20. Galaxies: From Here to the Horizon

Thus the explorations of space end on a note of uncertainty… Eventually, we reach the dim boundary – the utmost limits of our telescopes. There we measure shadows, and we search among ghostly errors of measurement for landmarks that are scarcely more substantial.

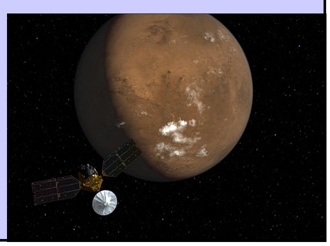
Edwin Hubble (1889 – 1953)
American astronomer

Agenda

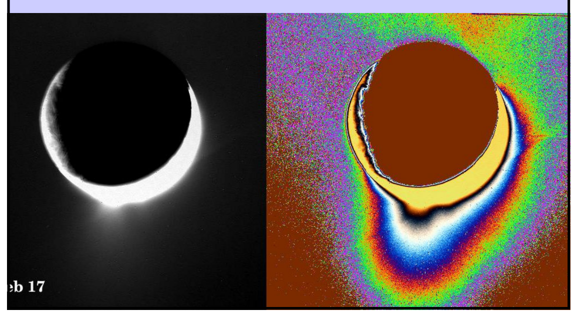
- Announce:
  - Test next week
  - HW2: Black Hole tutorial
- Astronomical News
- Ch. 20– Galaxies: From Here to the Horizon
- Hand back “Waves on a String” lab
- Questions on “Index of Refraction” lab

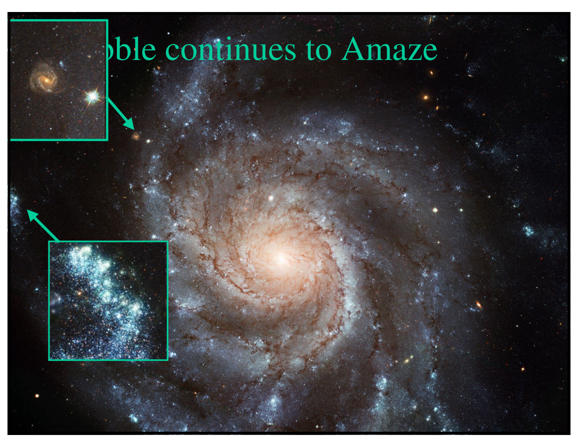
MRO

- Mars Reconnaissance Orbiter
- Examine Mars' surface, atmosphere and underground layers in great detail from a low orbit
- Scout possible landing sites and relaying communications



Water on Saturn’s Moon Enceladus





20.1 Islands of Stars

Our goals for learning:

- How do we study the lives of Galaxies?

A Universe of Galaxies

- In 1995, the Hubble Space Telescope observed a patch of sky in the Big Dipper for 10 days.
  - many galaxies, each one an island of stars like our own Milky Way, were detected
  - by counting them and correcting for the entire sky, we estimate that there are over 80 billion galaxies in the observable Universe

Movie. Click to play.

- We study the life cycles of galaxies in the same way we do stars.
  - we piece together a life story by observing many different galaxies at various stages of their lives
- Studying life cycles of galaxies is more difficult than that of stars.
  - young galaxies are only found at very great distances

20.2 Galaxy Types

Our goals for learning:

- What are the three major types of galaxies?
- What is the major difference between spiral and elliptical galaxies?
- How are galaxy types different in clusters of galaxies?

Classification of Galaxies

- Using a system invented by Edwin Hubble, astronomers classify galaxies into three major types:
  - Spiral
  - Elliptical
  - Irregular
- The sizes of all three types span a wide range, from
  - dwarf galaxies
    - which contain 100 million (10^8) stars
- to
  - giant galaxies
    - which contain 1 trillion (10^{12}) stars

Spiral Galaxies



- have a *disk component* and bulge & halo (*spheroidal component*)
- disk contains an ISM of gas & dust
- relative sizes of bulge/disk & amount of ISM vary among galaxies
- appear white because they contain both blue & red stars

Spiral Galaxies

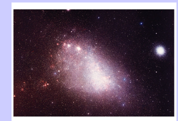
- Some spiral galaxies have a bar of stars cutting through their centers.
  - spiral arms are attached to the ends of the bar
  - we call them **barred spiral galaxies**
- Some astronomers have suggested that the Milky Way is a barred spiral.
  - its bulge appears elongated


- Some galaxies have disks with *no* spiral arms.
  - we call then **lenticular galaxies**
  - they look like a lens seen edge-on
- They contain less cool gas than normal spirals.

