Surveying the Milky Way

How Astronomers Prepared a Detailed Map of the Nearby Regions of Space By the 1920's

Primary References:

Astronomy:The Evolving Universe, Michael Zeilik, Second Edition, Harper & Row, 1979.

Software: Starry Night Pro 3.1

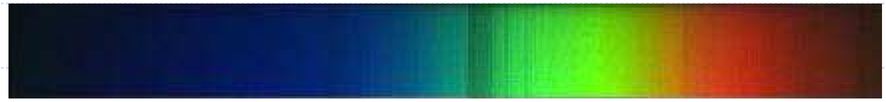
February, 2002

What Can We See?

- Looking between Cygnus and Scorpius with binoculars, the more intently we look at the sky in this region, the more stars we see.

Cygnus, Alson Wong, Celestron C9.25

Vocabulary



- **Spectrum** - light of various wavelengths emitted by a star.
- **Electromagnetic radiation** carries almost all of the information from celestial bodies to the Earth.
- Solar system objects like the Sun, planets, and asteroids are very close to us compared to other stars.
- **Luminosity** is the total amount of energy emitted by an object, a star or a light bulb, and is measured in Watts, like a 100 W light bulb.
- A **Kelvin** is a unit of temperature.
- 1 K = -273 C = -459 F.

Overview

- Historically, astronomers have attacked this puzzle by showing the key importance of distance measurements and the properties of stars.
- They eventually discovered that we live in a spiral galaxy... a vast, flat, pinwheel of stars, gas and dust.
- Our Sun is only one of billions of stars in our galaxy. It resides about three quarters of the way out from the center, in one of the spiral arms.

Herschel's Star Count

- In the latter part of the 18^{th} century, William Herschel used systematic observational techniques to attack the problem of the Milky Way's structure.
- He used the most powerful telescopes of his day to conduct a 'star count' in selected regions of the sky.
- He believed that the directions where he found large numbers of faint stars were places where the Milky Way extended the farthest.

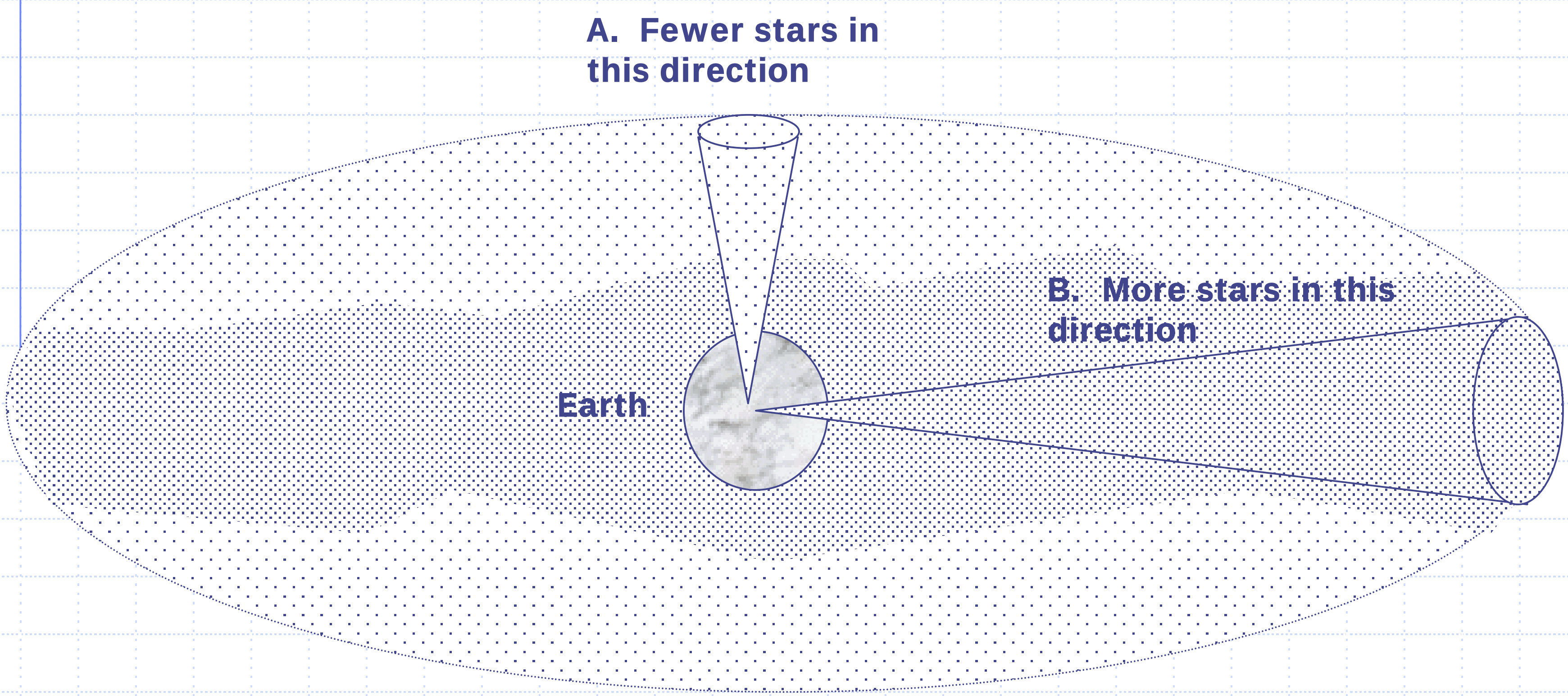
Assumptions

- As a starting point, Herschel assumed:
  - Brightness means nearness (or faintness means farness)
  - All stars were essentially the same and gave off the same amount of light. They were equally **luminous**. (Reasonable beginning assumption)
  - If all stars were placed the same distance from earth, they would all have the same brightness.

Herschel's Conclusions

- With this and other assumptions, Herschel's star counting program allowed him to estimate the distance to the edge of the galaxy.
- He concluded that the stars were arranged in a thin slab, with the Sun not far from the center of the galaxy.

Herschel's Counting Results



This implies that the Milky Way extends further in direction B than A.

Herschel's Hypothesis

M81 and M82, Jeff Ball, 130mm Astro-Physics

- Herscel believed that all spiral shaped nebulosities were distant stellar systems that could ultimately be resolved into stars by large enough telescopes. He thought these clouds were other galaxies, viewed from a great distance.

Modified Assumptions

- Herschel's assumptions were only a good *starting* point. They have since been modified as we've come to understand more about stars:
  - All stars are not the same and do not give off the same amount of light.
  - They are not equally luminous. (Correct assumption)

Brightness of a Star

Two factors determine the brightness of a star:

- **Luminosity** - how much energy it puts out in a given time
- **Distance** - how far it is from us

Double Cluster, Jeff Ball, 130mm Astro-Physics

Example

- A searchlight puts out more light than a penlight. That is, the searchlight is more **luminous**.
- If that searchlight is 5 miles away from you, however, it will not be as bright because light intensity decreases with distance squared. A searchlight 5 miles from you may look as bright as a penlight 6 inches away from you. The same is true for stars.

