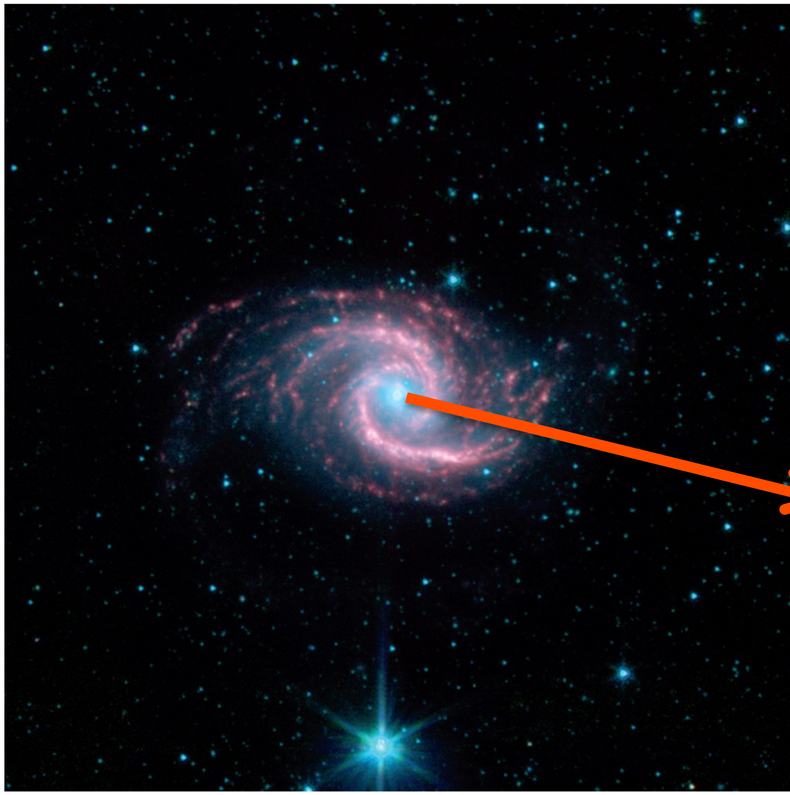
Astronomy 1 – Fall 2019



Problem 22-42b
Universe, Tenth Edition
NASA; JPL-Caltech; R. Kennicutt [University of Arizona]; and the SINGS Team

Theoretical Prediction of Black Hole *Shadow*

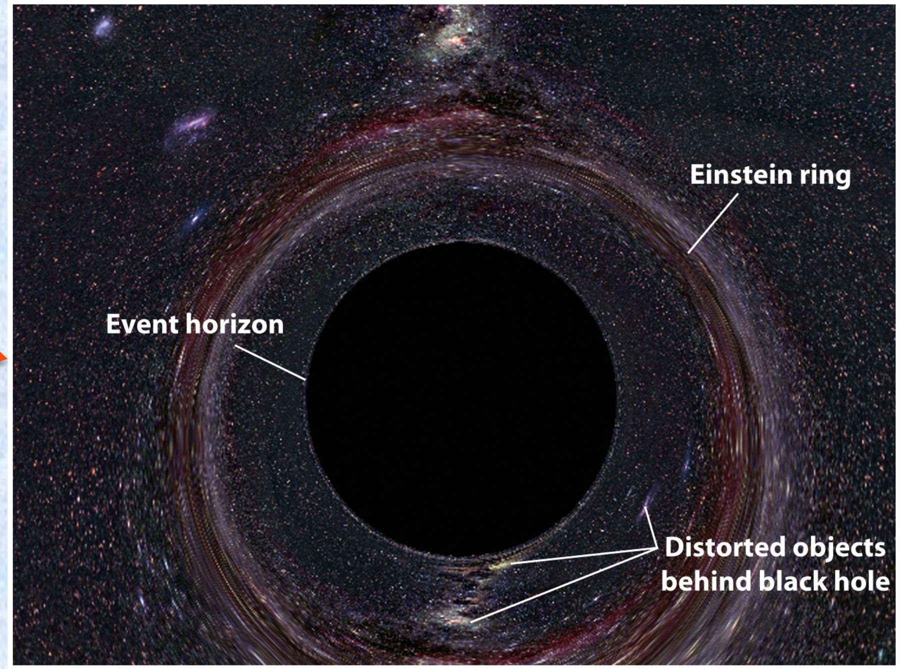


Figure 21-20
Universe, Tenth Edition
Andrew J. S. Hamilton/University of Colorado, Boulder

Announcement: We will not cover chapter 24. Only 4 HW problems this week. Review problems in Sections.

Lecture 14; November 24, 2019

Previously on Astro 1

- **The Special Theory of Relativity:**
  - The laws of physics are the same in any (inertial) reference frame
  - The speed of light is the same to all observers
  - An observer will note a slowing of clocks and a shortening of rulers that are moving with respect to them.
  - Space and time are aspects of a single entity called spacetime.
- **The General Theory of Relativity:**
  - Inertial mass and gravitational mass are the same
  - Gravity = acceleration
  - Gravity is nothing but the distortion of spacetime by mass
  - Predicts bending of light by gravity, gravitational redshift and gravitational waves
- **Black Holes:**
  - A stellar corpse with mass greater than 3 $\sim M_{\odot}$, will collapse under gravity. Will be so dense that not even light can escape.

Today on Astro 1

- Location of the Solar System in the Milky Way
  - Size, shape, and contents of the Milky Way
  - The Origin of Spiral Arms

- How we know that much of the matter in the Milky Way is "invisible", or *dark*.

- Evidence for a Supermassive Black Hole at the Center of the Milky way

William Herschel tried to locate the center of our Galaxy by counting the number of stars in different directions. This did not work because

A. stars are not uniformly distributed.
B. more distant stars are obscured by dust and gas.
C. there are very few stars near the center of our Galaxy.
D. most of the brighter stars are in the outer regions of our Galaxy.
E. interstellar reddening gave rise to an incorrect count.

Q22.1

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The distance to and location of the center of our Galaxy was first estimated by mapping out the positions of

A. globular clusters.
B. the spiral arms.
C. intense infrared sources.
D. strong radio sources.
E. x-ray sources.

Q22.4

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C. intense infrared sources.
D. strong radio sources.
E. x-ray sources.

(iClicker Question)

The diameter of the galaxy in light years is …

A. Much greater than the age of the Earth and Sun.
B. Much greater than the lifespan of a human.
C. Much less than the age of the Earth and Sun.
D. Much greater than the age of the Universe
E. Both B & C

(iClicker Question)

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E. Both B & C

Which of the following are *not* found in the halo of our Galaxy?

A. Relatively young objects

B. Relatively old objects

C. Low-mass stars

D. Population II stars

E. Metal-poor stars

Q22.6

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A. Relatively young objects
B. Relatively old objects
C. Low-mass stars
D. Population II stars
E. Metal-poor stars

A22.6

The Location of Our Solar System in the Milky Way Galaxy

Early Attempts with Star Counts Incorrectly Placed Sun at Center

1785 – William Herschel

Early 1900s – Jacobus Kapteyn

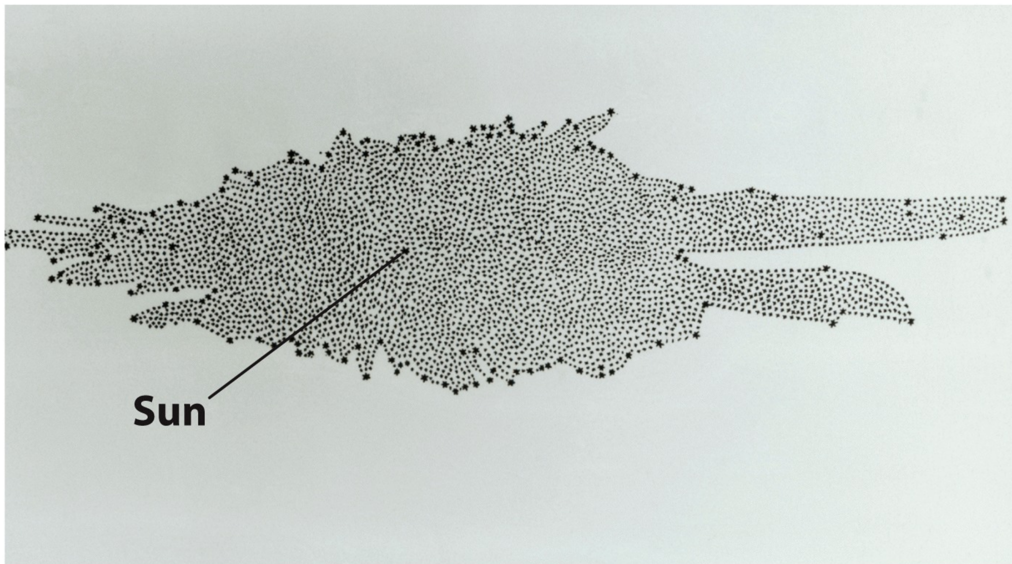

Figure 22-2
Universe, Tenth Edition
Dr. Jeremy Burgess/Science Source

1930s – Distances to Young Clusters

Robert Trumpler directly measured distances to open clusters.
➔ More distant clusters appeared dimmer and redder than expected for their distance.

iclicker Question on Sunset Experiment:
When a chemical reaction creates solid particles (crystals) in the solution, we will see…

A. The color of the solution will change, and the color of the light on the screen will remain the same.
B. The solution will remain clear, and the light on the screen will change colors.
C. The solution will turn red, and the light on the screen will turn greenish blue.
D. The solution will turn blue, and the light on the screen will turn orange or red.

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iclicker Question on Sunset Experiment:
When a chemical reaction creates solid particles (crystals) in the solution, the brightness of the light on the screen

A. Grows

B. Decreases

C. Remains the same

iclicker Question on Sunset Experiment:
When a chemical reaction creates solid particles (crystals) in the solution, the brightness of the light on the screen

A. Grows

B. Decreases

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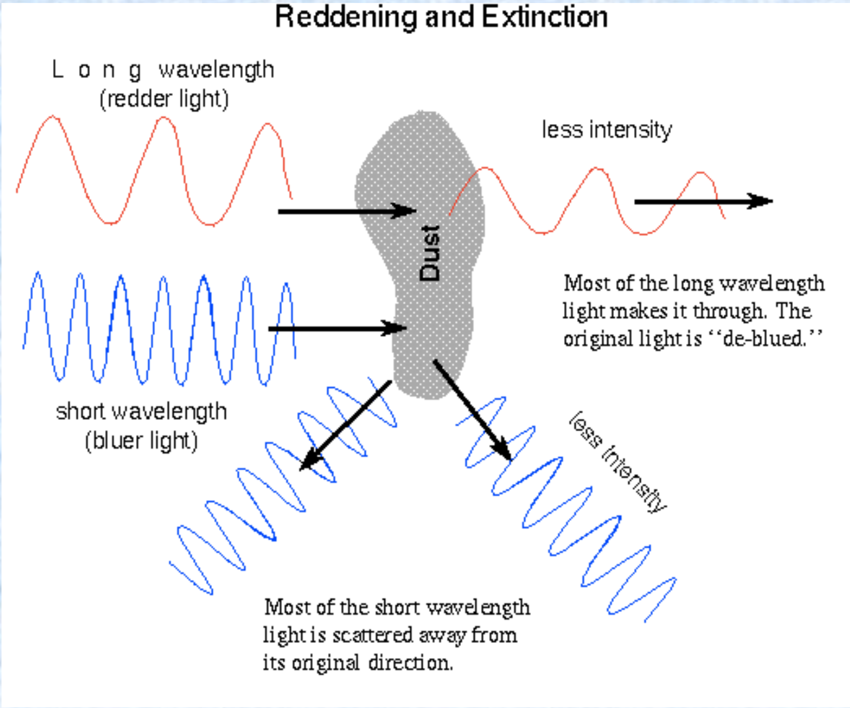
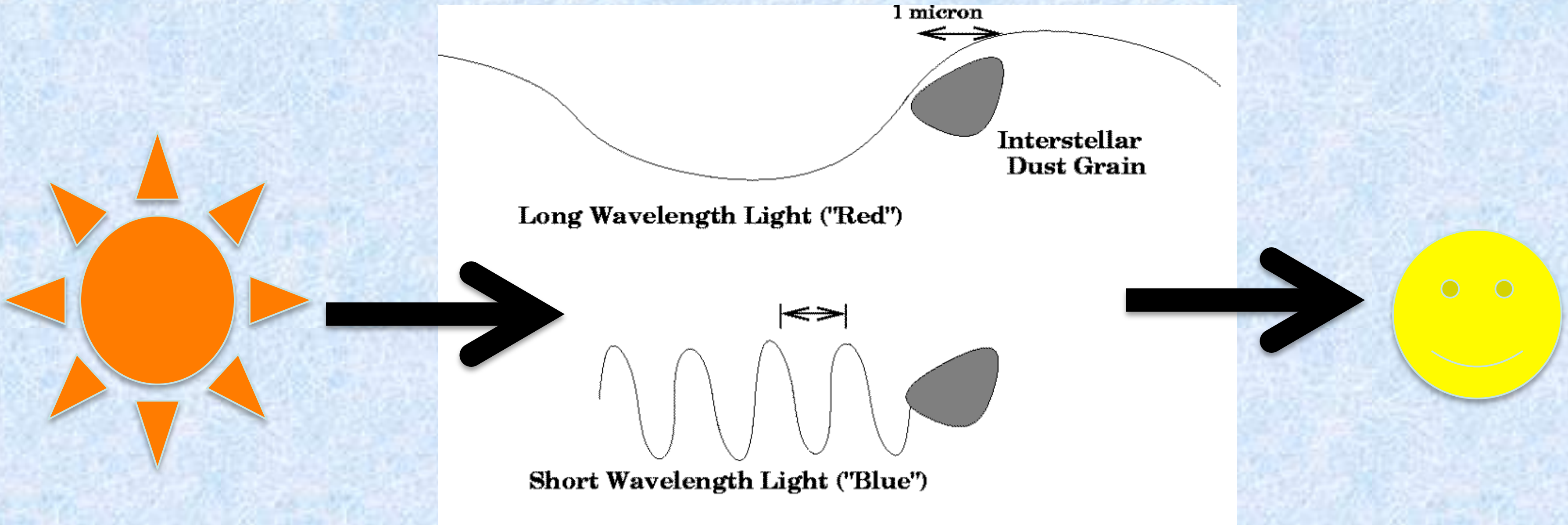
Discovery of Interstellar Dust

- 1930's
- More distant stars appeared too red.
- Explained by the dust between the stars.



Grains of graphite and silicon carbide have sizes ranging from a few molecules up to 0.1 um.

Discovery of Interstellar Dust Increased the Distances to Young Cluster



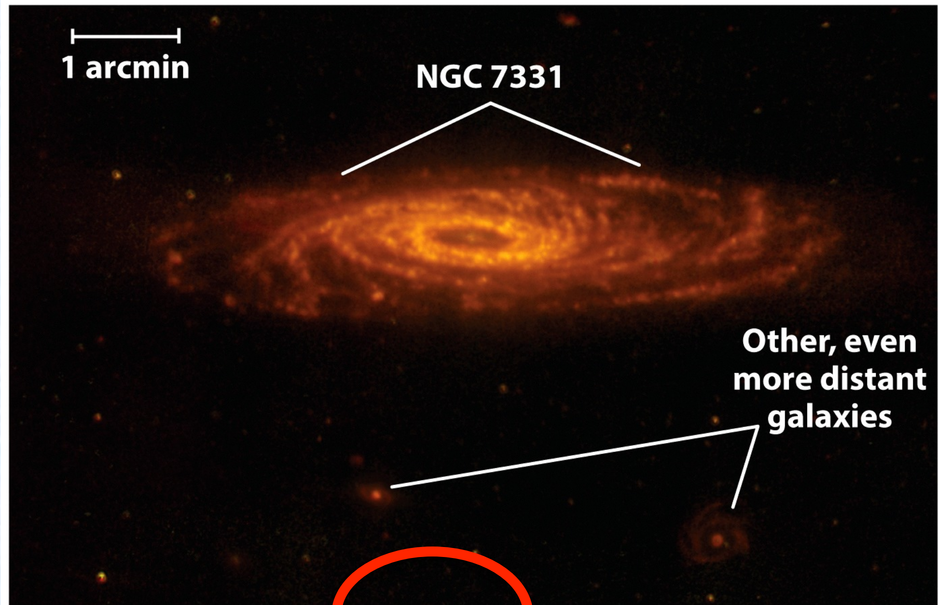
- Dust reddens *and attenuates* starlight.
- Distant stars appear fainter than they really are.
- *Why did this put the solar system at the 'center'?*
- Because astronomers could only detect stars in the nearby part of the galactic disk.