Elliptical Galaxies

- only have a *spheroidal component;* <u>no</u> *disk component*
- very little ISM, which is mostly low-density and ionized
- appear red because they contain mostly red stars

Irregular Galaxies



- "none of the above" category; neither spiral nor elliptical
- appear white & dusty with ISM
  - have more in common with the disk component of spirals
- distant galaxies are more likely to be irregular
  - they were more common when the Universe was young

Groups and Clusters

- Among large galaxies…
  - most (75–85%) are spirals
  - they tend to associate in loose **groups** of several galaxies
- Our Local Group is an example
  - dominated by two large spirals
    - the Milky Way
    - Great Galaxy in *Andromeda*

- Some galaxies associate in tightly bound **clusters**.
  - contain hundreds of galaxies
  - half of all large galaxies are elliptical
- Outside of clusters…
  - large ellipticals are rare (15%)
  - most dwarfs are elliptical

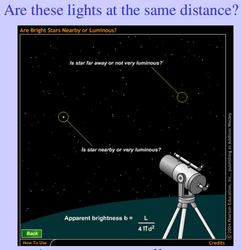
20.3 Measuring Cosmic Distances

Our goals for learning:

- What is a standard candle and how is it used to determine distance?
- What makes a good standard candle?
- Why do Cepheid variable stars make good standard candles?
- What is Hubble's Law and where is it applicable?
- Summarize the chain through which we build up measurements of distance throughout the Universe.

Standard Candles

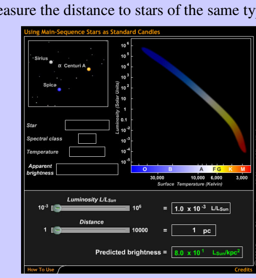
Are these lights at the same distance?



- Obviously not!
  - have the <u>same</u> apparent brightness, but <u>very</u> <u>different</u> luminosities
- If you knew the luminosity of…
  - a standard lighthouse beacon
  - or a *standard candle*
- you could measure the distance to each given their apparent brightness
- Astronomers call any astronomical object whose luminosity can be determined without knowledge of its distance a **standard candle**.
- We can then calculate the distance to any standard candle by…
  - measuring its apparent brightness and using the luminosity/distance formula

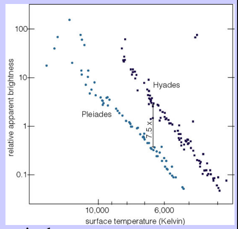
What Makes a Good Standard Candle?

- Well, we know the luminosity of our Sun, as well as all stars on the main sequence.
  - we know this by using the parallax method on nearby stars
  - we can measure the distance to stars of the same type which are far away



What Makes a Good Standard Candle?

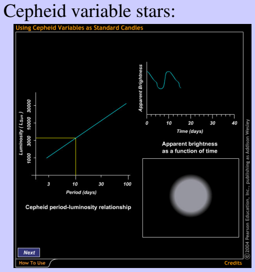
- For a cluster of stars, we can compare the entire main sequence.
  - we know distance to *Hyades* from parallax
  - by measuring how much fainter Pleiades' MS is, we can calculate its distance
- This is called **main-sequence fitting**.



- The problem with main-sequence fitting is that…
  - most main sequence stars are too faint to observe in other galaxies!
- So we need a more luminous standard candle to measure distances to galaxies.
  - we have already studied such a candle…**Cepheid variable stars**

What Makes a Good Standard Candle?

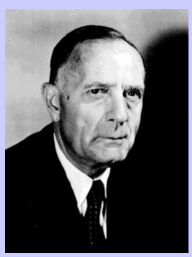
- Review of Cepheid variable stars:



- Cepheid variables make good standard candles because:
  - they follow a well-defined period-luminosity relationship
  - they are bright giants…luminous enough to see at great distances

Edwin Hubble
(1889-1953)

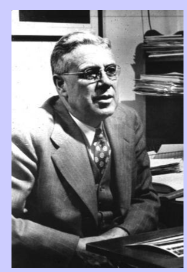
- He discovered Cepheid variables in the *Andromeda* galaxy.
- He calculated the distance to the *Andromeda* galaxy.
  - 2 million light years
  - it was **not** in the Milky Way
- He developed a classification scheme for galaxies.
- He has a space telescope named after him!