Inverse-Square Law

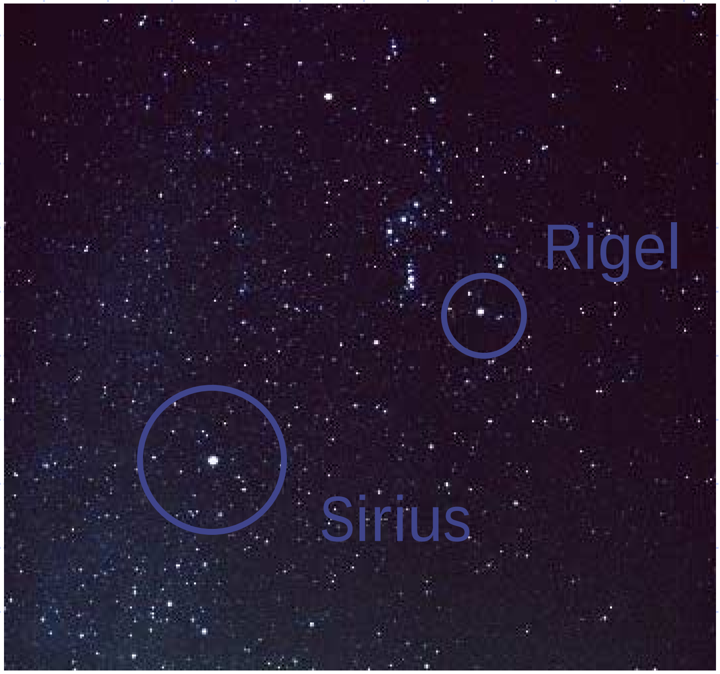
- This relationship is called an “inverse-square” relationship. As you move farther away from the bulb, the radiation is spread over a larger area.
  - The surface area of a sphere is directly related to its radius squared:

Surface Area of a Sphere = $4\pi r^2$

The light energy spreads out more and more on spheres that are larger and larger.

Example

- Anyone can tell that the star Sirius appears brighter than Rigel in Orion, but did you know that Rigel is really thousands of times more luminous than Sirius?



- Since stars are at different distances, this implies that Sirius is much brighter than Rigel because it is much closer.

The Parsec Standard

- Scientists needed a level playing field in order to compare the "absolute" brightness of many stars, so they decided to determine what a star's magnitude would be if it were placed 32.6 light-years (10 parsecs) away from Earth.
- After placing the stars at this distance we find an **absolute magnitude** range from –8 (bright) to +15 (dim) with Sirius being at +2, Rigel equal to -7 and the Sun close to the middle at +5.

The Magnitude Scale

- There are two kinds of Magnitudes:
  - Apparent Magnitude (m) – How bright a star appears from Earth.
    - Apparent magnitude is affected by how luminous the star is and how far away the star is from Earth.
  - Absolute Magnitude (M) – How bright a star would be from Earth if the star was placed 10 parsecs (32.6 ly) from Earth.
    - If all stars were placed the same standard distance from the Earth, then absolute magnitudes would represent differences in actual luminosities.

Inverse-Square Law

- The inverse-square law relates absolute and apparent magnitudes.
- If “d” is the distance to a star in parsecs, “m” is its apparent magnitude and “M” is its absolute magnitude:

$$m - M = 5 \log d - 5$$

Inverse-Square Law

- If we could figure out a star's Absolute Magnitude, and then measure how bright the star looks from Earth, we could use the Inverse-Square Law to figure out how far away it is.

Surveying the Milky Way

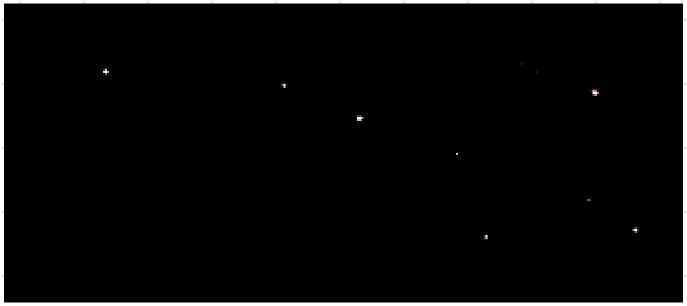
Stars Move Through Space

Stars Move

- In 1718, Edmund Halley compared positions he had found for the stars Arcturus and Sirius with those given by Ptolemy. He found that these stars had moved a considerable amount in 1500 years.
- He discovered that some of the ‘fixed’ stars were actually moving through space.

Movement of Big Dipper Stars

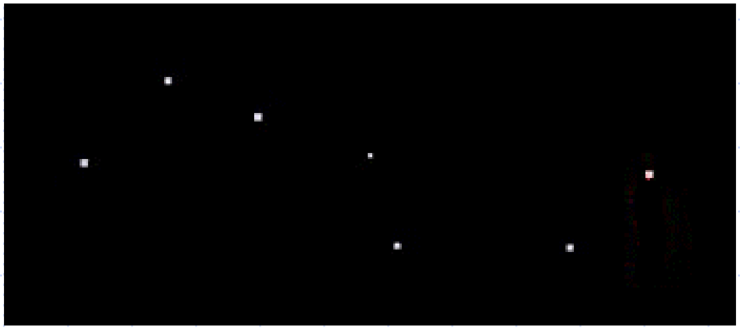
- Over 100,000 years the constellation of Ursa Major changes significantly.



