Volume	1.41×10^{18} km^3 1,300,000 × Earth
Mass	1.9885×10^{30} kg[5] 333,000 Earths[5]
Average density	1.408 g/cm^3 0.255 × Earth[5][12]
Center density (modeled)	162.2 g/cm^3[5] 12.4 × Earth
Equatorial surface gravity	274 m/s^2[5] 28 × Earth[12]
Moment of inertia factor	0.070[5] (estimate)
Escape velocity (from the surface)	617.7 km/s[12] 55 × Earth[12]
Temperature	Center (modeled): 1.57×10^7 K Photosphere (effective): 5,772 K Corona: ≈5×10^6 K
Luminosity (L_{sol})	3.828×10^{26} W≈3.75×10^{28} lm ≈98 lm/W efficacy
Color (B-V)	0.63
Mean radiance (I_{sol})	2.009×10^7 W·m $^{-2}$·sr $^{-1}$
Age	≈ 4.6 billion years (4.6×10^9 years)
Rotation characteristics	
Obliquity	7.25° (to the ecliptic) 67.23° (to the galactic plane)

- Energy production

Proton mass

$m_p = 1.67 \times 10^{-24} g$= 938 MeV/$c^2$

Particle # in 1 mole $N_A = 6.023 \times 10^{23}$ /mol

Energy conversion : 1eV =1.602x10^{-19} J

1eV energy release for 1 mole ($N_A = 6.023 \times 10^{23}$)

1eV x N_A =1.6x10^{-19}J $\times$ 6.023 $\times \frac{10^{23}}{\text{mol}} = \frac{9.649\times10^4 \text{J}}{\text{mol}}$

=96.49 kJ/mol=0.9649x10^5J/mol ≈ 10^5J/mol

Energy = (mass)xc^2

Ex) energy of 1g (=Mass of the Proton 1 mole)=1gxc^2

=0.9x10^{21}erg

=Energy of m=1g proton=mc^2= = 938MeVxN_A

=0.938x10^9 eV x N_A

=0.938x0.9649x10^{14}J=0.905x10^{14}J

=0.905x10^{21}erg≡ L_H t (let's take t=1 sec)

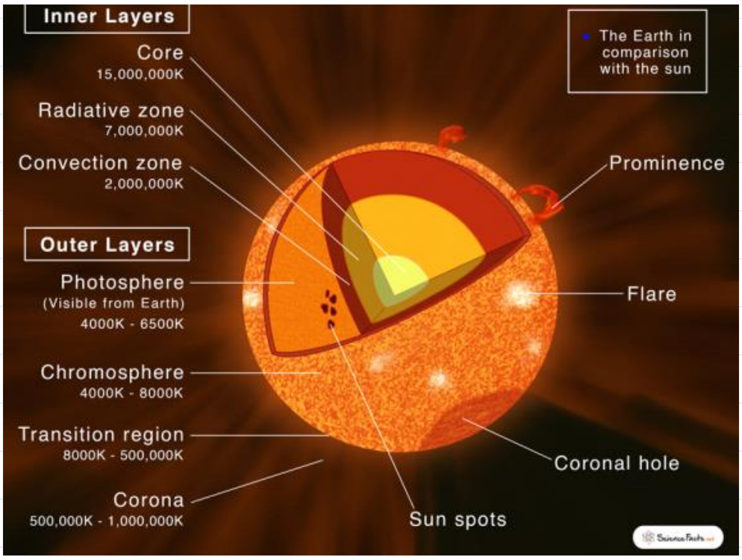
Cf) energy release per nuclear reaction

~MeV~$10^{-3} m_p c^2$~0.1% of the mass energy

Chemical reaction per atom or molecule

~ eV~10^{-6} of nuclear reaction

Mass loss/time = $\frac{L_\odot}{L_H} = \frac{3.828\times10^{33}}{0.9\times10^{21}}$=4.25x$10^{12}$ g/s



Rotation characteristics	
Obliquity	7.25° (to the ecliptic) 67.23° (to the galactic plane)
RA of North pole	286.13° 19 h 4 min 30 s
Dec of North pole	+63.87° 63° 52' North
Sidereal rot p(at equator)	25.05 d
(at 16° latitude)	25.38 d 25 d 9 h 7 min 12 s
(at poles)	34.4 d[5]
Rot vel (at equator)	7.189×10^3 km/h
Photospheric	**composition (by mass)**
Hydrogen	73.46%[17]
Helium	24.85%
Oxygen	0.77%
Carbon	0.29%
Iron	0.16%
Neon	0.12%
Nitrogen	0.09%
Silicon	0.07%
Magnesium	0.05%
Sulphur	0.04%

출처: <https://en.wikipedia.org/wiki/Sun>

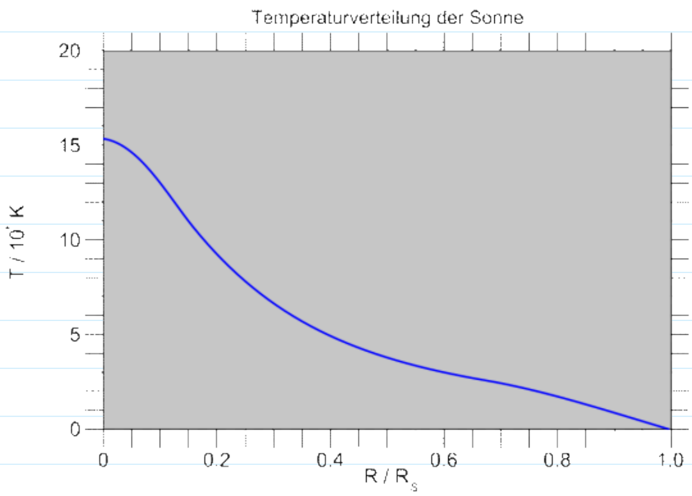
Structure :

- The **interior**

a sphere with radius R = 7×10^8m

- **Core** $0 \lesssim R \lesssim (0.20\sim0.25)\, R_\odot$
  - T & p are sufficient for H fuses into He.
- **Radiative zone** $0.20–0.25\, R_\odot \lesssim R \lesssim 0.7 R_\odot$
  - ρ drops from 20 g/cm^3 to 0.2 g/cm^3
  - T drops from approximately 7MK to 2MK
    This temp gradient is less than the adiabatic lapse rate and hence no convection.
  - energy transfer by means of thermal radiation & thermal conduction
  - Ions of H and He emit photons, whose mean free path is short.
    gradually shifting to longer wavelength
  - it takes an average of 171,000 years for gamma rays from the core of the Sun to leave the radiation zone. T of the plasma drops from 15 MK near the core down to 1.5 MK at the base of the convection zone.

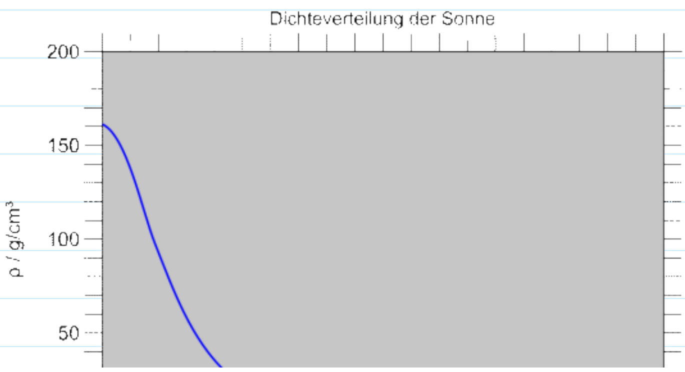
출처: <https://en.wikipedia.org/wiki/Radiation_zone>



Temperature profile in the Sun

출처: <https://en.wikipedia.org/wiki/Sun>

- **Tachocline**
  - the boundary region btw the radiative & convective zones.
- **Convective zone** $0.7 R_\odot \lesssim R \lesssim 1 R_\odot$
  - cool & diffuse enough for convection
    (At the top, T → 5,700 K,
    $\rho \rightarrow 0.2$ g/m^3 ≈ 1/6,000 $\rho_{\text{air at sea level}}$)



(At the top, T → 5,700 K,

$\rho \rightarrow$ 0.2 g/m^3 ≈ 1/6,000 $\rho_{\text{air at sea level}}$)

- Convection becomes the primary means of outward heat transfer
- Material heated at the tachocline picks up heat & expands, reducing its density & rising.
  - As a result, thermal cells carry the heat outward to photosphere.
  - With the material cooling just beneath the photospheric surface, its density increases, and it sinks to the base of the convection zone, and the convective cycle continues.
  - The thermal columns of the convection zone gives a granular appearance at the surface of the Sun, roughly hexagonal prisms : the solar granulation (the smallest scale) & supergranulation (larger scales).
  - Each cell ranges in size from 100 km to 1000 km across and may last up to half an hour (dynamical time scale !).
  - The gas moves outwards or inwards at speeds up to 7 km/s = 25,000 km/hour. (Measured through Doppler shifts.)
  - Turbulent convection sustains "small-scale" dynamo over the near-surface volume.

Visible Parts

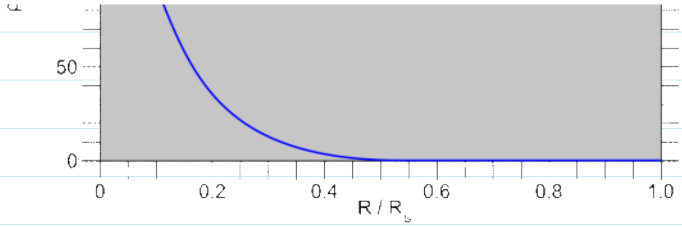
- 1) The **photosphere** : the deepest part directly observable with visible light
  - $T_{\odot \text{Surface}} = T_{\text{photosphere}}$ = 5,777 K

    $T_{\text{top,photosphere}}$ = 4,000 K

    $T_{\text{bottom,photosphere}}$ = 6,400 K
  - particle density ~10^{23} m^{-3} or 0.2 g/m^3 (about 0.37% of Earth's atmosphere at sea level)
  - H : Mostly in atomic form, ~3% ionized.
  - about 300 km thick. T minimum layer
  - Most visible light originates from this region.
  - The change in opacity from opaque below to transparent is due to the decreasing amount of H^- ions, which absorb visible light easily. Conversely, the visible light we see is produced as electrons react with H to produce H^-.
  - limb darkening : an image of the Sun appears brighter in the center than on the edge or *limb* of the solar disk

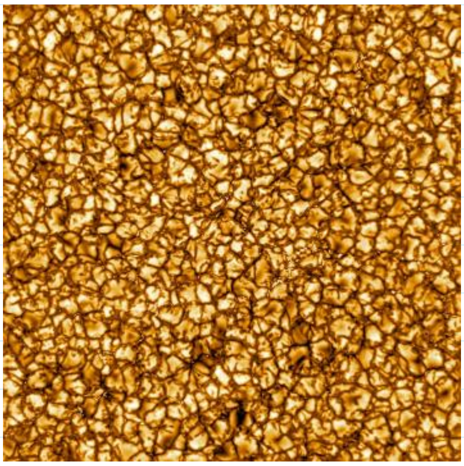
(∵ the top is cooler than the bottom)

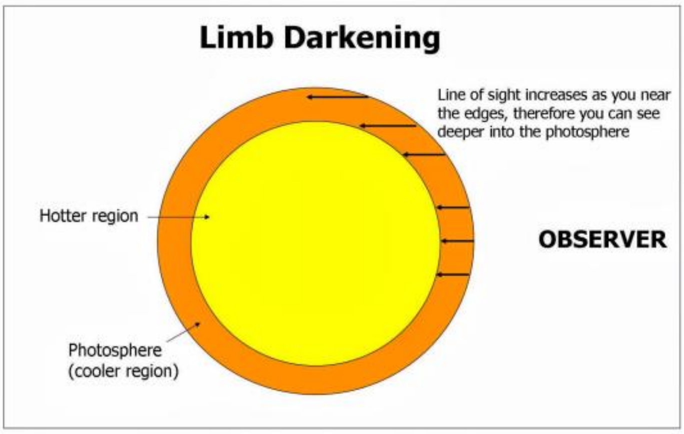
solar flares & coronal mass ejections

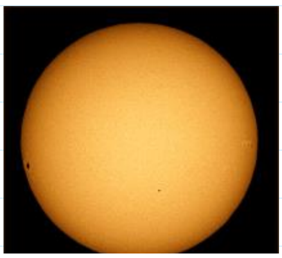


Density profile

출처: <https://en.wikipedia.org/wiki/Sun>





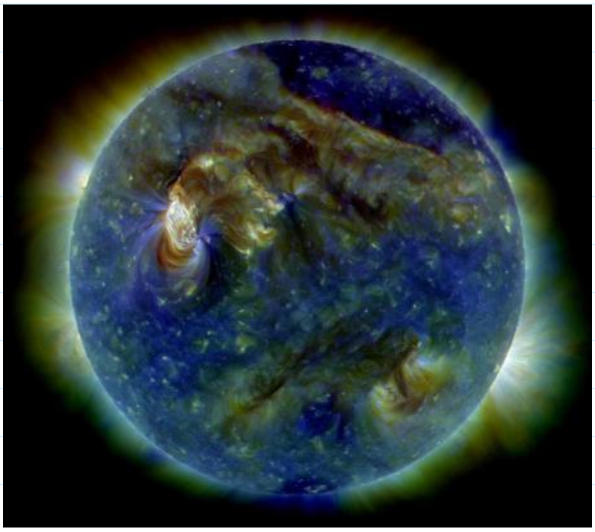


(∵ the top is cooler than the bottom)

solar flares & coronal mass ejections

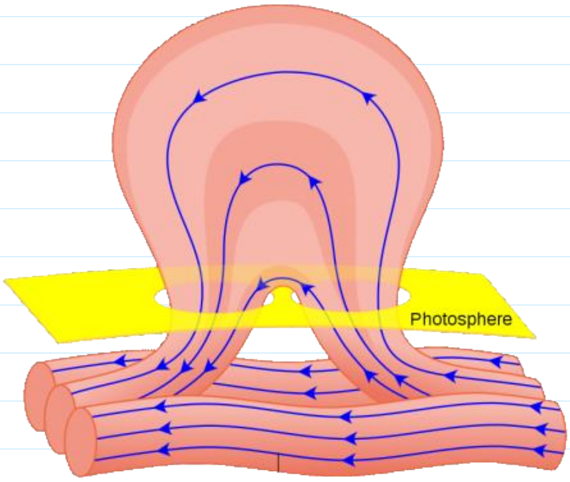
originate around sunspot groupings.

- Solar flares are large outbursts similar to eruptive prominences, but larger and more energetic.
- Solar flares increase the amount of particles which escape into the solar wind.
- If the particles ejected from the flare hit the Earth, then we get intense auroral displays.
- A negative effect is that the solar wind particles can disrupt radio transmissions.
- Flares occur in active regions around sunspots. Intense magnetic fields penetrate the photosphere to link the corona to the solar interior.
- The occurrence varies following the 11-year solar cycle. It can range from several per day during solar maximum to less than one every week during solar minimum. Large flares are less frequent.
- Flares are powered by the sudden (timescales of minutes to tens of minutes) release of magnetic energy in the corona. The same energy releases may produce coronal mass ejections (CMEs).
- The magnetic reconnection leads charged particles, electrons, protons, and heavier ions, to near the speed of light, interacting with the plasma medium, to this extreme acceleration, through the sudden release of energy. The material contained violently expand outwards forming a coronal mass ejection. can be accelerated to the GeV range and beyond.
- Solar flares affect all layers (photosphere, chromosphere, & corona). The plasma medium is heated to tens of MK, Flares produce electromag radiation across the electromag spectrum at all wavelengths, from radio waves to gamma rays. Most flares not visible to the naked eye.
- X-rays and UV radiation emitted by solar flares can affect Earth's ionosphere and disrupt long-range radio communications



On August 1, 2010, the Sun shows a C3-class solar flare (white area on upper left), a solar tsunami (wave-like structure, upper right) and multiple filaments of magnetism lifting off the stellar surface.

출처: <https://en.wikipedia.org/wiki/Solar_flare>



Magnetic Field Lines

A simplified diagram of the magnetic field of an active region.

- X-rays and UV radiation emitted by solar flares can affect Earth's ionosphere and disrupt long-range radio communications. Direct radio emission at decimetric wavelengths may disturb the operation of radars and other devices.

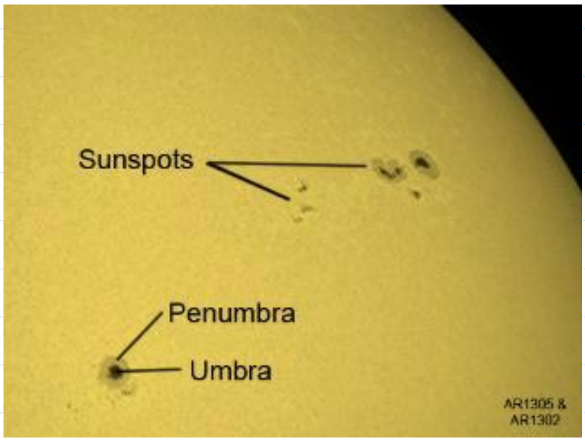
출처: <https://en.wikipedia.org/wiki/Solar_flare>

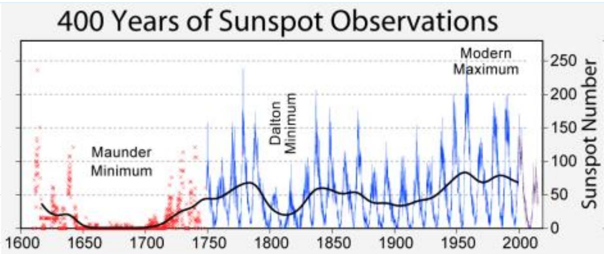
A simplified diagram of the magnetic field of an active region.

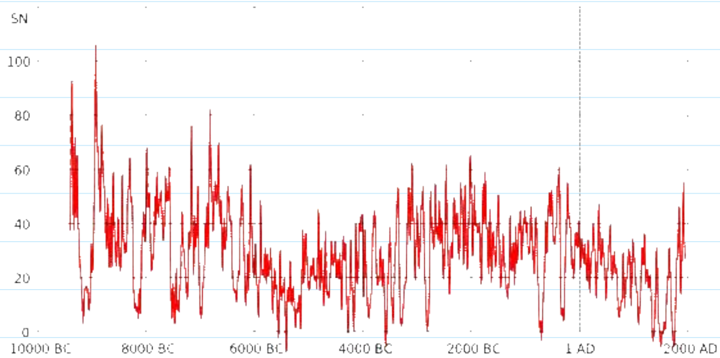
출처: <https://en.wikipedia.org/wiki/Active_region>

Sunspots

- Movements of spots reveal that the Sun rotates with a period close to one month.
- Equator rotates faster than the higher lattitudes. (Differential Rotation)
- photos of the Sun in many different wavelengths (updated daily) http://umbra.nascom.nasa.gov/images/latest.html

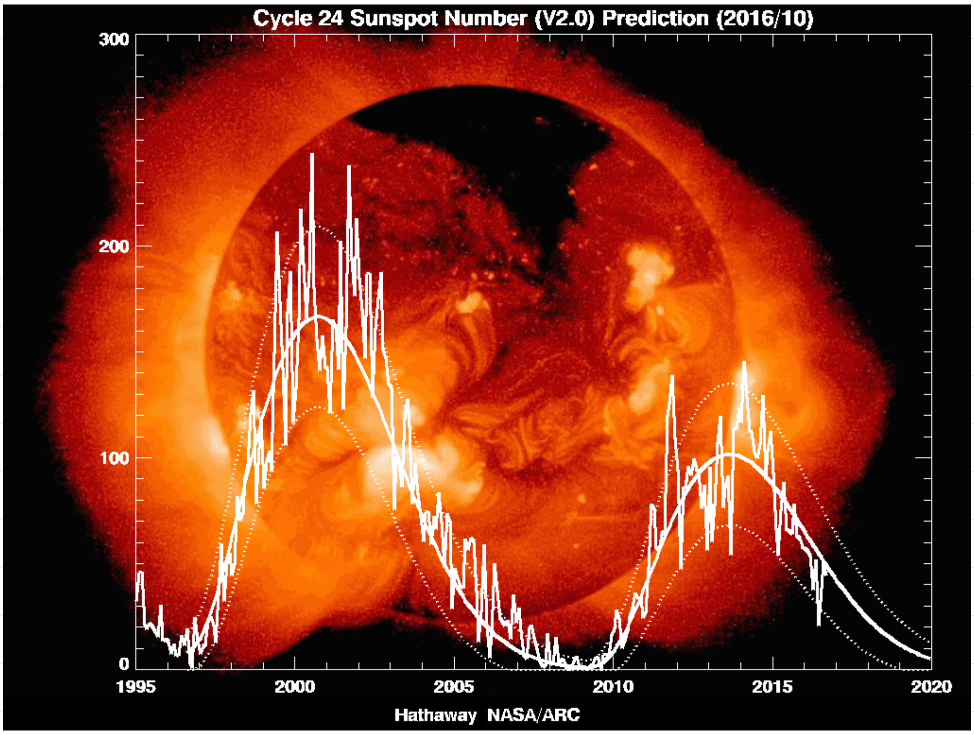






400-year history of sunspot numbers, showing Maunder and Dalton minima, and the Modern Maximum (left) and 11,000-year sunspot reconstruction showing a downward trend over 2000 BC – 1600 AD followed by the recent 400 year uptrend

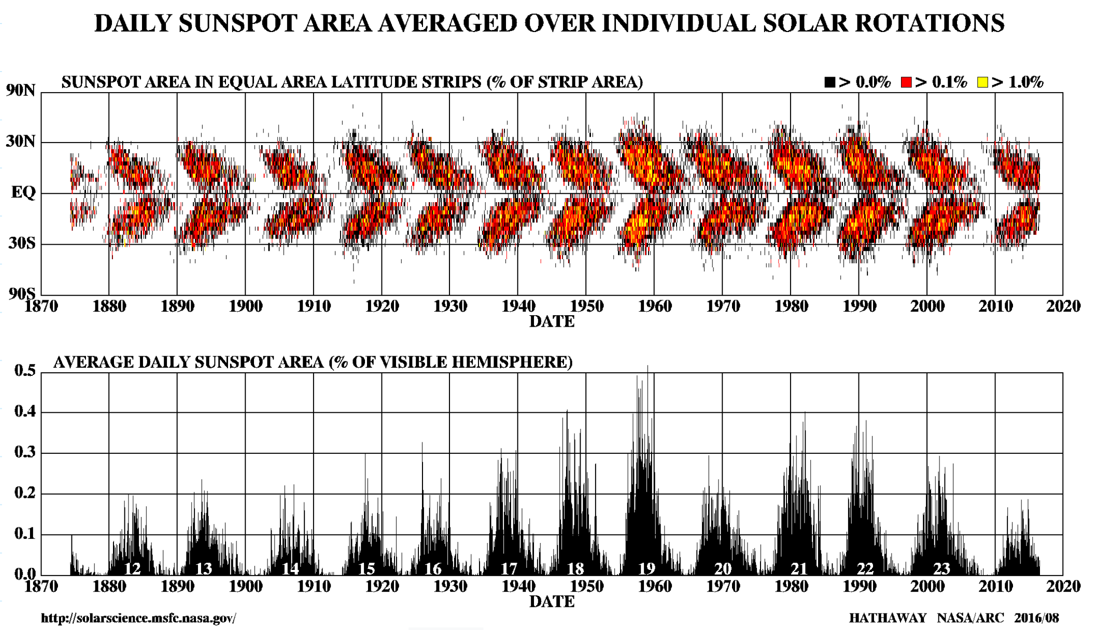
출처: <https://en.wikipedia.org/wiki/Sunspot>



Sunspot Cycle Predictions

출처: <https://solarscience.msfc.nasa.gov/SunspotCycle.shtml>

- As the number of sunspots increases, the number of flares and other forms of activity increases.
- The luminosity of the Sun also increases when there are lots of spots! (Bright plages also increase when sunspots increase.)
- The time at which there is a maximum number of spots is called Solar Maximum.
- The most recent Solar Maximum occurred late in 2000.
- The period of time from 1645 to 1715 is known as the Maunder minimum was a time with a very low number of sunspots.
- During the Maunder minimum Europe had colder than usual weather.



