16. Properties of Stars

All men have the stars," he answered, "but they are not the same things for different people. For some, who are travelers, the stars are guides. For others they are no more than little lights in the sky. For others, who are scholars, they are problems. For my businessman they were wealth. But all these stars are silent. You – you alone – will have the stars as no one else has them."

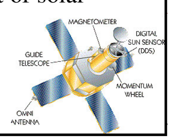
Antoine de Saint-Exupery (1900 – 1944)
from The Little Prince

Agenda

- Observation next Wednesday 6pm (Great Lawn outside Pell):
  - Moon, Venus, Mars (maybe others)
  - Motor drive (long extension cord)
- Multimedia Projects need to be on my notebook **before** class next Thursday (CD/DVD, email, USB key,….no punch cards or floppy!)…other needs expressed by Tuesday
- TRACE Pix
- Ch. 16

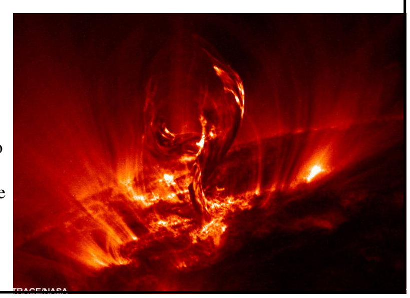
NASA's TRACE

- To follow the evolution of magnetic field structures from the solar interior to the corona.
- To investigate the mechanisms of the heating of the outer solar atmosphere.
- To investigate the triggers and onset of solar flares and mass ejections.

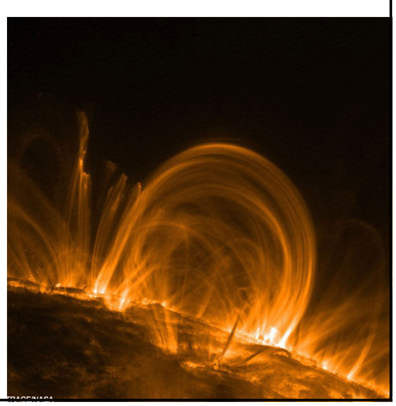


TRACE Pix

- 1 million degrees on 19 July 2000
- shows a filament in the process of lifting off from the surface of the Sun
- dark matter is relatively cool, around 20,000 degrees
- From footpoint to peak, this rapidly evolving structure measures 75,000 miles

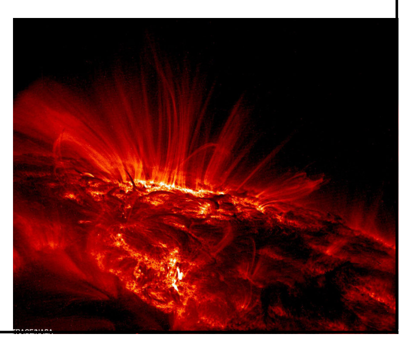


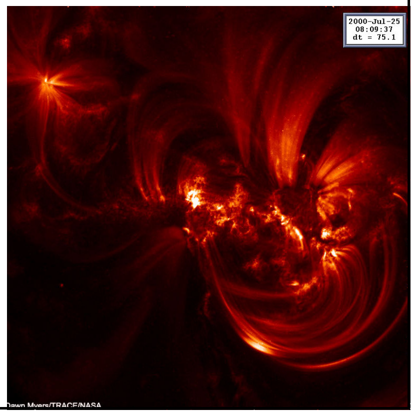
- Extending above the photosphere, clusters of majestic, hot coronal loops span 30 or more times the diameter of planet Earth

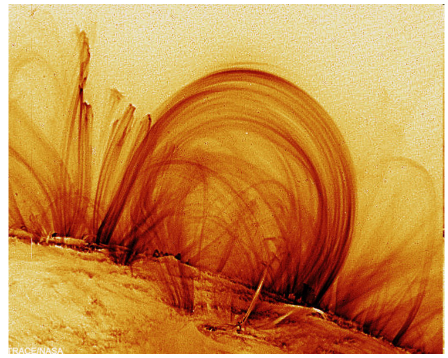


TRACE Pix

- On a relatively quiet day on the Sun is busy
- An ultraviolet image shows bright, glowing arcs of gas flowing around the sunspots