Milton Humason
(1891-1972)

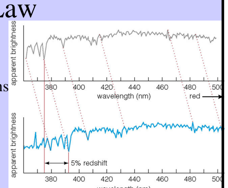
- A former mule-team driver who dropped out of 8th grade.
- He took spectra and measured the redshifts of many galaxies.
- He worked with Hubble, who measured the distances to those same galaxies.
- They plotted distance vs. velocity and formulated :

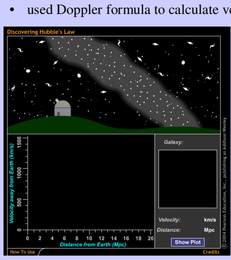
Hubble's Law: $v = H_o d$



Hubble's Law

- Hubble supplied the distance to a galaxy.
  - using Cepheid or "brightest star" standard candles
- Humason measured the shift to longer wavelengths of absorption lines in the galaxy's spectrum.
  - used Doppler formula to calculate velocity

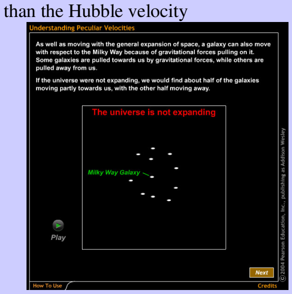




- Plot resulted in a straight line.
  - the farther away a galaxy was, the faster it was moving away from us
  - velocity increased *linearly* with distance
- $v = H_o d$
- H_o, the slope of the line, is called Hubble's constant [km/s per Mpc]

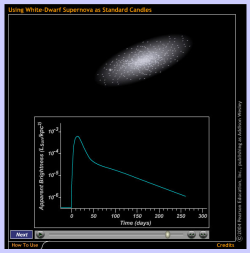
Where Hubble's Law Applies

- Hubble's Law does not apply to the nearest galaxies.
  - gravitational tugs from nearby galaxies cause velocities greater than the Hubble velocity

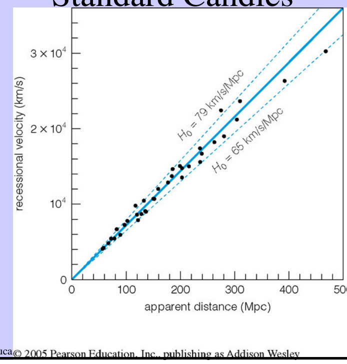


Distant Standard Candles

- When galaxies do obey Hubble's Law, the distances we calculate from redshifts are only as accurate as our measurement of H_o.
- To obtain a more accurate value of H_o, we need standard candles which allow us to measure even greater distances.
- White Dwarf Supernovae
  - all have the same peak luminosity
  - 10 billion Suns
  - we calibrate them in nearby galaxies which contain Cepheids
  - can be observed in galaxies billions of light years away
- One problem:
  - must be lucky to be observing a galaxy when one explodes

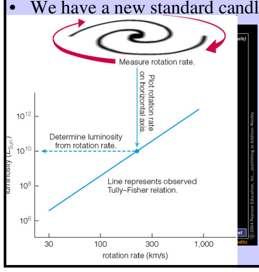


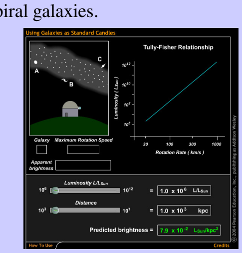
White Dwarf Supernovae as Standard Candles



The Tully-Fisher Method

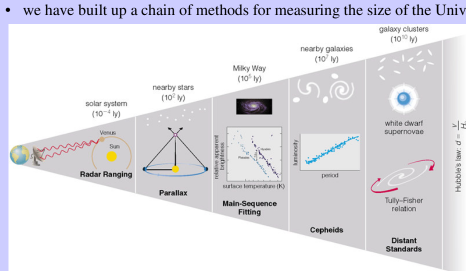
- Mass of a spiral galaxy determines its rotation rate and its luminosity.
  - there should been a relationship between rotation rate & luminosity
  - we use radio telescopes to measure the 21-cm line of rotating H gas in the disk
  - faster rotating spiral galaxies are more luminous
- We have a new standard candle…spiral galaxies.





The Distance Chain

- The most accurate methods for measuring distance…
  - have the shortest range of applicability, so…
  - we use them to calibrate the next-most accurate method, and so on until…
  - we have built up a chain of methods for measuring the size of the Universe!