Then How Did We Find Our Place in the Milky Way?

The Milky Way Might Look Like NGC 7331 from a Distance

Infrared emission from stars in NGC 7331 at 3.6 and 4.5 μm

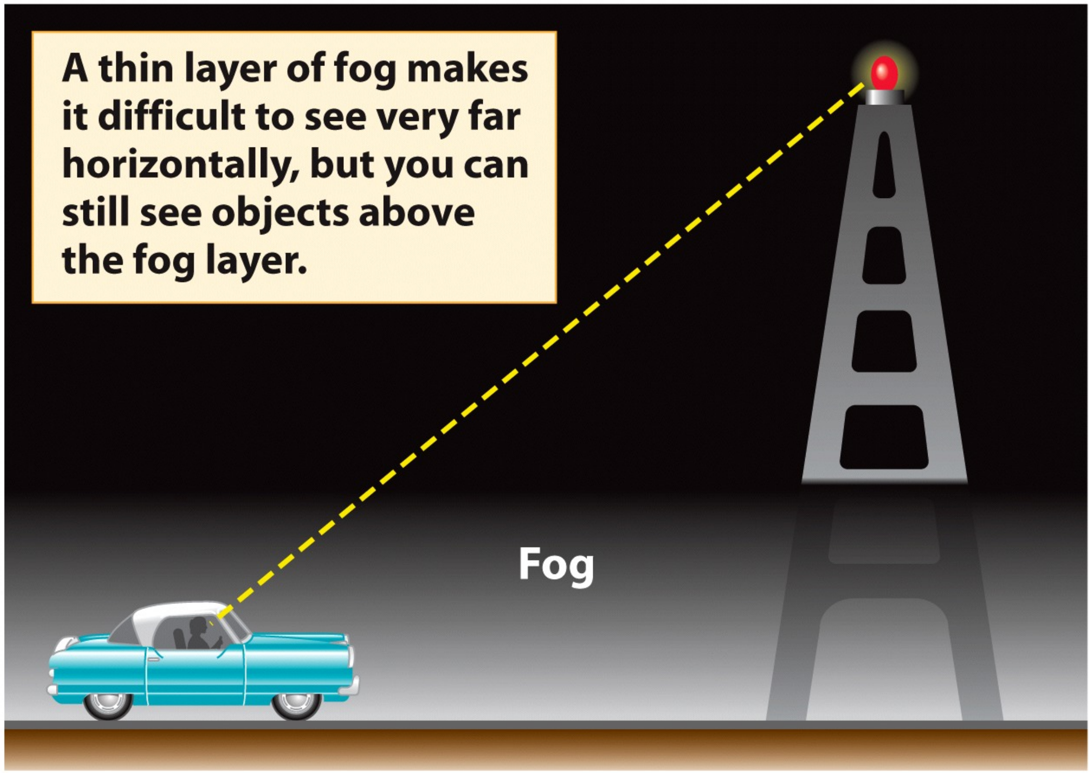
Figure 22-8b
Universe, Tenth Edition
NASA; JPL-Caltech; M. Regan [STScI]; and the SINGS Team



Infrared emission from dust in NGC 7331 at 5.8 and 8.0 μm

Figure 22-8a
Universe, Tenth Edition
NASA; JPL-Caltech; M. Regan [STScI]; and the SINGS Team

i.e., Look above the "Fog"



Determining your position in the fog

Figure 22-3a
Universe, Tenth Edition

The Dust Layer is Thin

Astronomers looked for Cepheid variabled above the dust, but didn't find them.

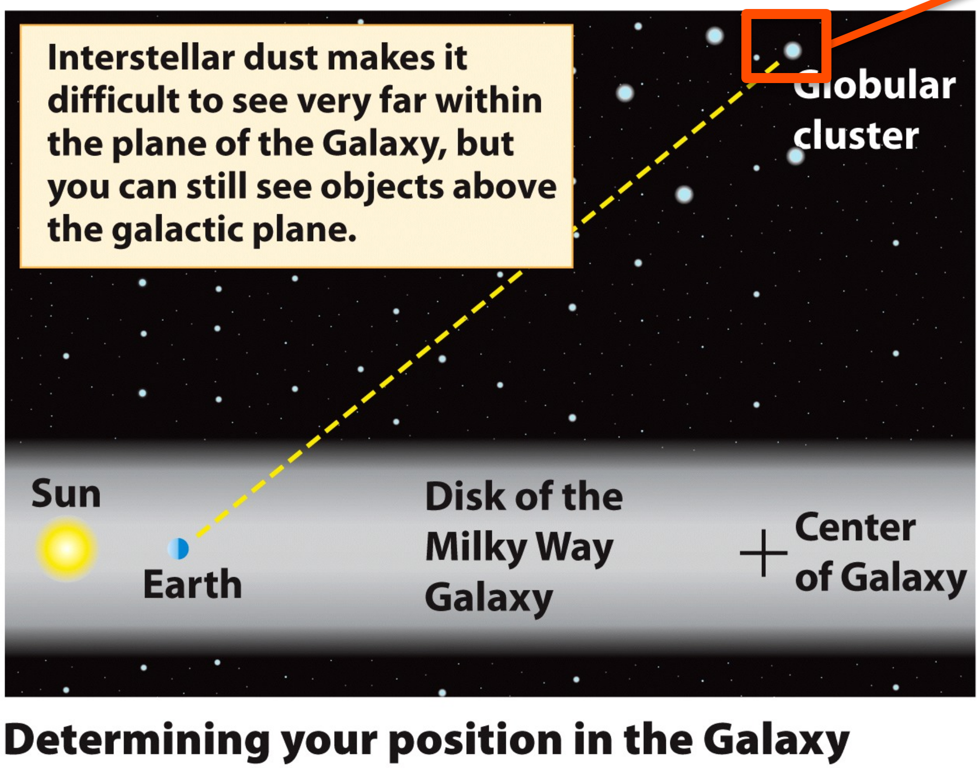


Figure 22-3b
Universe, Tenth Edition

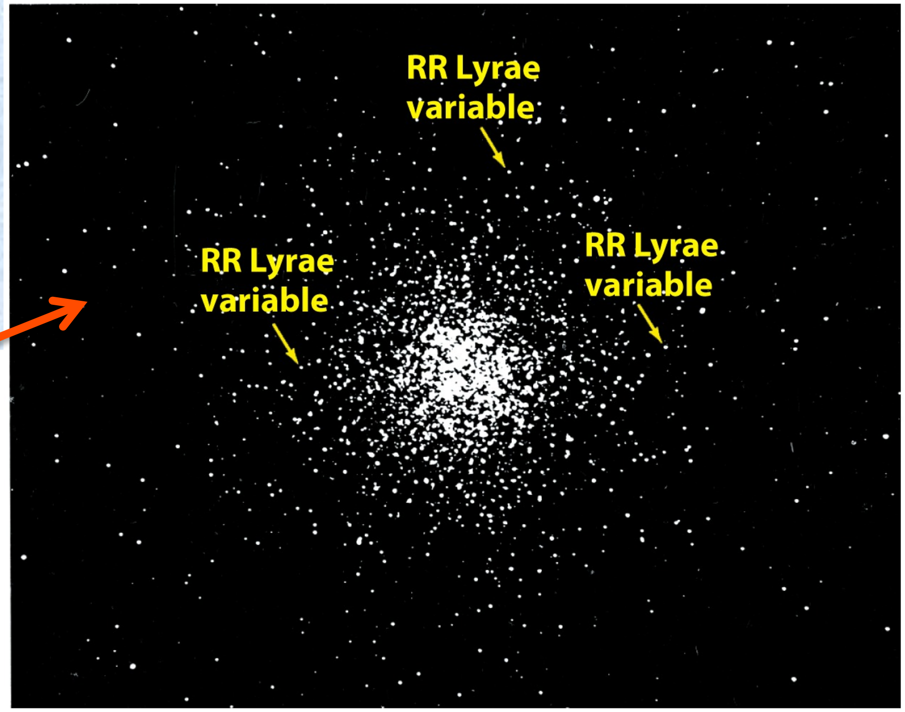


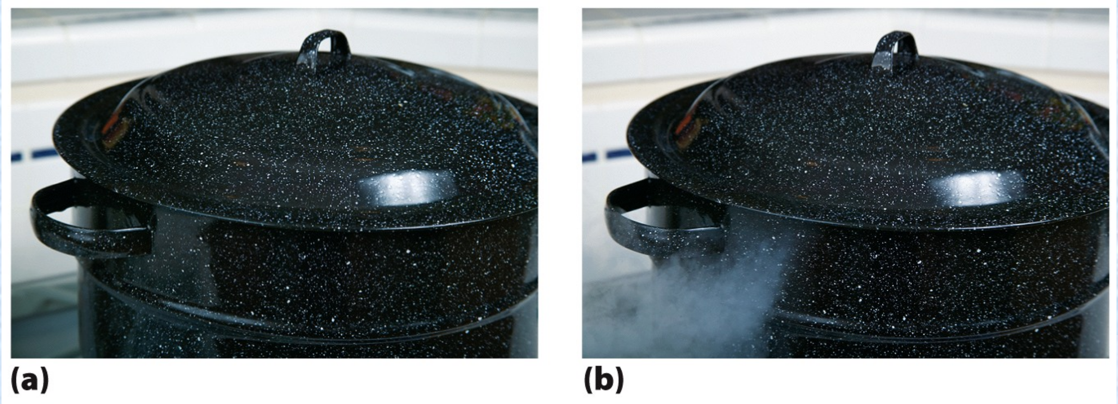
Figure 22-5
Universe, Tenth Edition
Harvard-Smithsonian Center for Astrophysics

They found another class of variable stars and named them after the prototype, **RR Lyrae**.

Review: Pulsating Stars

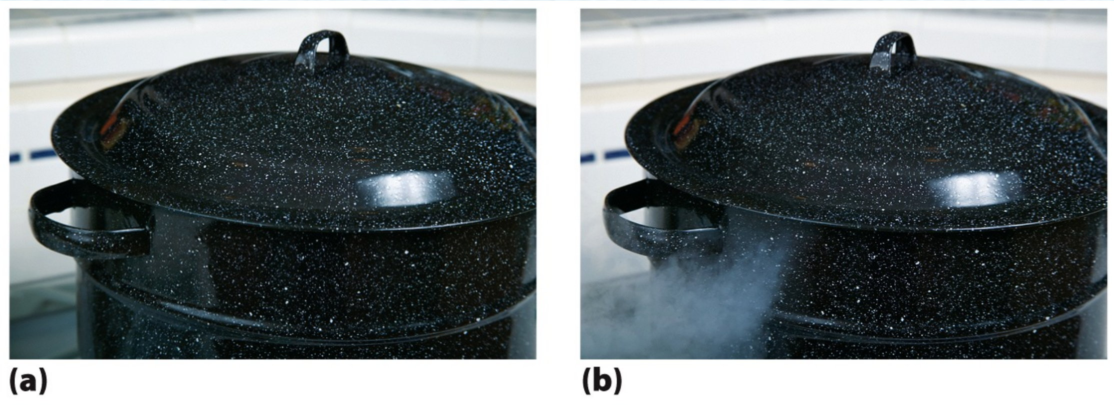
- Compression produces a hotter star.
- In normal stars, the opacity to radiation decreases at higher temperature and density, allowing the radiation to escape more easily. An equilibrium structure is maintained.
- Pulsation occurs if a star becomes more opaque to radiation when compressed. Then more energy is trapped, and the star becomes unstable because the pressure builds up.

If pressure builds up, then the star expands.



What Determines Opacity, or "Opaque-ness" to Radiation?

The compostion of the star, especially the ionization state of helium and hydrogen. For Cepheids, it works like this ...



a) Compression ➔ star is at its hottest (most ionized) ➔ helium atoms absorb radiation (opaque) ➔ star expands
b) Expansion ➔ causes cooling ➔ helium becomes more transparent (less ionized) ➔ radiation escapes more easily ➔ star contracts

In Part of the HR Diagram the Opacity Does Increase with Temperature

- Cepheids are pulsating supergiants with $M = 4$ to $20\ M_0$.
- RR Lyrae stars have lower masses than Cepheids, about $0.5\ M_0$.
- RR Lyraes are horizontal branch stars
- RR Lyraes are hotter than Cepheids; the opacity change involves He^+ and He^{++}.
- *Why do "old" star clusters contain RR Lyrae stars but not Cepheid variables?*