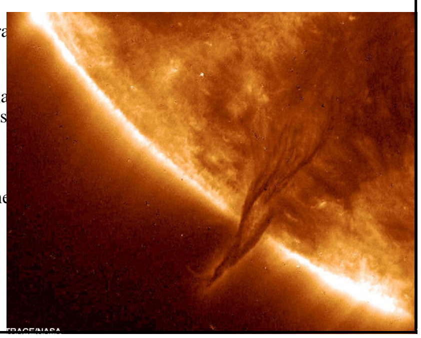


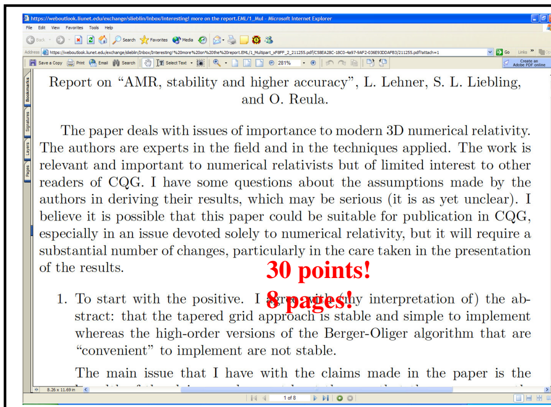




- Prominence observed on May 21, 1998
- This solar phenomena can persist for several days and even several months.
- The dark material in this image has a temperature ranging from 5,000 to 10,000 Kelvin, while the surrounding material has a temperature of about 1 million Kelvin.

TRACE Pix





Report on "AMR, stability and higher accuracy", L. Lehner, S. L. Liebling, and O. Reula.

The paper deals with issues of importance to modern 3D numerical relativity. The authors are experts in the field and in the techniques applied. The work is relevant and important to numerical relativists but of limited interest to other readers of CQG. I have some questions about the assumptions made by the authors in deriving their results, which may be serious (it is as yet unclear). I believe it is possible that this paper could be suitable for publication in CQG, especially in an issue devoted solely to numerical relativity, but it will require a substantial number of changes, particularly in the care taken in the presentation of the results.

1. To start with the positive. I agree with (my interpretation of) the abstract: that the tapered grid approach is stable and simple to implement whereas the high-order versions of the Berger-Oliger algorithm that are "convenient" to implement are not stable.

The main issue that I have with the claims made in the paper is the

Why does the Earth's atmosphere get thinner at higher altitudes?

1. Because temperature increases with altitude.
2. Because temperature decreases with altitude.
3. Because pressure decreases with altitude.
4. Because gravitational force decreases with altitude.
5. At higher altitudes, faster moving molecules escape, thereby reducing the density of the gas.

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Which of the following can be used to directly measure the Sun's mass?

1. Solar luminosity and Earth-Sun distance.
2. Solar temperature and Earth-Sun distance.
3. Solar rotation rate and Earth-Sun distance.
4. Earth's mass and orbital period.
5. Venus-Sun distance and the length of a Venetian year.

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5. **Venus-Sun distance and the length of a Venetian year.**

Is the number of solar neutrinos zipping through our bodies significantly lower at night?

1. Yes, the passage of *all* solar neutrinos through the Earth stops at night.
2. Yes, the passage of a significant number of solar neutrinos through the Earth stops at night.
3. No, the Earth is not thick enough to stop a significant number of solar neutrinos.
4. No, the number of solar neutrinos created by the Sun remains the same whether it's day or night.

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If fusion in the solar core ceased today, worldwide panic would break out tomorrow as the Sun would begin to grow dimmer.

1. Yes, because the Earth would quickly freeze over.
2. Yes, because the Earth would no longer be bound to the solar system and would drift into space.
3. Yes, because the Sun would collapse and the planets would soon follow.
4. No, it takes thousands of years for photons created in nuclear reactions at the solar core to reach the surface.
5. No, the Sun would continue to glow brightly for billions of years because of gravitational contraction.