50,000 BC

1 BC

50,000 AD



Swiftness Means Nearness

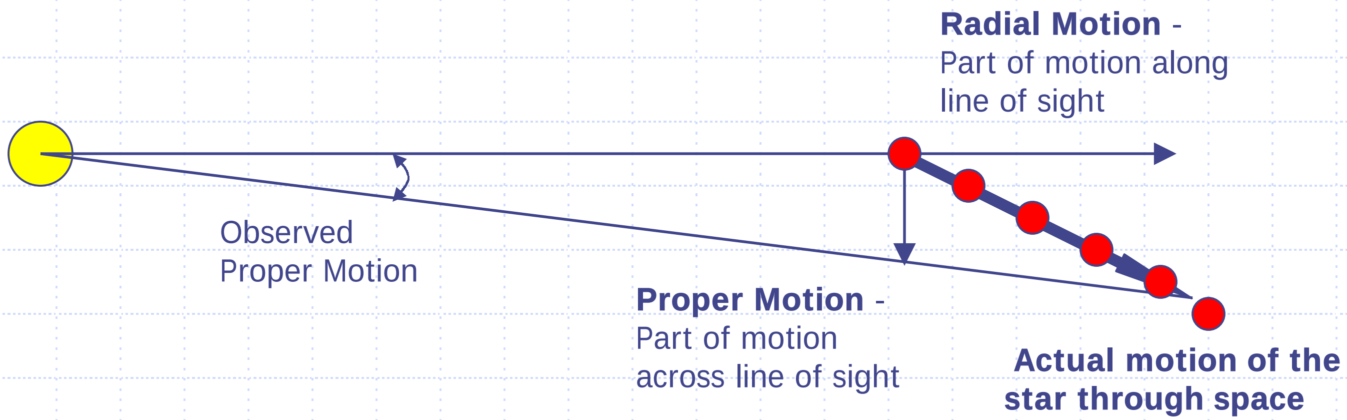
- As seen from Earth, the change in position of a star due to its motion in space with respect to other stars is called its “Proper Motion.”
- In estimating stellar distances, a rule of thumb is, “swiftness means closeness” (slowness means farness.)

Components of a Star's Motion

- The motion of stars consists of two components:
  - **Proper Motion** across our line of sight
  - Motion along our line of sight called **Radial Velocity**
- Radial velocity is measured by using the Doppler Effect.
  - The frequency of the spectrum is increased if the star is moving toward you (shifted toward the blue end of the spectrum) and the frequency is decreased if the star is moving away from you (shifted toward the red end of the spectrum).

Components of a Star's Motion

- Using both proper motion and radial velocities, and if we know the distance to a star, we can determine its motion through space.

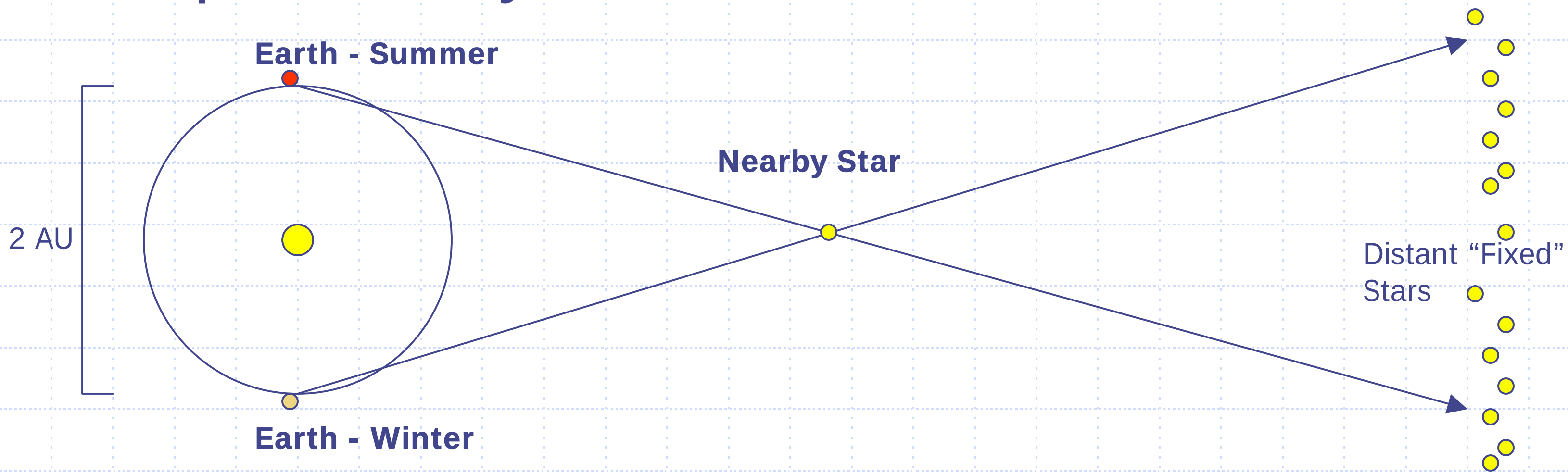


Measuring Distances to Stars

- Astronomers can only directly measure distances to nearby stars by using heliocentric (Sun-centered) trigonometric parallaxes.

Parallax Explained

- Imagine your finger held out at arms length is a star, the distant background to be more distant stars, and your eyes the sighting positions of the Earth in orbit around the sun separated by a time of 6 months.



The Challenge

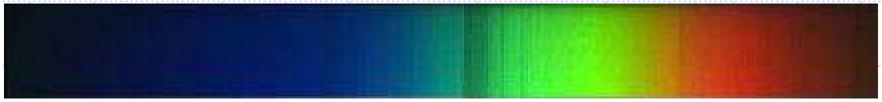
- Visually, parallax can be detected only by careful observation and measurement of a star's position.
- If a star is within about 400 light years, astronomers can measure its distance using heliocentric (Sun-centered) parallax. But what if it's not?
- **If we could figure out a star's luminosity *independent* of any distance measurement we could determine its distance.**

Surveying the Milky Way

The H-R Diagram:

The Key To The Stars

Background



- In 1905, Ejnar Hertsprung discovered that the widths of the dark lines in a star’s spectrum are related to its luminosity.
- Hertsprung independently found distances to groups of stars of the same spectral class (color) using a method called “statistical parallaxes.”
- In general, he found that stars of the same spectral type with narrow, dark spectral lines are more luminous than those with broad lines.
- This discovery led to a way of distinguishing between large and small stars by using their spectra.

Temperature and Spectrum

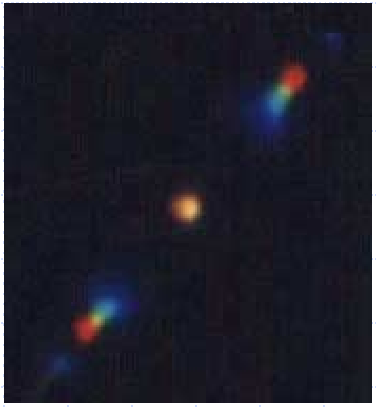
- Some stars are extremely hot, while others are cool. You can tell by the color of light that the stars give off.
- If you look at the coals in a charcoal grill, you know that the red glowing coals are cooler than the white hot ones. The same is true for stars. A blue or white star is hotter than a yellow star, which is hotter than a red star.

Spectra Examples

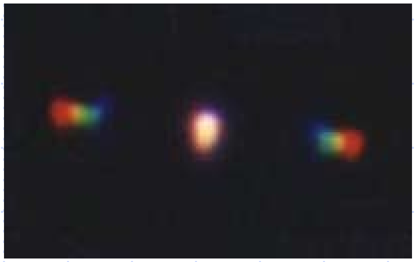
- If you look at the strongest color or wavelength of light emitted by the star, then you can calculate its temperature **(temperature in degrees Kelvin = 3 x 10^6 / wavelength in nanometers)**.
- A star's spectrum can also tell you the chemical elements that are in that star because different elements (for example, hydrogen, helium, carbon, calcium) absorb light at different wavelengths.