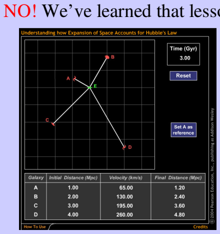
20.4 Measuring Cosmic Ages

Our goals for learning:

- Describe how the Universe expands.
- How is Hubble's constant related to the age of the Universe?
- Why is lookback time a better way to describe the locations of distant objects than distances in light-years?
- What defines the size of the observable Universe?

An Expanding Universe

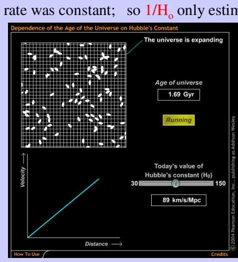
- The consequence of Hubble's Law is
  - most galaxies are moving away from us
  - if all galaxies swarm out through a void
  - then the Milky Way is at the center of the Universe
- NO! We've learned that lesson already!



- The Universe itself is expanding.
  - the galaxies expand with it
  - there is no center or edge to the Universe
- From any galaxy's point of view, other galaxies are all moving away from it.

The Age of the Universe

- In the context of an expanding Universe…
  - H_o tells us the rate at which galaxies are moving apart from one another
  - so if we run he clock backward to when the galaxies were all at one point
  - then $1/H_o$ tells us how long it took the Universe to expand to its current size
  - *if* the expansion rate was constant; so $1/H_o$ only estimates age of Universe

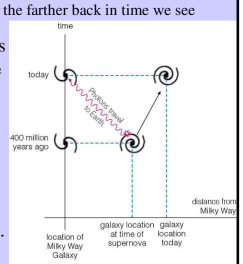


The Age of the Universe

- Our best measurement of the Hubble Constant…
  - comes from the *Wilkinson Microwave Anisotropy Probe*
  - announced by NASA in February 2003
- H_o = 71 km/s per Mpc
- So, the age of the Universe, $1/H_o$ = 13.7 billion years

Lookback Time

- Since the speed of light is finite…
  - it takes time for light to travel vast distances
  - light reaching us from a galaxy 4×10^8 l.y. away took 4×10^8 years to arrive
  - we refer to this as **lookback time**
  - the farther out into the Universe we look, the farther back in time we see
- At vast distances, long lookback times
  - it makes more sense to use lookback time instead of distance
  - consider the spacetime diagram at right
- What is the distance to this galaxy?
  - distance when the photons were emitted
  - distance when the photons are received
- But there is no ambiguity that it took 4×10^8 yrs for the photons to get here.



Size of the Observable Universe

- As pointed out earlier, the Universe has no edge…
  - but it does have a horizon
- The **cosmological horizon** is the place where the lookback time equals the age of the Universe.
  - we can not see beyond this horizon, because we would be looking at a time before the Universe even existed!
  - our observable Universe grows 1 light year in size every year

What have we learned?

- How do we study the lives of galaxies?
  - We have to piece together observations of different galaxies at different stages of their lives to reconstruct the overall life cycles of galaxies.

What have we learned?

- What are the three major types of galaxies?
  - (1) Spiral galaxies, which have prominent disks and spiral arms. (2) Elliptical galaxies, which are rounder and redder than spiral galaxies and contain less cool gas and dust. (3) Irregular galaxies, which are neither disk-like nor rounded in appearance.
- What is the major difference between spiral and elliptical galaxies?
  - A spiral galaxy has both a disk and a spheroidal component that includes the bulge and halo. An elliptical galaxy has a similar spheroidal component but lacks a prominent disk component.

What have we learned?

- How are galaxy types different in clusters of galaxies?
  - Outside clusters, most large galaxies are spirals; only about 15% of the large galaxies outside clusters are elliptical galaxies. Within clusters, elliptical galaxies are much more common, representing up to about half the large galaxies in the central regions of clusters.

What have we learned?

- What is a standard candle and how is it used to determine distance?
  - A standard candle is an object whose luminosity can be determined without knowledge of its distance. We can therefore determine the distance to a standard candle by measuring its apparent brightness and applying the luminosity-distance formula [Section 16.2].
- What makes a good standard candle?
  - A good standard candle is so bright that it can be seen at large distances and has a well-established luminosity so that we can confidently use its luminosity to calculate its distance.

What have we learned?

- Why do Cepheid variable stars make good standard candles?
  - Cepheids are very bright variable stars that follow a well-known period–luminosity relation — measuring their period of variability tells us their luminosity.
- What is Hubble's Law and where is it applicable?
  - Hubble's Law tell us that more distant galaxies are moving away faster: $v = H_0 \times d$. It allows us to determine a galaxy's distance from the speed at which it is moving away from us, which we can measure from its Doppler shift. Hubble's Law applies only to galaxies that are far enough away that any motion due to gravitational pulls from other galaxies is small compared with their overall motion.