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If you want to see a lot of sunspots, just wait for the time of solar maximum.

1. Yes, the number of sunspots peak at solar maximum.
2. No, the number of sunspots peak at solar minimum.
3. No, the number of sunspots is random and does not depend on whether it is the time of solar minimum or maximum.

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1. **Yes, the number of sunspots peak at solar maximum.**
2. No, the number of sunspots peak at solar minimum.
3. No, the number of sunspots is random and does not depend on whether it is solar minimum or maximum.

16.1 Snapshot of the Heavens

Our goals for learning:

- How can we learn about the lives of stars, which last millions to billions of years?
- What two basic physical properties do astronomers use to classify stars?

How can we Study the Life Cycles of Stars?

- A star can live for millions to billions of years.
  - we will never observe a particular star evolve from birth to death
  - so how can we study stellar evolution?
- The key is that all stars were not born at the same time.
  - the stars which we see today are at different stages in their lives
  - we observe only a brief moment in any one star's life
  - by studying large numbers of stars, we get a "snapshot" of one moment in the history of the stellar community
  - we can draw conclusions just like we would with human census data…we do stellar demographics!
- The stars we observe also have different masses.
  - by counting stars of different masses, we can determine how long stars of a given mass remain in a certain stage of life

Classification of Stars

- Stars were originally classified based on:
  - their brightness
  - their location in the sky
- This classification is still reflected in the names of the brightest stars…those we can see with our eyes:

Order of brightness within a constellation → β

Latin Genitive of the constellation → Orionis

β Orionis

δ Geminorum

Classification of Stars

- The old classification scheme told us little about a star's true (physical) nature.
  - a star could be very bright because is was very close to us; not because it was truly bright
  - two stars in the same constellation might not be close to each other; one could be much farther away
- In the 20th Century, astronomers developed a more appropriate classification system based on:
  - a star's **luminosity**
  - a star's **surface temperature**
- Since these properties depend on a star's mass and its stage in life:
  - measuring them allows us to reconstruct stellar life cycles

16.2 Stellar Luminosity

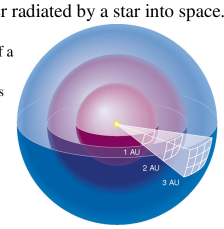
Our goals for learning:

- What is luminosity and how do we determine it?
- How do we measure the distance to nearby stars?
- How does the magnitude of a star depend on its apparent brightness?

Luminosity of Stars

Luminosity – the total amount of power radiated by a star into space.

- **Apparent brightness** refers to the amount of a star's light which reaches us *per unit area*.
  - the farther away a star is, the fainter it appears to us
  - how much fainter it gets obeys an *inverse square law*
  - its apparent brightness decreases as the $(\text{distance})^2$

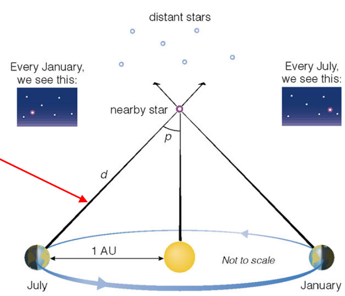


- The apparent brightness of a star depends on two things:
  - How much light is it emitting: luminosity (L) [watts]
  - How far away is it: distance (d) [meters]

$$\text{App Bright} = L / 4\pi d^2$$

Measuring Distances to Stars

This is a right triangle



$\sin p = 1 \text{ AU}/ d$

if $p \ll 1$; $\sin p \approx p$

$d = 1 \text{ AU}/ p$

convert p into arcsec

$d = 206{,}265 \text{ AU}/ p$

Measuring Distances to Stars

let's define

1 parsec ≡ 206,265 A.U. = 3.26 light years

$$d = 1 / p$$

If p is in arcsec and d is in parsecs

A star with a parallax of 1 arcsec is 1 parsec distant

The Brightness of Stars

Astronomers still use an ancient method for measuring stellar brightness which was proposed by the Greek astronomer Hipparchus (c. 190 – 120 B.C.)

Magnitude Scale

This scale runs backwards:
The bigger the number, the fainter the star
Brightest stars are #1, next brightest are #2, etc.