Butterfly diagram showing paired Spörer's law behavior

출처: <https://en.wikipedia.org/wiki/Sunspot>

Observation: Location of Sunspots

- At the beginning of each 11-year cycle the sunspots appear at high lattitudes.
- As the cycle progresses, the sunspots appear closer to the equator.

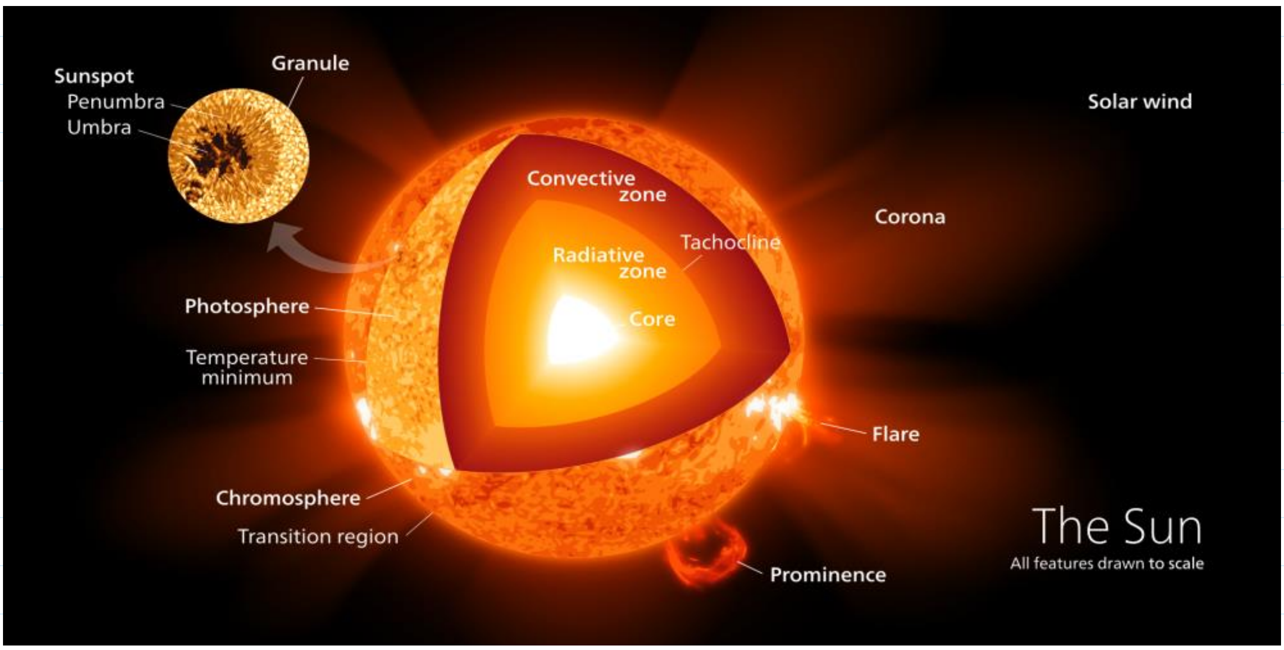
Sunspots

- appear within active regions on the Sun's photosphere, with high magnetic fields (1,000 x average), usually in pairs of opposite magnetic polarity
- last from a few days to a few months, (groups of sunspots last weeks or months)
- 16 km $\lesssim$ diameter $\lesssim$160,000 km. expand and contract moving across the surface at a few hundred m/s .
- spots are darker, lower surface T caused by magnetic flux inhibiting convection.
- Accompany other active region phenomena such as coronal loops, prominences, flares, mass ejections, aurora on Earth and reconnection events.
- **Sunspot** number varies according to the approximately 11-year solar cycle.
- Over the solar cycle, sunspot populations rise quickly and then fall more slowly. This period is linked to a variation in the solar magnetic field that changes polarity with this period.
- Similar phenomena indirectly observed on stars other than the Sun are commonly

called starspots, and both light and dark spots have been measured.

- two parts: its center umbra, the darkest part, where the mag field is approximately vertical (normal to the Sun's surface) and the surrounding penumbra, which is lighter, where the mag field is more inclined.
- T_{umbra} ≈3,000–4,500K, T_{penumbra} ≈5,780K. a single sunspot brighter than the full moon, with a crimson-orange color.
- expand & contract while moving across
- sunspots are the counterparts of mag flux tubes in the convective zone "wound up" by differential rotation.
- If the stress on the tubes reaches a certain limit, a loop of the tube may project through the photosphere, the Sun's visible surface. Convection is inhibited at the puncture points;
- Sunspots usually appear in groups.
- Magnetic pressure should tend to remove field concentrations, causing the sunspots to disperse, but sunspot lifetimes are measured in days to weeks.
- Early, sunspots appear at higher latitudes and then move towards the equator as the cycle approaches maximum. Spots from two sequential cycles co-exist for several years during the years near solar minimum.
- Sunspot numbers also change over **long periods**.
- Sunspot number is correlated with the intensity of solar radiation over the period since 1979, when satellite measurements became available. The variation is on the order of 0.1% of the solar constant

출처: <https://en.wikipedia.org/wiki/Sunspot>



The structure of the Sun
출처: <https://en.wikipedia.org/wiki/Sun>

The **atmosphere**

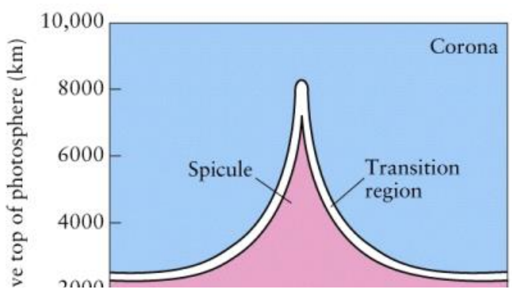
- a gaseous "halo", only seen during an eclipse.
- The coolest or minimum T≈ 4,100 K above the photosphere allows the existence of simple molecules such as carbon monoxide and water, which can be detected via their absorption spectra.
- The chromosphere, transition region, & corona are much hotter than the surface of the Sun.

출처: <https://en.wikipedia.org/wiki/Sun>

- 2) The **chromosphere**
  - about 2000 km thick.
  - $T_{\text{bottom,chromosphere}} \approx 4{,}100K$,
    increases gradually with altitude up to $T_{\text{top,chromosphere}} \approx 20{,}000$ K .
  - emission and absorption line spectrum.
  - visible as a colored flash at the beginning and end of total solar eclipses.
  - In the upper part of the chromosphere helium becomes partially ionized.
  - The red colour results from **the emission of Balmer-alpha photons** : electrons from the n=3 to the n=2 level.
  - The emission lines can only occur if the gas is very hot and the density is very low. (we do not look straight through !)
  - The chromosphere is hotter (but less dense) than the photosphere.
  - **Spicules**:
  - dynamic jet of plasma, ~300km diameter,
  - last for about 15 minutes;
  - usually associated with regions of high magnetic flux about 100 times that of the solar wind.
  - rise at a rate of 20 km/s
  - 3,000–10,000 km altitude above the photosphere before collapsing & fading away.
  - about 3,000,000 active spicules at any one time on the Sun's chromosphere.

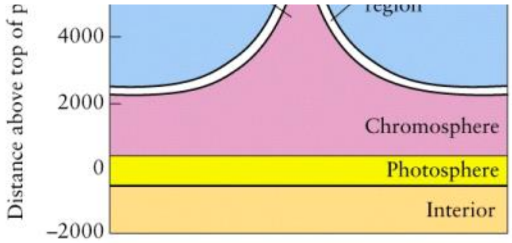
출처: <https://en.wikipedia.org/wiki/Spicule_(solar_physics)>

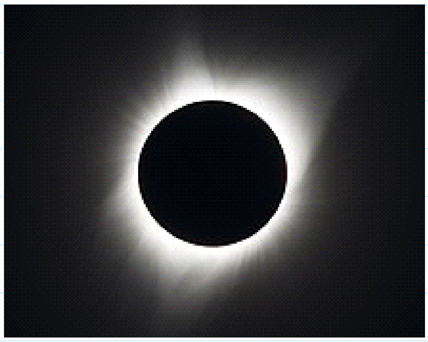
- 3) the **transition region** : thin (≈ 200 km)
  - Rapid T rise 20,000K → 1,000,000K
  - facilitated by the full ionization of He in the transition region, which significantly reduces radiative cooling of the plasma.
  - forms a kind of nimbus around chromospheric features such as spicules and filaments, and is in constant, chaotic motion.
  - not easily visible from Earth's surface, but readily observable from space by instruments for the extreme UV portion of the spectrum.



- 4) the **corona**
  - a particle density ~10^{15} m^{-3} - 10^{16} m^{-3} in the low corona, near the surface of the Sun.
  - The average T of the corona and solar wind ≈ 1–2 MK;

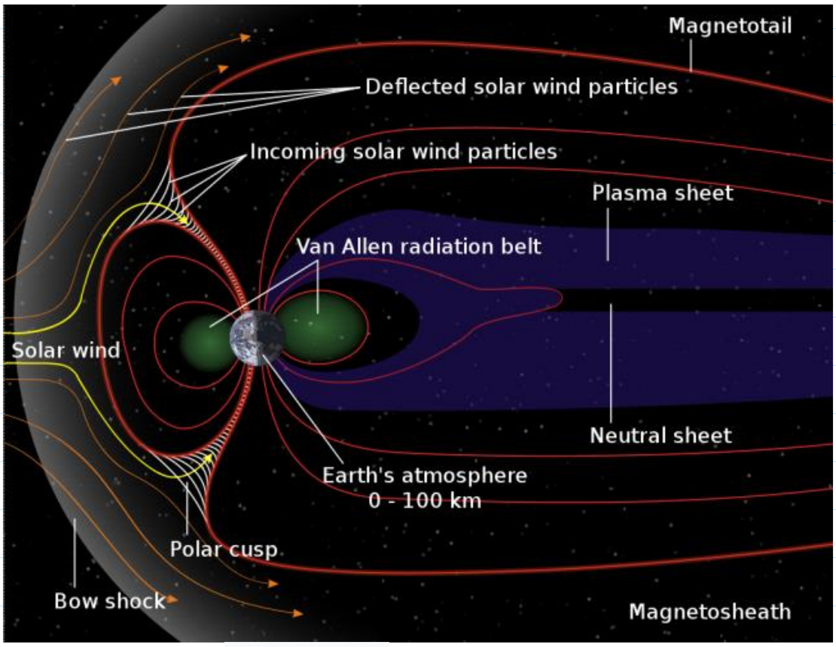
- The average T of the corona and solar wind
  ≈ 1–2 MK;
  In the hottest regions, T=8–20MK.
- At least some of its heat is known to be
  from magnetic reconnection.
- Emits X-rays (e.g., highly ionized iron)
- the **solar wind** : A flow of plasma outward
  from the Sun into interplanetary space.
- accelerated up to 200-400km/s
- The solar wind particles flow through-out the solar system beyond Pluto
- Further Evidence for the Solar Wind
  - A comet's tail always points away from the Sun, no matter in what direction it moves.
  - The particles in the solar wind push outwards on the gas sublimating from the comet so that the tail points away from the Sun.





During a total solar eclipse, the solar corona can be seen with the naked eye, during the brief period of totality

출처: <https://en.wikipedia.org/wiki/Sun>



Schematic of Earth's magnetosphere. The solar wind flows from left to right.

출처: <https://en.wikipedia.org/wiki/Solar_wind>

Aurora

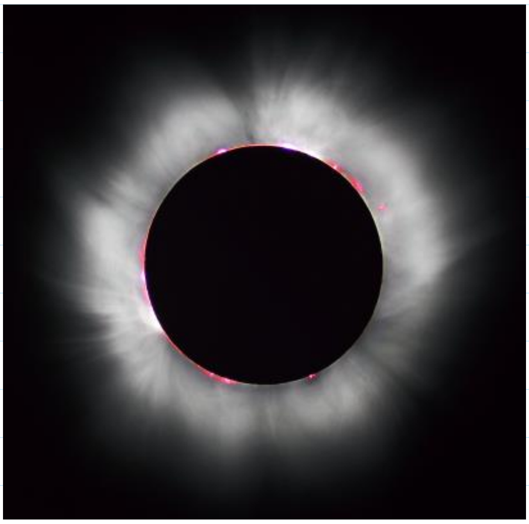
- When solar wind particles hit molecules in the Earth's atmosphere, they cause the atoms to get excited.
- The electrons in the excited atoms then jump down to a lower state and give off coloured light.
- The green and red aurora are usually due to electronic transitions in Oxygen.
- There is almost always an auroral oval over the Earth's north and south magnetic poles.
- The size of the auroral oval and the intensity of the emissions depend on the strength of the solar wind.
- A **prominence**(태양홍염), (a **filament** when viewed against

- The size of the auroral oval and the intensity of the emissions depend on the strength of the solar wind.

- A **prominence**(태양홍염), (a **filament** when viewed against the solar disk), is a large, bright, gaseous feature extending outward from the Sun's surface, often in a loop shape.
- The prominences are loops of gas which arch over sunspot regions.
- divides prominences into three classes : the active region prominences,

quiescent prominences,

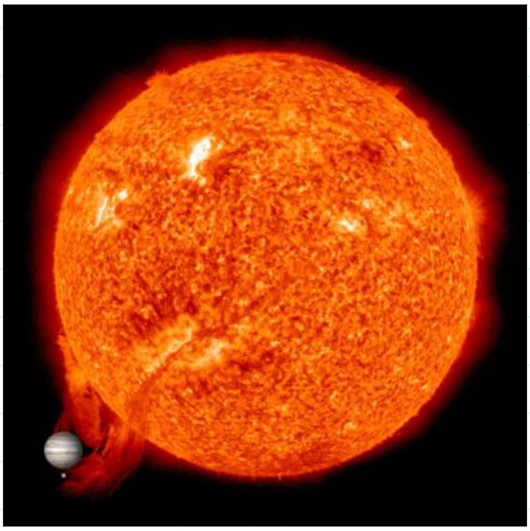
and intermediate prominences.



Solar prominences (in red) visible around the edge of the Sun during a solar eclipse.

출처: <https://en.wikipedia.org/wiki/Solar_prominence>

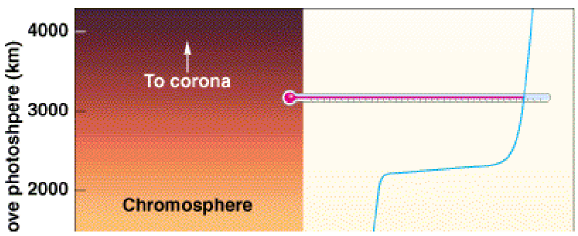
- Active region prominences are at the centers of active regions with strong magnetic field
- quiescent prominences are in the weak background field far from any active regions.
- In between these two lies the intermediate prominences
- Active region prominences are usually found in the lower latitudes, having lifetimes of only a few hours to days, are more eruptive whereas quiescent prominences are typically found in the higher latitudes around the polar crown, lifetimes ranging from weeks to months, less eruptive.
- Quiescent prominences generally reach much greater heights than active region prominences.
- The spectra of active region prominences is identical to that of the upper chromosphere having strong He II lines but very weak ionized metal lines.
- On the other hand, the spectra of quiescent prominences is identical to the spectra measured at 1500 km in the chromosphere with strong H, He I, and ionized metal lines, but weak He II lines.



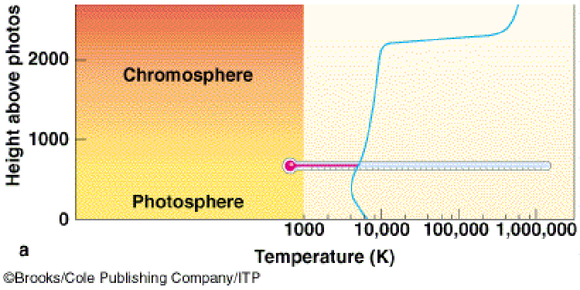
An erupting solar prominence as seen in He II 304 Å, with images of Jupiter and Earth for size comparison.

출처: <https://en.wikipedia.org/wiki/Solar_prominence>

- Prominences are more likely to erupt when the magnetic fields near the sunspots are changing.
- Eruption : Some prominences throw out matter from the Sun into space at speeds ranging from 600 km/s to more than 1,000 km/s.
- anchored to the Sun's surface and extend outwards into the solar corona.
- While the corona consists of extremely hot ionized gases, known as plasma, which do not emit much visible light, prominences contain much cooler plasma, similar in composition to that of the chromosphere.
- The prominence plasma is typically a hundred times more luminous and dense than the coronal plasma.
- All prominences form in filament channels above divisions between regions of opposite photospheric magnetic polarity called polarity inversion lines (PIL), polarity reversal boundaries (PRB), or neutral lines.



between regions of opposite photospheric magnetic polarity called polarity inversion lines (PIL), polarity reversal boundaries (PRB), or neutral lines.



- They form over timescales of about a day and may persist in the corona for several weeks or months, looping hundreds of thousands of kilometers into space.
- Some prominences break apart and may then give rise to coronal mass ejections.
- A typical prominence extends over roughly a solar radius.
- The quiescent prominences are very stable and can last weeks or months.

출처: <https://en.wikipedia.org/wiki/Solar_prominence>

Coronal Mass Ejection

- When an eruptive prominence or a solar flare occurs, a coronal mass ejection (CME) can also take place.
- A CME is a stream of plasma (charged particles) ejected from the corona.

- 5) the **heliosphere**
  - The tenuous outermost atmosphere of the Sun filled with the solar wind plasma.
  - This outermost layer of the Sun is defined to begin at the distance where the flow of the solar wind becomes *superalfvénic*—that is, where the flow becomes faster than the speed of Alfvén waves, at approximately 20 solar radii (0.1 AU).
  - Turbulence and dynamic forces in the heliosphere cannot affect the shape of the solar corona within, because the information can only travel at the speed of Alfvén waves.
  - The solar wind travels outward continuously through the heliosphere, forming the solar magnetic field into a spiral shape, until it impacts the heliopause more than 50 AU from the Sun.
  - In December 2004, the Voyager 1 probe passed through a shock front that is thought to be part of the heliopause.
  - August 25 2012, Voyager 1 probe had passed through the heliopause at ≈122 AU from the sun and entered the interstellar medium, suggested by recording a marked increase in cosmic ray collisions and a sharp drop in lower energy particles from the solar wind.
  - The heliosphere has a heliotail which stretches out behind it due to the Sun's movement.

  출처: <https://en.wikipedia.org/wiki/Sun>

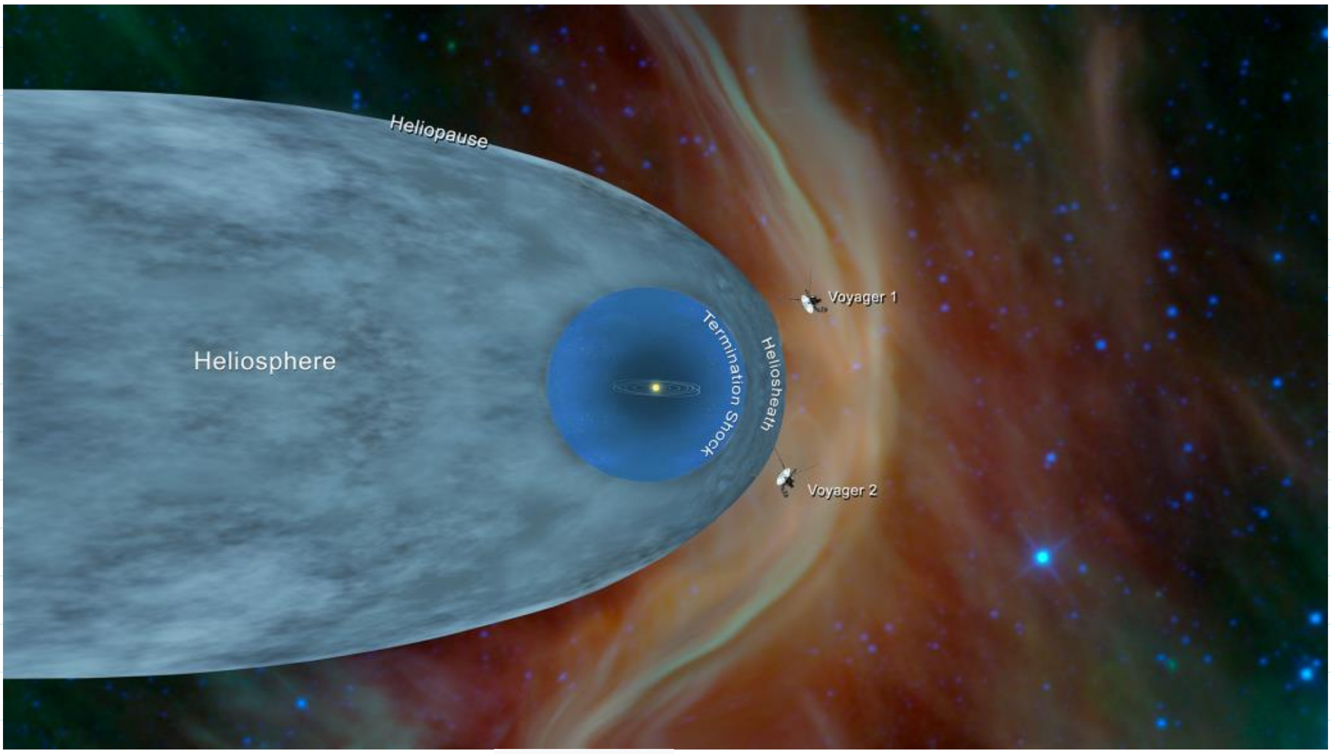


Diagram of the heliosphere as it travels through the [interstellar medium](https://en.wikipedia.org/wiki/Interstellar_medium):

a. Heliosheath: the outer region of the heliosphere; the solar wind is compressed and turbulent

b. Heliopause: the boundary between solar wind and interstellar wind where they are in equilibrium.

출처: <https://en.wikipedia.org/wiki/Heliosphere>

hydrostatic equilibrium :

The balance between gravity and net gas pressure

- If hydrostatic equilibrium broken, restored on a **dynamical timescale** ~ 15 min for the Sun

- Central Temperature
  T_c = 15 million K
- Central Density
  &rho$_c$ = 150 tons/m^3
- Central Pressure
  $P_c = 10^{11}$ atm

Source of Solar energy

- How much energy a hot ball of gas it temperature T~10^6 contain ?
  - one atom has energy, on average, approx

    $k_B T = 1.3806503 \times 10^{-23}$ J K^{-1} x 10^6 K = 1.4×10^{-17} J
  - We have 10^{57} atoms, so the total energy stored

    E ~ 10^{40} J
- Sun luminosity is 4 x 10^{26} Watt, i.e that much Joules per second
- I.e amount of stored energy in hot gas is enough for time t

  t = 10^{40} J / 4 x 10^{26} W = 2 x 10^{13} sec = 10^6 years

  Thermal timescale is too short ! Need another source of energy !

The Thermonuclear Core

- All reactants are the nuclei of the atoms which have positive charge. But positive charges repel!
- The hydrogen nuclei must have very high energy in order to fuse. This requires very high temperature.
- The only place where the temperatures are high enough is in the central region of Sun. (Inner 1/4 of the

star by radius)

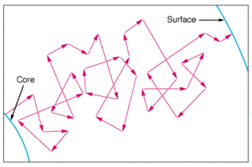
- Even then, it takes on average 10^{10} years for an individual proton to succesfully mate with another one. **Hydrogen burning is very slow**

Main Sequence Stars

- The Sun is a type of star called a **Main Sequence star**.
- All Main Sequence stars have a hot core where Hydrogen fusion takes place.
- There are a number of different types of main sequence stars, with different masses and sizes, but they all have similar chemical composition and Hydrogen fusion is what keeps them in hydrostatic equilibrium.

Transport of Energy

- The energy generated in the centre of the Sun must be transported outwards.
- Two methods of energy transport occur in the Sun:
  1. **Radiation** : photons carry energy from the core to the surface at about 70% of the distance to the surface.
     - The motion of the photons is slow since they keep on being scattered by the gas particles.
     - Photon's motion is a random walk.
     - With each collision, the photon loses energy.