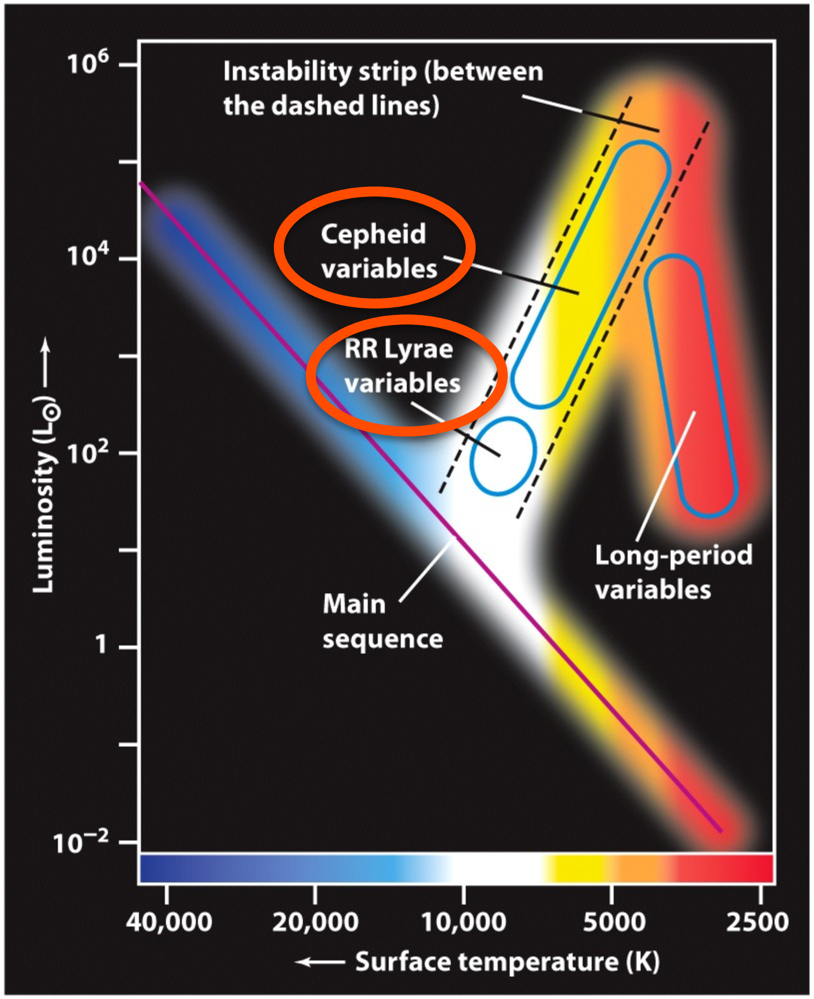


Figure 19-17
Universe, Tenth Edition

The Pulsation of RR Lyrae Variables

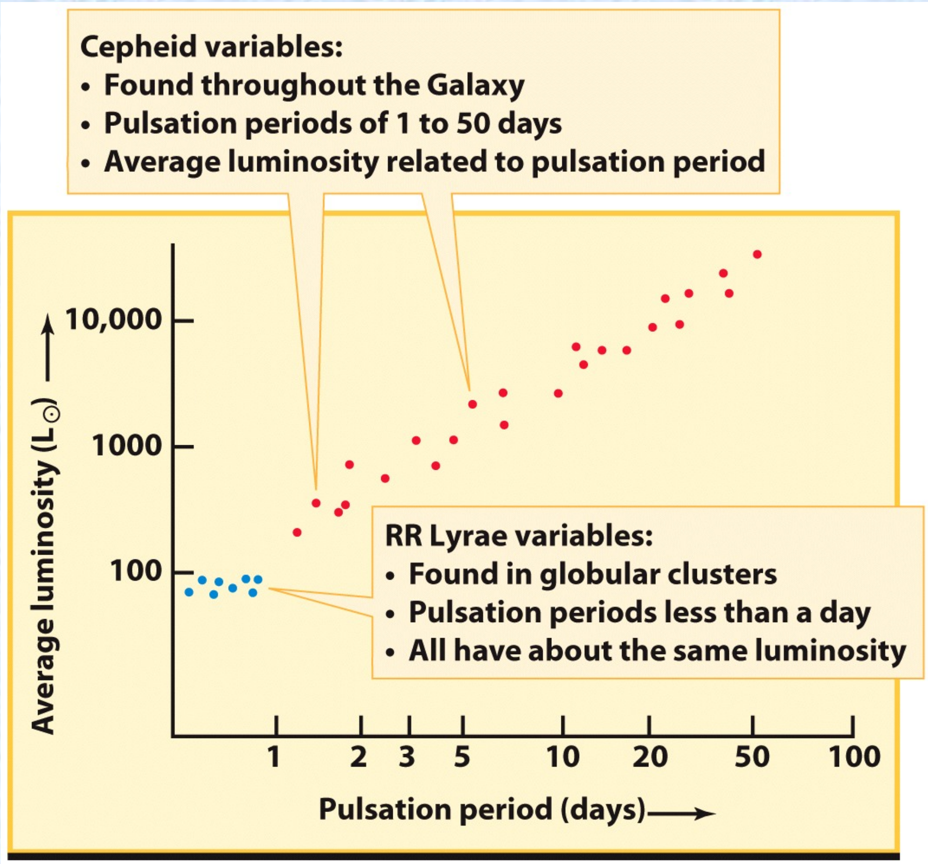


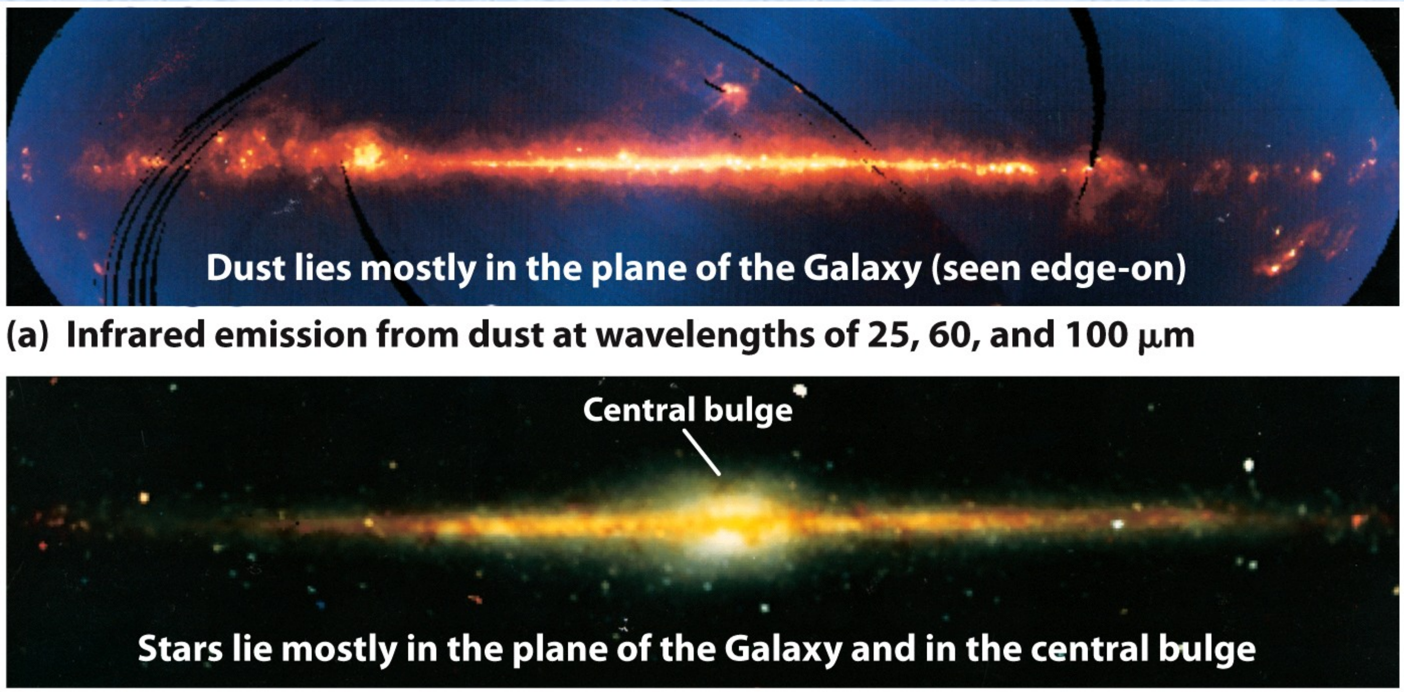
Figure 22-4
Universe, Tenth Edition

- The halo of the Milky Way contains globular clusters.
- RR Lyrae variables offer a way to measure distances to globular clusters.
- Two results:
  1. The halo is big.
  2. The halo stars formed before the galactic disk.

47. Box 19-2 An RR Lyrae star whose peak luminosity is 100 $L_\odot$ is in a globular cluster. At its peak luminosity, this star appears from Earth to be only 1.47×10^{-18} as bright as the Sun. Determine the distance to this globular cluster (**a**) in astronomical units (au) and (**b**) in parsecs.

View Towards Galactic Center

RR Lyraes are also found in the **bulge**, so the bulge contains some very old stars.



(a) Infrared emission from dust at wavelengths of 25, 60, and 100 μm

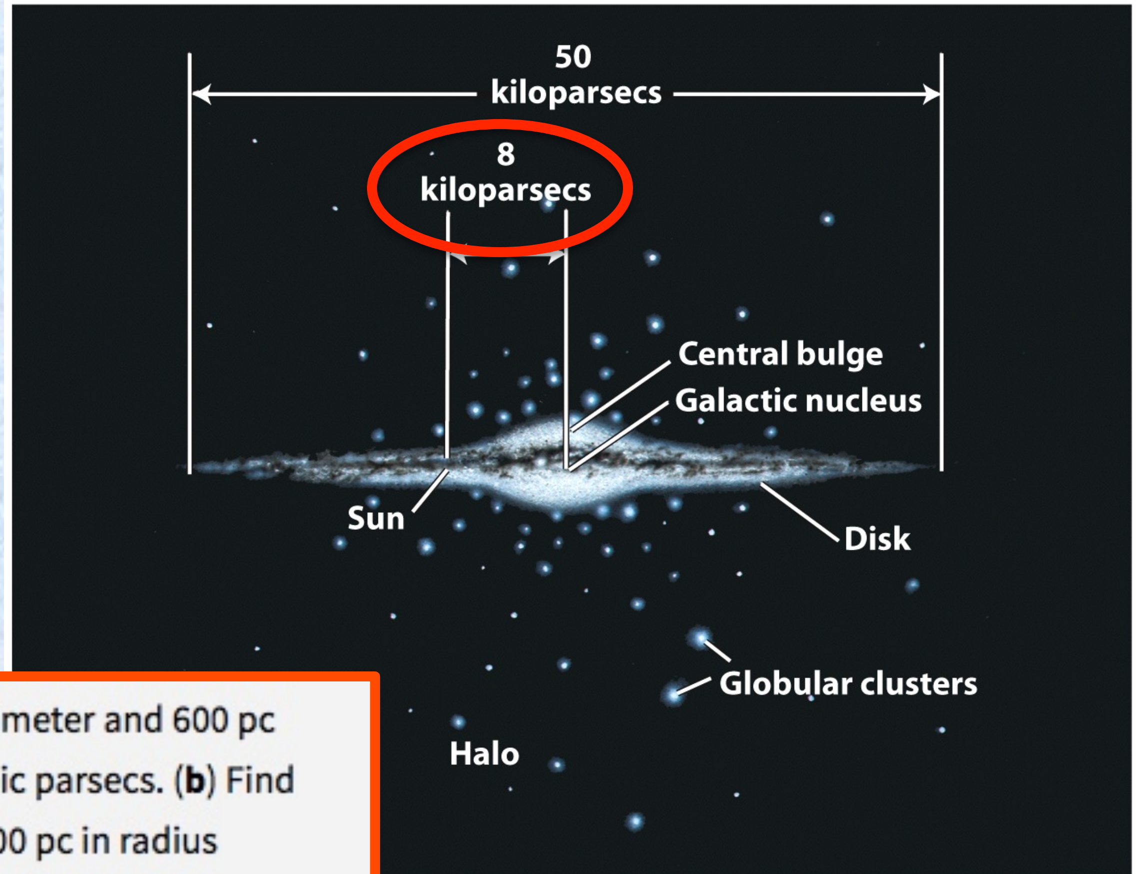
(b) Infrared emission from dust at wavelengths of 1.2, 2.2, and 3.4 μm

Figure 22-6
Universe, Tenth Edition
NASA

However, unlike globular clusters, where all the stars are old, *the center of the galaxy also contains some very young stars*.

Structure of the Milky Way Galaxy

Note that television broadcasts have traveled about 26 parsecs in the past 85 years.
No one at the Galactic Center knows that we're here yet☺



46. The disk of the galaxy is about 50 kpc in diameter and 600 pc thick. (**a**) Find the volume of the disk in cubic parsecs. (**b**) Find the volume (in cubic parsecs) of a sphere 300 pc in radius centered on the Sun. (**c**) If supernovae occur randomly throughout the volume of the galaxy, what is the probability that a given supernova will occur within 300 pc of the Sun? If there are about three supernovae each century in our galaxy, how often, on average, should we expect to see one within 300 pc of the Sun?

Galaxy Bulges and Halos Formed before Disks

Figure 22-10
Universe, Tenth Edition
NASA, ESA, The Hubble Heritage Team [STScI/AURA] and A. Riess [STScI]

The Origin of Spiral Arms.
1. The Wrapping Problem

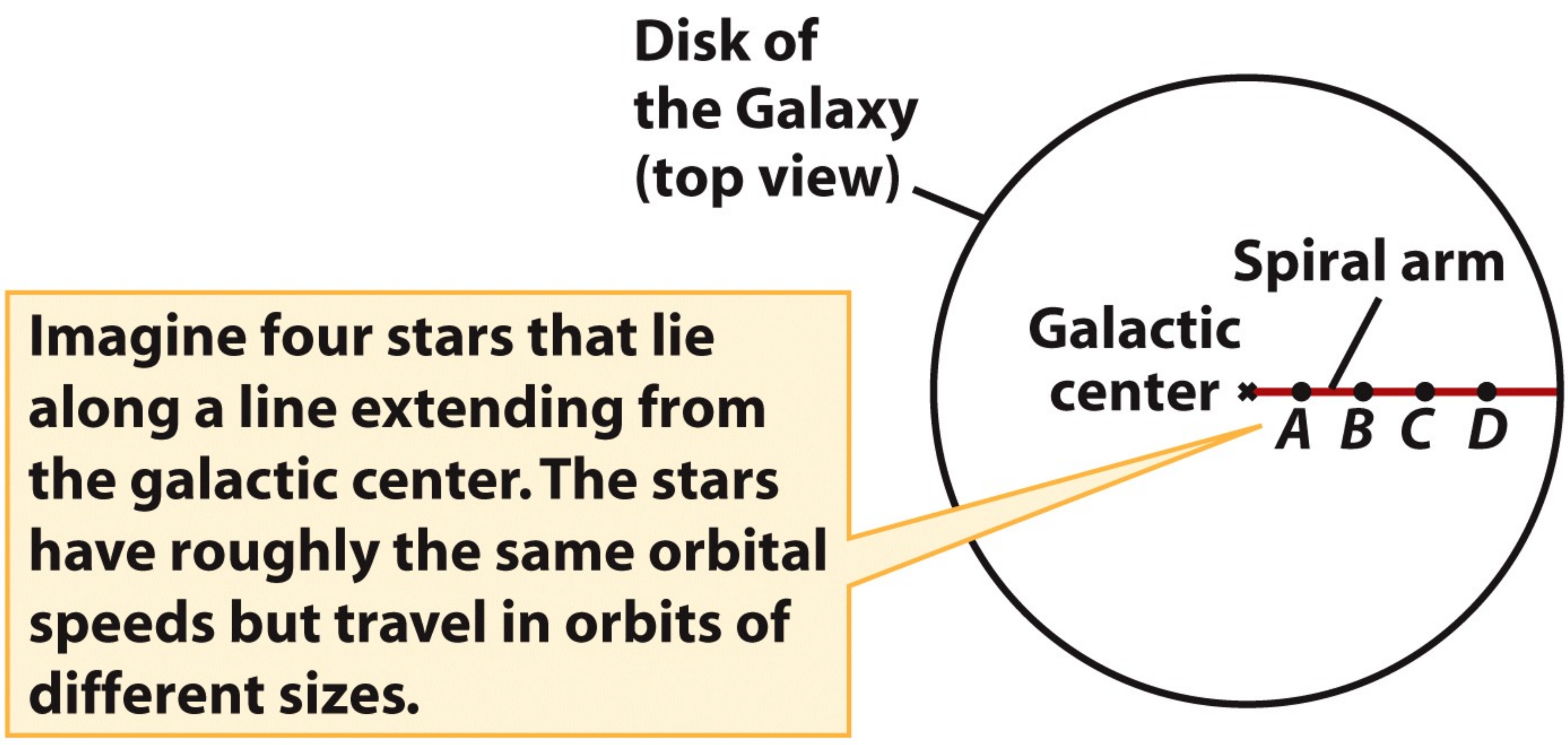


Figure 22-22a
Universe, Tenth Edition

The Wrapping Problem (cont’d)