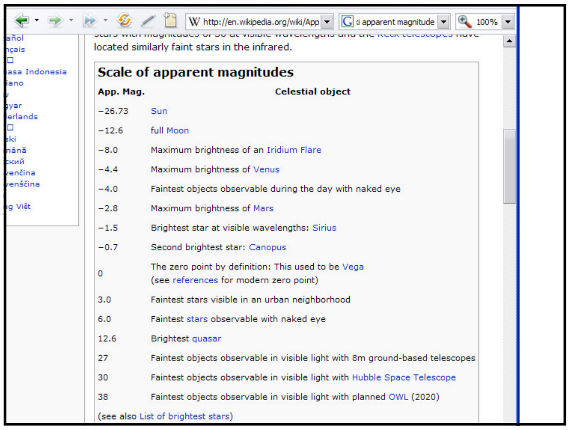
The Modern Magnitude System

apparent magnitude $= -2.5 \log (\text{app bright})$

- brightness of a star as it *appears* from Earth
- each step in magnitude is 2.5 times in brightness

absolute magnitude

- the apparent magnitude a star *would* have *if* it were 10 pc away



located similarly faint stars in the infrared.

Scale of apparent magnitudes

App. Mag.	Celestial object
−26.73	Sun
−12.6	full Moon
−8.0	Maximum brightness of an Iridium Flare
−4.4	Maximum brightness of Venus
−4.0	Faintest objects observable during the day with naked eye
−2.8	Maximum brightness of Mars
−1.5	Brightest star at visible wavelengths: Sirius
−0.7	Second brightest star: Canopus
0	The zero point by definition: This used to be Vega (see references for modern zero point)
3.0	Faintest stars visible in an urban neighborhood
6.0	Faintest stars observable with naked eye
12.6	Brightest quasar
27	Faintest objects observable in visible light with 8m ground-based telescopes
30	Faintest objects observable in visible light with Hubble Space Telescope
38	Faintest objects observable in visible light with planned OWL (2020)

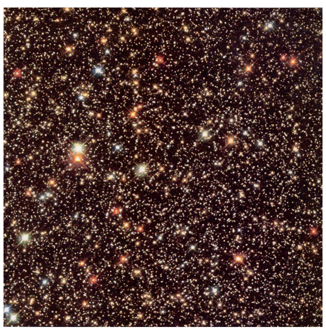
(see also List of brightest stars)

16.3 Stellar Surface Temperature

Our goals for learning:

- How are stars classified into spectral types?
- Does a star's spectral type depend on its composition?
- What are the two main elements in all stars?

Colors of Stars



Stars come in many different colors.

The color tells us the star's *temperature* according to Wien's Law.

Bluer means hotter!

Spectral Type Classification System

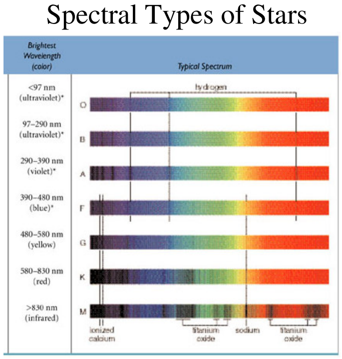
O B A F G K M (L)

Oh Be A Fine Girl/Guy, Kiss Me!

50,000 K ← 3,000 K

Temperature

Spectral Types of Stars



Spectral Types of Stars

Spectral Type	Example(s)	Temperature Range	Key Absorption Line Features
O	Stars of Orion's Belt	>30,000 K	Lines of ionized helium, weak hydrogen lines
B	Rigel	30,000 K–10,000 K	Lines of neutral helium, moderate hydrogen lines
A	Sirius	10,000 K–7,500 K	Very strong hydrogen lines
F	Polaris	7,500 K–6,000 K	Moderate hydrogen lines, moderate lines of ionized calcium
G	Sun, Alpha Centauri A	6,000 K–5,000 K	Weak hydrogen lines, strong lines of ionized calcium
K	Arcturus	5,000 K–3,500 K	Lines of neutral and singly ionized metals, some molecules
M	Betelgeuse, Proxima Centauri	<3,500 K	Molecular lines strong