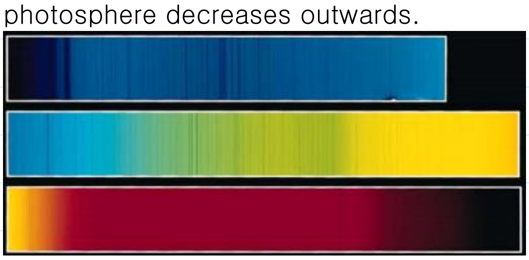
- 

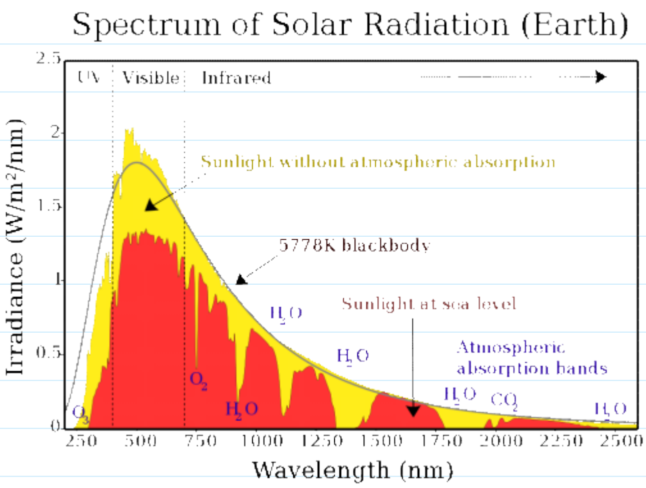
- It takes about one million years for a photon to travel from the core to the surface!

  2. **Convection** : gas particles move, carrying energy outwards.
     - The convective zone is the outer 30% of the Sun.
     - Convection cells bring hot gas upwards and cool gas downwards in circular motions.

The Sun's Spectrum is an Absorption Spectrum

- Since the photosphere is cooler but less dense than the interior region it is the screen that allows the continuous blackbody spectrum to be seen through.
- Only at the wavelengths at which atoms in the photosphere can absorb light will photons be impeded in their outward travel.
- The result is an absorption spectrum, a continuous blackbody spectrum with dark absorption lines superimposed on it.
- The fact that we see an absorption spectrum when we look at the photosphere is evidence that the temperature of the photosphere decreases outwards.





Solar irradiance spectrum above atmosphere and at surface. Extreme UV and X-rays are produced (at left of wavelength range shown) but comprise very small amounts of the Sun's total output power.

출처: <https://en.wikipedia.org/wiki/Sunlight>

- The spectrum ≈ that of a black body with $T \approx$ 5,800 K.

- The Sun emits EM radiation across most of the electromagnetic spectrum.
- Gamma ray :
  - Although the Sun produces gamma rays as a result of the nuclear-fusion process, internal absorption and thermalization convert these super-high-energy photons to lower-energy photons before they reach the Sun's surface. As a result, the Sun does not emit gamma rays from this process.
  - but it does emit gamma rays from solar flares.
- The Sun also emits X-rays, ultraviolet, visible light, infrared, and even radio waves;
- the only direct signature of the nuclear process is the emission of neutrinos.
- Although the solar corona is a source of extreme ultraviolet and X-ray radiation, these rays make up only a very small amount of the power output of the Sun (see spectrum at right).
- significant radiation power on the Earth's atmosphere spans a range of 100 nm to about 1 mm. This band can be divided into five regions in increasing order of wavelengths:
  - **Ultraviolet C** or (UVC) range, 100 to 280 nm.
  - Due to absorption by the atmosphere very little reaches Earth's surface.
  - This spectrum of radiation has germicidal properties, as used in germicidal lamps.
  - **Ultraviolet B** or (UVB) range, 280 to 315 nm.
  - It is also greatly absorbed by the Earth's atmosphere,
  - along with UVC causes the photochemical reaction leading to the production of the ozone layer.
  - It directly damages DNA and causes sunburn.
  - In addition to this short-term effect it enhances skin ageing and significantly promotes the development of skin cancer, but is also required for vitamin D synthesis in the skin of mammals.
  - **Ultraviolet A** or (UVA), 315 to 400 nm.
  - This band was once held to be less damaging to DNA, and hence is used in cosmetic artificial sun tanning (tanning booths and tanning beds) and PUVA therapy for psoriasis.
  - However, UVA is now known to cause significant damage to DNA via indirect routes (formation of free radicals and reactive oxygen species), and can cause cancer.
  - **Visible range** or **light** 380 to 700 nm.
  - As the name suggests, this range is visible to the naked eye.
  - It is also the strongest output range of the Sun's total irradiance spectrum.
  - **Infrared** range that spans 700 nm to 1 mm.
  - It comprises an important part of the electromagnetic radiation that reaches Earth.
  - Scientists divide the infrared range into three types on the basis of wavelength:
    - Infrared-A: 700 nm to 1,400 nm
    - Infrared-B: 1,400 nm to 3,000 nm
    - Infrared-C: 3,000 nm to 1 mm.

출처: <https://en.wikipedia.org/wiki/Sunlight>

Stars - Brightness and Distance

Apparent magnitude (***m***) is a measure of the brightness.
출처: <https://en.wikipedia.org/wiki/Apparent_magnitude>

The scale is reverse logarithmic: the brighter an object is, the lower its magnitude number.

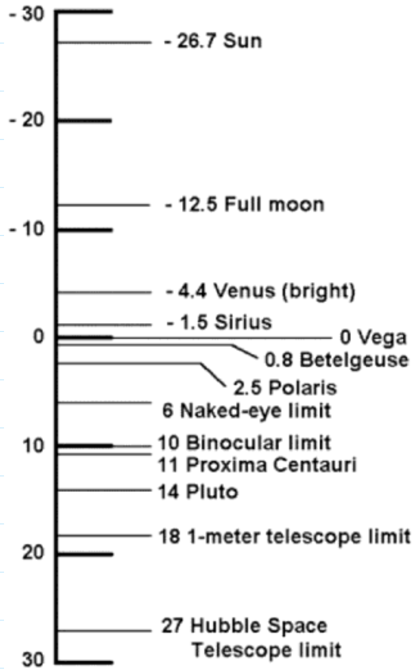
$\Delta m = 1.0 \quad \leftrightarrow \quad \sqrt[5]{100} \approx 2.512.$

$\Delta m = 2.0 \quad \leftrightarrow \quad (\sqrt[5]{100})^2 \approx 6.31,$ (15.85, 39.8, 100)

출처: <https://en.wikipedia.org/wiki/Absolute_magnitude>

Absolute magnitude (M) = a measure of the intrinsic luminosity
= the apparent magnitude at 10 pc (32.6 ly) or a parallax of 0.1″ (100 milliarcsec),

Ex) the **absolute visual magnitude** M_V in V(visual) band (in the UBV photometric system).
An absolute *bolometric* magnitude (M_{bol}) = total luminosity over all wavelengths,



Examples

$m(\odot)$=-26.7 $\quad$ M_V ($\odot$) =+4.83. $\quad$ M_{bol} ($\odot$) = 4.75

m(Venus) = −4.2

m(Sirius) = −1.46. M_V (Sirius) =+ 1.4,

m_V(Rigel) = 0.12, $\quad$ M(Rigel)=−7.0 $\quad$ distance= 860 ly:

m_V(Vega) = 0.03 parallax = 0.129″,

−26.7(Sun) ≤ m ≤ +31.5 (by Hubble Space Telescope)

The faintest stars visible with the naked eye ≈ +6.5.

M(Deneb) =−7.2, M(Naos)=−6.0, M(Betelgeuse)=−5.6

−10 ≤ M(star) ≤ +17

M_B (Milky Way) ≈ −20.8.

M_V (M87, giant elliptical galaxy) =-22

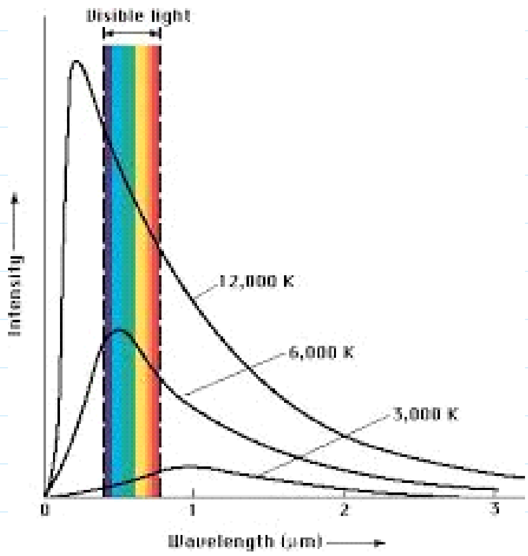
M_V (CTA-102, AGN(quasar)) =-32, the most luminous objects

Apparent magnitude

Extinction rates within the Milky Way galaxy Δm ≈1~2 /kpc

Temperature & Color of Stars

Wien's displacement law "Wien's law"



the spectral radiance of black-body radiation per unit wavelength,

peaks at the wavelength λ_{peak} given by:

$$\lambda_{\text{peak}} = \frac{b}{T}$$

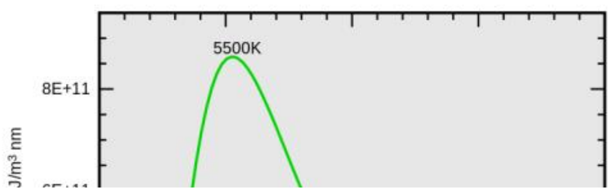
where

b =2.897 771 955×10^{-3}m·K≈2,898 μm·K

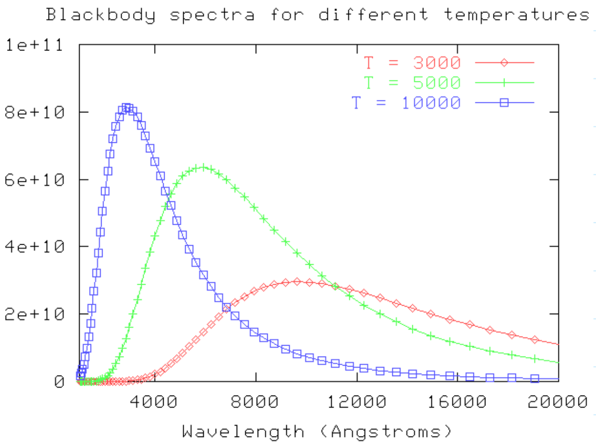
Wien's displacement constant,

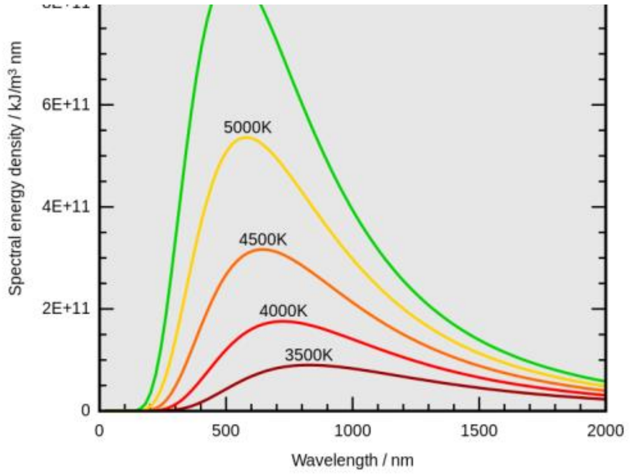
Ex)

T	λ_{peak}
3,000	966.0 nm
4,000	724.5 nm
4,500	644.0 nm
5,000	579.6 nm
5,500	526.9 nm
5,778	501.6 nm



5,000	579.6 nm
5,500	526.9 nm
5,778	501.6 nm
6,000	483.0 nm
10,000	289.8 nm





Black-body radiation as a function of wavelength for various temperatures. Each temperature curve peaks at a different wavelength and Wien's law describes the shift of that peak.
출처: <https://en.wikipedia.org/wiki/Wien%27s_displacement_law>

Color		Wavelength	Frequency
	Red	~ 700–635 nm	~ 430–480 THz
	Orange	~ 635–590 nm	~ 480–510 THz
	Yellow	~ 590–560 nm	~ 510–540 THz
	Green	~ 560–520 nm	~ 540–580 THz
	Cyan	~ 520–490 nm	~ 580–610 THz
	Blue	~ 490–450 nm	~ 610–670 THz
	Violet	~ 450–400 nm	~ 670–750 THz

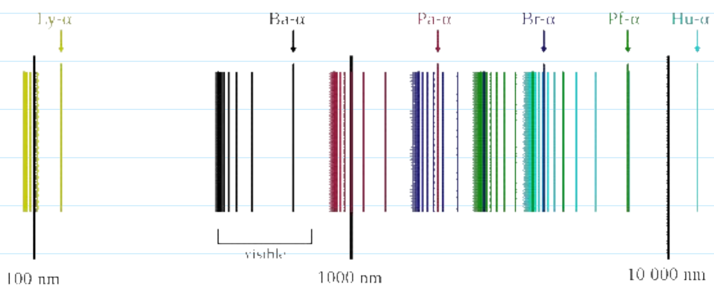
The colors of the visible light spectrum
출처: <https://en.wikipedia.org/wiki/Color>

Color	λ(nm)	ν(THz)	ν_b(μm^{-1})	E(eV)	E(kJ mol^{-1})
Infrared	> 1000	< 300	< 1.00	< 1.24	< 120
Red	700	428	1.43	1.77	171
Orange	620	484	1.61	2.00	193
Yellow	580	517	1.72	2.14	206
Green	530	566	1.89	2.34	226
Cyan	500	600			
Blue	470	638	2.13	2.64	254
Violet (visible)	420	714	2.38	2.95	285
Near ultraviolet	300	1000	3.33	4.15	400
Far ultraviolet	< 200	> 1500	> 5.00	> 6.20	> 598

Color, wavelength, frequency and energy of light

출처: <https://en.wikipedia.org/wiki/Color>

Spectrum
Ex) Hydrogen

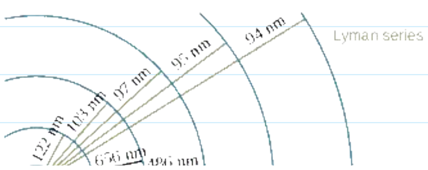


The spectral series of hydrogen, on a logarithmic scale.
출처: <https://en.wikipedia.org/wiki/Hydrogen_spectral_series>

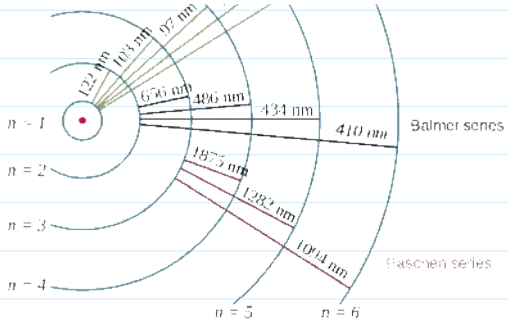
Rydberg formula

$$\frac{1}{\lambda} = Z^2 R_\infty \left(\frac{1}{n'^2} - \frac{1}{n^2}\right)$$

where
the Rydberg constant
R_∞ = 1.096 77×10^7 m^{-1} for H
1.097 37×10^7 m^{-1}
for heavy metals
출처: <https://en.wikipedia.org/wiki/Hydrogen_spectral_series>



$$\frac{1}{R_\infty} = 9.112\,670\,505 \times 10^{-8} m$$

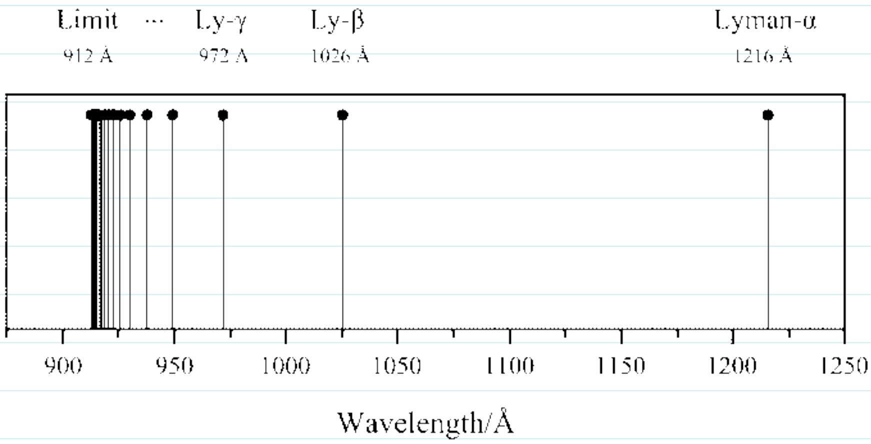


$$\frac{1}{R_\infty} = 9.112\,670\,505 \times 10^{-8} m$$
$$= 0.9112670505 \times 10^{3} \text{Å}$$
$$= 0.9112670505 \times 10^{2} nm$$

Electron transitions and their resulting wavelengths for hydrogen. Energy levels are not to scale.

출처: <https://en.wikipedia.org/wiki/Hydrogen_spectral_series>

Lyman Series ($n' = 1$) $n \geq 2$, UV spectrum



n	λ(nm)
2	121.57
3	102.57
4	97.254
5	94.974
6	93.780
∞	91.175

출처: <https://en.wikipedia.org/wiki/Hydrogen_spectral_series>

Lyman series of hydrogen atom spectral lines in the ultraviolet

출처: <https://en.wikipedia.org/wiki/Hydrogen_spectral_series>

Balmer Series ($n' = 2$) $n \geq 3 \rightarrow n' = 2$ Visible emission spectrum

The four visible hydrogen emission spectrum lines in the Balmer series.
H-alpha is the red line at the right.

출처: <https://en.wikipedia.org/wiki/Hydrogen_spectral_series>

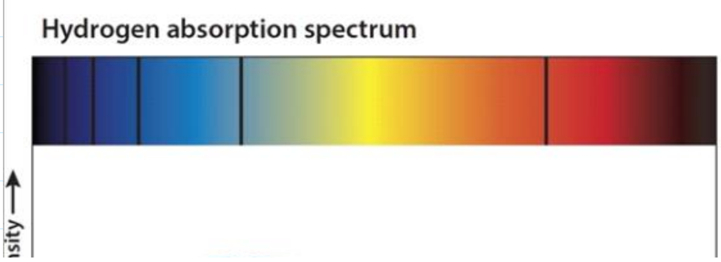
n	λ(nm)
3	656.3
4	486.1
5	434.0
6	410.2
7	397.0
∞	364.6

출처: <https://en.wikipedia.org/wiki/Hydrogen_spectral_series>

$n \geq n' \rightarrow n' = 3{,}4,$ IR Spectrum
Paschen($n' = 3$),
Bracket(4),Pfund(5), Humphreys(6)

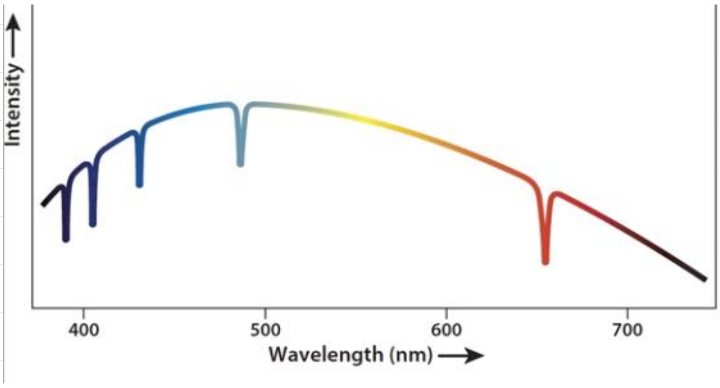
Paschen($n' = 3$)

n	λ(nm)
4	1875
5	1282
6	1094
7	1005

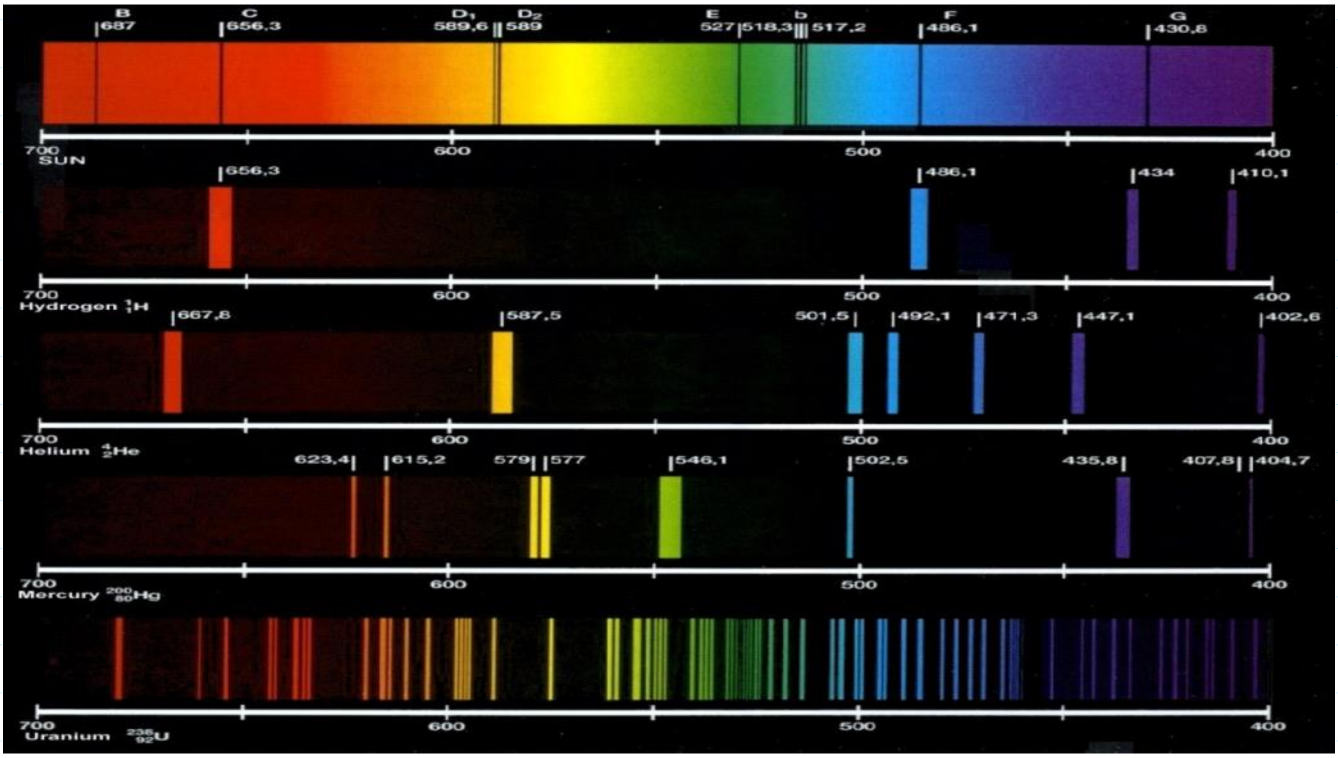


6	1094
7	1005
8	954.6
∞	820.4

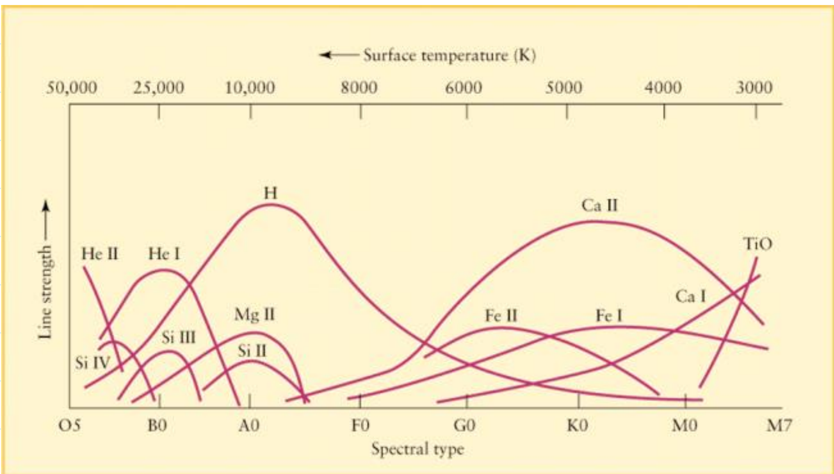
출처: <https://en.wikipedia.org/wiki/Hydrogen_spectral_series>



Hot → emission spectrum
Cold → absorption spectrum



Temperature dependence of the spectrum absorption line



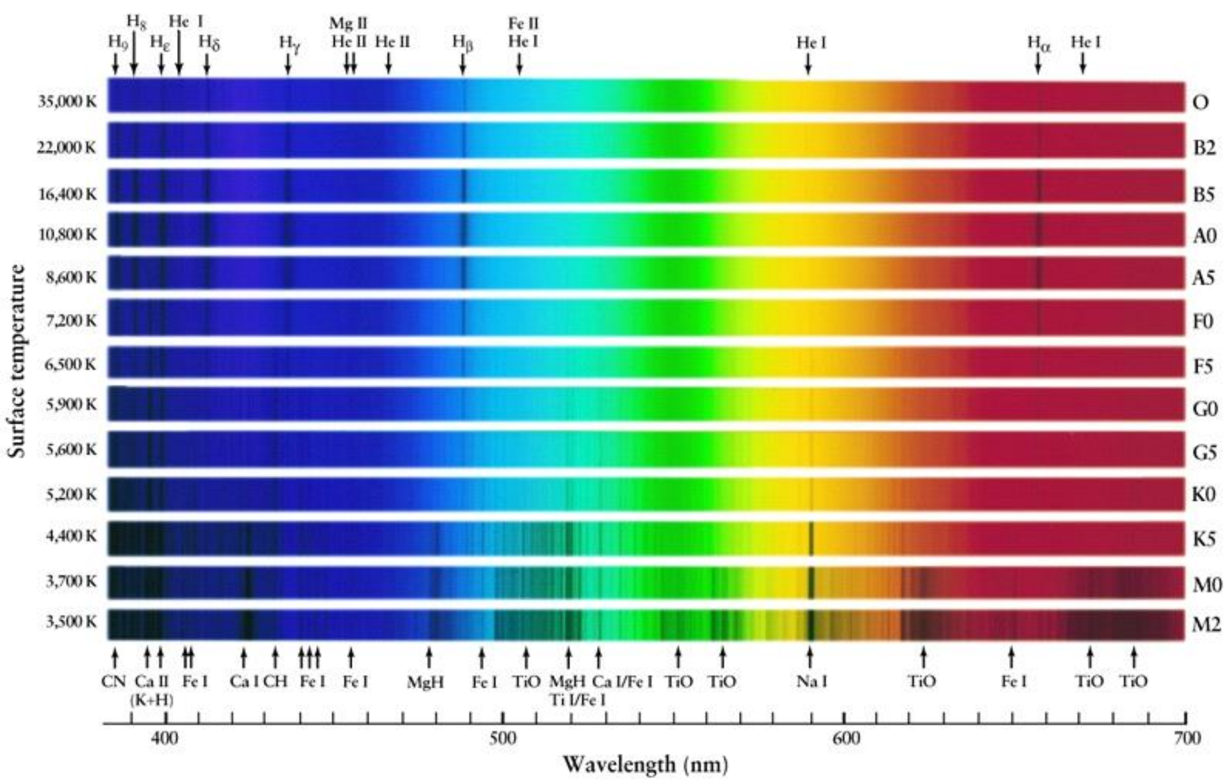
- Need to be hot enough to have properly excited atoms,
- and not too hot to pull out all electrons from the levels that are responsible for those lines.