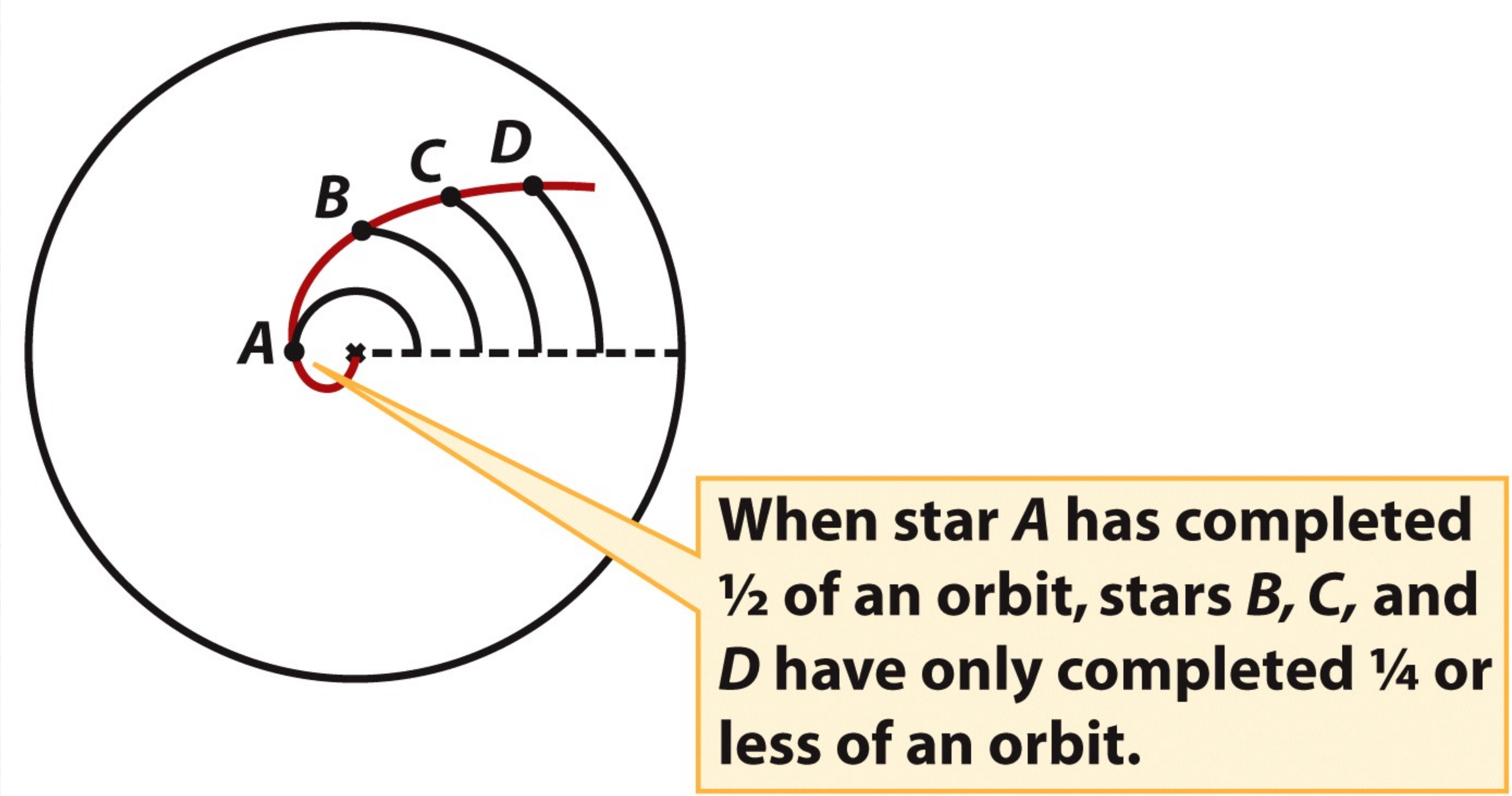


Figure 22-22b
Universe, Tenth Edition

The Wrapping Problem (cont’d)

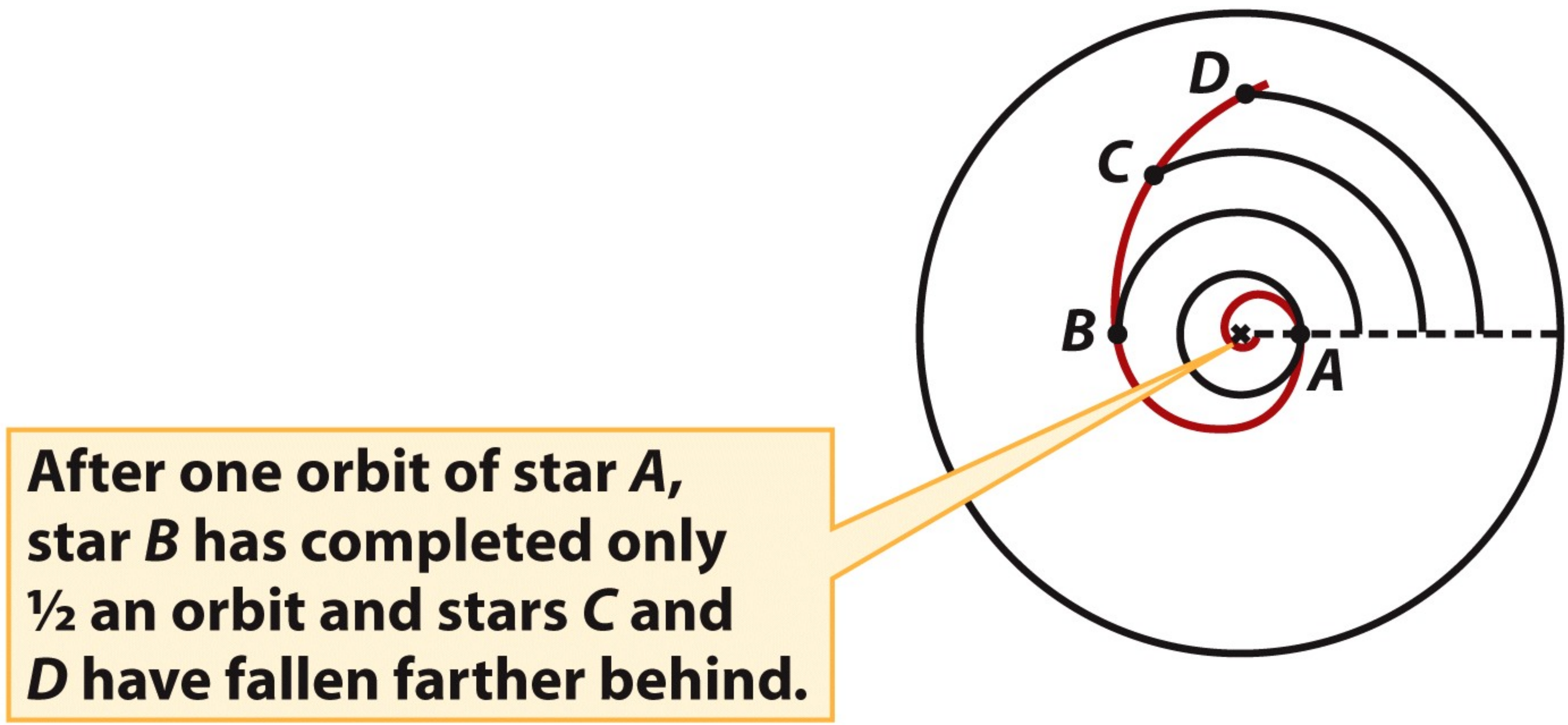


Figure 22-22c
Universe, Tenth Edition

The Wrapping Problem (cont'd)