Spectral Types of Stars

- Spectral types are defined by the:
  - existence of absorption lines belonging to various elements, ions, & molecules in a star's spectrum
  - the relative strengths of these line
- However, spectral type is not determined by a star's composition.
  - all stars are made primarily of Hydrogen & Helium
- Spectral type is determined by a star's surface temperature.
  - temperature dictates the energy states of electrons in atoms
  - temperature dictates the types of ions or molecules which exist
  - this, in turn, determines the number and relative strengths of absorption lines in the star's spectrum
  - this fact was discovered by Cecilia Payne-Gaposchkin in 1925

16.4 Stellar Masses

Our goals for learning:

- What is the most important property of a star?
- What are the three major classes of binary star systems?
- How do we measure stellar masses?

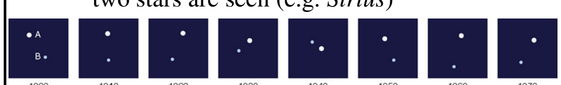
Masses of Stars

- Mass is the single most important property of any star.
  - at each stage of a star's life, mass determines… why?
    - what its luminosity will be
    - what its spectral type will be
- The mass of a star can only be measured directly by …
  - observing the effect which gravity from another object has on the star
- This is most easily done for two stars which orbit one another…a binary star!

Binary Stars

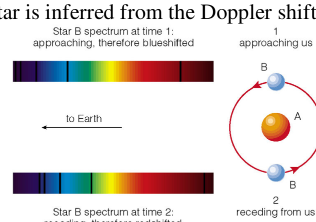
(two stars which orbit one another)

- Optical doubles
  - two unrelated stars which are in the same area of the sky
- Visual binaries
  - a binary which is spatially resolved, i.e. two stars are seen (e.g. *Sirius*)



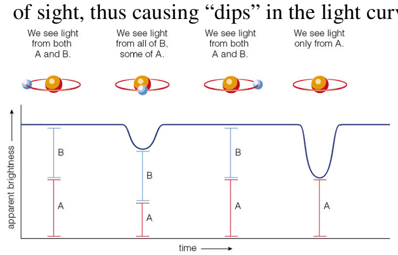
Binary Stars

- Spectroscopic binaries
  - a binary which is spatially unresolved, i.e only one star is seen; the existence of the second star is inferred from the Doppler shift of lines.



Binary Stars

- Eclipsing binaries
  - a binary whose orbital plane lies along our line of sight, thus causing “dips” in the light curve.



Binary Stars

- The stars orbit each other via gravity.
- So the laws of Kepler & Newton apply!
- Remember Newton’s version of Kepler’s Third Law:

$$P^2 = 4\pi^2 a^3 / G (m_1 + m_2)$$

- If you can measure the orbital period of the binary (P) and the distance between the stars (a), then you can calculate the sum of the masses of both stars ($m_1 + m_2$).

16.5 The Hertzsprung-Russell Diagram

Our goals for learning:

- What is the Hertzsprung-Russell (HR) diagram?
- What are the major features of the HR diagram?
- How do stars differ along the main sequence?
- What determines the length of time a star spends on the main sequence?
- What are Cepheid variable stars and why are they important to astronomers?

The Hertzsprung-Russell Diagram

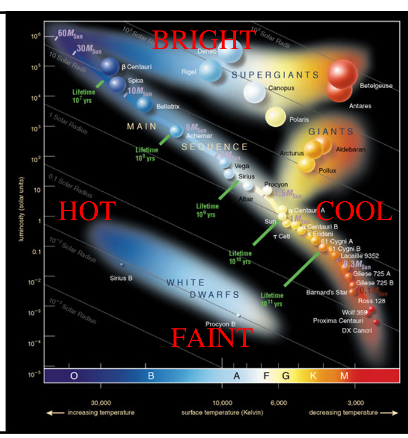
- Very useful diagram We plot two major properties of stars:
  - Temperature (x) vs. Luminosity (y)
  - Spectral Type (x) vs. Absolute Magnitude (y)
- Stars tend to group into certain areas