- Ex) H-Balmer absorption lines: jump up from n=2 level.
  - Balmer absorption is larger if more atoms are in n=2.
  - T higher → less atoms in n=2 → weaker line
    - If ionized→ cannot absorb → absorp lines disappear.
  - Lower T more atoms in ground state → weaker line.
    - All atoms in GS → no Balmer absorption

- Same with other lines in more complex atoms:

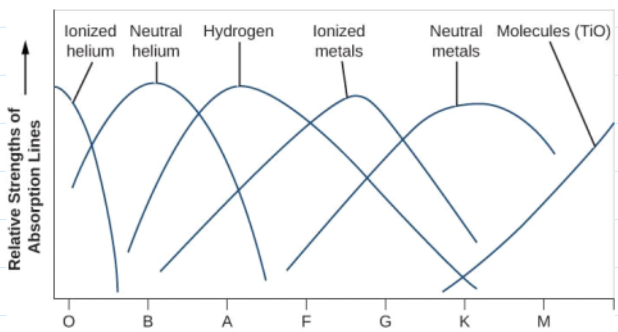
The Spectral Sequence from Coolest to Hottest:

Type	T		Examples
M0	3,900 K	Red Stars, weakest H absorption (most H in GS)	Betelgeuse
K0	5,200 K	Hotter than M, so more H absorption than M	Aldebaran, Pollux
G0	5,900 K	Hotter than K, so more H absorption than K	The Sun, Capella
F0	7,500 K	Hotter than G, so more H absorption than G	Procyon, Polaris
A0	11,000 K	Darkest H Absorption lines	Sirius, Castor, Mizar
B0	30,000 K	Hotter than A, so less absorption than A (more H ionized)	Rigel, Regulus
O5	50,000 K	Hotter than B, so even less absorption (most H ionized)	Mintaka (Right-most belt star in Orion)



Star classification

Different star classes are characterized by the prominence of certain spectral lines



Types of Spectra

Molecular Lines Strongest in M spectra

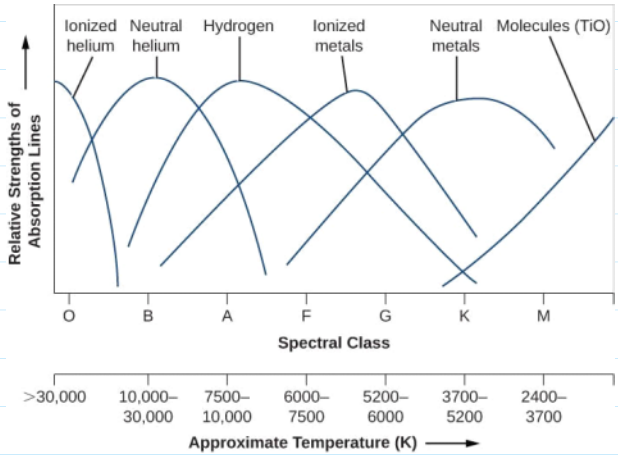
Neutral Metals Strongest in G,K, and M

Hydrogen Lines Strongest in A spectra

Neutral Helium Strongest in B

Ionized Helium Strongest in O

출처: <https://pages.uoregon.edu/jimbrau/astr122/Notes/Chapter17.html>



출처: <https://people.highline.edu/iglozman/classes/astronotes/hr_diagram.htm>

Neutral Metals Strongest in G,K, and M
Hydrogen Lines Strongest in A spectra
Neutral Helium Strongest in B
Ionized Helium Strongest in O

출처: <https://pages.uoregon.edu/jimbrau/astr122/Notes/Chapter17.html>

TABLE 17.2 Stellar Spectral Classes

Spectral Class	Approximate Surface Temperature (K)	Noteworthy Absorption Lines	Familiar Examples
O	30,000	Ionized helium strong; multiply ionized heavy elements; hydrogen faint	Mintaka (O9)
B	20,000	Neutral helium moderate; singly ionized heavy elements; hydrogen moderate	Rigel (B8)
A	10,000	Neutral helium very faint; singly ionized heavy elements; hydrogen strong	Vega (A0), Sirius (A1)
F	7000	Singly ionized heavy elements; neutral metals; hydrogen moderate	Canopus (F0)
G	6000	Singly ionized heavy elements; neutral metals; hydrogen relatively faint	Sun (G2), Alpha Centauri (G2)
K	4000	Singly ionized heavy elements; neutral metals strong; hydrogen faint	Arcturus (K2), Aldebaran (K5)
M	3000	Neutral atoms strong; molecules moderate; hydrogen very faint	Betelgeuse (M2), Barnard's Star (M5)

Morgan–Keenan (MK) system

using the letters O,B,A,F,G,K,& M from O (the hottest) to M (the coolest).
subdivided by numerals (0-9) with 0 being hottest and 9 being coolest.

Class	Effective temperature	Vega-relative chromaticity	Chromaticity (D65)	M-S mass	M-S radius	M-S luminosity (bolometric)	Hydrogen lines	Fraction of all M-S stars	Approximate main-sequence life span (yr)
O	≥ 30,000 K	blue	blue	≥ 16 M☉	≥ 6.6 R☉	≥ 30,000 L☉	Weak	~0.00003%	~10 million
B	10,000–30,000 K	blue white	deep blue white	2.1–16 M☉	1.8–6.6 R☉	25–30,000 L☉	Medium	0.13%	~100 million
A	7,500–10,000 K	white	blue white	1.4–2.1 M☉	1.4–1.8 R☉	5–25 L☉	Strong	0.6%	~1 billion
F	6,000–7,500 K	yellow white	white	1.04–1.4 M☉	1.15–1.4 R☉	1.5–5 L☉	Medium	3%	~5 billion
G	5,200–6,000 K	yellow	yellowish white	0.8–1.04 M☉	0.96–1.15 R☉	0.6–1.5 L☉	Weak	7.6%	~10 billion
K	3,700–5,200 K	light orange	pale yellow orange	0.45–0.8 M☉	0.7–0.96 R☉	0.08–0.6 L☉	Very weak	12.1%	~50 billion
M	2,400–3,700 K	orange red	light orange red	0.08–0.45 M☉	≤ 0.7 R☉	≤ 0.08 L☉	Very weak	76.45%	~100 billion

출처: <https://en.wikipedia.org/wiki/Stellar_classification#Yerkes_spectral_classification>

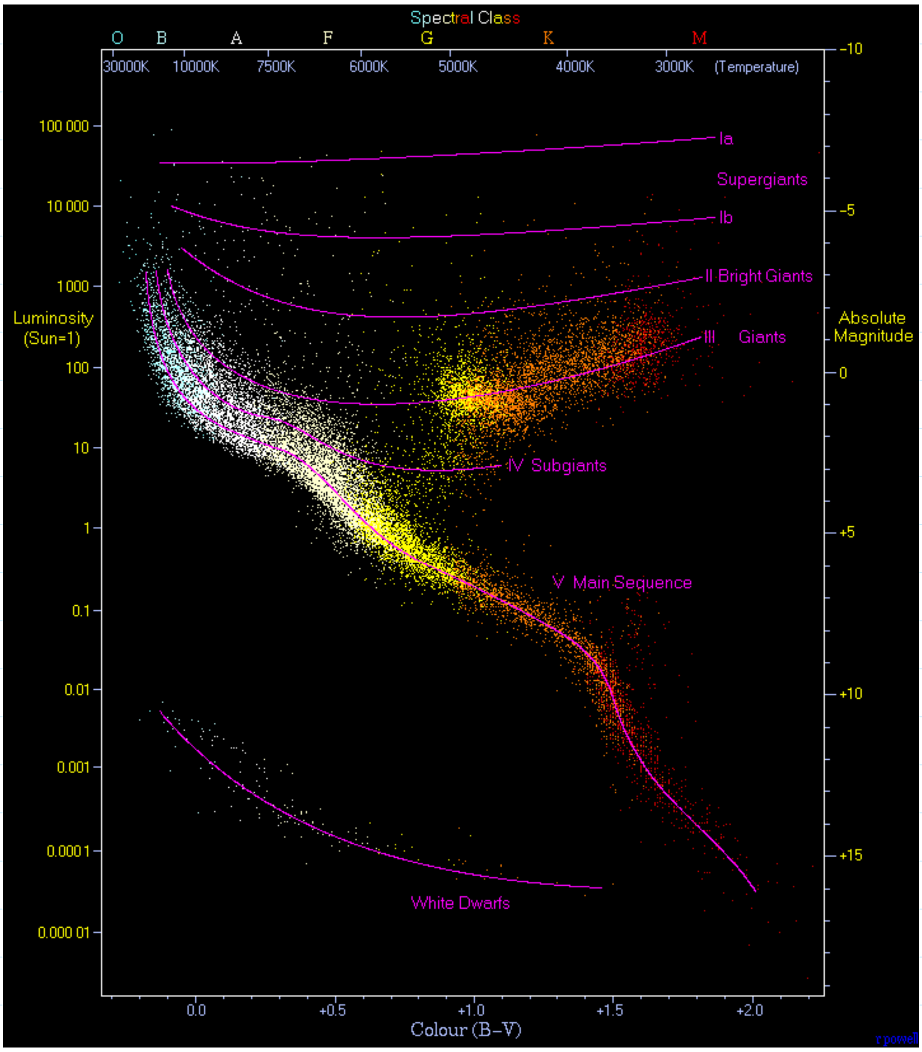
luminosity class

luminosity class

0 or *Ia+* : *hypergiants*,
class *I* : *supergiants*,
class *II* : bright *giants*,
class *III* : regular *giants*,
class *IV* : *sub-giants*,
class *V* : *main-seq* stars,
Class *sd* (*VI*): *sub-dwarfs*,
class *D*(*VII*) : *white dwarfs*.

Ex) **The Sun** ⊙
on the MS
$L_\odot = 1$ ($M_\odot$ =4.8)
B-V = 0.66
T= 5780 K,
spectral type G2V

Aldebaran
is a Red Giant:
Spectral Type
K5III

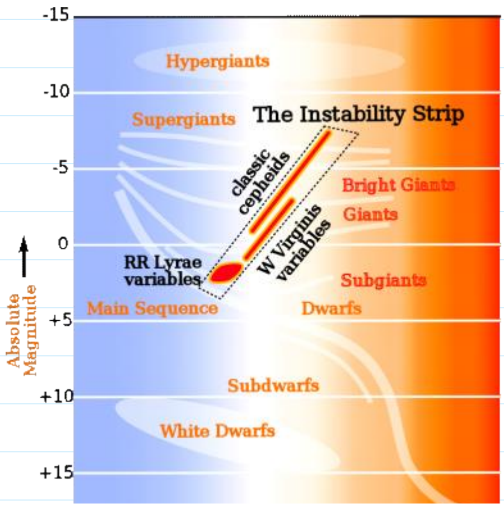


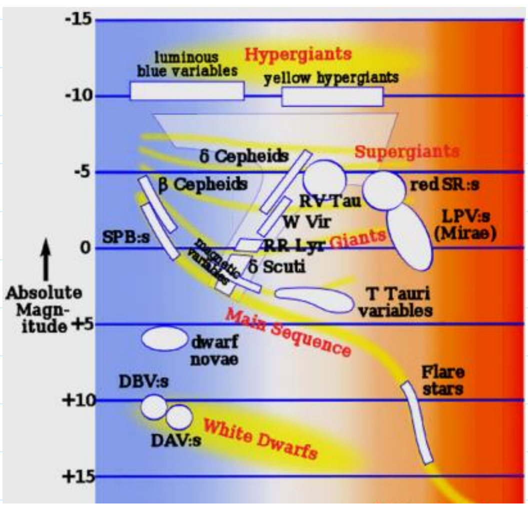
An observational Hertzsprung–Russell diagram with 22,000 stars plotted
출처: <https://en.wikipedia.org/wiki/Hertzsprung%E2%80%93Russell_diagram>

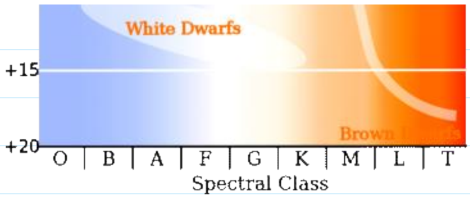
Hertzsprung-Russell (HR) Diagram (Ejnar Hertzsprung and Henry Norris Russell (1913))

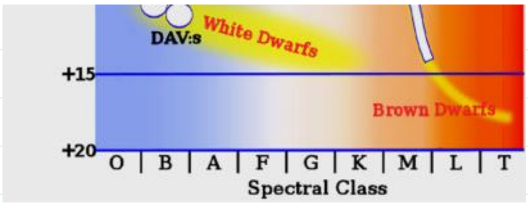
Plot of L versus T (for nearby stars with known distance d, brightness b and spectral class)
- the luminosity L from d and b.
- the surface temperature T from spectral type (or colour)

Modern data relies on parallaxes for thousands of nearby stars from Hipparcos satellite



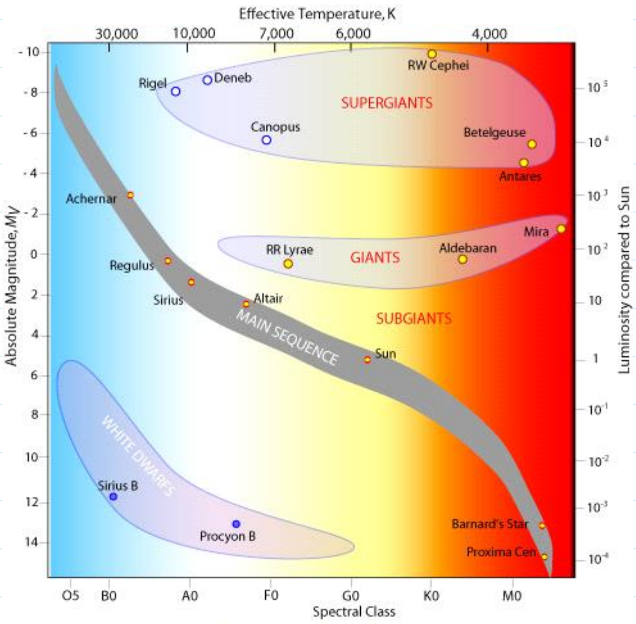




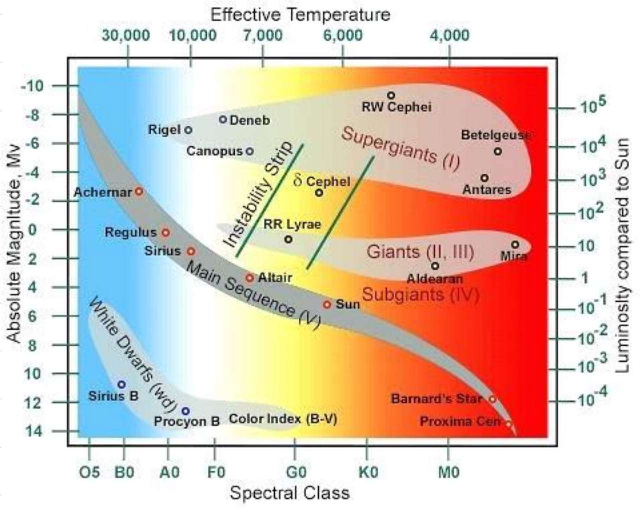


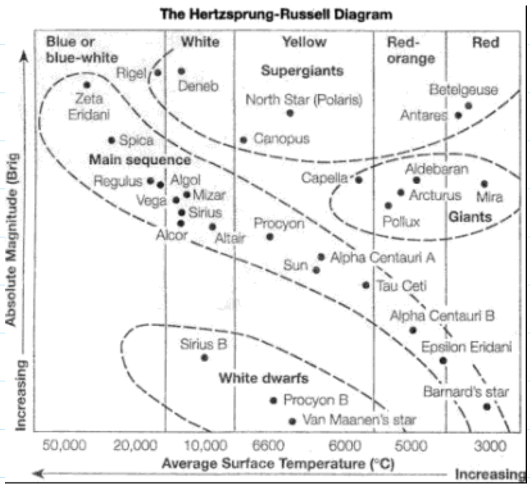
An HR diagram with the [instability strip]

출처: <https://en.wikipedia.org/wiki/Hertzsprung%E2%80%93Russell_diagram>



Hertzsprung-Russell Diagram



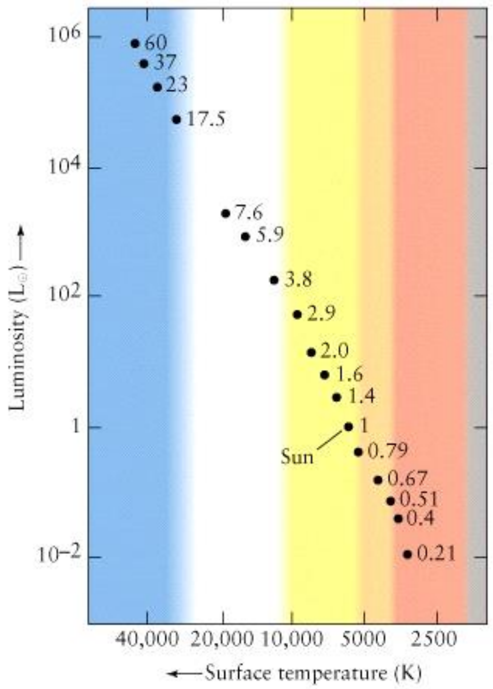


The H–R Diagram

- Temperature decreases to the right
  blue colour is on the left and
  red colour is on the right.
- The luminosity (or power) of the stars
  increases upwards.
- Most stars (90%) lie on the diagonal band
  running from top left to bottom right
  : the **Main Sequence (MS)**

The **Main Sequence** star Properties

- The hotter (their surface T),
  the more powerful they are.
- (Super)Giants :
  Stars more luminous than the MS stars.
- White Dwarfs :
  Stars less luminous than the MS stars.



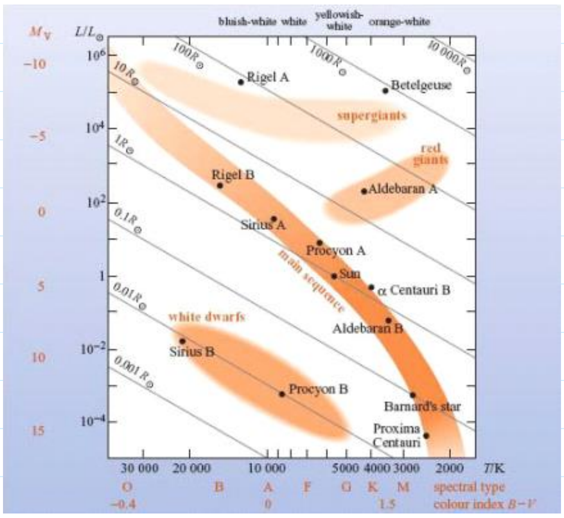
Mass
Mass (and metalicity, etc) determines
the properties of a star
(birth → evolution → death, etc.)

Star mass ranges

$0.08\ M_\odot \lesssim M_{\text{Star}} \lesssim 100 M_\odot$:

- If $M_{\text{Star}} \gtrsim 100 M_\odot$,
  stars release too much energy
  through nuclear fusion
  and are unstable.
- If $M_{\text{Star}} \lesssim 0.08\ M_\odot$,
  stars are too small to sustain
  nuclear fusion.
  : brown dwarfs.

출처: <https://people.highline.edu/iglozman/classes/astronotes/hr_diagram.htm>



출처: <https://www.open.edu/openlearn/science-maths-technology/comparing-stars/content-section-1.1>

Radii of Stars:
MS, Giants and Dwarfs

A star's luminosity
- the Stefan-Boltzmann law -

$L = 4\pi R^2 \sigma T^4$

This allows to determine
The **radius R** of a star from the L & T

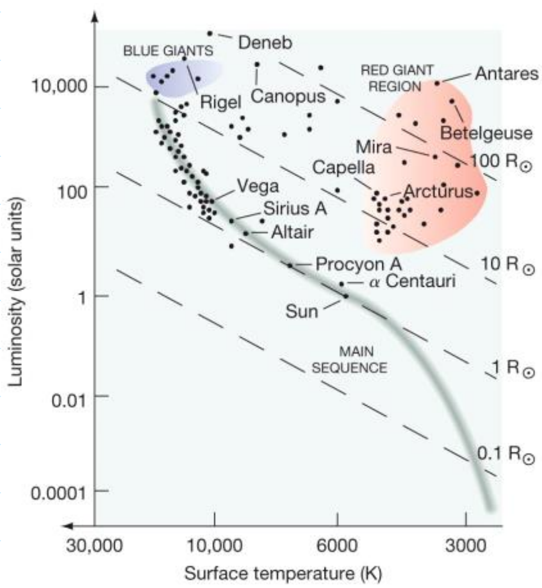
$R = (L / (4\pi\sigma T^4))^{1/2}$

or,

$\mathbf{log\,R} = 1/2\ \mathbf{logL} + 2\mathbf{log(1/T)} - 1/2\log(4\pi\sigma)$

On H-R diagram the stars

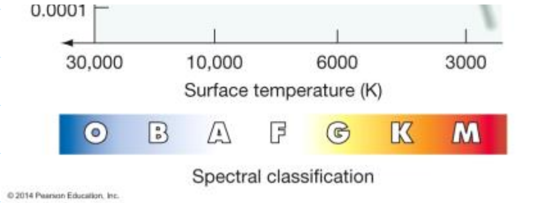
- of the same temperature,
  lie on a vertical line
- of the same luminosity,
  lie on a horizontal line
- of the same radius,
  lie on an inclided line



Therefore

- Two stars of the same T
  ⇝ the larger star is more luminous.
- Two stars of the same L
  ⇝ the larger star is cooler.