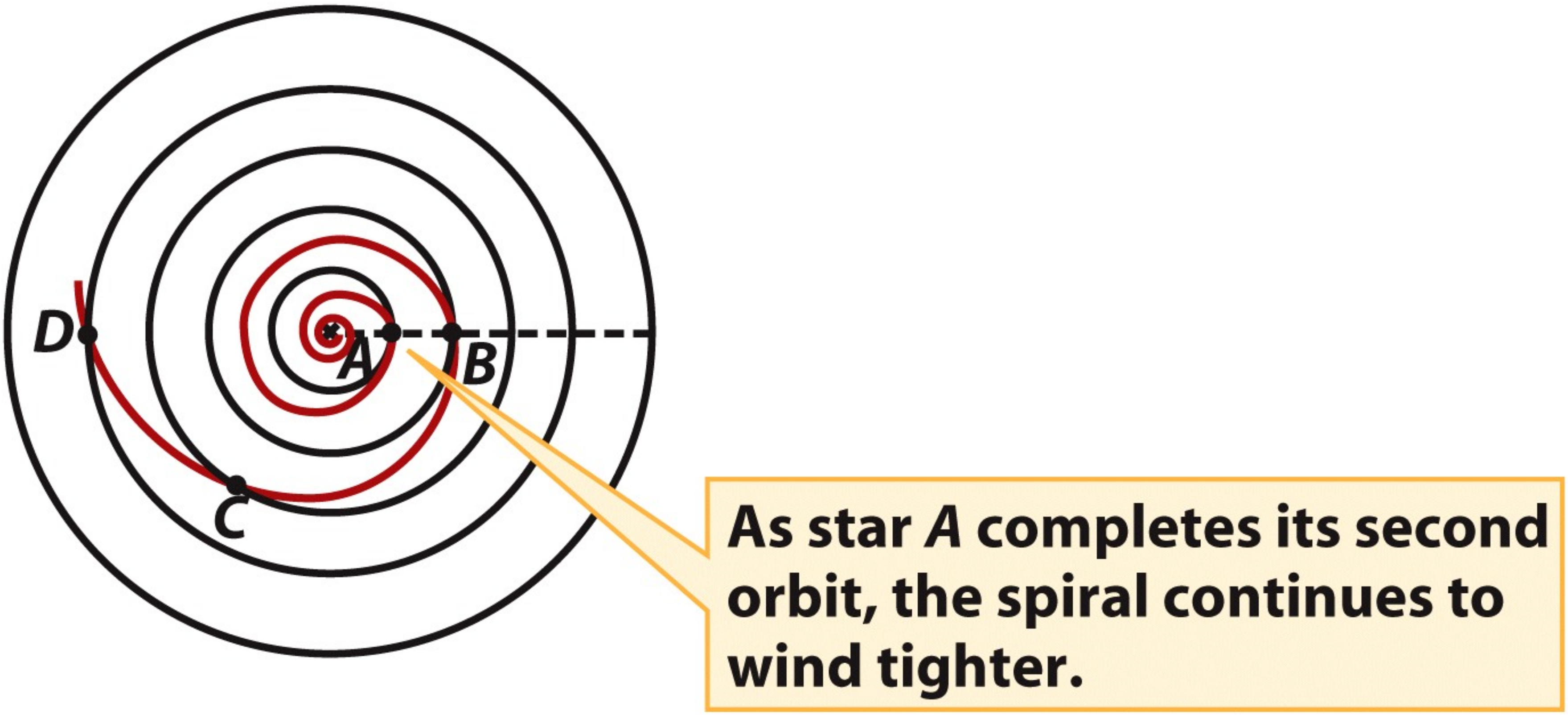


Figure 22-22d
Universe, Tenth Edition

The Origin of Spiral Arms.
2. The Density Wave Solution

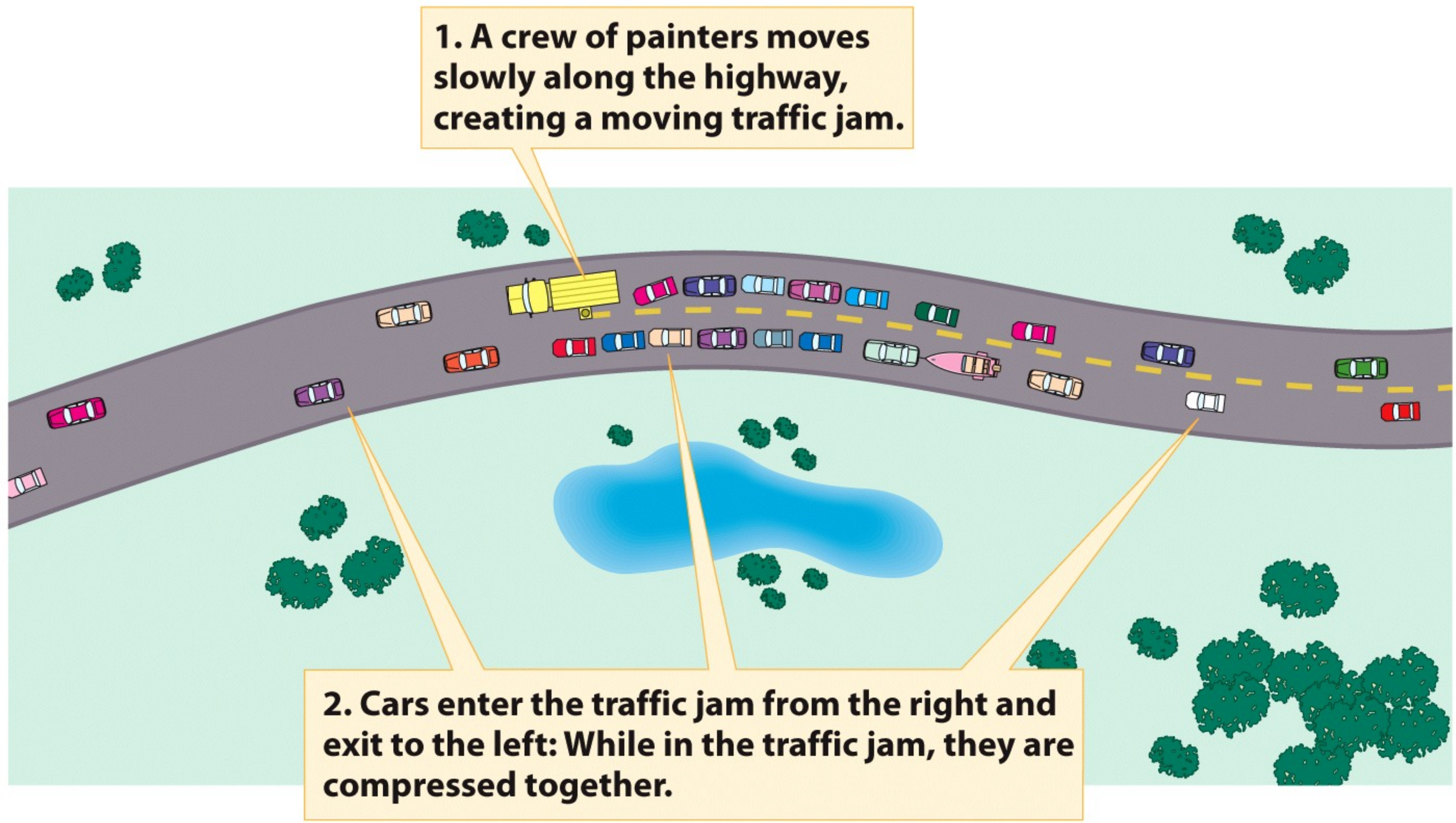


Figure 22-23
Universe, Tenth Edition

Density Wave Theory.
Stars Form Where the Gas Clouds Pile Up

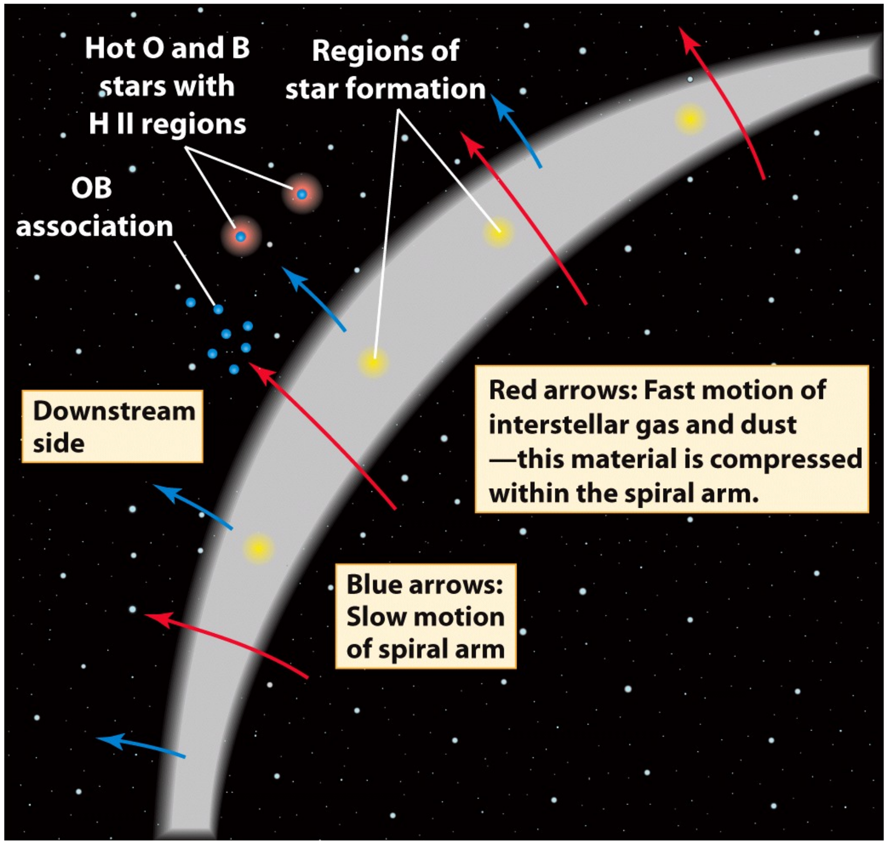
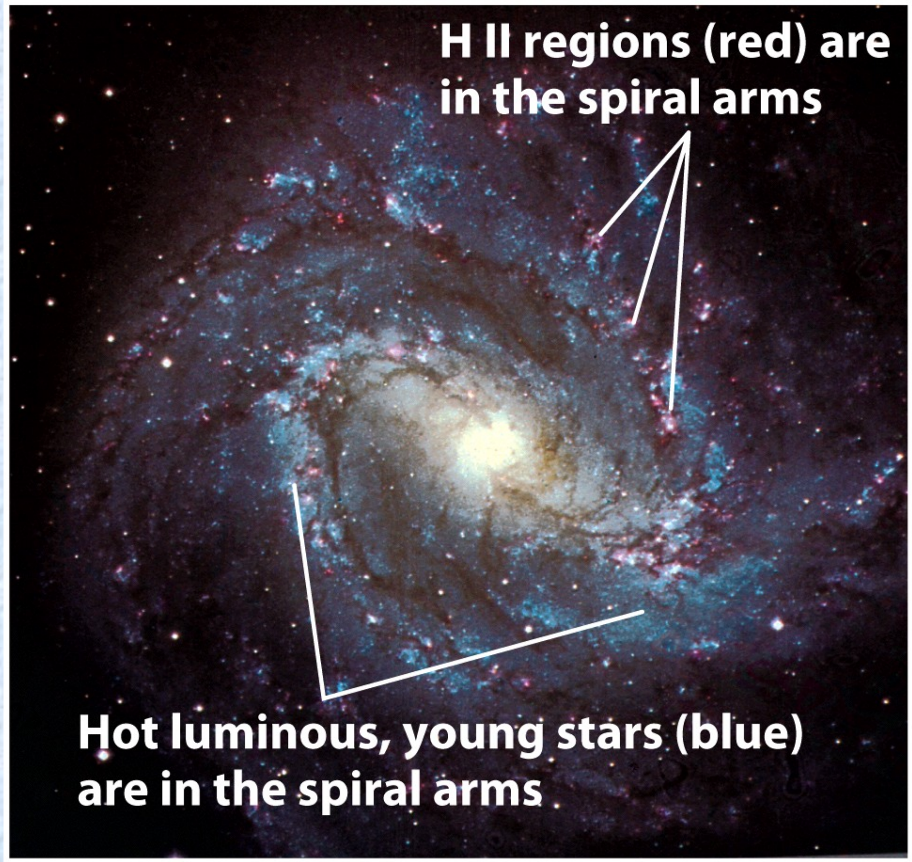


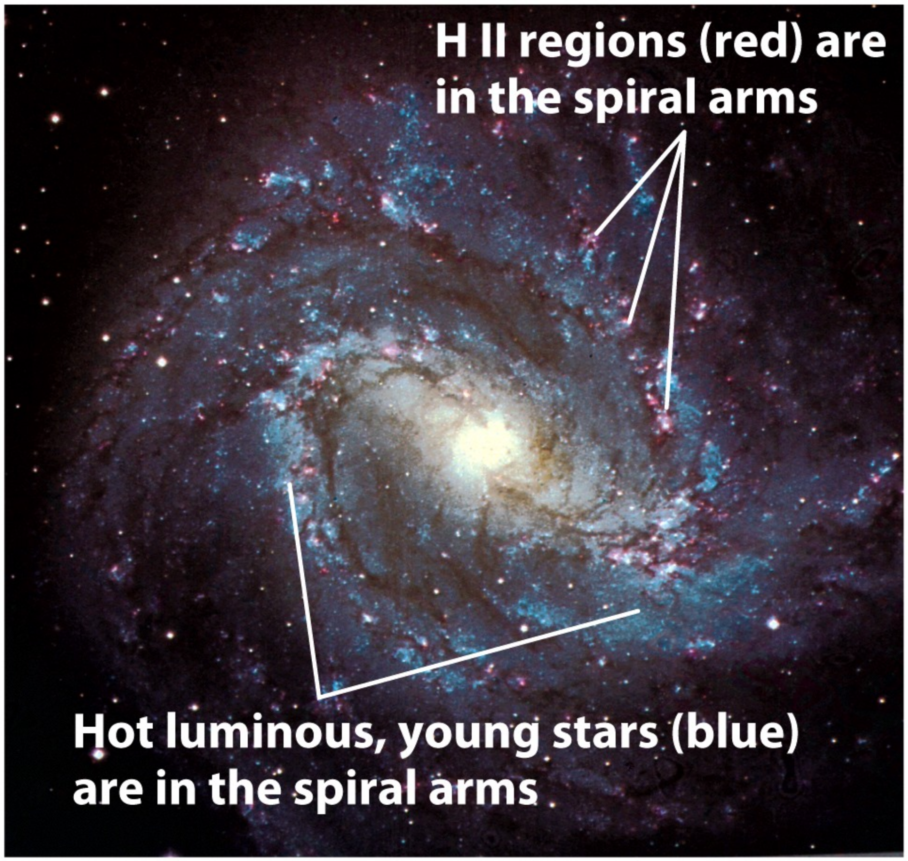
Figure 22-24
Universe, Tenth Edition



Visible-light view of M83

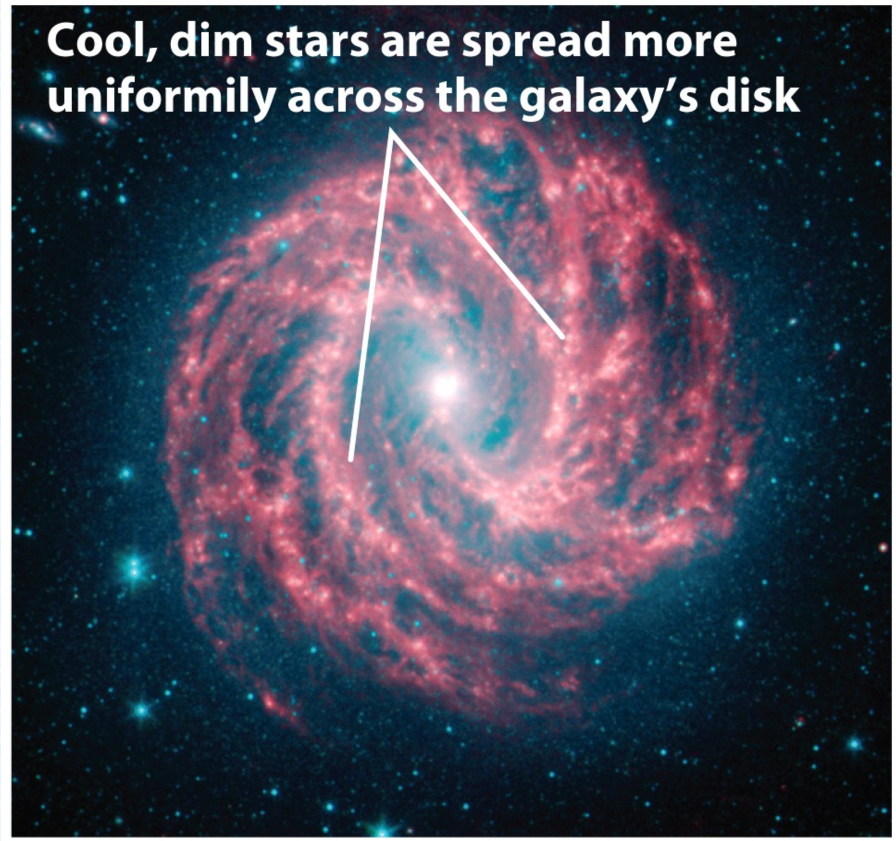
Figure 22-15a
Universe, Tenth Edition

Old Stars Are More Spread Out Than Young Stars



Visible-light view of M83

Figure 22-15a
Universe, Tenth Edition

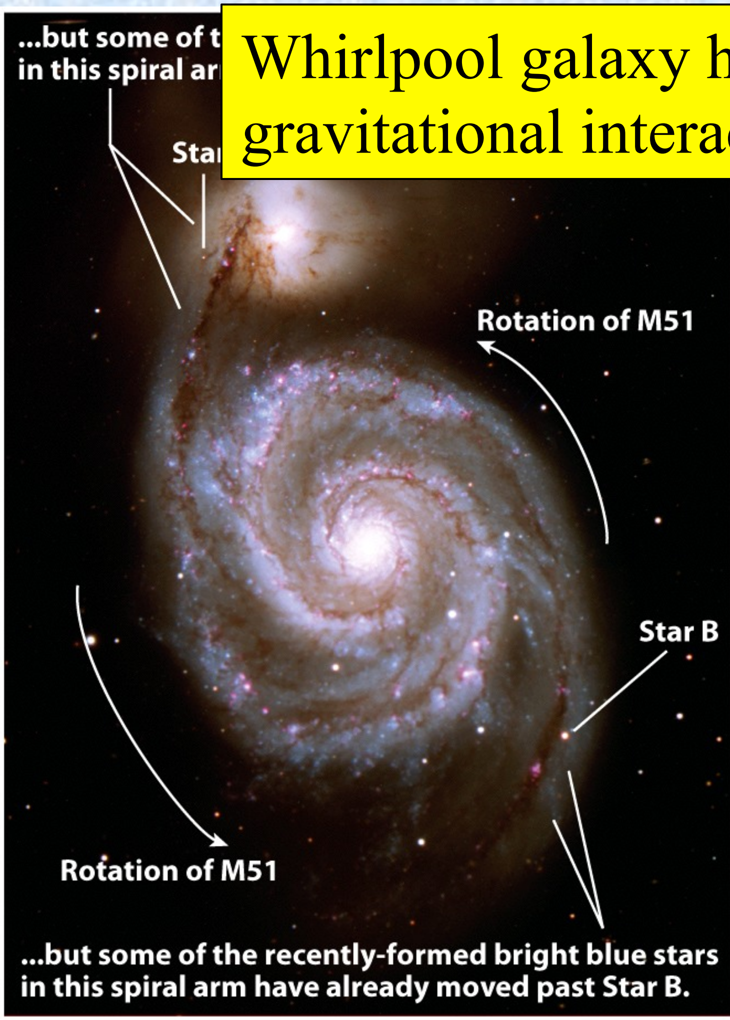


Near-infrared view of M83

Figure 22-15c
Universe, Tenth Edition
NASA/JPL-Caltech

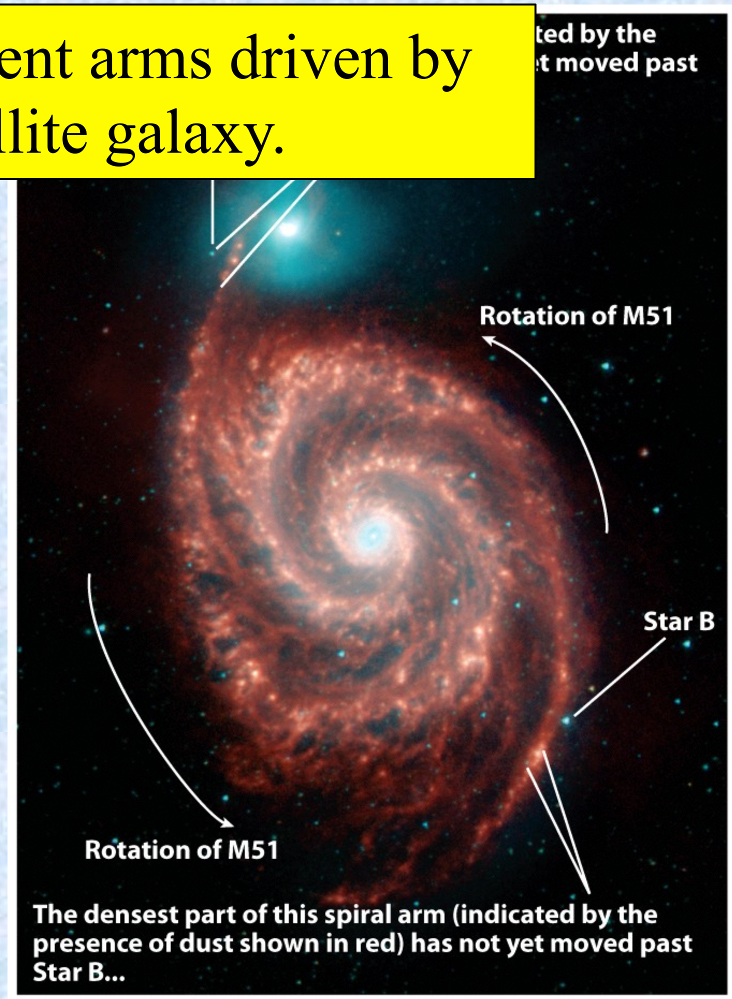
What Powers Density Waves?
Example 1: Grand Design Spirals

Whirlpool galaxy has two prominent arms driven by gravitational interaction with satellite galaxy.



A visible-light view of M51 shows the locations of young stars

Figure 22-25b
Universe, Tenth Edition
DSS



An infrared view of M51 shows the locations of dust

Figure 22-25a
Universe, Tenth Edition
NASA, JPL-Caltech, and R. Kennicutt [Univ. of Arizona]

... But Not All Spiral Galaxies Have a Close Satellite Galaxy

Grand-design spiral galaxy

Figure 22-26a
Universe, Tenth Edition
Gemini Observatory—GMOS Team

Flocculent spiral galaxy

Figure 22-26b
Universe, Tenth Edition
Olivier Vallejo [Observatoire de Bordeaux], HST, ESA, NASA

Density waves can be driven by interactions with multiple satellites and/or internal processes (bar instability), but gravity always provides the energy.

But wait, there’s a whole lot more to galaxies that we can’t see!

Most astronomers think that there is dark matter in our Galaxy because

A. stars in the outer edges of our Galaxy move faster than expected.
B. stars in the outer edges of our Galaxy move slower than expected.
C. large amounts of matter can be seen at infrared wavelengths.
D. large amounts of matter can be seen at radio wavelengths.
E. large amounts of matter can be seen at x-ray wavelengths.