Spectra Examples

- **Procyon** is a mid- temperature star like our Sun. Its spectrum has fairly balanced colors of the rainbow.



- **Rigel** is a star twice the temperature of our Sun and so its spectrum is brighter in blue.



- **Betelgeuse** is a star only half the temperature of our Sun and so its spectrum is not only brighter in red but also has almost no blue light.

Star's Color Means Temperature

- Red stars are cooler than blue stars
- Stars of the same spectral class have the same temperature.
- All G-stars like the Sun have surface temperatures of about 6000 K.
- Stars radiate heat in a special way, like a **blackbody**.

Blackbody Radiation

- A "blackbody" is an object that absorbs completely any radiation that falls on it.
- Because it absorbs radiation, it must heat up and also give off radiation.
- A graph of blackbody radiation intensity versus radiation wavelength has a characteristic shape that depends only on the temperature of the body and not on anything else, like it's composition.

Luminosity Depends on Size

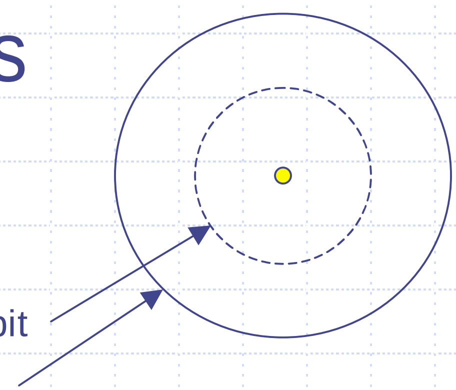
- Betelgeuse is of the same spectral type as Proxima Centauri. (So they have about the same surface temperatures, about 3000 K)
- Betelgeuse is 100 million times more luminous than Proxima Centauri.
- The difference must be one of **size**. Betelgeuse must be much larger than Proxima Centauri and have greater surface area.

Luminosity Equation

- The luminosity of a star depends upon both its **surface temperature** and **surface area**.
- For a spherical blackbody:

$$L = (4\pi r^2)(\sigma T^4) \text{ watts}$$

↑ Luminosity ↑ Surface Area of a Sphere ↑ Temperature



Star Color Means Temperature

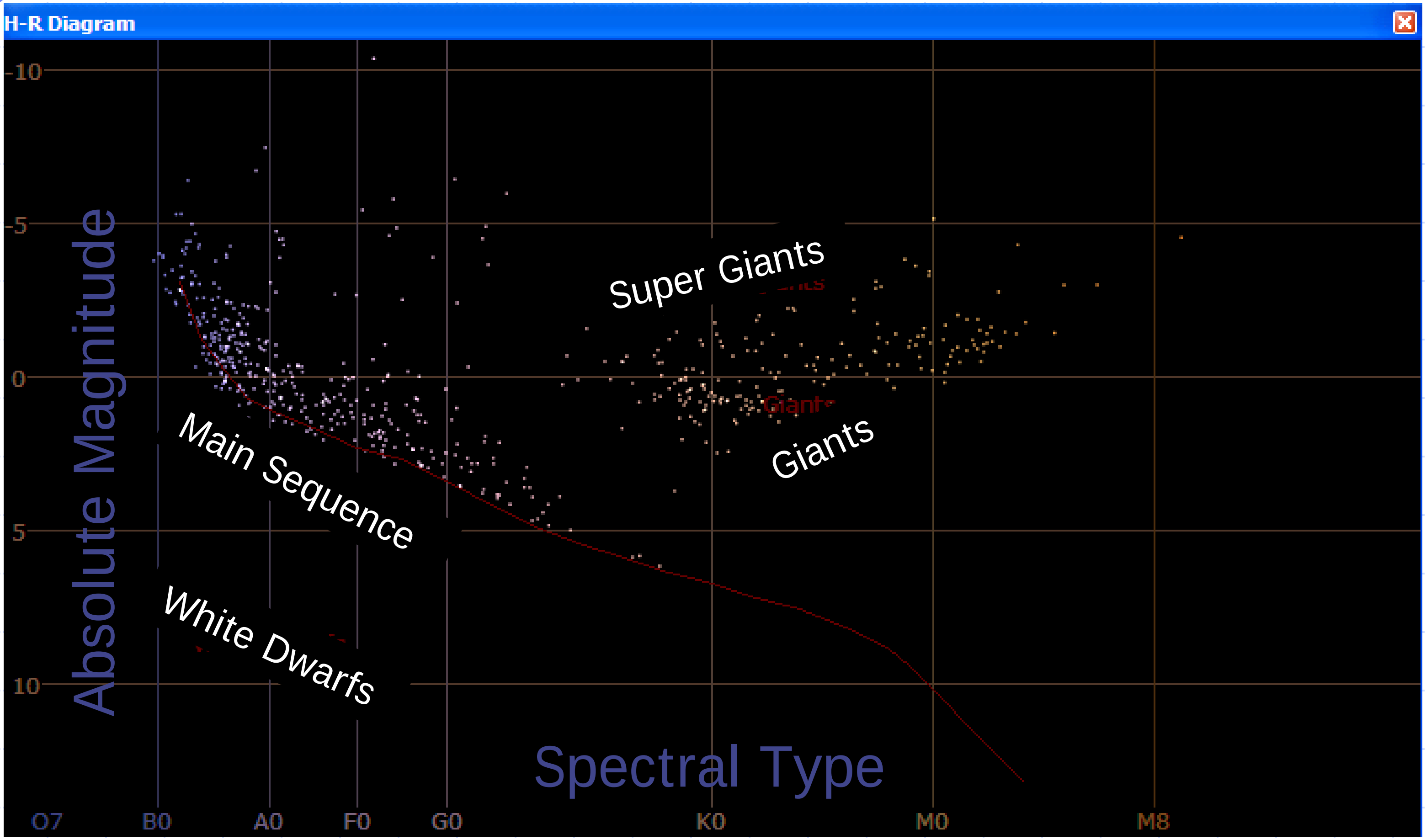
Spectral Classes of Stars			
Spectral Class	Color	Ave.Temp. (K)	Familiar Examples
O	Blue-violet	30,000	Mintaka (delta Orionis)
B	Blue-white	20,000	Rigel, Spica
A	White	10,000	Vega, Sirius
F	Yellow-white	8,000	Canopus, procyon
G	Yellow	6,000	Sun, Capella
K	Orange	4,000	Arcturus, Aldebaran
M	Red-orange	3,000	Antares, Betelgeuse

The Hertzprung-Russel Diagram

(Luminosity – Temperature Diagram)

- Henry Russel determined stellar parallaxes arriving at distances. He used the distances and the stars' apparent magnitudes to calculate their absolute magnitudes then plotted them with respect to their spectral class.
- Plotting absolute magnitude versus spectral class for a group of stars is called a Hertzsprung-Russel Diagram.
- Today the H-R Diagram guides astronomers to the physical properties of stars.