For the same T,
- Giants above the MS
  are larger than MS stars
- Supergiants above the giants
  are larger than the giants
- White dwarfs below the MS
  are smaller than MS stars



H-R Diagram is plot of Luminosity vs. Spectral Class

출처: <https://pages.uoregon.edu/jimbrau/astr122/Notes/Chapter17.html>

are larger than the giants

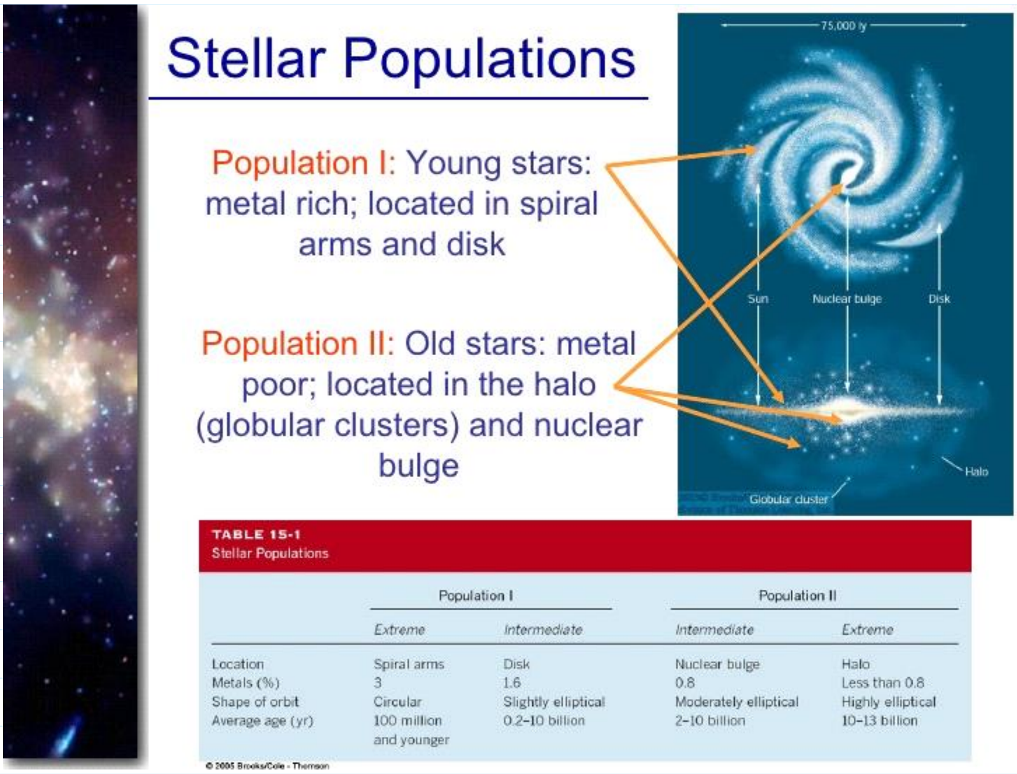
- White dwarfs below the MS
  are smaller than MS stars
- Terminology:
  Red dwarfs = type (K and) M MS stars.

  Along the MS,
- Higher T, then
  higher L and also
  (slightly) larger R

List of brightest stars

Rank	Visual mag(m_V)	Proper name[6]	Bayer		Distance (ly)	Spectral class
1	−26.74	Sun			1.5823820×10^{5}	G2 V
2	−1.46	Sirius	α	CMa	8.6	A0mA1 Va, DA2
3	−0.74	Canopus	α	Car	310	A9 II
4	−0.27 (0.01 + 1.33)	Rigil Kentaurus & Toliman	α	Cen	4.4	G2 V, K1 V
5	−0.05	Arcturus	α	Boo	37	K0 III
6	0.03 (−0.02–0.07var)	Vega	α	Lyr	25	A0 Va
7	0.08 (0.03–0.16var)	Capella	α	Aur	43	K0 III, G1 III
8	0.13 (0.05–0.18var)	Rigel	β	Ori	860	B8 Ia
9	0.34	Procyon	α	CMi	11	F5 IV-V
10	0.46 (0.40–0.46var)	Achernar	α	Eri	139	B6 Vep
11	0.50 (0.0–1.6var)	Betelgeuse	α	Ori	700	M1-M2 Ia-ab
12	0.61	Hadar	β	Cen	390	B1 III
13	0.76	Altair	α	Aql	17	A7 V
14	0.76 (1.33 + 1.73)	Acrux	α	Cru	320	B0.5 IV, B1 V
15	0.86 (0.75–0.95var)	Aldebaran	α	Tau	65	K5 III
16	0.96 (0.6–1.6var)	Antares	α	Sco	550	M1.5 Iab-Ib, B2.5 V
17	0.97 (0.97–1.04var)	Spica	α	Vir	250	B1 III-IV, B2 V
18	1.14	Pollux	β	Gem	34	K0 III
20	1.25 (1.21–1.29var)	Deneb	α	Cyg	2,615	A2 Ia
22	1.39	Regulus	α	Leo	79	B8 IVn
25	1.62 (1.98 + 2.97)	Castor	α	Gem	52	A1 V, Am
49	1.98 (1.86–2.13var)	Polaris	α	UMi	430	F7 Ib

출처: <https://en.wikipedia.org/wiki/List_of_brightest_stars>



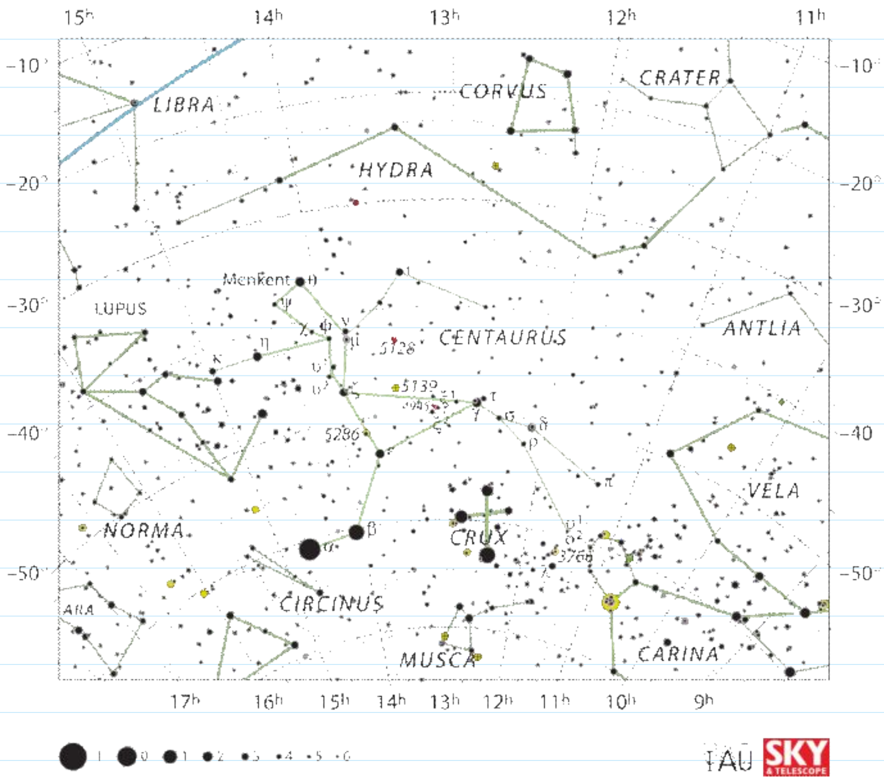
	Population I		Population II	
	Extreme	Intermediate	Intermediate	Extreme
Location	Spiral arms	Disk	Nuclear bulge	Halo
Metals (%)	3	1.6	0.8	Less than 0.8
Shape of orbit	Circular	Slightly elliptical	Moderately elliptical	Highly elliptical
Average age (yr)	100 million and younger	0.2–10 billion	2–10 billion	10–13 billion

Red dwarfs and other low-mass stars still remain on the main sequence when more massive stars have moved off the main sequence allows the age of star clusters to be estimated by finding the mass at which the stars move off the main sequence.

- This provides a lower limit to the age of the Universe and also allows formation timescales to be placed upon the structures within the Milky Way, such as the Galactic halo and Galactic disk.

- All observed red dwarfs contain "metals", which in astronomy are elements heavier than hydrogen and helium.
- The Big Bang model predicts that the first generation of stars should have only hydrogen, helium, and trace amounts of lithium, and hence would be of low metallicity.
- With their extreme lifespans, any red dwarfs that were a part of that first generation (population III stars) should still exist today.
- Low-metallicity red dwarfs, however, are rare.
- The accepted model for the chemical evolution of the universe anticipates such a scarcity of metal-poor dwarf stars because only giant stars are thought to have formed in the metal-poor environment of the early universe.
- As giant stars end their short lives in supernova explosions, they spew out the heavier elements needed to form smaller stars. Therefore, dwarfs became more common as the universe aged and became enriched in metals.
- While the basic scarcity of ancient metal-poor red dwarfs is expected, observations have detected even fewer than predicted, the discrepancy confirmed by improved detection methods.

출처: <https://en.wikipedia.org/wiki/Red_dwarf>



Omega Centauri

Class	VIII[1]
Constellation	Centaurus
Right ascension	$13^h\ 26^m\ 47.28^s$[2]
Declination	−47° 28′ 46.1″[2]
Distance	156kly (4.84kpc)
Appa mag (V)	3.9[4]
Appar dim (V)	36′.3
Phys charact	
Mass	$4\times10^6\ M_\odot$
Radius	86 ± 6 ly[7]
Metallicity	[Fe/H]= −1.35dex
Estimated age	11.52 Gyr[8]
Other designations	NGC 5139, GCl 24, ω Centauri, Caldwell 80, Mel 118

출처: <https://en.wikipedia.org/wiki/Omega_Centauri>

Star clusters

- Star clusters are groups of stars formed at the same time out of the same cloud of gas.
- In any typical star cluster, there is a large range of masses for the stars.

- Two main types of star clusters can be distinguished:
  - globular clusters are tight groups of hundreds to millions of old stars which are gravitationally bound, while
  - open clusters are more loosely clustered groups of stars, generally containing fewer than a few hundred members, and are often very young.
  - Open clusters become disrupted over time by the gravitational influence of giant molecular clouds as they move through the galaxy, but cluster members will continue to move in broadly the same direction through space even though they are no longer gravitationally bound; they are then known as a stellar association, sometimes also referred to as a *moving group*.

Ex) Star clusters visible to the naked eye include the Pleiades, Hyades, and 47 Tucanae.

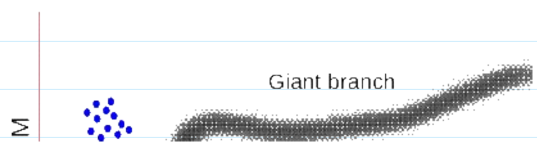
Globular clusters

Omega Centauri (ω Cen, NGC 5139)

- is a globular cluster that was first identified as a non-stellar object by Edmond Halley in 1677.
- Located at a distance of 17kly (5.24kpc),
- the largest known globular cluster in the Milky Way at a diameter ~ 150 ly.
- the most massive globular cluster in the Milky Way : # stars ~ 10M, a total mass ≈ 4 Mx$M_\odot$.
- Omega Centauri is very different from most other galactic globular clusters to the extent that it is thought to have an origin as the core remnant of a disrupted dwarf galaxy.

출처: <https://en.wikipedia.org/wiki/Omega_Centauri>

A **blue straggler** is a main-sequence star in an open or globular cluster that is more luminous and bluer than stars at the main sequence turnoff point for the cluster.



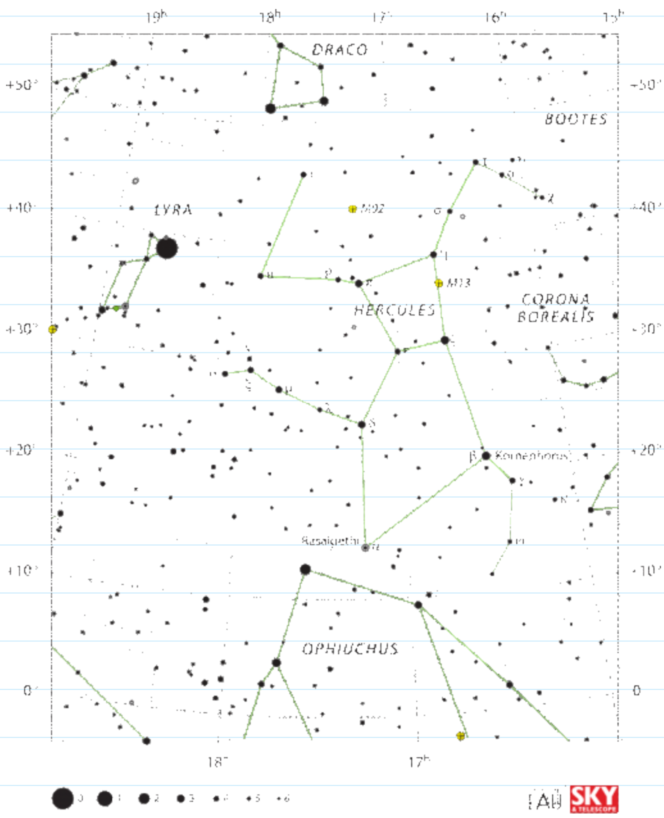
the Pleiades, Hyades, and 47 Tucanae.

Globular clusters

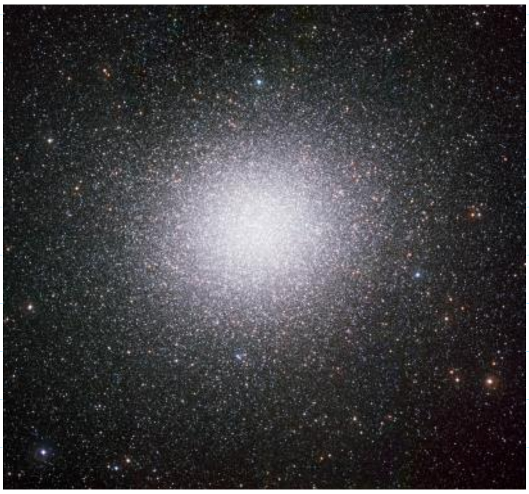
- are roughly spherical groupings of from 10 thousand to several million stars packed into regions of from 10 to 30 light-years across.
- They commonly consist of very old Population II stars – just a few hundred Myr younger than the universe itself – mostly yellow and red, with masses less than two solar masses.[1]
- Such stars predominate within clusters because hotter and more massive stars have exploded as supernovae, or evolved through planetary nebula phases to end as white dwarfs.
- Yet a few rare blue stars exist in globulars, thought to be formed by stellar mergers in their dense inner regions; these stars are known as blue stragglers(청색 낙오성).
- In our Galaxy, globular clusters are distributed roughly spherically in the galactic halo, around the Galactic Centre, orbiting the centre in highly elliptical orbits.
- greatly improved distance measurements to globular clusters using the Hipparcos satellite and increasingly accurate measurements of the Hubble constant resolved the paradox, giving an age for the universe of about 13 billion years and an age for the oldest stars of a few hundred million years less.
- Our Galaxy has about 150 globular clusters, some of which may have been captured cores of small galaxies stripped of stars previously in their outer margins by the tides of the Milky Way, as seems to be the case for the globular cluster M79.
- The giant elliptical galaxy M87 contains over a thousand globular clusters.
- A few of the brightest globular clusters are visible to the naked eye; the brightest, Omega Centauri, was observed in antiquity and catalogued as a star, before the telescopic age.
- The brightest globular cluster in the northern hemisphere is M13 in the constellation of Hercules.

Sketch of Hertzsprung–Russell diagram of a globular cluster, showing blue stragglers

출처: <https://en.wikipedia.org/wiki/Blue_straggler>



- M13 is 22–25kly away, diameter≈145ly,
- is composed of severalx10^5 stars,
- the brightest is the variable star V11 (V1554 Herculis), a red giant, with m_v = 11.95.
- Single stars were first resolved in 1779.
- the M13 star population is more than a hundred times more densely packed than that in the neighborhood of the Sun.
- They are so close together that they sometimes collide and produce new stars. The newly formed, young stars, so-called "blue stragglers", are particularly interesting to astronomers.
- The 1974 Arecibo message, which contained encoded information about the human race, DNA,



The globular cluster Omega Centauri

출처: <https://en.wikipedia.org/wiki/Omega_Centauri>

- The 1974 Arecibo message, which contained encoded information about the human race, DNA, atomic numbers, Earth's position and other information, was beamed towards M13 as an experiment in contacting potential extraterrestrial civilizations in the cluster.

출처: <https://en.wikipedia.org/wiki/Messier_13>

Open clusters

- Unlike the spherically distributed globulars, they are confined to the galactic plane, and are almost always found within spiral arms.
- usually contain up to a few hundred (or thousand) members, within a region up to about 30 light-years across.
- often dominated by hot young blue stars, because although such stars are short-lived in stellar terms, only lasting a few tens of millions of years, open clusters tend to have dispersed before these stars die.
- a few rare exceptions as old as a few billion years, such as Messier 67 (the closest and most observed old open cluster) for example.[2] They form H II regions such as the Orion Nebula.
- Being much less densely populated than globular clusters, they are much less tightly gravitationally bound, and over time, are disrupted by the gravity of giant molecular clouds and other clusters. Close encounters between cluster members can also result in the ejection of stars, a process known as 'evaporation'.
- The most prominent open clusters are the Pleiades and Hyades in Taurus. The Double Cluster of h+Chi Persei can also be prominent under dark skies.
- Establishing precise distances to open clusters enables the calibration of the period-luminosity relationship shown by Cepheids variable stars, which are then used as standard candles. Cepheids are luminous and can be used to establish both the distances to remote galaxies and the expansion rate of the Universe (Hubble constant). Indeed, the open cluster NGC 7790 hosts three classical

The **Pleiades** (/ˈpliː.əˌdiːz, ˈpleɪ-, ˈplaɪ-/), (**The Seven Sisters**, **Messier 45**),

- is an open star cluster, with core radius is about 8 ly and tidal radius is about 43 ly.
- over 1,000 members. Its light is dominated by young (middle-aged), hot B-type stars (blue stars) that have formed within the last 100 million years, up to 14 of which can be seen with the naked eye.
- It is among the star clusters nearest to Earth, and is the cluster most obvious to the naked eye in the night sky.
- were probably formed from a compact configuration that resembled the Orion Nebula.
- will survive for about another 250 million years, after which it will disperse due to gravitational interactions with its galactic neighborhood.
- Together with the open star cluster of

used to establish both the distances to remote galaxies and the expansion rate of the Universe (Hubble constant). Indeed, the open cluster NGC 7790 hosts three classical Cepheids which are critical for such efforts.

- More than 1,100 open clusters have been discovered within the Milky Way Galaxy, and many more are thought to exist.

출처: <https://en.wikipedia.org/wiki/Open_cluster>

Hyades Cluster

Constellation	Taurus
Right ascension	$4^h\ 27^m$
Declination	+15° 52′
Distance	153 ly (47 pc)
Appar mag (V)	0.5
Appar dimen (V)	330′
Phys charact	
Mass	400 $M_\odot$
Radius	10 ly (core radius)
Estimated age	625 Myr
Notable features	Closest open cluster
Other designations	Caldwell 41, Cr 50, Mel 25

출처: <https://en.wikipedia.org/wiki/Hyades_(star_cluster)>

Pleiades

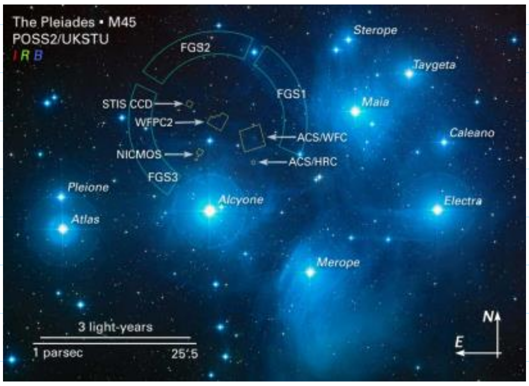
Constellation	Taurus
Right ascension	$03^h\ 47^m\ 24^s$[1]
Declination	+24° 07′ 00″[1]
Distance	444 ly (136 pc)
Appar mag(V)	1.6[6]
Appar dimen (V)	110′ (arcmin)
Other designations	Seven Sisters, M45, Cr 42,

출처: <https://en.wikipedia.org/wiki/Pleiades>

neighborhood.

- Together with the open star cluster of the Hyades, the Pleiades form the Golden Gate of the Ecliptic.
- The total mass contained in the cluster is about 800 solar masses and is dominated by fainter and redder stars.
- The cluster contains many brown dwarfs, They may constitute up to 25% of the total population of the cluster, although they contribute less than 2% of the total mass.
- Astronomers have made great efforts to find and analyse brown dwarfs in the Pleiades and other young clusters, because they are still relatively bright and observable, while brown dwarfs in older clusters have faded and are much more difficult to study.

출처: <https://en.wikipedia.org/wiki/Pleiades>



Embedded clusters

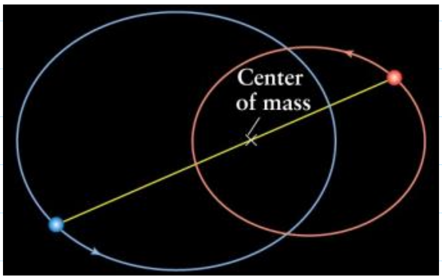
- are groups of very young stars that are partially or fully encased in an Interstellar dust or gas which is often impervious to optical observations. Embedded clusters form in molecular clouds, when the clouds begin to collapse and form stars. There is often ongoing star formation in these clusters, so embedded clusters may be home to various types of young stellar objects including protostars and pre-main-sequence stars. An example of an embedded cluster is the Trapezium Cluster in the Orion Nebula. In ρ Ophiuchi cloud (L1688) core region there is an embedded cluster.
- The embedded cluster phase may last for several million years, after which gas in the cloud is depleted by star formation or dispersed through radiation pressure, stellar winds and outflows, or supernova explosions. In general less than 30% of cloud mass is converted to stars before the cloud is dispersed, but this fraction may be higher in particularly dense parts of the cloud. With the loss of mass in the cloud, the energy of the system is altered, often leading to the disruption of a star cluster. Most young embedded clusters disperse shortly after the end of star formation.
- The open clusters found in the Galaxy are former embedded clusters that were able to survive early cluster evolution. However, nearly all freely floating stars, including the Sun,[7] were originally born into embedded clusters that disintegrated.

Super star clusters

- are very large regions of recent star formation, and are thought to be the precursors of globular clusters.
- Examples include Westerlund 1 in the Milky Way.

출처: <https://en.wikipedia.org/wiki/Star_cluster>

Binary Stars



- Most stars are not isolated in space.
- About one half of all stars which we see are in a double or multiple star system, all orbiting about the common centre-of-mass of the system.
- This is not accidental! The process of star formation tends to cause many stars to be formed close to each other.
- In a binary system, each star moves on an elliptical path with the COM at the focus for both ellipses.
  and distances between each star and the COM
  satisfying $r_1M_1 = r_2M_2$.

61 Cygni /ˈsɪɡni/

- is a binary star system in the constellation Cygnus, consisting of a pair of K-type dwarf stars
  - K5V 0.70 $M_\odot$ 0.665$R_\odot$ 0.153$L_\odot$ 4,526 K 6.1Gyr
  - K7V 0.63 $M_\odot$ 0.595 $R_\odot$ 0.085 $L_\odot$ 4,077 K 6.1 Gyr
- orbital period of about 659 years.
- Of apparent magnitude 5.21 and 6.05, respectively, they can be seen with binoculars in city skies or with the naked eye in rural areas without photopollution.
- 61 Cygni first attracted the attention due to its large proper motion first demonstrated in 1804.
- In 1838, measured its distance, the first distance estimate for any star other than the Sun.
- and first star to have its stellar parallax measured.
- the seventh-highest proper motion, and the highest among all visible stars or systems.
- No planets have been confirmed yet.