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Astronomers measure the motions of stars and gas clouds using the Doppler shift

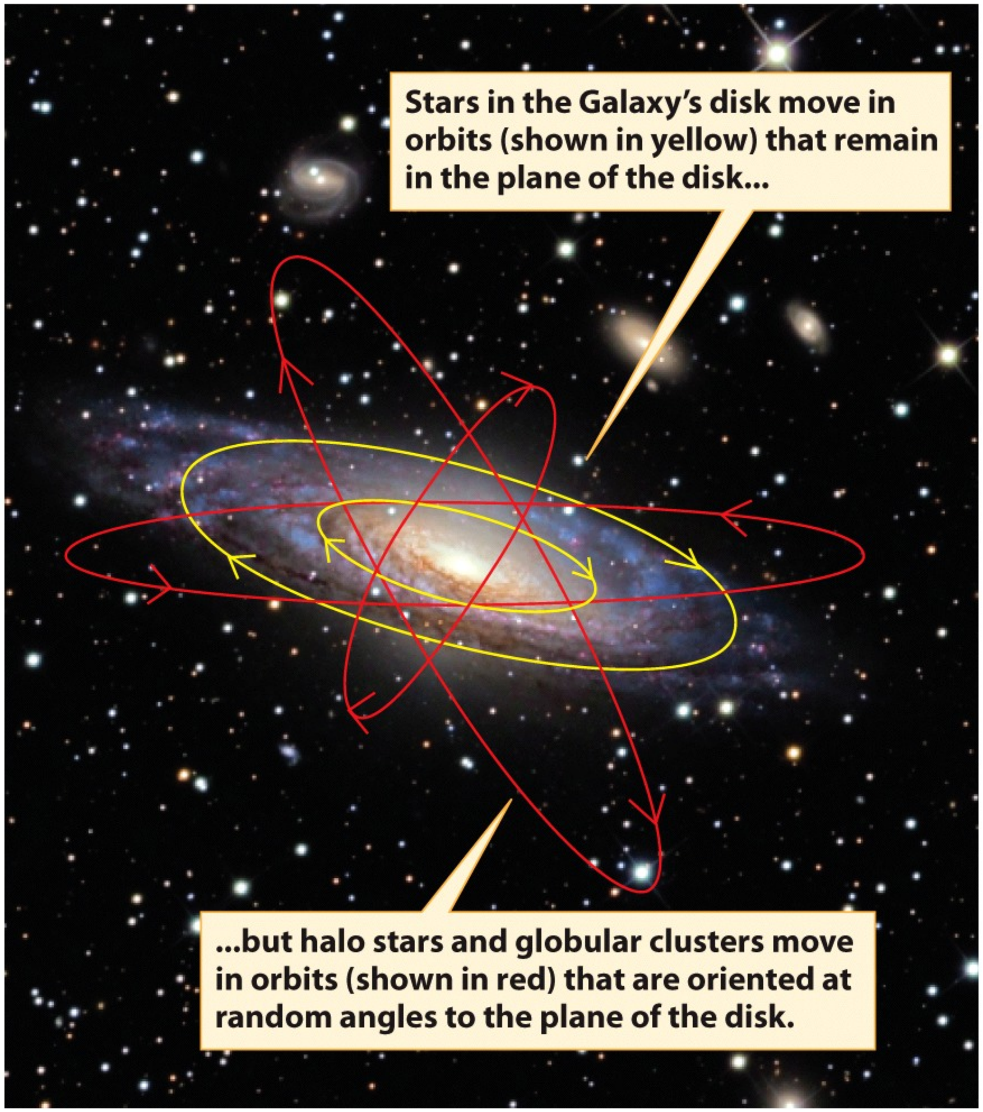
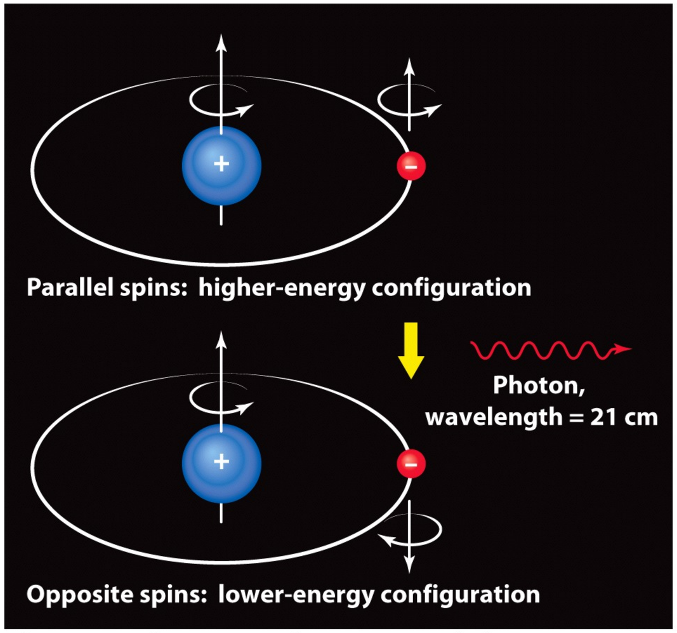


Figure 22-9
Universe, Tenth Edition
Russell Croman/Science Source

21-cm (radio) emission line from neutral hydrogen



The magnetic energy of a proton and electron depends on their relative spin orientation

Figure 22-11b
Universe, Tenth Edition

21-cm emission shows that hydrogen gas is concentrated along the plane of the Galaxy

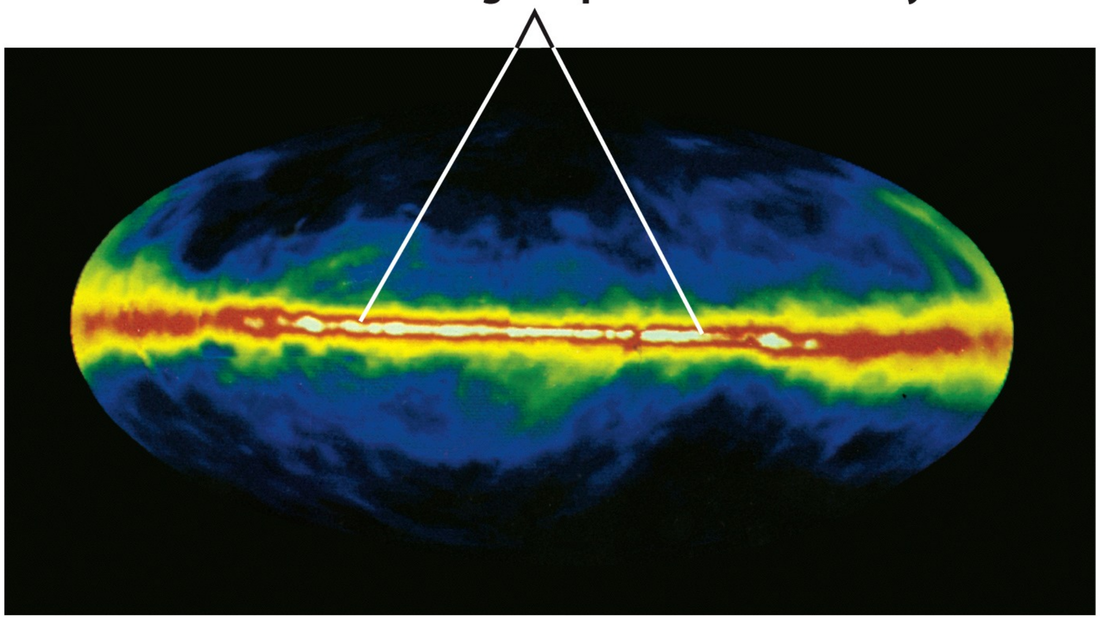
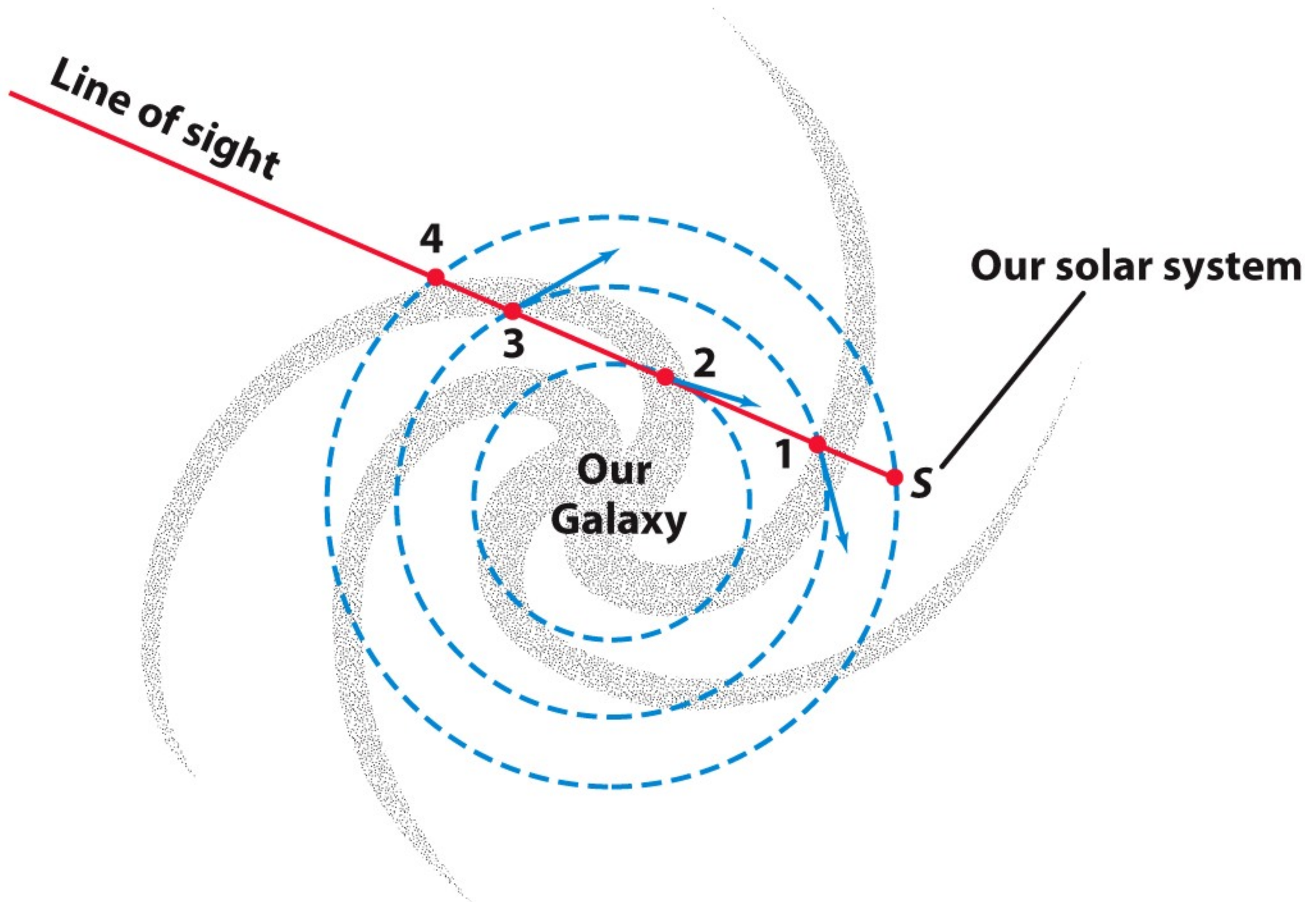


Figure 22-12
Universe, Tenth Edition
Courtesy of C. Jones and W. Forman, Harvard-Smithsonian Center for Astrophysics



• **Hydrogen clouds 1 and 3 are approaching us: They have a moderate blueshift.**
• **Hydrogen cloud 2 is approaching us at a faster speed: It has a larger blueshift.**
• **Hydrogen cloud 4 is neither approaching nor receding: It has no redshift or blueshift.**

Figure 22-13
Universe, Tenth Edition

(b) If our Galaxy rotated like a solid disk, the orbital speed would be greater for stars and gas in larger orbits.