What have we learned?

- Summarize the chain through which we build up measurements of distance throughout the universe.
  - Radar ranging gives us the Earth-Sun distance (1 AU). Knowing this distance allows us to calculate distances to nearby stars from their parallax. Main-sequence fitting allows us to measure the distances to numerous Cepheids, allowing us to establish the their period-luminosity relation. This relationship then allows us to measure distances to nearby galaxies in which we can observe Cepheids. Distances to nearby galaxies help us calibrate the brightnesses of white dwarf supernovae and the Tully–Fisher relation between galaxy luminosity and rotation speed. We then use white dwarf supernovae and the Tully-Fisher relation to determine the value of H_0 in Hubble's Law, which can be used to measure vast distances in the universe.

What have we learned?

- Describe how the universe expands.
  - We say that the universe is expanding because its galaxies are continually moving farther apart. However, it is not a ball of galaxies expanding into empty space. As far as we can tell, the universe has no center and no edges. We can visualize how the universe expands without having a center or an edge by imagining the surface of an expanding balloon. Each point on the surface of the balloon moves away from every other point, but the surface itself has no edges and no point on the surface is more central than any other point.

What have we learned?

- How is Hubble's constant related to the age of the universe?
  - Hubble's constant tells us the rate at which galaxies are moving apart, so we can use it to determine how long it has been since they started moving apart. In particular, the inverse of Hubble's constant tells us how long it would have taken the universe to reach its present size if the expansion rate had never changed. This is only a rough estimate of the true age of the universe, because the expansion rate almost certainly has changed through time.

What have we learned?

- Why is lookback time a better way to describe the locations of distant objects than distances in light-years?
  - When we state that a galaxy's lookback time is, say, 400 million years, it means that its light has traveled for 400 million years to reach us at Earth. There is no ambiguity in this meaning. In contrast, if we state its "distance" is 400 million light-years, it is not clear whether we mean its distance today or its distance at the time light left the galaxy — which would have been smaller than the distance today because galaxies were closer together in the past.
- What defines the size of the observable universe?
  - The size of the observable universe is defined by the cosmological horizon — the place at which the lookback time is equal to the age of the universe. We cannot see beyond the cosmological horizon because it would mean looking back to a time before the universe existed.

Using Hubble's law, $d=v/H_0$, calculate the distance to a galaxy that is moving away from us at 10,000 km/s. Assume H_0=70 km/s/Mpc.

1. 143 pc.
2. 143 Mpc.
3. 143 light years.
4. 10,000 light years.
5. 70 Mpc.

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What do we see when we look beyond the cosmological horizon?

1. Galaxies that are just about to form.
2. Galaxies that are about to enter the universe.
3. White dwarfs that are about to go supernova.
4. The beginning of the universe.
5. We cannot look beyond the cosmological horizon because we cannot look back to a time before the universe began.

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If you want to find elliptical galaxies, you'll have better luck looking in clusters of galaxies than elsewhere in the universe.

1. Yes, galaxy clusters have a much higher percentage of elliptical galaxies than do other parts of the universe.
2. Yes, elliptical galaxies are found exclusively in galaxy clusters.
3. No, elliptical galaxies are more commonly found away from galaxy clusters.
4. No, elliptical galaxies are never found in galaxy clusters.
5. No, you would have an equal chance of finding an elliptical galaxy in any environment in the universe.

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If the standard candles you are using are less luminous than you think they are, then the distances you determine from them will be too small.

1. Yes, because they are less luminous, they are further away.
2. No, because they are less luminous, they are closer than you think and your distance determination is too large.
3. No, standard candles produce the same measurement at the telescope no matter what distance they are.
4. It depends on the standard candle: if they are Cepheid variables, they will still pulsate at the same rate no matter what distance they are from you.

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Galaxy A is moving away from me twice as fast as Galaxy B. That probably means it's twice as far away.

1. Yes, Hubble's law states that the distance of a galaxy from you is directly proportional to the velocity that it moves away from you.
2. No, it's the other way round: Galaxy B is twice as far as Galaxy A.
3. No, the velocity that a galaxy moves away from you is independent of its distance from you.
4. No, you have to measure the distance to the galaxies using standard candles before making this statement.

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