Early observations

1753, it was a double star.

His observations led to the conclusion that binary stars were separated enough that they would show different movements in parallax over the year.

It was in this record he christened the system as the "Flying Star".[32]

suggested to determine its distance through parallax measurements, along with two other possibilities, Delta Eridani and Mu Cassiopeiae.[31]

61 Cygni

Constellation	Cygnus
61 Cygni A	
Right ascension	21h 06m 53.940s[1]
Declination	+38° 44′ 57.90″[1]
Apparent mag (V)	5.21[1]
61 Cygni B	
Right ascension	21h 06m 55.31s
Declination	+38° 44′ 31.4″
Apparent mag(V)	6.05[2]
Characteristics	
61 Cyg A	
Spectral type	K5V
Variable type	BY Dra[4]
61 Cyg B	
Spectral type	K7V
Variable type	Flare star[5]
Astrometry	
61 Cygni A	
Radial vel (R$_v$)	-65.94[6] km/s
Proper motion(μ)	RA: 4164 mas/yr Dec.:3250mas/yr
Parallax (π)	286 mas
Distance	11.4 ly (3.5 pc)
Absol mag(M$_V$)	7.506[8]
61 Cygni B	
Radial velocity (R$_v$)	-64.43[9] km/s

It was in this record he christened the system as the "Flying Star".[30] suggested to determine its distance through parallax measurements, along with two other possibilities, Delta Eridani and Mu Cassiopeiae.[31]

출처: <https://en.wikipedia.org/wiki/61_Cygni>

Binary observations[edit]

Due to the wide angular separation between 61 Cygni A and B, and the correspondingly slow orbital motion, it was initially unclear whether the two stars in the 61 Cygni system were a gravitationally bound system or simply a juxtaposition of stars.[38] von Struve first argued for its status as a binary in 1830, but the matter remained open.[38]

However, by 1917 refined measured parallax differences demonstrated that the separation was significantly less.[39] The binary nature of this system was clear by 1934, and orbital elements were published.[40]

In 1911, Benjamin Boss published data indicating that the 61 Cygni system was a member of a comoving group of stars.[41] This group containing 61 Cygni was later expanded to include 26 potential members. Possible members include Beta Columbae, Pi Mensae, 14 Tauri and 68 Virginis. The space velocities of this group of stars range from 105 to 114 km/s relative to the Sun.[42][43]

Observations taken by planet search programs show that both components have strong linear trends in the radial velocity measurements.[44]

출처: <https://en.wikipedia.org/wiki/61_Cygni>

Absol mag (M_V)	7.506[8]
61 Cygni B	
Radial velocity (R_v)	-64.43[9] km/s
Proper motion (μ)	RA: 4,106 mas/yr Dec.: 3,156mas/yr
Parallax (π)	286 mas
Distance	11.4 ly (3.5 pc)
Absol mag (M_V)	8.228[8]
Orbit[11]	
Companion	61 Cygni B
Period (P)	678 ±34 yr
Semi-maj axis(a)	24.272 ±0.592"
Eccentricity (e)	0.49 ±0.03
Inclination (i)	51 ±2°
Details	
61 Cygni A	
Mass	0.70 $M_\odot$
Radius	0.665$R_\odot$
Luminosity	0.153 $L_\odot$
Temperature	4,526 K
Metallicity [Fe/H]	−0.20[14] dex
Rotation	35.37 d[16]
Age	6.1Gyr
61 Cygni B	
Mass	0.63 $M_\odot$
Radius	0.595 $R_\odot$
Luminosity	0.085 $L_\odot$
Temperature	4,077 K
Metallicity [Fe/H]	−0.27[14] dex
Rotation	37.84 d[16]
Age	6.1 Gyr
Other designations	
GJ 820 A/B, Struve 2758,	ADS 14636, V1803 Cygni,
61 Cygni A V1803 Cygni,	HD 201091,
61 Cygni B:	HD 201092

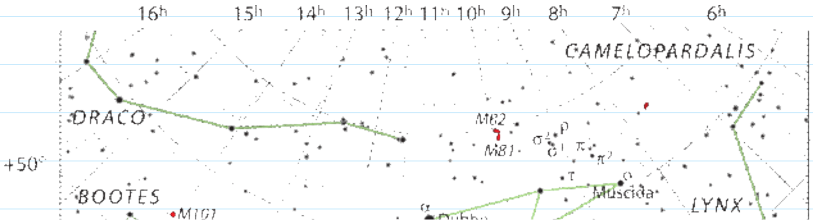
출처: <https://en.wikipedia.org/wiki/61_Cygni>

Types of Binary
(or Double) Star Systems

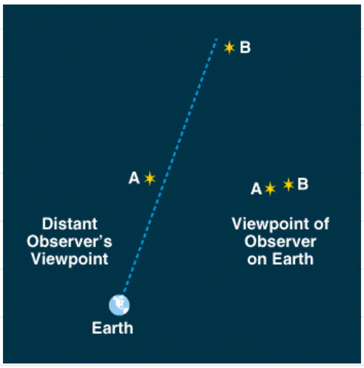
An Optical Double

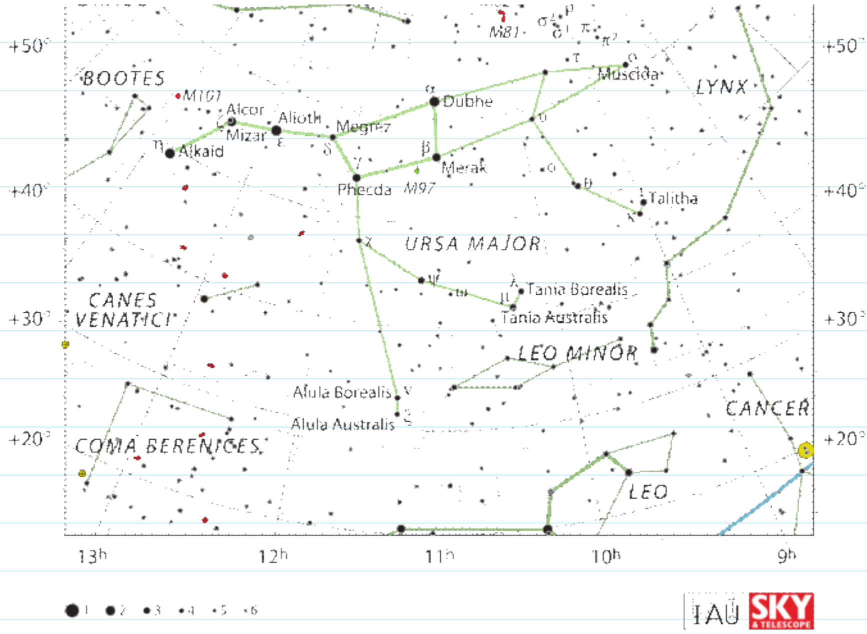
- This is not a true binary star system, just a chance alignment of two stars in the same line-of-sight.
- Example : the stars Alcor and Mizar in the Big Dipper
  - appear to be in the same location "zeta" of the sky
  - at the location of Mizar there are actually two stars, Alcor and Mizar.
  - The distance between Alcor and Mizar is about 1 pc.

Constellation **Ursa Major**



and Mizar is about 1 pc.





출처: <https://en.wikipedia.org/wiki/Ursa_Major>

Mizar /ˈmaɪzɑːr/ **ζ Ursae Majoris** (**Zeta Ursae Majoris**).

- It forms a well-known naked eye double star with the fainter star Alcor, (separation minutes of arcsec)
- and each of which is a spectroscopic binary, forming a quadruple star system.
- The whole system lies about 83 light-years away from the Sun, as measured by the Hipparcos astrometry satellite, Its combined apparent magnitude is 2.04.
- and is part of the Ursa Major Moving Group.

출처: <https://en.wikipedia.org/wiki/Mizar>

- The two visible stars are referred to as
  ζ¹ Ursae Majoris or Mizar A and
  ζ² Ursae Majoris, or Mizar B.
- The spectroscopic components are generally referred to as
  Mizar Aa, Ab,
  Mizar Ba, and Bb.
- Mizar, together with Alcor and many of the other bright stars in Ursa Major, is a member of the Ursa Major Moving Group.[22]
- Mizar was the first telescopic binary discovered, most probably by Benedetto Castelli who in 1617 asked Galileo Galilei to observe it.

Mizar + Alcor Sextuplet system

- Visual Binary (naked eye double star): 83ly
  Mizar (ζ Ursae Majoris) + Alcor (80 Ursae Majoris)
  - 12 minutes of arc, 0.5~1.5 ly separation
  - Gravitational boundedness to be confirmed
  - Mizar+Alcor sextuplet
  - Mizar (ζ UMa) :quadruple star system

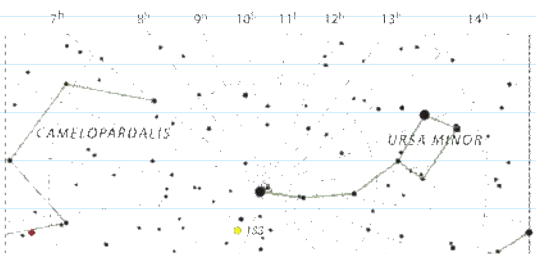
Mizar A&B visual binary (the first telescopic binary)

- Mizar A(ζ^1 Ursae Majoris) +Mizar B (ζ^2 Ursae Majoris)
  - 14.4 arcsec, 380AU, ~1,000yr revol period
  - each is a spectroscopic binary.
  - Combined apparent magnitude =2.04

Each of Mizar A&B : a Spectroscopic binary

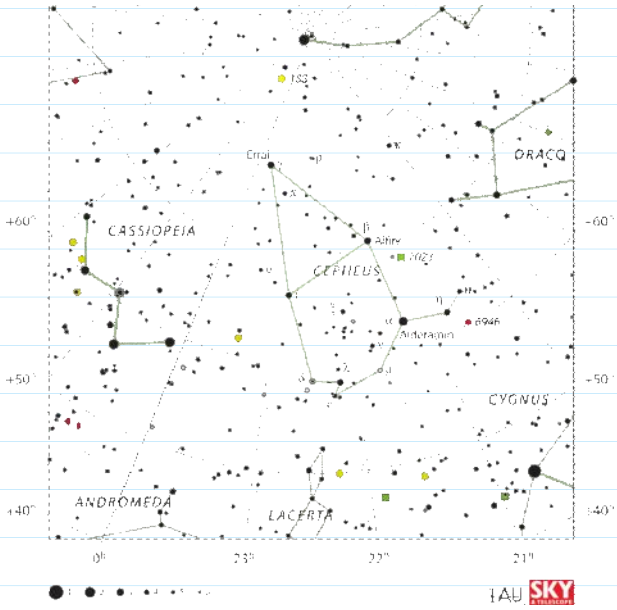
- **ζ¹ Ursae Majoris** : Spectroscopic binary (the 1st)
  (Mizar A) : Mizar Aa + Mizar Ab
  A2Vp A2Vp
  Revol period 20days 13hr
- **ζ² Ursae Majoris**: Spectroscopic binary
  (Mizar B) : Mizar Ba + Mizar Bb
  Period 1/2 yr

- **Alcor** A&B : binary :
  - Alcor A + Alcor B : mv=3.99,
    A5V M3-4V, red dwarf
  - B is 1 sec of arc away from A
  - 1.2ly away from the Mizar quadruple system
  - Distance 81.7ly(25pc)



Castelli who in 1617 asked Galileo Galilei to observe it.

- Later, around 1650, Riccioli wrote of Mizar appearing as a double.[24] The secondary star (Mizar B) comes within 380 AU of the primary (Mizar A) and the two take thousands of years to revolve around each other.[25]
- Mizar A was the first spectroscopic binary to be discovered.
- The two components of Mizar A are both about 35 times as bright as the Sun, and revolve around each other in about 20 days 12 hours and 55 minutes.
- In 1908, Mizar B was also found to be a spectroscopic binary, its components completing an orbital period every six months.[8]

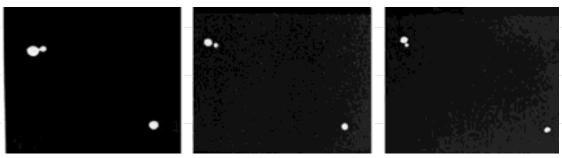


출처: <https://en.wikipedia.org/wiki/Mizar>

A Visual Binary

- A double star system where you can see both stars and they appear to move around each other is a **visual binary**.

- Example
  the star system Kruegar 60.
  - The photos below show that from 1908 to 1920 the visual binary completed about 1/4 of a revolution.



1908 1915 1920

Kruger 60 (DO Cephei)

- a binary star system, red dwarf stars,
- located 13 ly (4pc)
- orbit every 44.6 yr.
  Average separation : 9.5 AU.
  (varies between 5.5 AU (periastron) and 13.5(apastron))

- Component A M_A=0.27 $M_\odot$ and R_A=0.35 $R_\odot$.
- Component B M_B=0.18 $M_\odot$ and R_B=0.24 $R_\odot$
- Component B is a flare star,
  the variable star designation "DO Cephei".

Kruger 60 A/B

Constellation	Cepheus
Kruger 60 A	
Right ascension	22h 27m 59.4677s
Declination	+57° 41′ 45.150″
Appar mag (V)	9.59
Kruger 60 B	
Right ascension	22h 27m 59.568s
Declination	+57° 41′ 45.28″
Appar mag (V)	11.40
Characteristics	
Spectral type	M3V/M4V
Variable type	None/Flare star
Astrometry	
Radial vel (R_v)	−33.1/−31.9 km/s
Proper motion (μ)	RA: −870.23mas/yr Dec.: −471.10mas/yr
Parallax (π)	247.5 ± 1.5 mas
Distance	13.2 ly (4.0 pc)
Absol mag (M_V)	11.76/13.46
Details	
Krueger 60 A	
Mass	0.271 $M_\odot$
Radius	0.35 $R_\odot$
Luminosity	0.010 $L_\odot$

Mass	0.271 $M_\odot$
Radius	0.35 $R_\odot$
Luminosity	0.010 $L_\odot$
Temperature	3,180 K
Metallicity	–0.04
Krueger 60 B	
Mass	0.176 $M_\odot$
Radius	0.24 $R_\odot$
Luminosity	0.0034 $L_\odot$
Temperature	2,890 K
Orbit[7]	
Primary	Kruger 60 A
Companion	Kruger 60 B
Period **(P)**	44.67 yr
Semi-maj axis **(a)**	2.383″
Eccentricity **(e)**	0.410

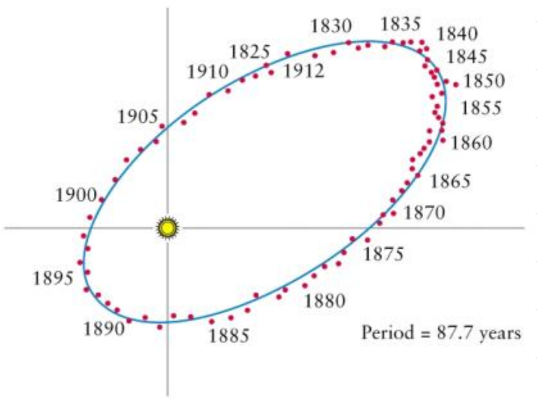
출처: <https://en.wikipedia.org/wiki/Kruger_60>

- Component B is a flare star,
  the variable star designation "DO Cephei".
  - an irregular flare, typically doubles in brightness and then returns to normal over an 8-minute period.
- This system is orbiting through the Milky Way at a distance from the core that varies from 7–9 kpc with an orbital eccentricity of 0.126–0.130.
- The closest approach to the Sun within 1.95 pc will occur in about 88,600 years.
- Kruger 60 has been proposed as the origin of interstellar comet 2I/Borisov by Dybczyński, Królikowska, and Wysoczańska.

출처: <https://en.wikipedia.org/wiki/Kruger_60>

Example 2 of a Visual Binary : 70 Ophiuchi.

- The figure shows a plot of one star with respect to the other over time.
- Over the course of 87.7 years, the star makes one full orbit.



70 Ophiuchi

Constellation	Ophiuchus
70 Ophiuchi	
Right ascension	18^h 05^m 27.285^s[1]
Declination	+02° 29′ 00.36″[1]
Appar mag **(V)**	4.00 - 4.03[2]
A	
Right ascension	18^h 05^m 27.371^s[3]
Declination	+02° 29′ 59.32″[3]
Appar mag **(V)**	4.13
B	
Right ascension	18^h 05^m 27.462^s[4]
Declination	+02° 29′ 56.22″[4]
Appar mag **(V)**	6.07
Characteristics	
Spectral type	K0V + K4V[5]
Appar mag **(B)**	4.97/7.26[3]
Appar mag **(R)**	3.6/5.6
Variable type	BY Dra or RS Cvn
Astrometry	
Radial vel **(R_v)**	−6.87[8] km/s
Proper motion **(μ)**	RA: 124.16 mas/yr Dec.: −963mas/yr
Parallax **(π)**	196.72±0.83 mas
Distance	16.6ly (5.0 pc)
Absol mag **(M_V)**	+5.49
Orbit[8]	
Period **(P)**	88.38±0.017 yr
Semi-maj axis **(a)**	4.554±0.0052″

70 Ophiuchi

- a binary star system in the constellation Ophiuchus.
- located 16.6 ly away from the Earth. At mag 4 it appears as a dim star visible to the unaided eye away from city lights.

Variability

- 70 Ophiuchi is a variable star
  - with a magnitude range for the two stars combined of 4.00 to 4.03.
  - The type of variability is uncertain and not clear which of the two causes the variations.
  - Maybe either a BY Draconis variable or an RS Canum Venaticorum variable,

- Maybe either a BY Draconis variable or an RS Canum Venaticorum variable,
- a period of 1.92396 days has been measured.

Binary star

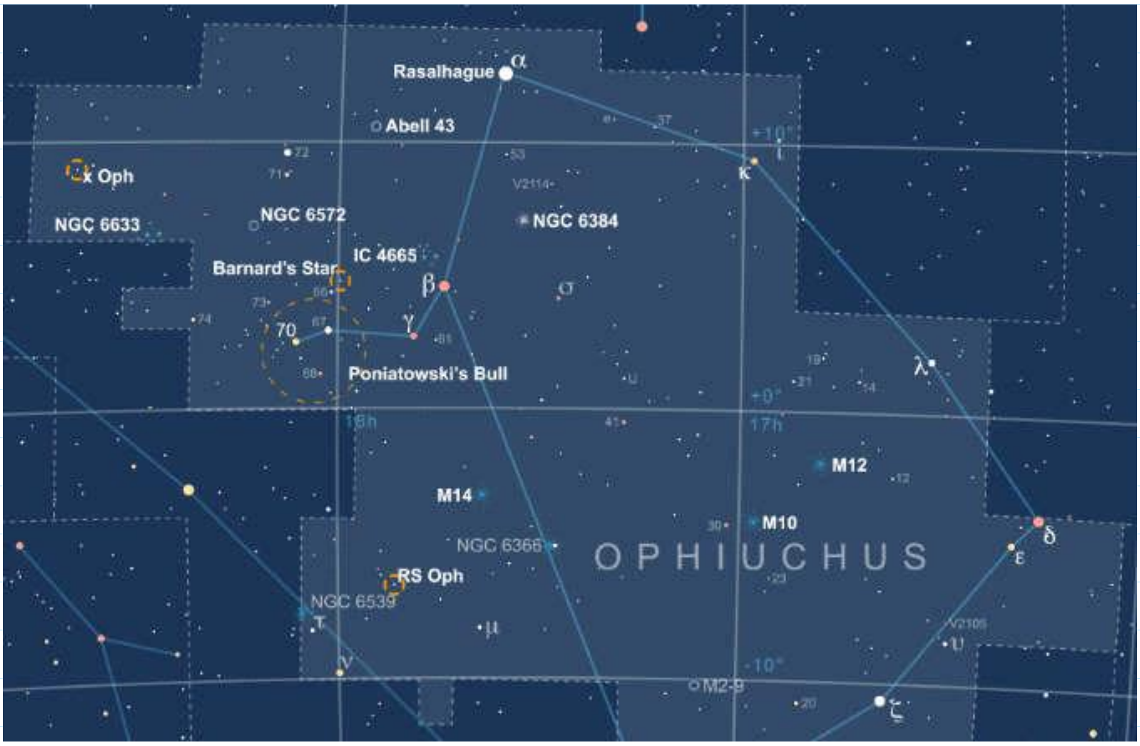
- The primary star is a yellow-orange main sequence dwarf of spectral type K0, while the secondary is an orange dwarf of spectral type K4.[5]
- The two stars orbit each other at an average distance of 23.2 AU. But since the orbit is highly elliptical (at *e*=0.499), the separation between the two varies from 11.4 to 34.8 AU, with one orbit taking 88.38 years to complete.

Claims of a planetary system : controversial

출처: <https://en.wikipedia.org/wiki/70_Ophiuchi>

Orbit	
Period (P)	88.38±0.017 yr
Semi-maj axis (a)	4.554±0.0052″
Eccentricity (e)	0.4992±0.00039
Details	
70 Oph A	
Mass	0.90 $M_\odot$
Radius	0.91 $R_\odot$
Luminosity (bolo)	0.59 ± 0.02[11] $L_\odot$
Surface gravity (log *g*)	4.5 cgs
Temperature	5,300 K
Metallicity [Fe/H]	+0.04[13] dex
Rotation	19.7 days[13]
Age	1.9 Gyr
70 Oph B	
Mass	0.70 ± 0.07 $M_\odot$
Luminosity (bolo)	0.13 ± 0.03[10] $L_\odot$
Temperature	4,350 ± 150 K

출처: <https://en.wikipedia.org/wiki/70_Ophiuchi>



RS Oph lies in the large constellation of Ophiuchus, 3.75 degrees north-west of nu (ν) Oph. AN Graphic by Greg Smye-Rumsby.

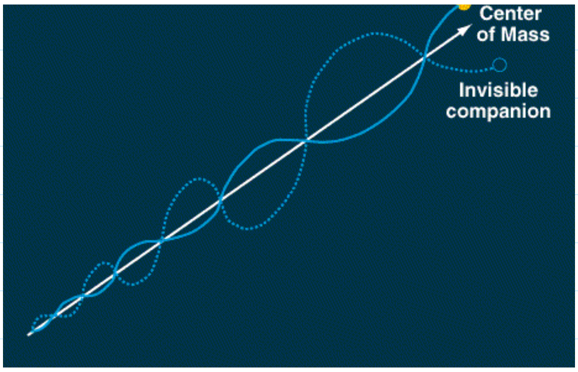
출처: <https://astronomynow.com/2021/08/10/rs-ophiuchi-in-a-rare-outburst-to-naked-eye-visibility/>

Astrometric Binary

If only one star is visible, but we can detect that it wobbles about an unseen centre-of-mass, then we have an **astrometric binary**.

detect that it wobbles about an unseen centre-of-mass, then we have an **astrometric binary**.

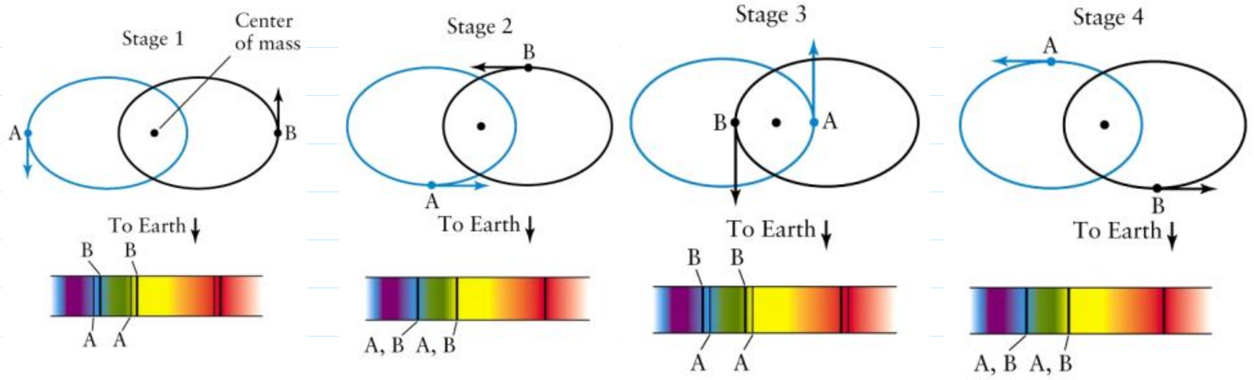
- The star Sirius is a binary system, but Sirius A is so much brighter than Sirius B that we only see Sirius A.
- Sirius B was first detected by observing the motion of the brighter Sirius A.