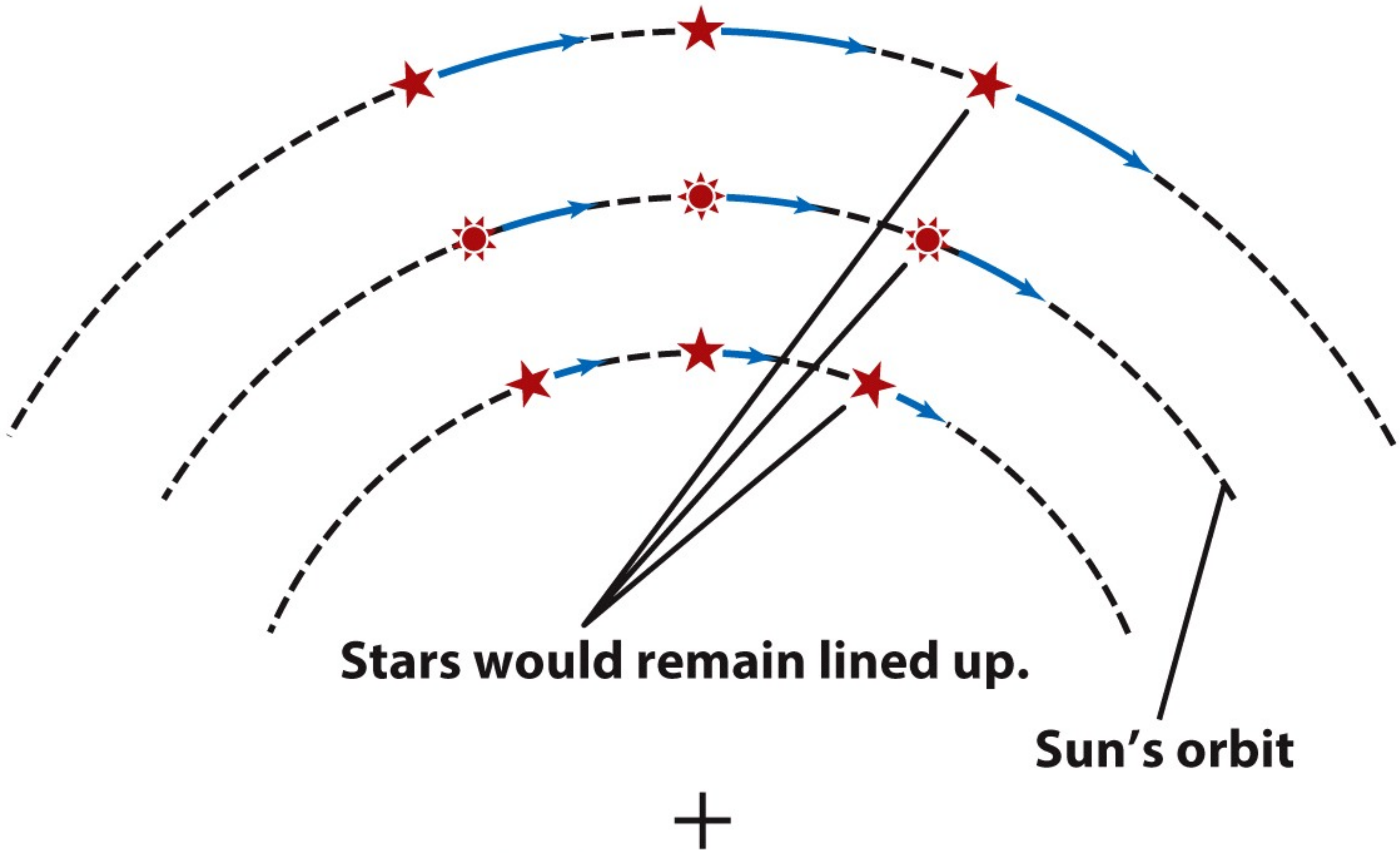


Figure 22-17b
Universe, Tenth Edition

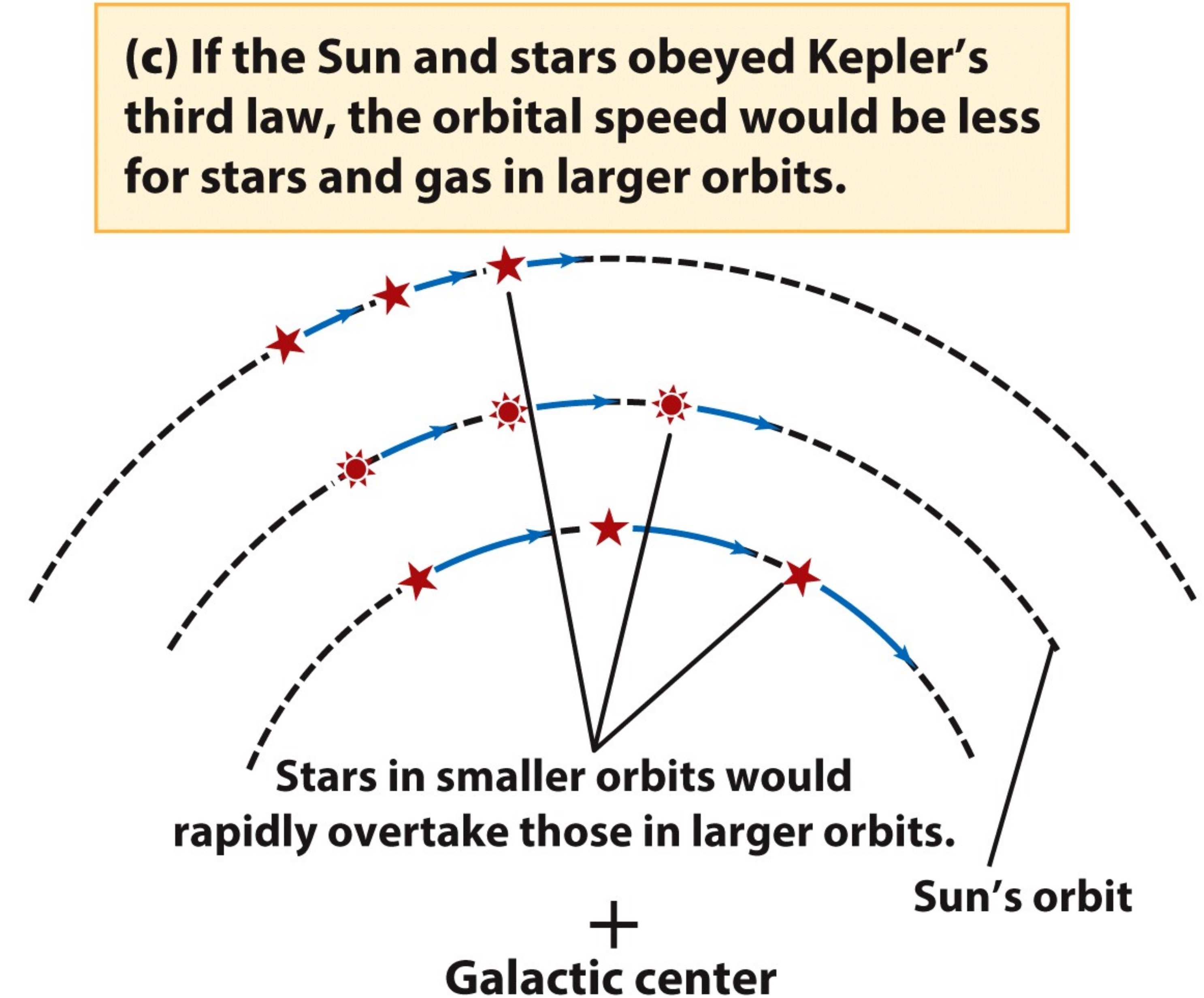


Figure 22-17c
Universe, Tenth Edition

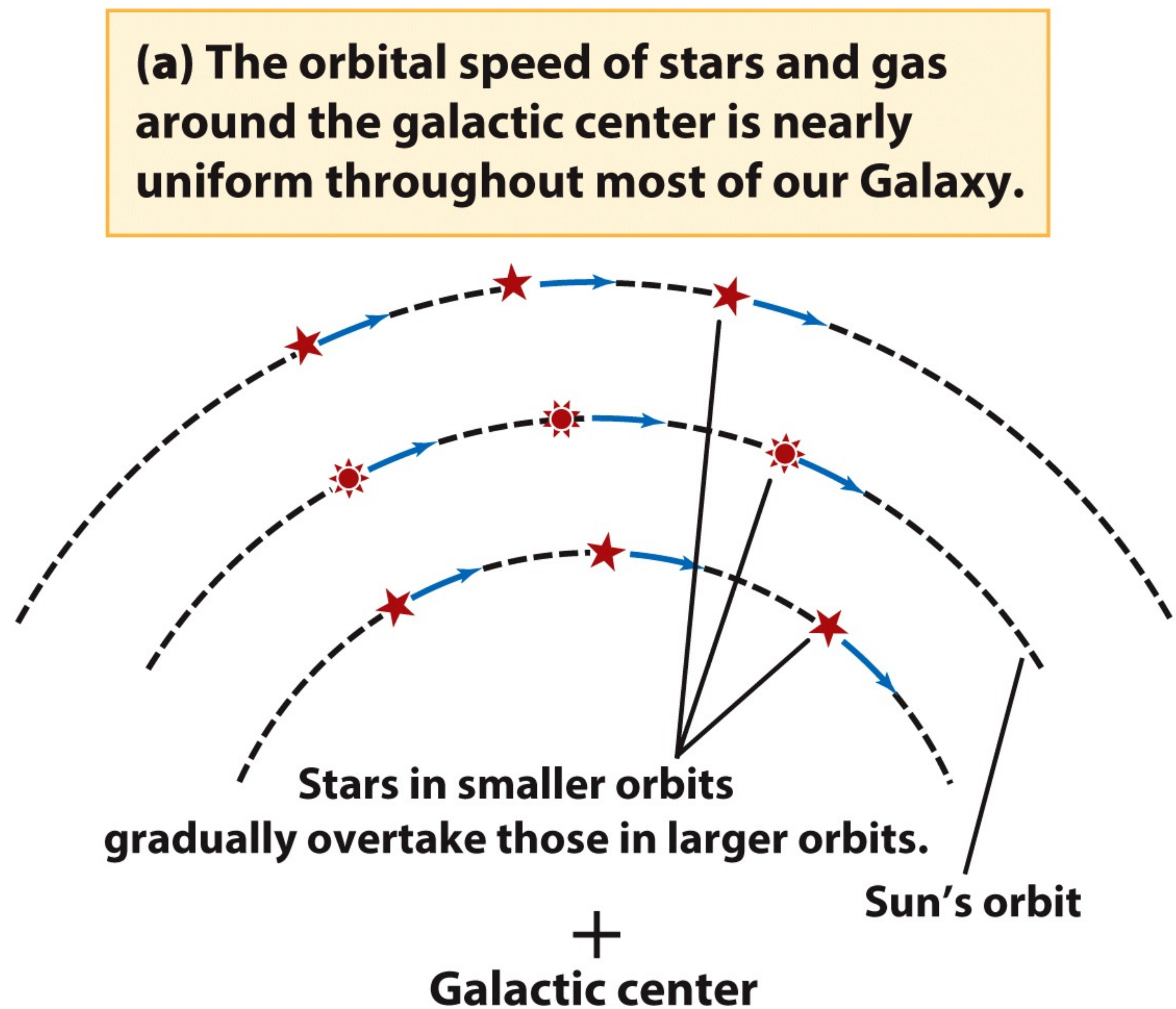


Figure 22-17a
Universe, Tenth Edition

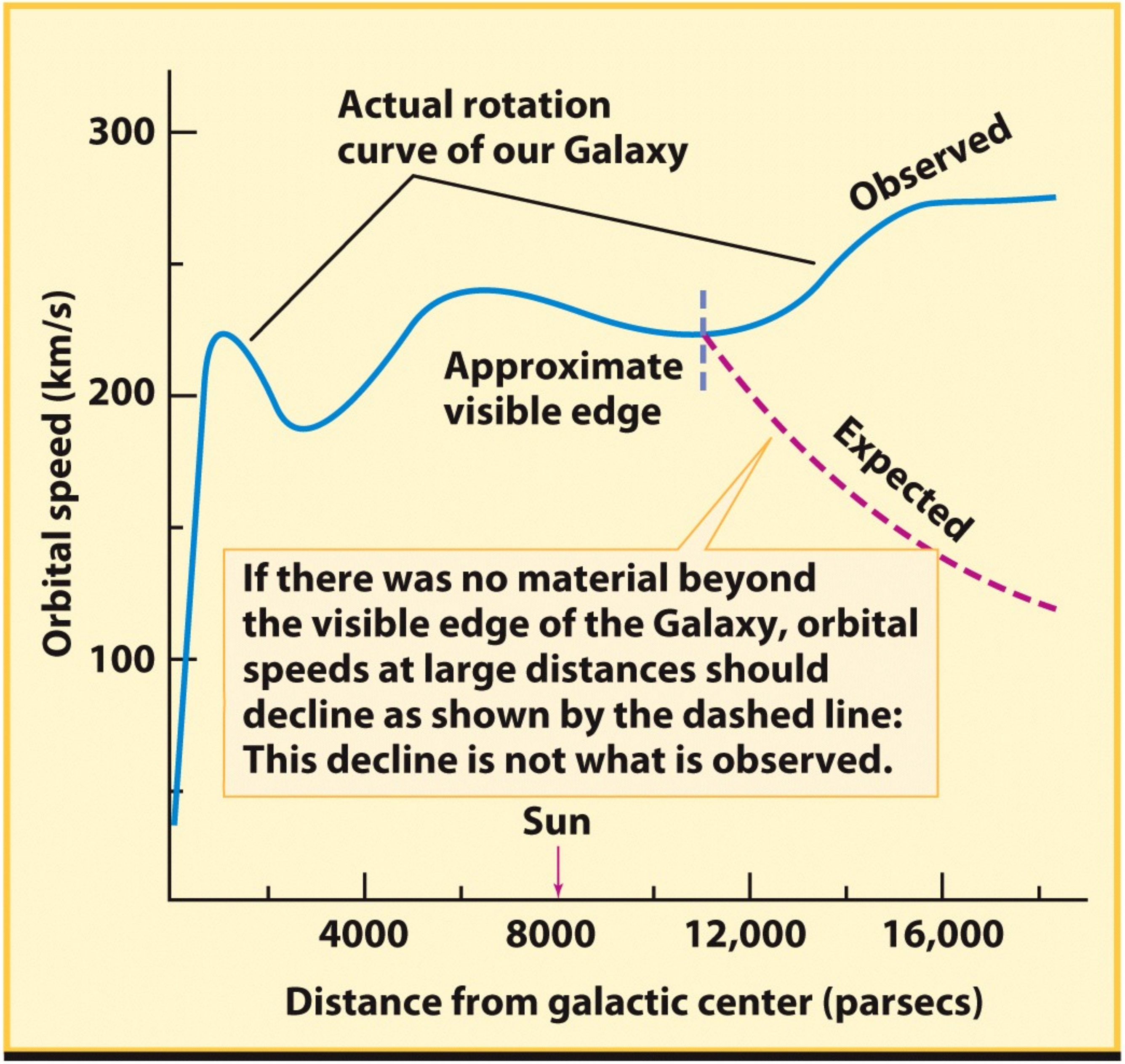
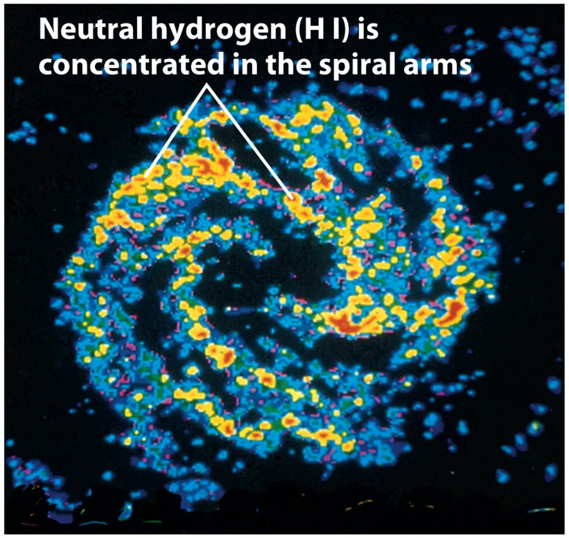


Figure 22-18
Universe, Tenth Edition

The Rotation Curves of All Spiral Galaxies Indicate the Presence of Extended Halos of Dark Matter



21-cm radio view of M83

Figure 22-15b
Universe, Tenth Edition
VLA, NRAO

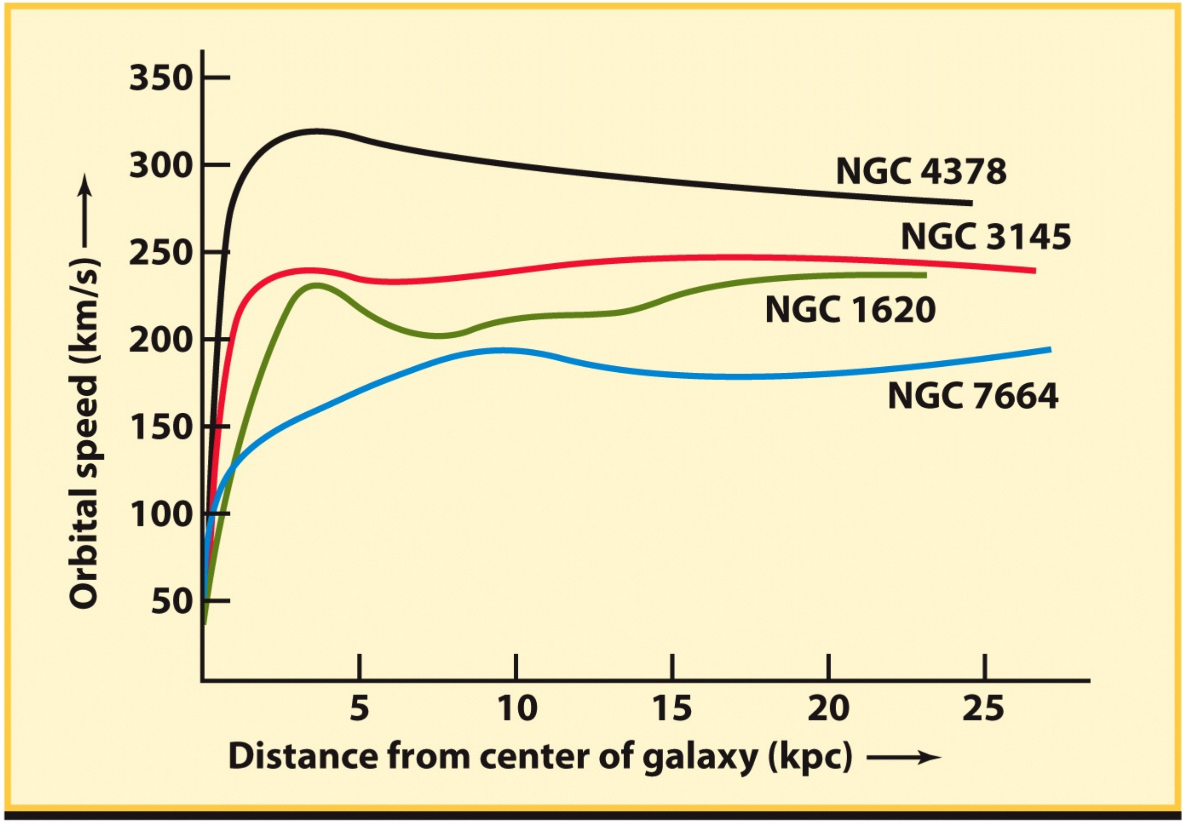
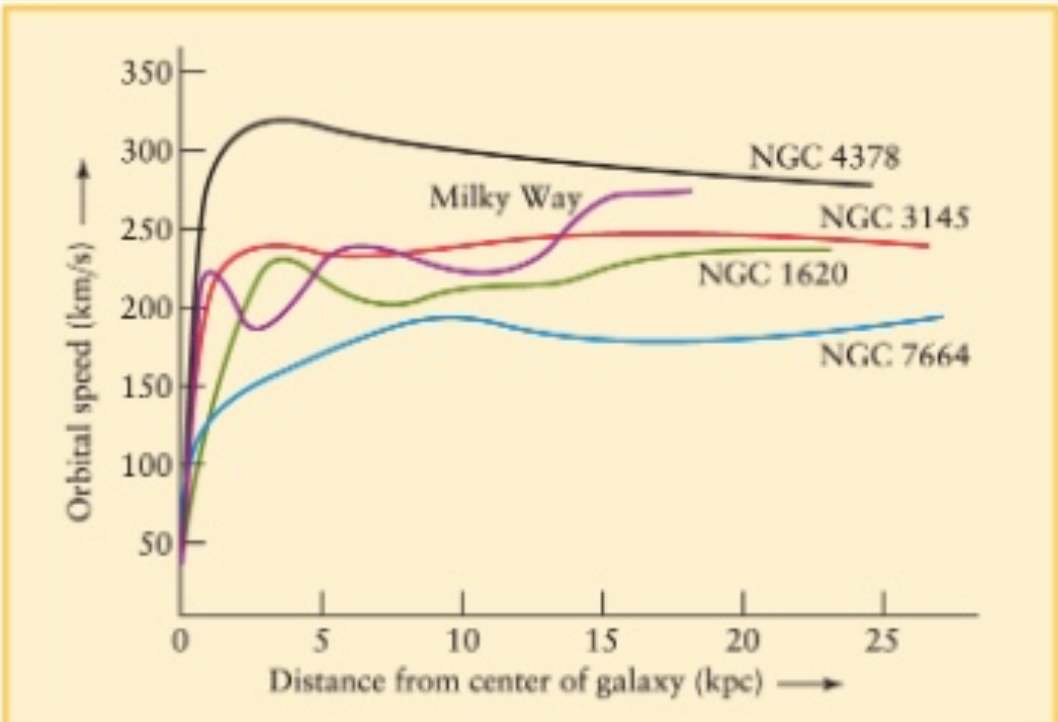


Figure 23-31
Universe, Tenth Edition

Homework Problems

47. Figure 23-31 shows the rotation curve of the Sa galaxy NGC 4378. Using data from that graph, calculate the orbital period of stars 20 kpc from the galaxy's center. How much mass lies within 20 kpc of the center of NGC 4378?