H-R Diagram



Stars visible to naked-eye before sunrise Feb. 15th.

(Starry Night Pro 3.1)

Use of the H-R Diagram

- Once an H-R Diagram has been completed for many stars, we can use it to infer distance to other stars:
  1. Find out the spectral type of the star.
  2. Use widths of certain spectral lines to determine the stars luminosity class. (An M-type star could be a dwarf (main sequence), giant, or supergiant.
  3. Use the H-R Diagram to determine the star's absolute magnitude.
     - You now know how bright the star looks and how bright the star would look if it was 10 pc away.

Bringing It All Together

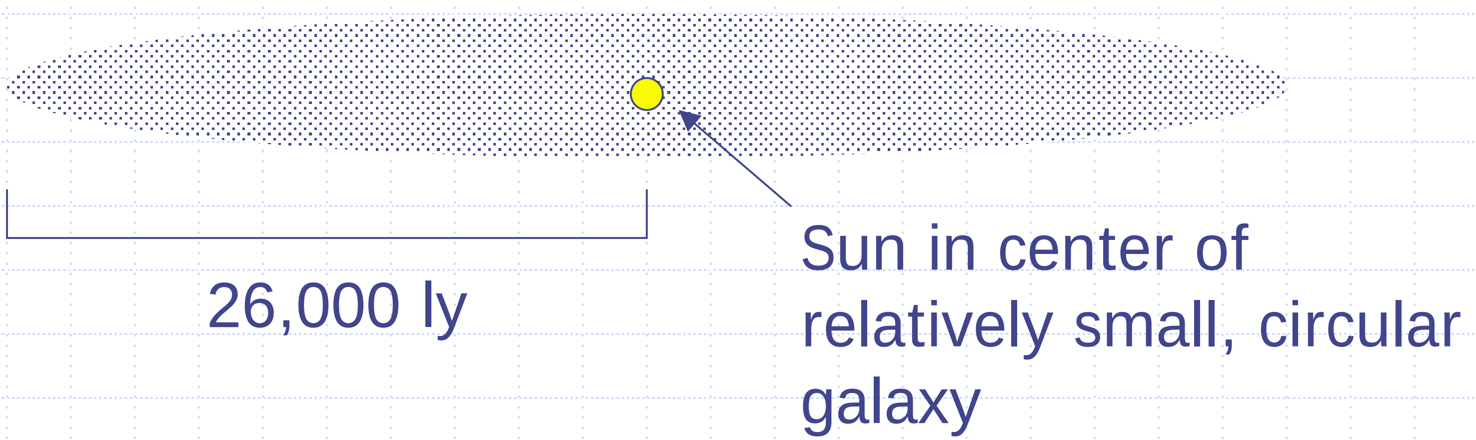
Parallaxes

Spectral Type ✥ Luminosity

H-R Diagram

Kapteyn Universe

- In 1922, Jacobus Kapteyn used statistical methods and the H-R Diagram and determined a galaxy structure like this:



Affects of Dust and Gas

- Kapteyn worried about dust and gas in space that might make stars appear dimmer than they really were.
- The light from the farthest stars would be affected most and lead to a misleadingly small picture of the galaxy.

Affects of Dust and Gas

- Interstellar dust and gas dims the light of the stars behind it.

Scorpius, Alson Wong,
Celestron C9.25

A New Distance Indicator

- While studying variable stars in the Magellanic Cloud, Henrietta Leavitt discovered that when the apparent magnitudes of a certain type of variable star were plotted against their periods, a definite relationship existed.
- The longer the period, the greater their luminosity.

Period-Luminosity Relationship

- Hertzprung determined from Leavitt's data that a unique relationship existed between the luminosity of a "Cepheid Variable" star and its period.
- To find the distance to cepheids, we use the following method:

Cepheid Distance Method

1. Find a cepheid variable star.
2. Measure its period (a relatively task that doesn’t depend on any knowledge of the star’s distance or spectral class.)
3. Find the star’s absolute magnitude from the period-luminosity relationship.
4. Knowing the star’s apparent magnitude, calculate its distance.

Shapley Dethrones the Sun

- In the 1920's, Harlow Shapley proposed a radical idea about the size of the Milky Way and the sun's position within it.
- The observational foundation rested on using the period-luminosity relationship of cepheids.
- His model evicted the sun from its central status in the Milky Way, the second significant move of humankind away from 'special' status in the universe.

Globular Clusters Have Cepheids

- When Shapley realized that the variable stars he had observed in globular clusters had the properties of cepheids, he used the period-luminosity method to determine their distance.
- What he determined shocked the astro-nomical community.

Globular Cluster M13

The Galaxy is Much Bigger ...

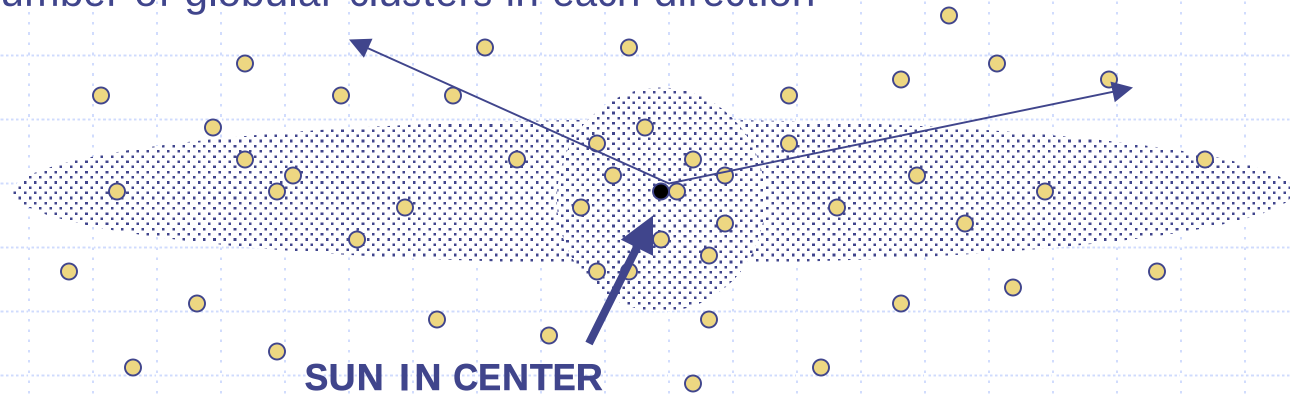
- Globular clusters do not follow the distribution of stars in the galaxy by sticking along the plane. They are widely distributed with an odd concentration in the direction of Sagittarius.
- Using a period-luminosity scale that he had personally calibrated, Shapley determined the globular cluster M13 to be 100,000 ly distant. The number was staggering. It placed the globular clusters outside the boundaries of the Milky Way as mapped by Kapteyn.