Spectroscopic Binary

- We see only one source of light.
- The spectrum of the star shows Doppler shifts which change from redshift to blueshift periodically.
- This means that the star is moving in a periodic orbit
- When the star moves towards us, we see a blueshift.
- When the star moves away from us, we see a redshift.
- The period of time from redshift to blueshift back to redshift again is the orbital period.
- Examples of spectroscopic binaries:
  - Mizar A is actually a spectroscopic binary composed of two stars.
  - Mizar B is also a spectroscopic binary composed of two stars.
  - Mizar is actually a 4-star system.

Star A's light is blueshifted. Star B's light is redshifted.	No Doppler shifts occur.	Star A's light is redshifted. Star B's light is blueshifted.	No Doppler shifts occur.



Stellar Velocities in a Spectroscopic Binary

- From the Doppler shift data, we can reconstruct the component of the stars' velocities in our line of sight.
- The true velocities are only known if the binary's inclination angle with our line of sight is known.
- A typical velocity curve is shown.

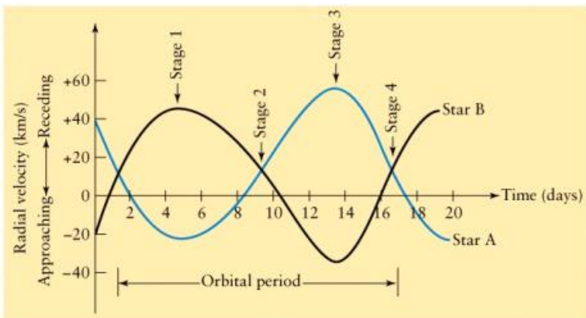
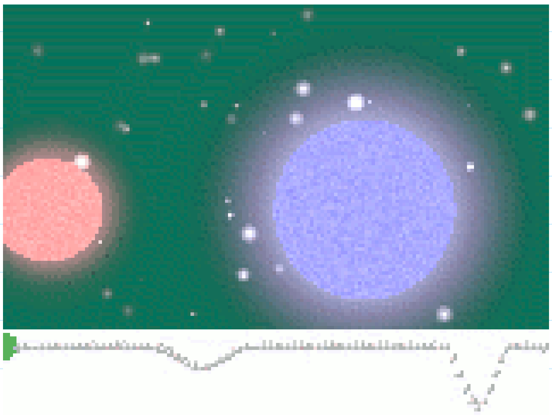


Figure 19-24

Extra-Solar Planets

- This method is used to find planets around other stars.
- When a star has a planet, the system's centre-of-mass is not exactly at the centre of the star.
- (For example the centre-of-mass of the Solar system is close to the surface of the Sun.)
- The star will "wobble" around the centre-of-mass and its light will be periodically redshifted and blueshifted.
- This reveals the presence of an invisible planet!
- About 429 planets around other stars have been detected mostly using this indirect method.
- Most of the planets detected have masses similar to Jupiter but orbit at distances much closer to the star than Jupiter does.

Eclipsing Binary



- Suppose that the plane of the orbit is in the same plane as your line-of-sight.
- Then one star will pass between you and the other star, causing an eclipse.
- Over a period of time you will see the light from the system get dimmer for a short time as the dimmer star passes in front of the brighter star.
- By measuring the duration of the eclipses, we can find out the size of each star.

Algol variables or **Algol-type binaries** are a class of eclipsing binary stars

- An Algol binary is a semidetached binary system
  - the primary component is an early type, main sequence star that does not fill its Roche lobe,
  - while the cooler, fainter, larger, less massive secondary component lies above the main sequence in a H–R diagram and fills the Roche lobe.
  - Early in its history, the secondary star would have been more massive, evolving first to overfill its Roche lobe. After rapid mass exchange, the lobe-filling star became less massive than its companion.
- Brightness variations
  - primary minimum : When the cooler component passes in front of the hotter one,
  - the secondary minimum : when the hotter component passes in front of the cooler one.
- The period is very regular determined by the revolution period of the binary.
  typically a few days, (most Algol variables are quite close binaries, with short periods)
  - The shortest known period is 0.1167 days (~2:48 hours, HW Virginis);
  - the longest is 9892 days (27 years, Epsilon Aurigae).
- Over long periods of time, various effects can cause the period to vary:
  in some Algol binaries, mass transfer may cause monotonic increases in period;
  magnetically active component of the pair or magnetic braking of a third component can change.
- Component stars of Algol binary systems have a spherical, or slightly ellipsoidal shape, unlike the so-called beta Lyrae variables and W Ursae Majoris variables, where the two components are so close that gravitational effects lead to serious deformations of both stars.
- Generally the amplitudes of the brightness variations are of the order of one magnitude, the largest known being 3.4 magnitudes (V342 Aquilae).
- In most cases the brighter component is found to have a B, A, F, or G class.

- [Algol](https://en.wikipedia.org/wiki/Algol), the prototype of this type of variable star : variability recorded in 1667, explained in 1782.
- Many thousands of Algol binaries are now known:

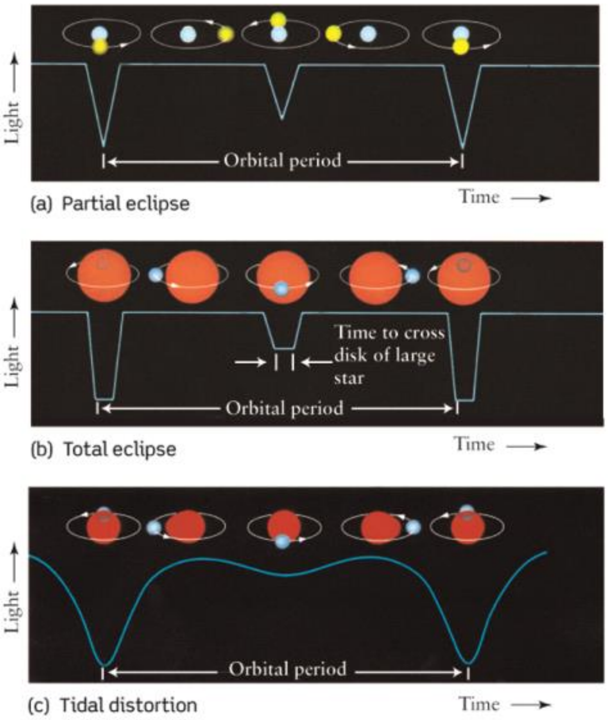
출처: <https://en.wikipedia.org/wiki/Algol_variable>

Example: Algol (**Beta Persei**, **β Persei**, **Beta Per**, **β Per**) "Demon Star" (in ancient Arabic)

- The star Algol is about 93ly from the Sun in the constellation Perseus.
- Every 2.87 days it dims for about 10 hours.
- Normally Algol's apparent magnitude is 2.1, so it is easily seen in the city.
- During the eclipse, it dims to magnitude 3.4, so it is only barely visible in the city.

- about 7.3 million years ago, Algol passed within 9.8 ly of the Solar System, and

  its apparent magnitude was about −2.5, brighter than the Sirius today.
  The total Algo sytem mass about 5.8 solar masses might have given enough gravity to perturb the Oort cloud somewhat and hence increase the number of comets entering the inner Solar System.



(a) Partial eclipse

(b) Total eclipse

(c) Tidal distortion

Algol (Beta Persei, β Persei, Beta Per, β Per), the Demon Star,

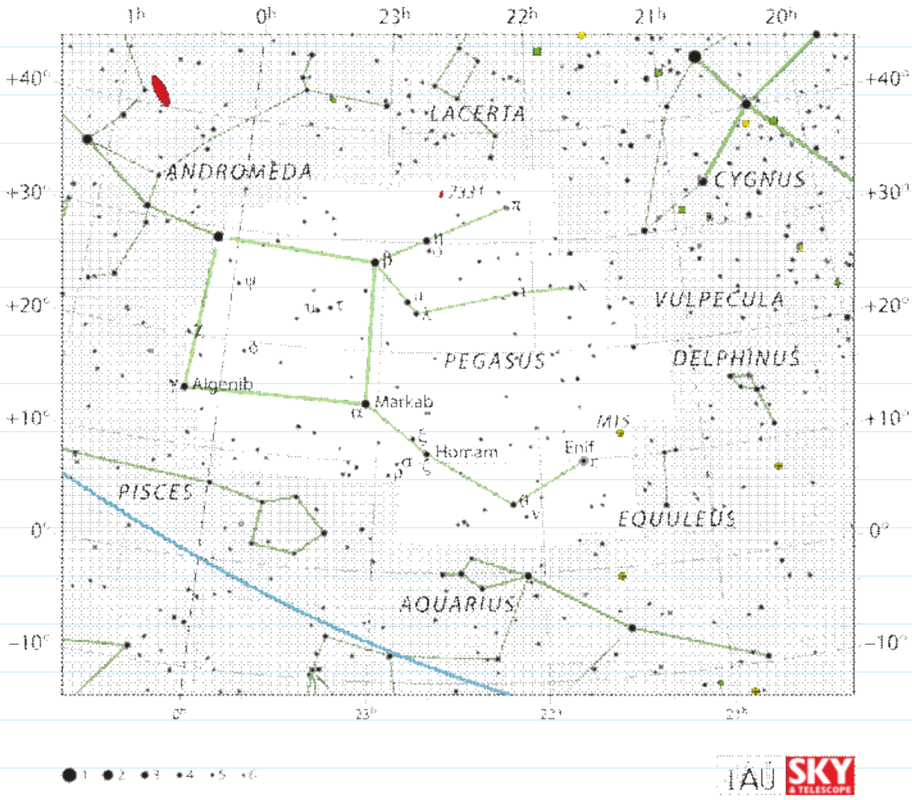
- is a bright multiple star in the constellation of Perseus, about 93ly from the Sun, with three confirmed (Aa1, Aa2, Ab) & two suspected (B, C)
- Three stars (Beta Persei Aa1, Aa2, and Ab)
  - β Persei Aa1 & Aa2 :
    - an eclipsing binary (their orbital plane contains the line of sight to the Earth.
      - β Persei Aa1 B8V 13,000K 3.17 $M_\odot$ 2.73 $R_\odot$ 182 $L_\odot$ the hot luminous primary
      - β Persei Aa2 K0IV 4,500K 0.70$M_\odot$ 3.48 $R_\odot$ 7$L_\odot$ the cooler, larger, and fainter
    - Separation : 0.062au from each other,
    - Algol's magnitude : near-constant at 2.1, with regular dips to 3.4
      (The eclipse when the brighter primary star occults the fainter secondary is very shallow and can only be detected photoelectrically.)
      every 2.86 days during the roughly 10-hour-long partial eclipses.
  - Algol Ab : (A7m 1.76 $M_\odot$ 1.73 ± 0.33 $R_\odot$ 10$L_\odot$ 7,500K) the third star in the system
    - is at an average distance of 2.69 au from the pair,
    - the mutual orbital period of the trio is 681 Earth days.
  - Algol B & C : two very faint stars, about one arcmin distant.
- The total mass of the system ≈ 5.8 $M_\odot$ (the mass ratios of Aa1, Aa2, and Ab : 4.5 to 1 to 2).
- The bright triple star used to be, and still sometimes are, referred to as β Per A, B, and C.

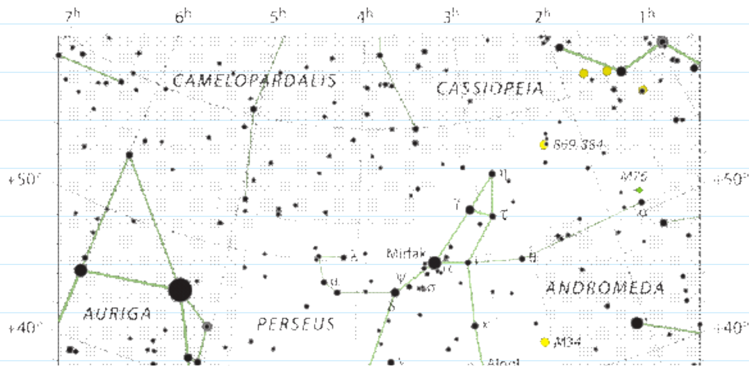
the Algol paradox in the theory of stellar evolution:

- If components of a binary star form at the same time, massive stars evolve much faster than the

less massive stars.
  - However, the more massive component Algol Aa1 is still in the main sequence, while the less massive Algol Aa2 is a subgiant star at a later evolutionary stage.
- Solution - by mass transfer:
  - when the more massive star became a subgiant, it filled its Roche lobe,
  - and most of the mass was transferred to the other star, which is still in the main sequence. The gas flow between the primary and secondary stars in Algol has been imaged.
- This system also exhibits x-ray and radio wave flares.
  - The x-ray flares are caused by the magnetic fields of the A and B components interacting with the mass transfer.
  - The radio-wave flares might be created by magnetic cycles similar to those of sunspots, but because the magnetic fields of these stars are up to ten times stronger than the field of the Sun, these radio flares are more powerful and more persistent. The secondary component was identified as the radio emitting source in Algol using Very-long-baseline interferometry.

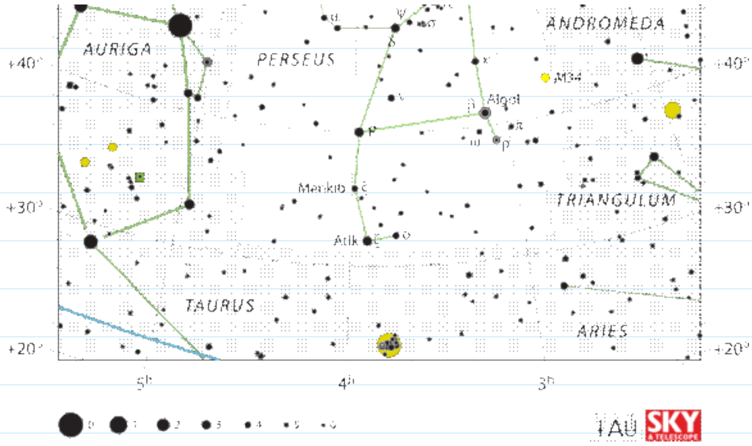
출처: <https://en.wikipedia.org/wiki/Algol>





Algol

Constellation	Perseus
Right ascens	$03^h\ 08^m\ 10.13245^s$[1]
Declination	+40° 57′ 20.3280″[1]
Appar mag (V)	2.12 (- 3.39)
Characteristics	
Spectral type	**Aa1**: B8V **Aa2**: K0IV



Spectral type	Aa1: B8V Aa2: K0IV Ab: A7m
Variable type	EA/SD[3]
Astrometry	
Radial vel (R_v)	3.7 km/s
Prop motion(μ)	RA: 2.99[1] mas/yr Dec.:−1.66[1] mas/yr
Parallax (π)	36.27 ± 1.40[1] mas
Distance	90 ly (28 pc)
β Per Aa1	
Absol mag (M_V)	−0.07
β Per Aa2	
Absol mag (M_V)	2.9
β Per Ab	
Absol mag (M_V)	2.3

Details	
β Per Aa1	
Mass	3.17 ± 0.21 $M_\odot$
Radius	2.73 ± 0.20 $R_\odot$
Luminosity	182 $L_\odot$
Temperature	13,000[7] K
Age	570 Myr
β Per Aa2	
Mass	0.70 ± 0.08 $M_\odot$
Radius	3.48 ± 0.28 $R_\odot$
Luminosity	6.92[5] $L_\odot$
Temperature	4,500[7] K
β Per Ab	
Mass	1.76 $M_\odot$
Radius	1.73 $R_\odot$
Luminosity	10.0[5] $L_\odot$
Temperature	7,500[7] K

Orbit[6]	
Primary	β Per Aa1
Companion	β Per Aa2
Period (P)	2.867328 days
Semi-maj axis(a)	0.00215"
Eccentricity (e)	0
Inclination (i)	98.70°
Orbit[6]	
Primary	β Per A
Companion	β Per B
Period (P)	680.168 days
Semi-maj axis(a)	0.09343"
Eccentricity (e)	0.227
Inclination (i)	83.66°
Periastr epoch (T)	2446927.22

Other designations	
Algol, Gorgona, Gorgonea Prima, Demon Star, El Ghoul, β Persei, β Per,	26 Persei, BD+40° 673, FK5 111, GC 37 33, HD 19356, HIP 1 4576, HR 936, PPM 4 5864, SAO 38592.

출처: <https://en.wikipedia.org/wiki/Algol>

Planetary Eclipses

- Another interesting example is one of the new planets found orbiting another star (HD 209458).
    - **HD 209458** is an 8th-mag star in the constellation Pegasus.
    - It is a G0V star, and is thus very similar to the Sun. at a distance of about 159ly.

  출처: <https://en.wikipedia.org/wiki/HD_209458>

- In this case eclipses have been detected.
    - In 1999, the first known to detect transiting extrasolar planet. The planet received the designation *HD 209458 b*.
    - the planet transits makes the star dimmed by about 2% every 3.5 days.
    - The variable star designation for HD 209458 is **V376 Pegasi**.
    - the prototype of the variable class "EP", defined as stars showing eclipses by their planets.

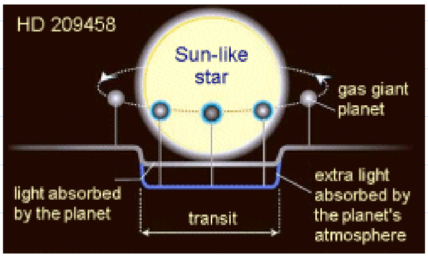
  출처: <https://en.wikipedia.org/wiki/HD_209458>

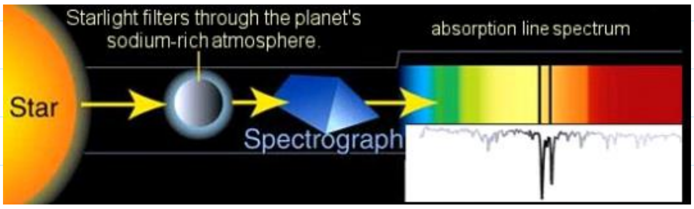
- When the eclipse occurs, light from the star passes through the planet's atmosphere. The spectral lines which suddenly appear during the eclipse give us the chemical composition of the planet's atmosphere.

  ◦ the emission spectrum of this planet analyzed in 2009. The spectrum taken in 2020 did indeed feature either sodium or vanadium oxide, but not the water. Later study in 2021 did not find any planetary atmosphere at all.

출처: <https://en.wikipedia.org/wiki/HD_209458>

- The planet's size is similar to Jupiter.





Using Binaries to Weigh Stars

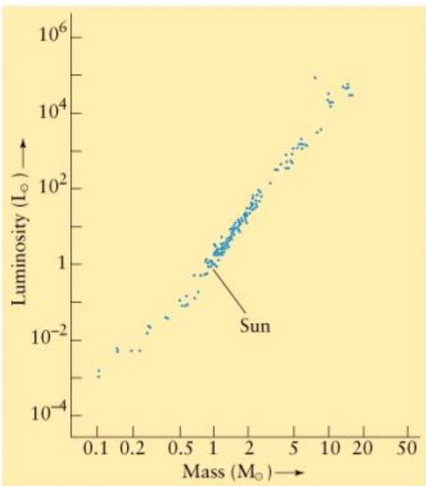
- Binary star systems are important because they allow us to find the masses of stars.
- Newton's laws of motion (F=ma) allow us to derive Kepler's equation for orbital motion.
- Kepler's equation:
  $(M_1 + M_2) \times P^2 = a^3$,
  where
  - $M_1 + M_2$ is the sum of the masses of the two stars, units of the Sun's mass
  - a = distance between the two stars, measured in AU
  - P = time for one full orbit, measured in years
- The orbital period is usually easy to measure.
- If you can find the orbital separation (a), then you can solve for the sum of the masses.
- If you can also see the distances between the stars and the centre of mass you can also use the Centre-of-Mass equation $a_1M_1 = a_2M_2$ to relate the two masses.
- Combining the two equations (Kepler's equation and the COM equation) we can solve for the two stars' masses.

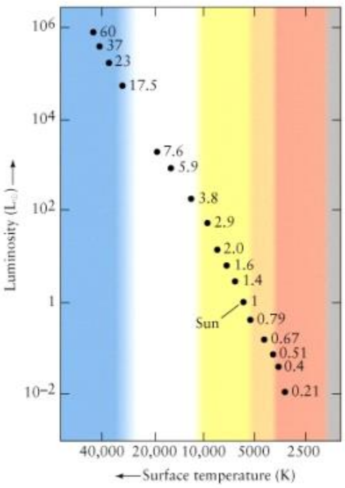
Back Next

What are the masses of the stars?

- We can find the masses of the stars in binary systems.
- For stars which are members of the main sequence, mass is correlated with surface temperature and luminosity.
- Main Sequence stars: Heavier stars are hotter and more powerful than light-weight stars.

  Star mass ranges $0.08\ M_\odot \lesssim M_{\rm Star} \lesssim 100 M_\odot$:

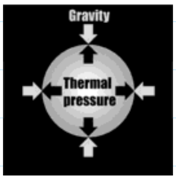




출처: <https://sites.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect13/lecture13.html>

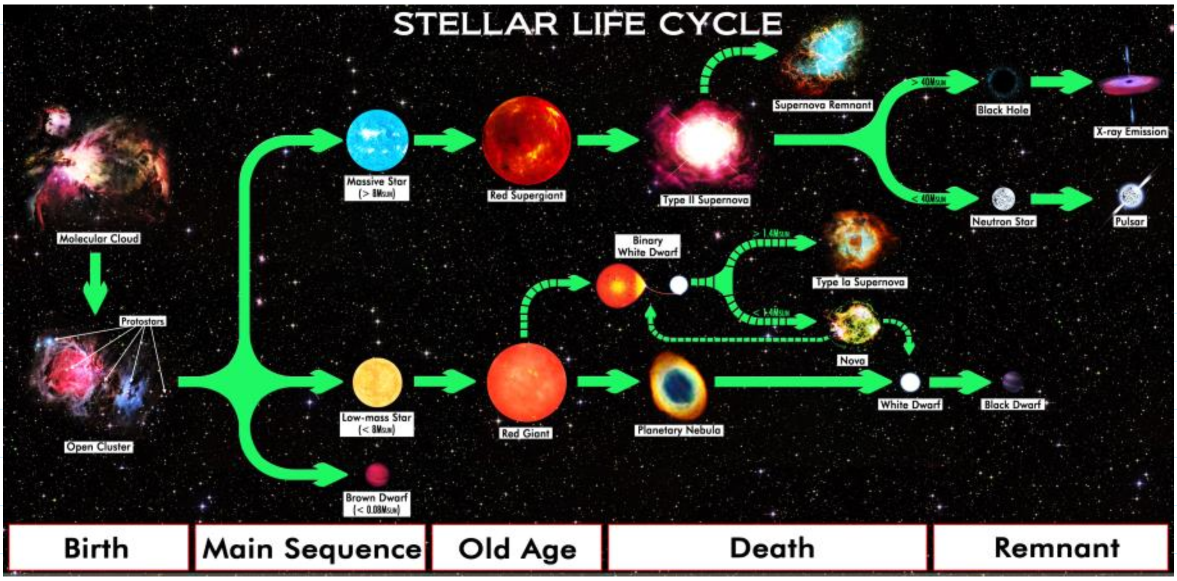
Star Evolution

Gravity : attractive->shrink



Repulsive pressure needed

1)thermal : nuclear reaction -> Star
If all the fuels are consumed,
Degeneracy pressure
1) Electron degeneracy : White Dwarf
2) Neutron degeneracy : Neutron Star
If no balance, collapsing : Black Hole



Detection of exoplanets[edit]

- The first confirmed detection of an exoplanet was in 1992, with the discovery of several terrestrial-mass planets orbiting the pulsar PSR B1257+12.
- The first confirmed detection of exoplanets of a main-sequence star was made in 1995, when a giant planet, 51 Pegasi b, was found in a four-day orbit around the nearby G-type star 51 Pegasi.