bright

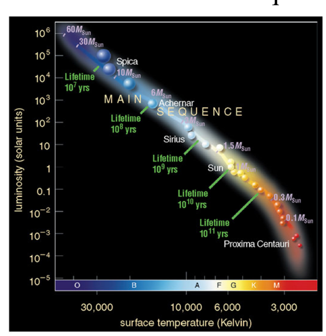
M_V

faint

hot Spectral type cool



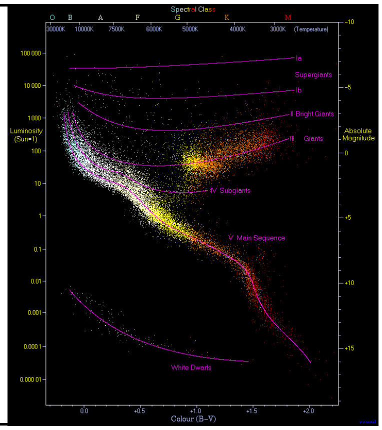
The Main Sequence (MS)



90% of all stars lie on the main sequence!

Let's see real data:

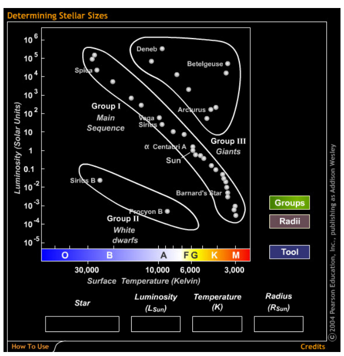
Here's 23,000 stars



Stellar Luminosity

- How can two stars have the same temperature, but vastly different luminosities?
- The luminosity of a star depends on 2 things:
  - surface temperature
  - surface area (radius)
  - $L = \sigma T^4 \, 4 \pi R^2$
- The stars have different sizes!!
- The largest stars are in the upper right corner of the H-R Diagram.

Regions of the H-R Diagram



Stellar Luminosity Classes

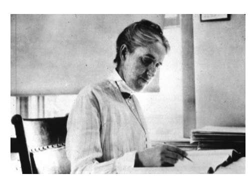
Class	Description
I	Supergiants
II	Bright giants
III	Giants
IV	Subgiants
V	Main sequence

Mass–Luminosity Relation

- All main sequence stars fuse H into He in their cores.
- Luminosity depends directly on mass because:
  - more mass means more weight from the star's outer layers
  - nuclear fusion rates must be higher in order to maintain gravitational equilibrium

Cepheid Variables

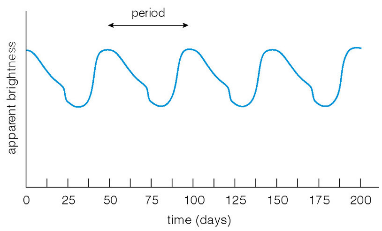
She studied the light curves of variable stars in the Magellenic clouds.



Henrietta Leavitt (1868-1921)

Same distance

Cepheid Variables



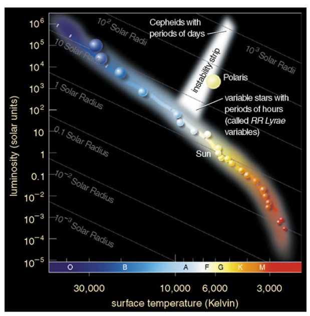
The brightness of the stars varied in a regular pattern.

Cepheid Variables

- Periods related to luminosities—**period-luminosity relation**
- Look for Cepheids, measure period, determine luminosity, and then we can get their distance via luminosity-distance formula:
  - Apparent brightness = luminosity / ($2 \pi d^2$)

The Instability Strip

There appears to be an almost vertical region on the H-R Diagram where all stars within it (except on the Main Sequence) are variable.



They pulsate due to partial ionization!

16.6 Star Clusters

Our goals for learning:

- What are the two major types of star cluster?
- Why are star clusters useful for studying stellar evolution?
- How do we measure the age of a star cluster?