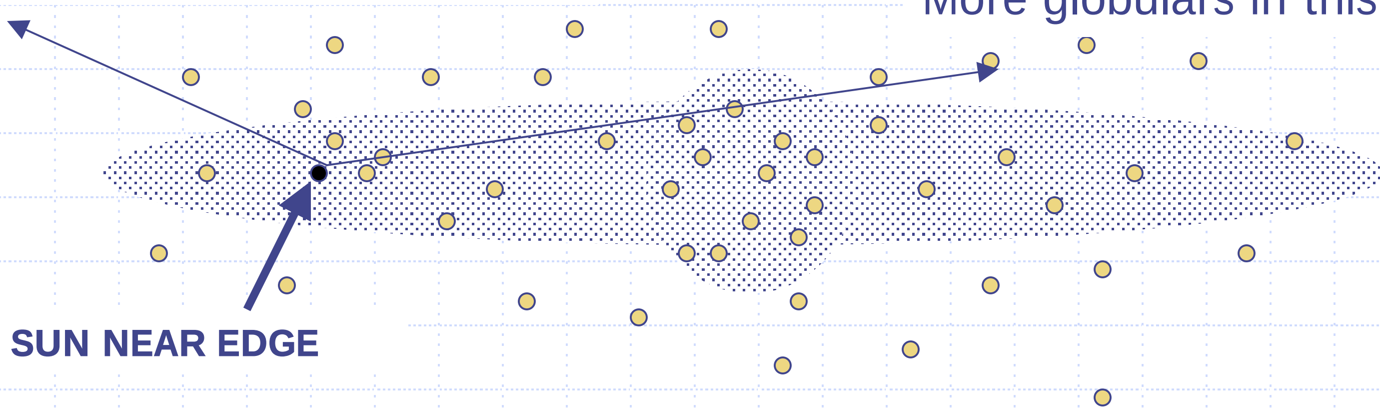
The Sun Isn't In The Center

- The non-uniform distribution of globulars in the sky was a nagging problem. If the globulars were gravitationally allied with the Milky Way, they should be in a uniform distribution throughout the galaxy.
- But the observed non-uniformity indicated that the Sun was NOT in the Milky Way's center, but much further out along the edge.

Non-uniform Globular Distribution

If the Sun was in the center of the galaxy, we'd count the same number of globular clusters in each direction





The Puzzle Comes Together

- Over the course of two centuries, astronomers have pieced together the construction of the Milky Way.
- The fitting together of the celestial map depended on the measurement of distances, which is in turn based on the fundamental properties of stars themselves and electromagnetic radiation.

Information From Light

- Stars have many features that can be measured by studying the light that they emit:
  - Temperature
  - Spectrum or wavelengths of light emitted
  - Brightness
  - Luminosity
  - Size (radius)
  - Mass
  - Movement (toward or away from us)

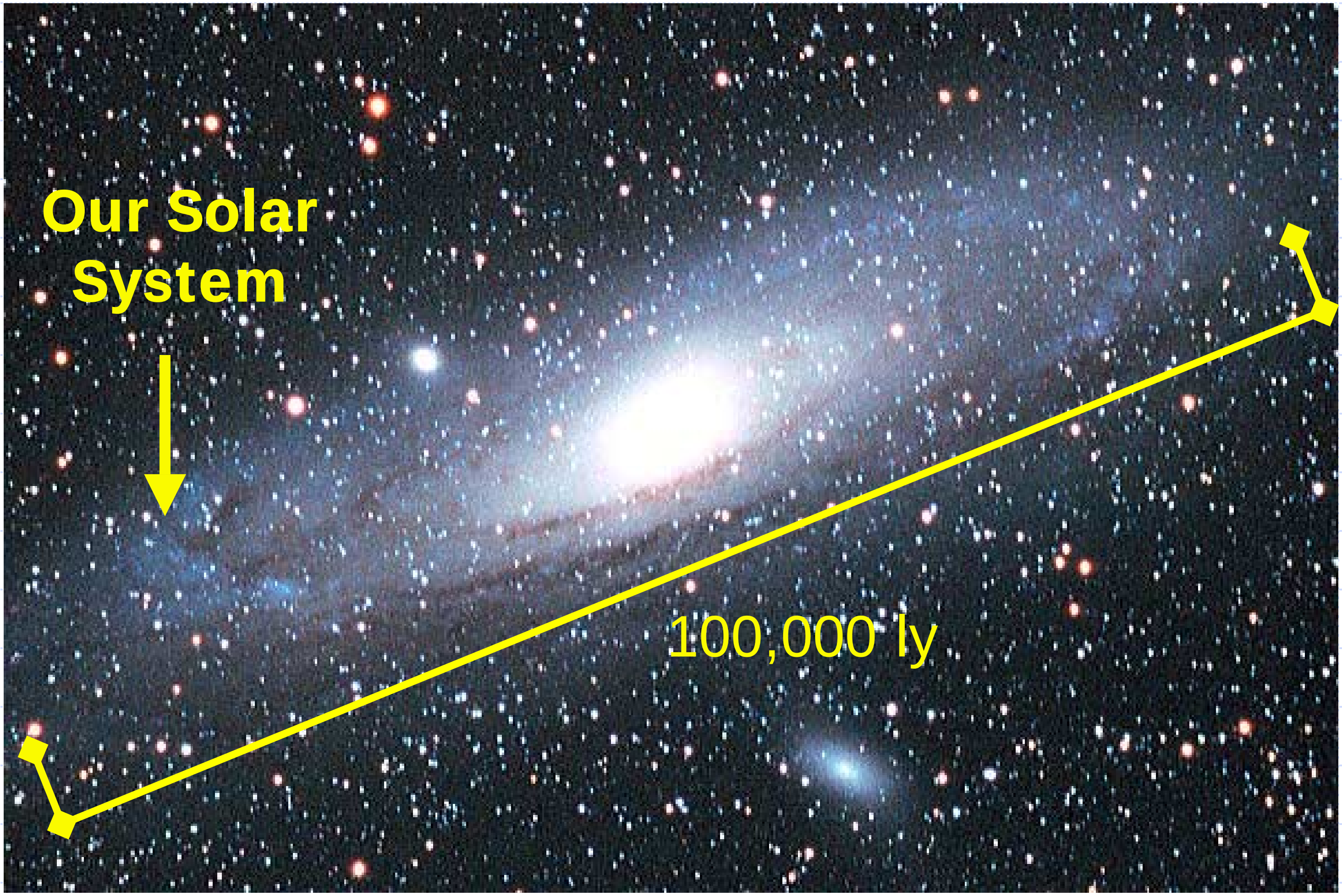
Summary

- Star counting by Herschel, and Kapteyn gave only the relative shape of the galaxy.
- Parallaxes were first used to calibrate the distance scale to nearby stars. Later, the H-R diagram was used to get the distances to the other stars.