출처: <https://en.wikipedia.org/wiki/Planetary_system>

Most Earth-like

Some extrasolar planets might be Earth-like, having conditions very similar to that of the Earth. the Earth similarity index or ESI for short goes from one (most Earth-like) to zero (least Earth-like). For a planet to be habitable it should have an ESI of at least 0.8. For comparison, the four solar terrestrial planets are included in this list.

Name	ESI	SFV	HZD	COM	ATM	Star	Habitability	Distance (ly)	Status	Year of discovery
Earth	1.00	0.72	−0.50	−0.31	−0.52	G	mesoplanet	0	Non-exoplanet, inhabited	prehistoric

Venus	**0.78**	**0.00**	**−0.93**	**−0.28**	**−0.70**	**G**	**hyperthermoplanet**	**close to zero**	**non-exoplanet**	**prehistoric**
Mars	**0.64**	**0.00**	**+0.33**	**−0.13**	**−1.12**	**G**	**hypopsychroplanet**	**close to zero**	**non-exoplanet**	**prehistoric**
Mercury	**0.39**	**0.00**	**−1.46**	**−0.52**	**−1.37**	**G**	**non-habitable**	**close to zero**	**non-exoplanet**	**prehistoric**
Tau Ceti e	0.78	0.00	−0.92	−0.15	+0.16	G	mesoplanet	11.9	unconfirmed	2012
Kapteyn b	0.67	0.00	+0.08	−0.15	+0.57	M	psychroplanet	12.7	unconfirmed	2014
Gliese 832 c	0.81	0.96	−0.72	−0.15	+0.43	M	mesoplanet	16.1	confirmed	2014
Gliese 581 d	0.53	0.00	+0.78	−0.14	+0.94	M	hypopsychroplanet	20.2	unconfirmed	2007
Gliese 667 Cc	0.84	0.64	−0.62	−0.15	+0.21	M	mesoplanet	23.6	confirmed	2011
HD 40307 g	0.74	0.04	−0.23	−0.14	+0.77	K	psychroplanet	41.7	confirmed	2012
Kepler-438b	0.88	0.88	−0.93	−0.14	−0.73	M	mesoplanet	472.9	confirmed	2015
Kepler-186f	0.64	0.00	+0.48	−0.17	−0.26	M	psychroplanet	492	confirmed	2014
Kepler-1229 b	0.79	0.00	−0.40	−0.15	+0.44	M	mesoplanet	769.7	confirmed	2016
Kepler-62e	0.83	0.96	−0.70	−0.15	+0.28	K	mesoplanet	1199.7	confirmed	2013
Kepler-62f	0.67	0.05	+0.45	−0.16	+0.19	K	psychroplanet	1199.7	confirmed	2013
Kepler-1410 b	0.88	0.63	−0.88	−0.16	−0.06	K	mesoplanet	1213.4	confirmed	2011
Kepler-442b	0.83	0.98	−0.72	−0.15	+0.28	K	mesoplanet	1291.6	confirmed	2015
Kepler-436b	0.79	0.33	−0.87	−0.14	+0.47	M	mesoplanet	1339.4	confirmed	2015
Kepler-452b	0.83	0.93	−0.61	-0.15	-0.30	G	mesoplanet	1402.5	confirmed	2015
Kepler-283c	0.79	0.85	−0.58	−0.14	+0.69	K	mesoplanet	1496.8	confirmed	2011
Kepler-443b	0.73	0.91	−0.4[illegible]	−0.13	+1.44	K	mesoplanet	2564.4		

출처: <https://simple.wikipedia.org/wiki/Extrasolar_planets>

Tau Ceti (τ Ceti)

- is a single star spectrally similar to the Sun,
- Main Seq. G8V, Mass≈ $0.78 M_{\odot}$, L=0.52 $L_{\odot}$.
- with an apparent magnitude of 3.5, it can be seen with the unaided eye
- At a distance =11.9 ly (3.65pc), it is the closest solitary G-class star.
- The star appears stable, with little stellar variation, and is metal-deficient.
- Observations have detected more than ten times as much dust surrounding Tau Ceti as is present in the Solar System.
- Because of its debris disk, any planet orbiting Tau Ceti would face far more impact events than Earth.

- Since December 2012, there has been evidence of planets
  - at least four planets—all confirmed being super-Earths—orbiting Tau Ceti, with two of these being potentially in the habitable zone.
  - There are an additional four unconfirmed planets, one of which is a Jovian planet between 3 and 20 AU from the star.

Tau Ceti

Constellation	Cetus
Pronunciation	/ˌtaʊ ˈsiːtaɪ/
Right ascension	$01^h\ 44^m$
Declination	−15° 56′
Appar mag (V)	3.50 ± 0.01[2]
Characteristics	
Evol stage	Main sequence
Spectral type	G8V
Astrometry	
Radial vel (R_v)	−16.68± 0.05[5] km/s
Prop motion (μ)	RA: −1721mas/yr Dec.:+ 854 mas/yr
Parallax (π)	274mas
Distance	11.9 ly (3.65 pc)
Absolute mag (M_V)	5.69±0.01[2]
Details	

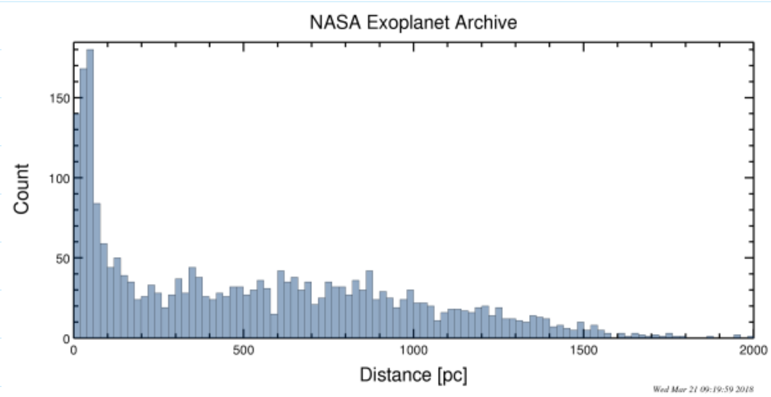
which is a Jovian planet between 3 and 20 AU from the star.

- The habitable zone for a star is where liquid water could be present on an Earth-like planet. For Tau Ceti, this is at a radius of 0.55–1.16 AU.
- The planets' estimated minimum masses are between two and six times the Earth's mass. Their orbital periods range from 14 to 640 days.

- One of them, **Tau Ceti e**,
  - appears to orbit at 0.552AU.
  - the planet would receive 1.71 times as much stellar radiation as Earth does.
  - This is slightly less than Venus, which gets 1.91 times Earth's.

• Given its stability, similarity and relative proximity to the Sun, Tau Ceti is consistently listed as a target for the Search for Extra-Terrestrial Intelligence (SETI).
• As seen from Tau Ceti, the Sun would be in the northern hemisphere constellation Boötes with an apparent magnitude of about 2.6.
• The Tau Ceti system is believed to have only one stellar component. A dim optical companion has been observed with magnitude 13.1and 137" distant from the primary. It may be gravitationally bound, but more likely to be a line-of-sight coincidence.

출처: <https://en.wikipedia.org/wiki/Tau_Ceti>



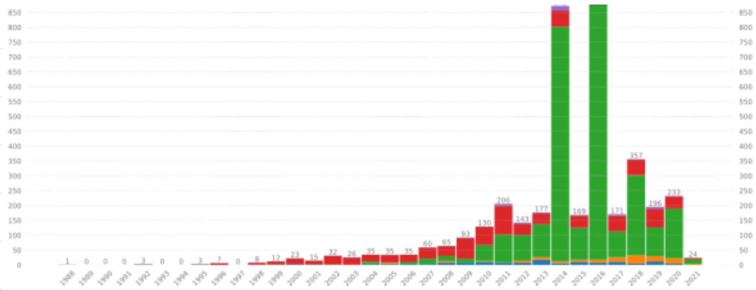
NASA histogram chart of confirmed exoplanets by distance

)	
Details	
Mass	0.78$M_\odot$
Radius	0.79 $R_\odot$
Luminosity	0.52 $L_\odot$
Lum(visual, L_V)	0.45$L_\odot$
Surf grav(log *g*)	4.4[7] cgs
Temperature	5,344±50[8] K
Metallicity	28±3% Sun
Metallicity [Fe/H]	−0.55dex
Rotation	34 days[10]
Age	5.8[11] Gyr
Other designations	
52 Cet, BD−16° 295, FK5 59, GJ 71, HD 10700, HIP 8102,	HR 509, SAO 147986, LFT 159, LHS 146, LTT 935[4]

출처:
<https://en.wikipedia.org/wiki/Tau_Ceti>

Epsilon Eridani

Constellation	Eridanus
Right ascension	03^h 32^m 55.84496^s[1]
Declination	−09° 27′ 29.7312″[1]
Appar mag (V)	3.736[2]
Characteristics	
Spectral type	K2V
Variable type	BY Dra[4][6]
Astrometry	
Radial velocity (R_v)	+15.5±0.9[7] km/s
Proper motion (μ)	RA: −975.17[1] mas/yr Dec.: 19.49[1] mas/yr
Parallax (π)	311.37 ± 0.1[8] mas
Distance	10.475 ± 0.003 ly



Discovered exoplanets each year with discovery methods, up to the present, with color indicating discovery method.[2]

- Direct imaging
- Microlensing
- Transit
- Radial velocity
- Timing

출처: <https://en.wikipedia.org/wiki/Exoplanet>

Parallax **(π)**	311.37 ± 0.1[8] mas
Distance	10.475 ± 0.003 ly (3.212 ± 0.001 pc)
Absol mag **(M_V)**	6.19[9]
Details	
Mass	0.82 $M_☉$
Radius	0.735 $R_☉$
Luminosity	0.34 $L_☉$
Temperature	5,084 K
Metallicity [Fe/H]	−0.13±0.04[15] dex
Rotation	11.2 days[16]
Age	400–800[17] Myr
Other	**designations**
Ran, ε Eri,	18 Eridani, HD 22049,

출처: <https://en.wikipedia.org/wiki/Epsilon_Eridani>

Epsilon Eridani (**ε Eridani**), formally named **Ran**,

- is a K2V star, 5,084 K 0.82 $M_☉$ 0.735 $R_☉$ 0.34 $L_☉$
- at a distance of 10.5ly (3.2pc) an apparent mag of 3.73.
- the 13th-nearest known star
  The 9th nearest solitary star or stellar system
  The 3rd-closest star/star system visible to the unaided eye.
  The 2nd-nearest K-type MS star (after Alpha Centauri B)
- The star is less than a billion years old.
- Because of its relative youth, Epsilon Eridani has a higher level of magnetic activity than the present-day Sun, with a stellar wind 30 times as strong.
- Its rotation period is 11.2 days at the equator. Epsilon Eridani is smaller and less massive than the Sun, and has a comparatively lower level of elements heavier than helium.[20] a temperature of about 5,000 K giving it an orange hue.
- It may be a member of the Ursa Major Moving Group of stars that share a similar motion through the Milky Way, implying these stars shared a common origin in an open cluster. Its nearest neighbour, the binary star system Luyten 726-8, will have a close encounter with Epsilon Eridani in approximately 31,500 years when they will be separated by about 0.93 ly (0.29 pc).
- Periodic changes in the radial velocity value yielded evidence of a giant planet orbiting the star, making it one of the closest star systems with a candidate exoplanet. In 2016 it was given the alternative name AEgir.
- The Epsilon Eridani system also includes two belts of rocky asteroids: at 3 AU & 20 AU from the star. The orbital

Magnetic activity

- Epsilon Eridani has a higher level of magnetic activity than the Sun, and thus the outer parts of its atmosphere (the chromosphere and corona) are more dynamic.
- The average magnetic field strength across the entire surface is 1.65 × 10^{-2} T, (cf: the (5–40) × 10^{-5} T in the Sun's photosphere).
- The overall magnetic activity shows co- existing 2.95 and 12.7 year activity cycles.
- The magnetic field on the surface of Epsilon Eridani causes variations in the hydrodynamic behaviour of the photosphere.
- Epsilon Eridani is classified as a BY Draconis variable because it has regions of higher magnetic activity that move into and out of the line of sight as it rotates.
- its equatorial region rotates with an average period of 11.2 days, which is less than half of the rotation period of the Sun.
- the surface of Epsilon Eridani, like

- The Epsilon Eridani system also includes two belts of rocky asteroids: at 3 AU & 20 AU from the star. The orbital structure could be maintained by a hypothetical second planet, which if confirmed would be Epsilon Eridani c.
- Epsilon Eridani hosts an extensive outer debris disk of remnant planetesimals left over from the system's formation.
- One of the nearest Sun-like stars with a planet, several observations in the search for extraterrestrial intelligence. From Epsilon Eridani, the Sun would appear as a 2.4-magnitude star in Serpens.

- Since 1943 the spectrum of Epsilon Eridani has served as one of the stable anchor points by which other stars are classified. Its metallicity, the fraction of elements heavier than helium, is slightly lower than the Sun's.
- In Epsilon Eridani's chromosphere, the abundance of iron is at 74% of the Sun's value. The proportion of lithium in the atmosphere is five times less than that in the Sun.
- Relatively weak absorption lines from absorption by hydrogen (Balmer lines) but strong lines of neutral atoms and singly ionized calcium (Ca II). The energy by fusion is transported outward from the core through radiation, which results in no net motion of the surrounding plasma. Outside of this region, in the envelope, energy is carried to the photosphere by plasma convection, where it then radiates into space.

Potential habitability

- The orbital radius at which the stellar flux from Epsilon Eridani matches the solar constant—where the emission matches the Sun's output at the orbital distance of the Earth—is 0.61 astronomical units (AU). That is within the maximum habitable zone of a conjectured Earth-like planet orbiting Epsilon Eridani, which currently stretches from about 0.5 to 1.0 AU.
- As Epsilon Eridani ages over a period of 20 billion years, the net luminosity will increase, causing this zone to slowly expand outward to about 0.6–1.4 AU. The presence of a large planet with a highly elliptical orbit in proximity to Epsilon Eridani's habitable zone reduces the likelihood of a terrestrial planet having a stable orbit within the habitable zone.
- A young star such as Epsilon Eridani can produce large amounts of ultraviolet radiation that may be

is less than half of the rotation period of the Sun.

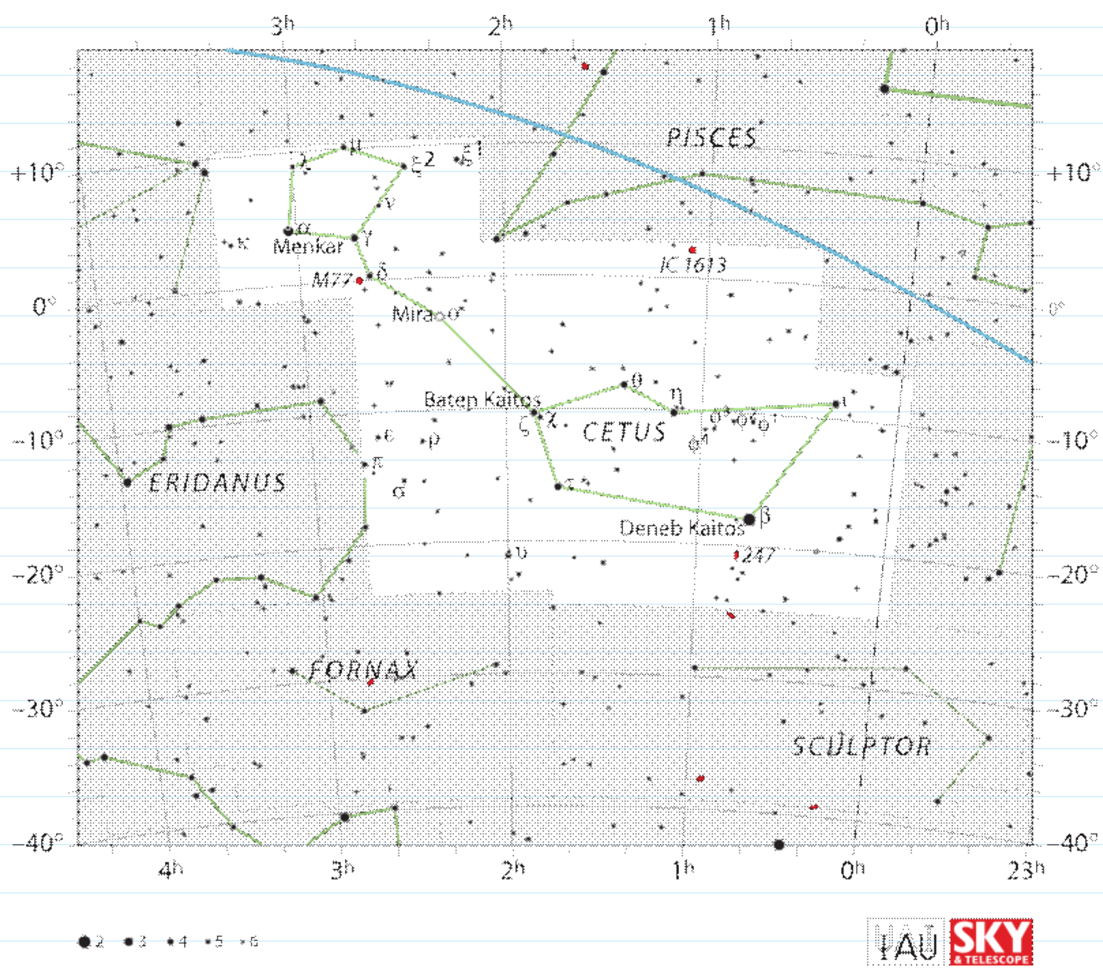
- the surface of Epsilon Eridani, like the Sun, is undergoing differential rotation i.e. the rotation period at equator differs from that at high latitude. The measured periods range from 10.8 to 12.3 days.
- The high levels of chromospheric activity, strong magnetic field, and relatively fast rotation rate of Epsilon Eridani are characteristic of a young star.
- the age of Epsilon Eridani in the range from 200 million to 800 million years. The low abundance of heavy elements in the chromosphere of Epsilon Eridani usually indicates an older star, because the interstellar medium (out of which stars form) is steadily enriched by heavier elements produced by older generations of stars. This anomaly might be caused by a diffusion process that has transported some of the heavier elements out of the photosphere and into a region below Epsilon Eridani's convection zone.
- The X-ray luminosity
  - is about 2×10^{28} ergs/s, more luminous in X-rays than the Sun at peak activity.
  - The source for this strong X-ray emission is Epsilon Eridani's hot corona.
  - Epsilon Eridani's corona appears larger and hotter than the Sun's, with $T = 3.4 \times 10^6$ K.
- The stellar wind emitted by Epsilon Eridani expands until it collides with the surrounding interstellar medium of diffuse gas and dust, resulting in a bubble of heated hydrogen gas (an astrosphere, the

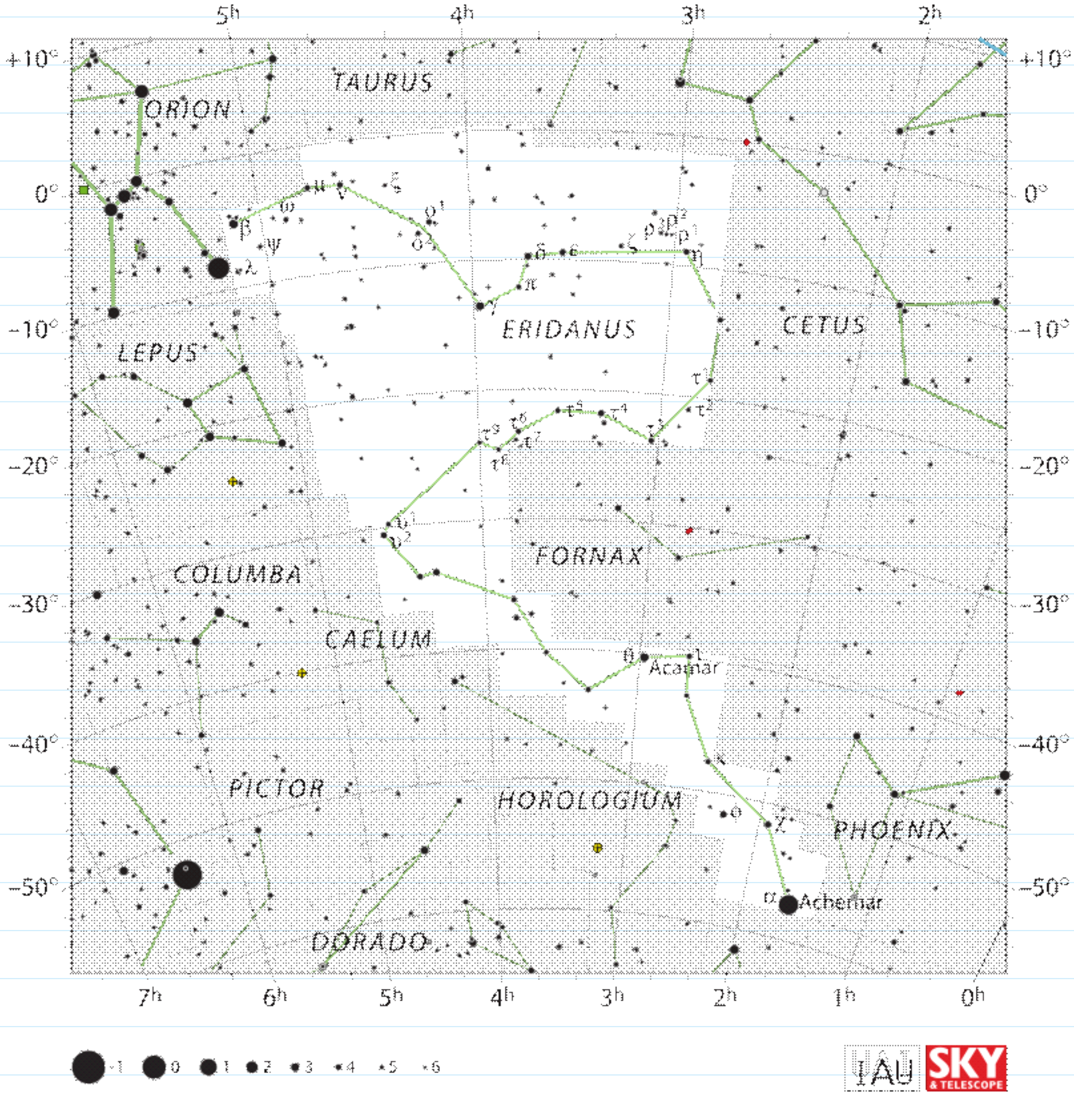
- A young star such as Epsilon Eridani can produce large amounts of ultraviolet radiation that may be harmful to life, but on the other hand it is a cooler star than our Sun and so produces less ultraviolet radiation to start with. The orbital radius where the UV flux matches that on the early Earth lies at just under 0.5 AU. Because that is actually slightly closer to the star than the habitable zone, this has led some researchers to conclude there is not enough energy from ultraviolet radiation reaching into the habitable zone for life to ever get started around the young Epsilon Eridani.

출처: <https://en.wikipedia.org/wiki/Epsilon_Eridani>

resulting in a bubble of heated hydrogen gas (an astrosphere, the equivalent of the heliosphere that surrounds the Sun).

- The absorption spectrum from this gas has been measured with the Hubble Space Telescope.
- Epsilon Eridani's hot corona results in a mass loss rate in Epsilon Eridani's stellar wind that is 30 times higher than the Sun's. This stellar wind generates the astrosphere that spans about 8,000 au (0.039 pc) and contains a bow shock that lies 1,600 au (0.0078 pc) from Epsilon Eridani.
- At its estimated distance from Earth, this astrosphere spans 42 arcminutes, which is wider than the apparent size of the full Moon.

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ORION
LEPUS
ERIDANUS
CETUS
COLUMBA
FORNAX
CAELUM
Acamar
PICTOR
HOROLOGIUM
PHOENIX
Achernar
DORADO
+10°
0°
-10°
-20°
-30°
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