Open Clusters

- 100's of stars
- 10^6 - 10^9 years old
- irregular shapes
- gas or nebulosity is sometimes seen
- Found in disk of galaxy

Pleaides (8 x 10^7 yrs)

Globular Clusters

- 10^5 stars
- 8 to 15 billion years old (10^{10} yrs)
- spherical shape
- NO gas or nebulosity

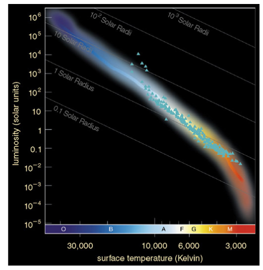
M 80 (1.2 x 10^{10} yrs)

Clusters are useful for studying stellar evolution!

- all stars are the same distance
  - use apparent magnitudes
- all stars formed at about the same time
  - they are the same age

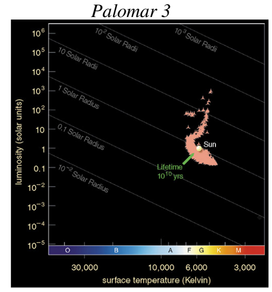
Plot an H-R Diagram!

Pleiades H-R Diagram

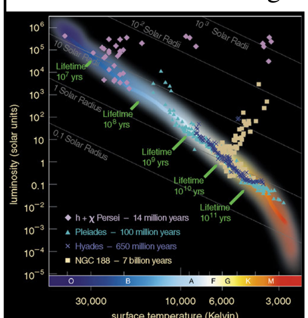


Globular Cluster H-R Diagram

Palomar 3



Cluster H-R Diagrams Indicate Age



- All stars arrived on the MS at about the same time.
- The cluster is as old as the most luminous (massive) star left on the MS.
- All MS stars to the left have already used up their H fuel and are gone.
- The position of the hottest, brightest star on a cluster's main sequence is called the *main sequence turnoff point*.

What have we learned?

- How can we learn about the lives of stars, which last millions to billions of years?
  - By taking observations of many stars, we can study stars in many phases of life, just as we might study how humans age by observing the humans living in a village at one time.
- What two basic physical properties do astronomers use to classify stars?
  - Stars are classified by their luminosity and surface temperature. These properties, in turn, depend primarily on a star's mass and its stage of life.

What have we learned?

- What is luminosity and how do we determine it?
  - A star's luminosity is the total power (energy per unit time) that it radiates into space. It can be calculated from a star's measured apparent brightness and distance, using the luminosity-distance formula: apparent brightness = luminosity / ($4\pi \times$ distance^2).
- How do we measure the distance to nearby stars?
  - The distance to nearby stars can be measured by parallax, the shift in theapparent position of a star with respect to more distant stars as the Earth moves around the Sun.
- How does the magnitude of a star depend on its apparent brightness?
  - The magnitude scale runs backward, so a star of magnitude 5 star is brighter than a star of magnitude 18.

What have we learned?

- How are stars classified into spectral types?
  - Stars are classified according to their spectra, with different spectral types generally corresponding to different temperatures. In order from hottest to coolest, the major spectral types are O, B, A, F, G, K, and M. These are subdivided into numbered categories; for example, the hottest A stars are type A0 and the coolest A stars are type A9, which is slightly hotter than F0.
- Does a star's spectral type depend on its composition?
  - No. All stars are made primarily of hydrogen and helium, and the main factor in determining a star's spectral type is its surface temperature.
- What are the two main elements in all stars?
  - Hydrogen and helium.

What have we learned?

- What is the most important property of a star?
  - A star's most important property is its mass, which determines its luminosity and spectral type at each stage of its life.
- What are the three major classes of binary star systems?
  - A visual binary is a pair of orbiting stars that we can see distinctly. An eclipsing binary reveals its binary nature because of periodic dimming that occurs when one star eclipses the other as viewed from Earth. A spectroscopic binary reveals its binary nature because we can see the spectral lines of one or both stars shifting back and forth as the stars orbit each other.

What have we learned?

- How do we measure stellar masses?
  - We can directly measure mass only in binary systems in which we are able to determine the period and separation of the two orbiting stars. We can then calculate mass using Newton's version of Kepler's third law.