Summary

- The big breakthrough was Leavitt's discovery of the period-luminosity relationship for cepheids.
- Once known in terms of absolute magnitude, this relationship could be used to find distances to globular clusters, that the galaxy was large, and with the Sun far from the center.

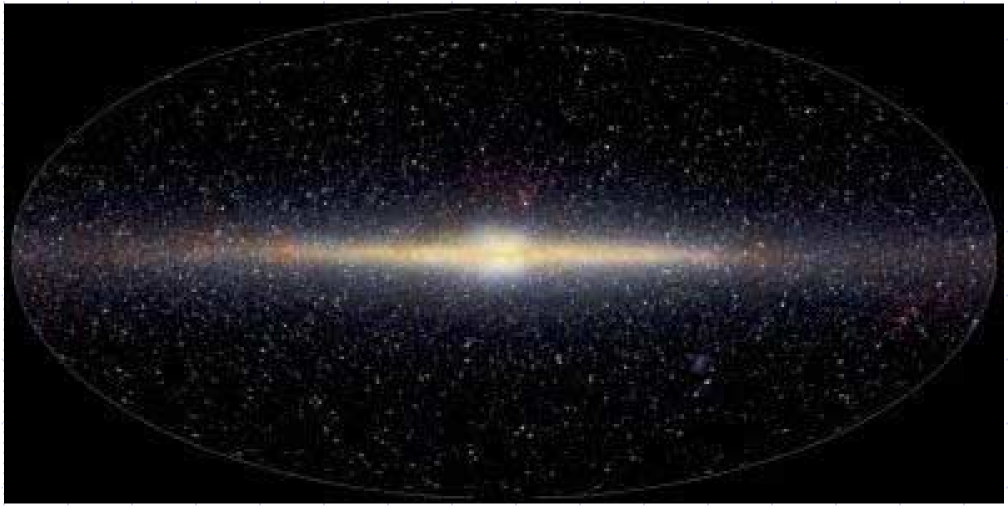
From our neighbor, the Andromeda Galaxy, we might look like this:



Summary

- By 1920, our galaxy was a much bigger, but better defined place, and our place within it was far less centralized.
- The rough survey of the local structure had been completed, but many, many details remained unexplored...

The Heart of the Milky Way



- An infrared image of our Galaxy taken by the NASA Cosmic Background Explorer (COBE) satellite. The galactic plane runs horizontally along the middle of the image. Absorption by interstellar dust is minimized at infrared wavelengths allowing a clearer view of the plane and center of our Galaxy.

Backup

-

Magnitude Scale

- The eye doesn't sense brightness in the simple way that you might expect. If an object has twice the luminosity, it doesn't appear twice as bright.
- Example:
  - Suppose you tried to estimate the brightness of a 100W and a 200W light bulb. The second bulb will not appear two times as bright because of how the human eye works.

Experiment
Inverse-Square Law

- The farther you move away from a light source, the dimmer it appears.
- Imagine this experiment:
  - Put a bare light bulb (any wattage) in a socket and turn it on.
  - Take a light meter and place it 1 m away from the light. Note the reading on the light meter. Call this one unit.
  - Now move the light meter 2 m away from the bulb. Its reading will be ¼ that at the 1 m position.
  - Move the light meter to a distance of 3 m, the reading will now be 1/9 that at 1 m.
  - At 4 m the reading would be 1/16...

Inverse-Square Law

- In equation form:

$$\frac{\text{New Brightness}}{\text{Old Brightness}} = \left(\frac{\text{Old Distance}}{\text{New Distance}}\right)^2$$

Or

$$\frac{b_2}{b_1} = \left(\frac{d_1}{d_2}\right)^2$$

Inverse-Square Law

- Example: If a star is 100 times brighter than another

$$100 = \left(\frac{d_1}{d_2}\right)^2$$

Where:

d_1 = distance to fainter star

d_2 = distance to brighter star

$$10 = \frac{d_1}{d_2}$$

$$10\,(d_2) = d_1$$

The distance to the fainter star is 10 times more than the brighter star.

Magnitude Scale

- The magnitude scale is defined so that a difference of 5 magnitudes corresponds to a brightness ratio of 100.
- A difference of 1 magnitude then amounts to a brightness ratio of 2.512.
- This strange number pops up because:
  - 2.512 x 2.512 x 2.512 x 2.512 x 2.512 = 100 Or $2.512^5 = 100$

Magnitude Difference	Equals a Brightness Ratio
0.0	1
2.5	10
5.0	100
7.5	1,000
10.0	10,000

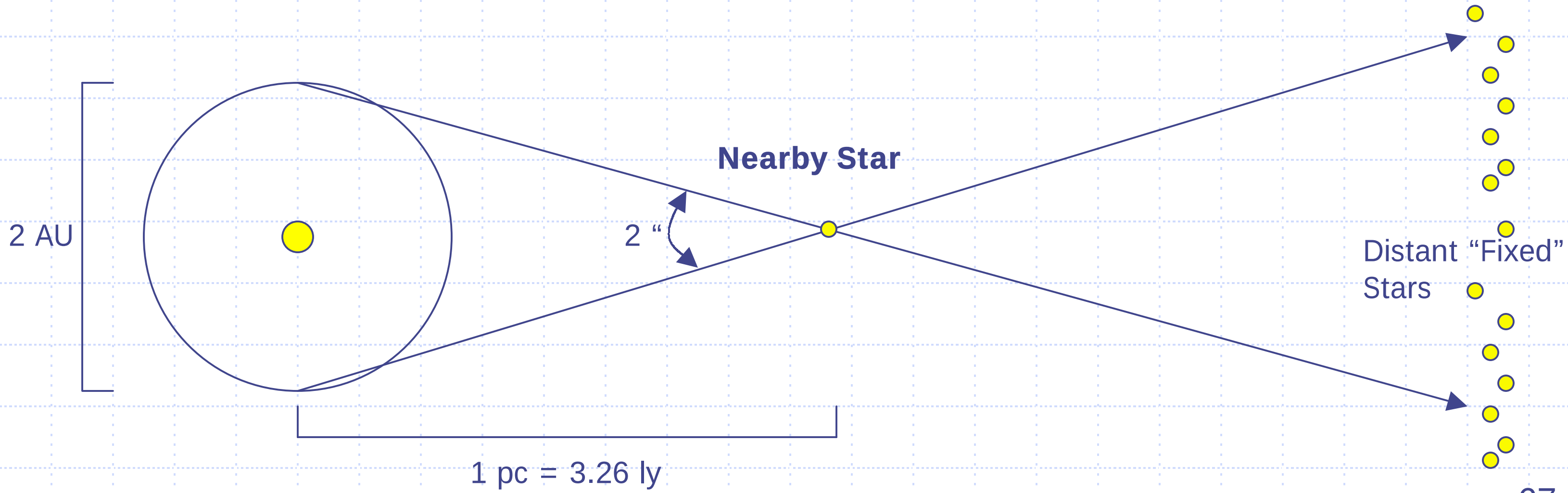
Apparent Magnitude

- As viewed from Earth, a star's brightness is it's "apparent magnitude." (m)
- Astronomers rank the brightness of stars using a magnitude scale in which fainter stars have higher numbers. A star of apparent magnitude +3 is fainter than one with an apparent magnitude of +2.
- The very brightest stars have magnitudes less than zero. Sirius has an apparent magnitude of –1.4 and is brighter than Vega with an apparent magnitude of 0.0.

Definition of a Parsec

- The distance at which the parallax of 1 AU is one second of arc is called a “parsec” (approximately 3.26 ly)
- (Practically speaking... 2 AU and 2” of arc)
- The inverse-square law relates absolute and apparent magnitudes. If d is the distance to a star in parsecs, m is its apparent magnitude and M is its absolute magnitude:

$$m - M = 5 \log d - 5$$



The Question of the Spiral Nebulas

- The question of Herschel's spiral nebula remained. Were they part of the Milky Way? No one knew because no distances had been determined for them.
- If they were galaxies like the Milky Way, then the distances to them must be immense.

Novas Seen

- In 1917 at Mt. Wilson Observatory, George Ritchey discovered a nova in a spiral nebula.
- Since it was known that a nova could occur in a cluster of stars but not in a cloud of gas, the spiral could not just be a nebula.
- Other photographic plates at Mt. Wilson were searched and 11 other novas were soon discovered.

Using Novas to Estimate Distance

- Since most novas seem to have about the same apparent magnitudes at maximum brightness, a simple method was devised to use novas to determine distances.
- The assumption was made that novas in our galaxy were the same as novas in other galaxies. Novas in our galaxy had about the same absolute magnitudes of –8.
- Astronomers used this to estimate that the novas in spiral nebula were very far away – outside of our galaxy.

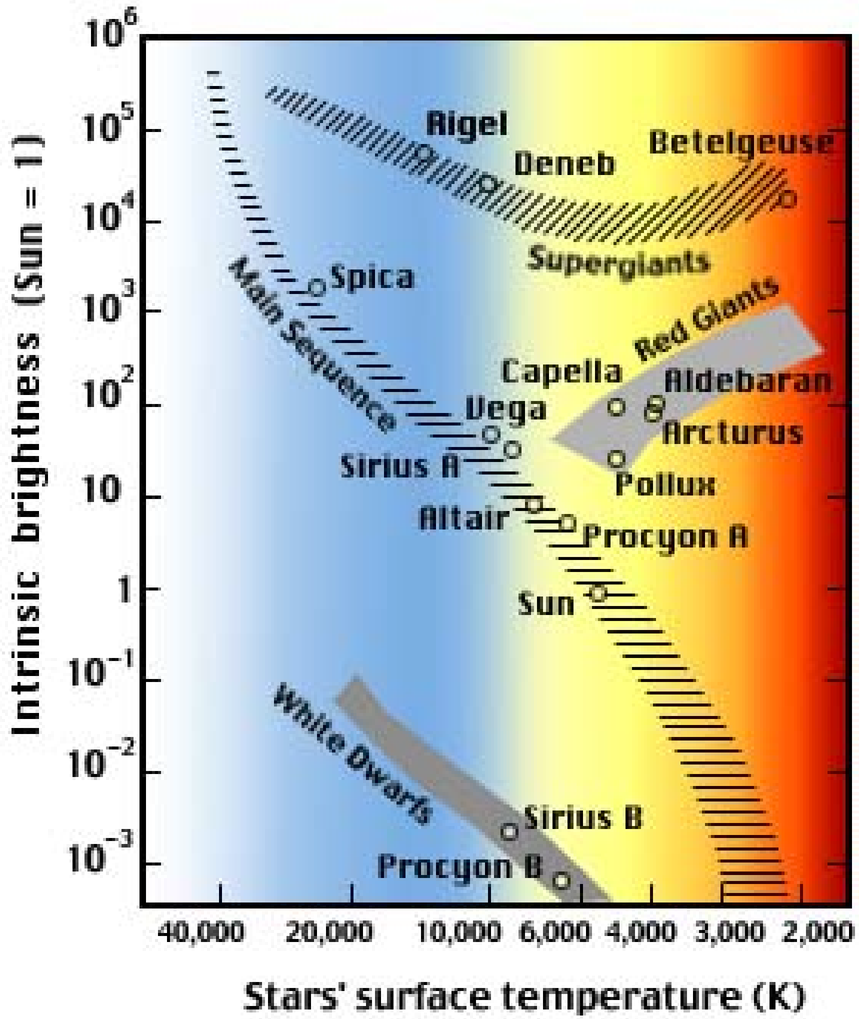
Definitions

- **absolute magnitude** - apparent magnitude of the star if it was located 10 parsecs from Earth
- **apparent magnitude** - a star's brightness as observed from Earth
- **luminosity** - total amount of energy emitted from a star per second
- **parsec** - distance measurement (3.3 light-years, 19.8 trillion miles, 33 trillion kilometers)
- **light year** - distance measurement (6 trillion miles, 10 trillion kilometers)
- **spectrum** - light of various wavelengths emitted by a star
- **solar mass** - mass of the sun; 1.99 x 10^{30} kg (330,000 Earth masses)
- **solar radius** - radius of the sun; 418,000 miles (696,000 km)

Website References

- http://www.howstuffworks.com/light.htm
- http://www.as.net/~takoonce/astro/index.htm

H-R Diagram



Intrinsic brightness (Sun = 1)
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
Rigel
Deneb
Betelgeuse
Supergiants
Spica
Main Sequence
Red Giants
Capella
Aldebaran
Vega
Arcturus
Sirius A
Pollux
Altair
Procyon A
Sun
White Dwarfs
Sirius B
Procyon B
40,000
20,000
10,000
6,000
4,000
3,000
2,000
Stars' surface temperature (K)