What have we learned?

- What is the Hertzsprung-Russell (HR) diagram?
  - It is the most important classification tool in stellar astronomy. Stars are located on the HR diagram by their surface temperature (or spectral type) along the horizontal axis and their luminosity along the vertical axis. Temperature decreases from left to right on the HR diagram.
- What are the major features of the HR diagram?
  - Most stars occupy the main sequence, which extends diagonally from lower right to upper left. The giants and supergiants inhabit the upper right region of the diagram, above the main sequence. The white dwarfs are found near the lower left, below the main sequence.

What have we learned?

- How do stars differ along the main sequence?
  - All main sequence stars are fusing hydrogen to helium in their cores. Stars near the lower right of the main sequence are lower in mass and have longer lifetimes than stars further up the main sequence. Lower mass main-sequence stars are also much more common than higher mass stars.
- What determines the length of time a star spends on the main sequence?
  - A star's mass determines how much hydrogen fuel it has and how fast it fuses that hydrogen into helium. The most massive stars have the shortest lifetimes because they fuse their hydrogen much faster than lower mass stars.

What have we learned?

- What are Cepheid variable stars and why are they important to astronomers?
  - A Cepheid variable is a type of very luminous pulsating variable star that follows a period–luminosity relation, which means we can calculate its luminosity by measuring its pulsation period. Once we know a Cepheid's luminosity, we can calculate its distance from the luminosity–distance formula. This property of Cepheids enables us to measure distances to many other galaxies in which these variable stars have been observed.

What have we learned?

- What are the two major types of star cluster?
  - Open clusters contain up to several thousand stars and are found in the disk of the galaxy. Globular clusters are much denser, containing hundreds of thousands of stars, and are found in both the halo and disk of the galaxy. Globular cluster stars are among the oldest stars known, with ages of about 12 to 15 billion years. Open clusters are generally much younger than globular clusters.
- Why are star clusters useful for studying stellar evolution?
  - The stars in star clusters are all at roughly the same distance and, since they were born at about the same time, are about the same age.
- How do we measure the age of a star cluster?
  - The age of a cluster is equal to the main-sequence lifetime of hottest and most luminous main-sequence stars remaining in the cluster. On an HR diagram of the cluster, these stars sit farthest to the upper left, defining the main-sequence turnoff point of the cluster.

Why does a photograph of a star field (e.g. Figure 16.4) show some stars to be larger than others?

1. Some stars are larger than others and therefore appear larger.
2. Some stars are nearer than others and therefore appear larger.
3. Both (1) and (2).
4. Photographs make brighter stars appear larger than fainter stars, although they should all be points of light.
5. Sometimes what looks like a single star is actually a small group of stars and therefore appears larger.

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Suppose two orbiting stars are moving in a plane perpendicular to our line of sight. What happens to the spectral features of the stars as they go around each other?

1. Their brightness periodically decreases and then increases.
2. The feature of one star stays the same but the other shifts from red to blue and back again.
3. The features of both stars shift from red to blue and back again.
4. The features stay the same but the overall color of the stars periodically shifts from red to blue and back again.
5. Nothing, the features stay exactly the same.

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What do the colors of stars in the Hertzsprung-Russel diagram tell us?

1. The size of the star.
2. The luminosity of the star.
3. The surface temperature of the star.
4. The core temperature of the star.
5. The mass of the star.

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Two stars that look very different must be made of different kinds of elements.

1. Yes, stars have a wide range of compositions.
2. Yes, stars appear different because of their different composition.
3. No, stars appear different due to their different ages and masses, not composition.
4. No, stars appear different because of their varying distances from us.

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Stars that begin their lives with the most mass live longer than less massive stars because it takes them a lot longer to use up their hydrogen fuel.

1. Yes, with more hydrogen to burn, massive stars can live for billions of years.
2. Yes, low mass stars run out of hydrogen very quickly and have very short lifetimes.
3. No, stars have similar lifetimes despite their different masses.
4. No, more massive stars are much more luminous than low mass stars and use up their hydrogen faster, even though they have more of it.

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