Geller et al., *Universe*, 11e, © 2019 W. H. Freeman and Company

Rotation Speeds Measured Beyond the Disk Using Satellite Galaxies

The Local Group of Galaxies

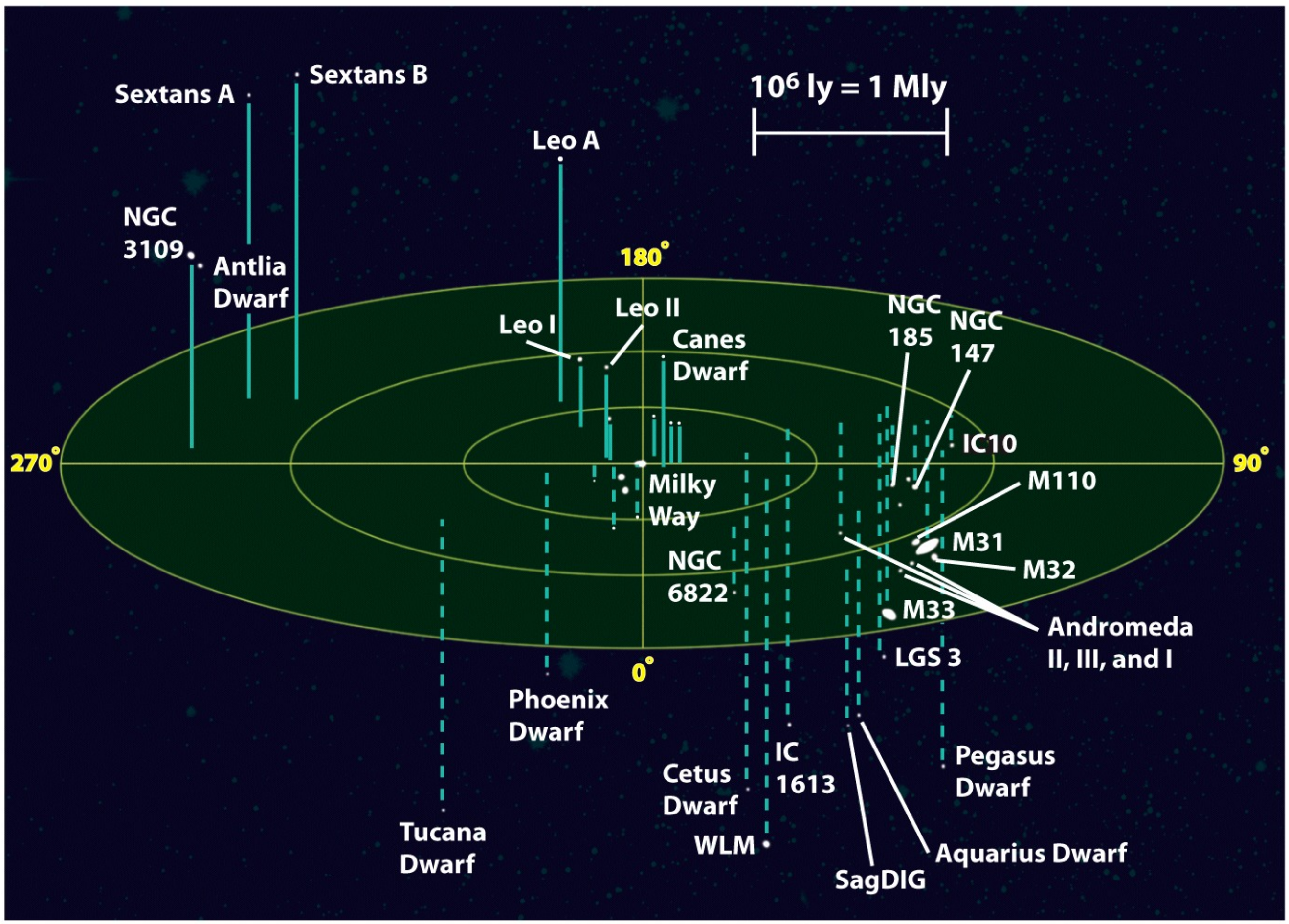


Figure 23-19
Universe, Tenth Edition

Dwarf Galaxy Leo I

Figure 23-9
Universe, Tenth Edition
NASA and The Hubble Heritage Team [STScI/AURA]

A Snack for the Milky Way

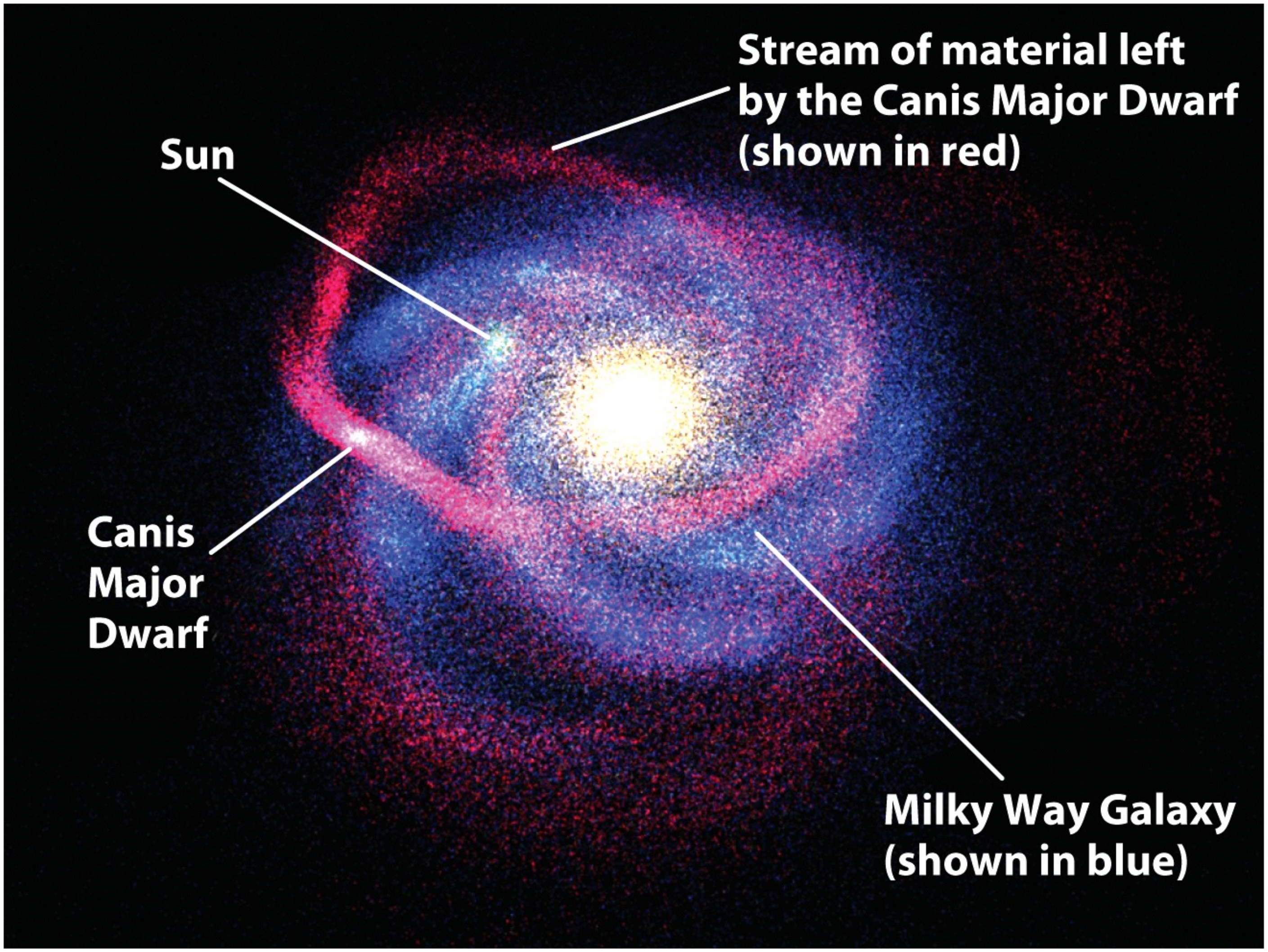
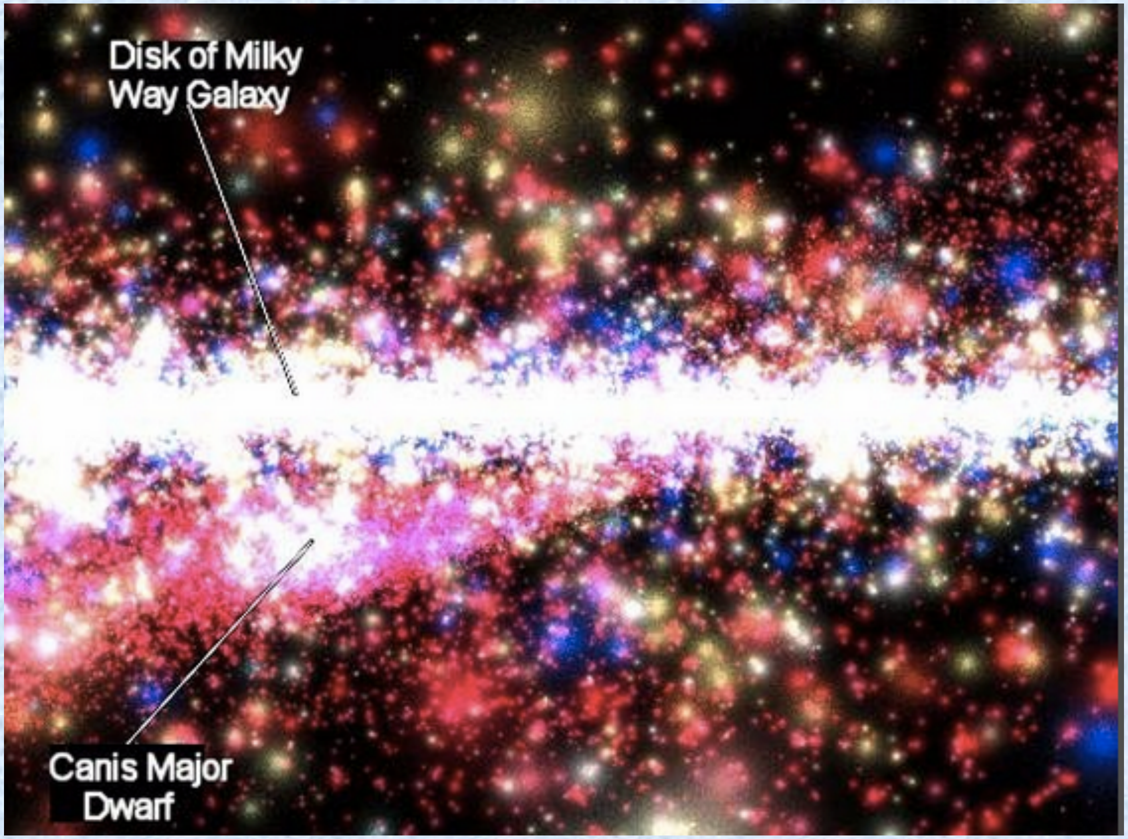


Figure 23-20
Universe, Tenth Edition
O. Lopez-Cruz and I. K. Shelton, University of Toronto/NOAO/AURA/NSF

Canis Major Dwarf



The Milky Way is still growing today!

The Dark Matter Halo

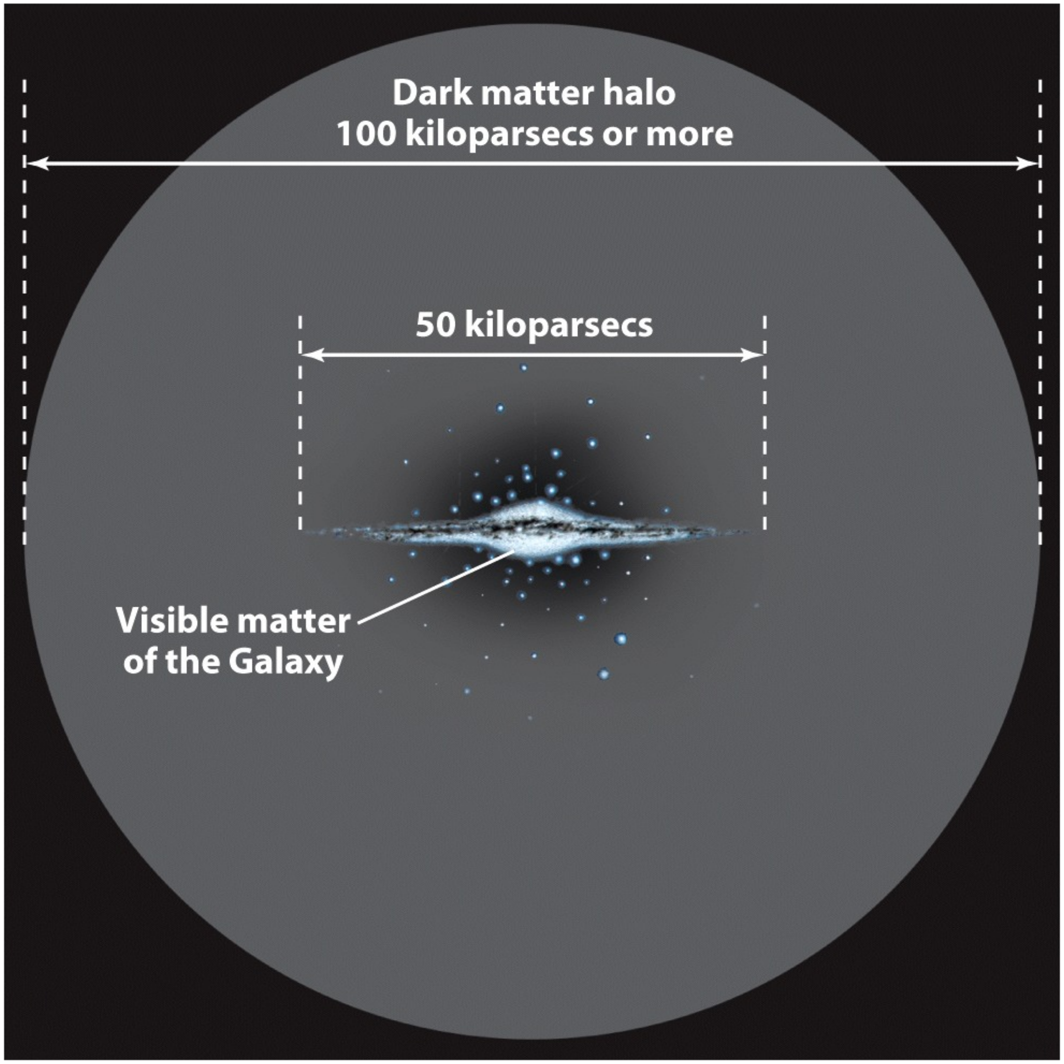


Figure 22-19
Universe, Tenth Edition

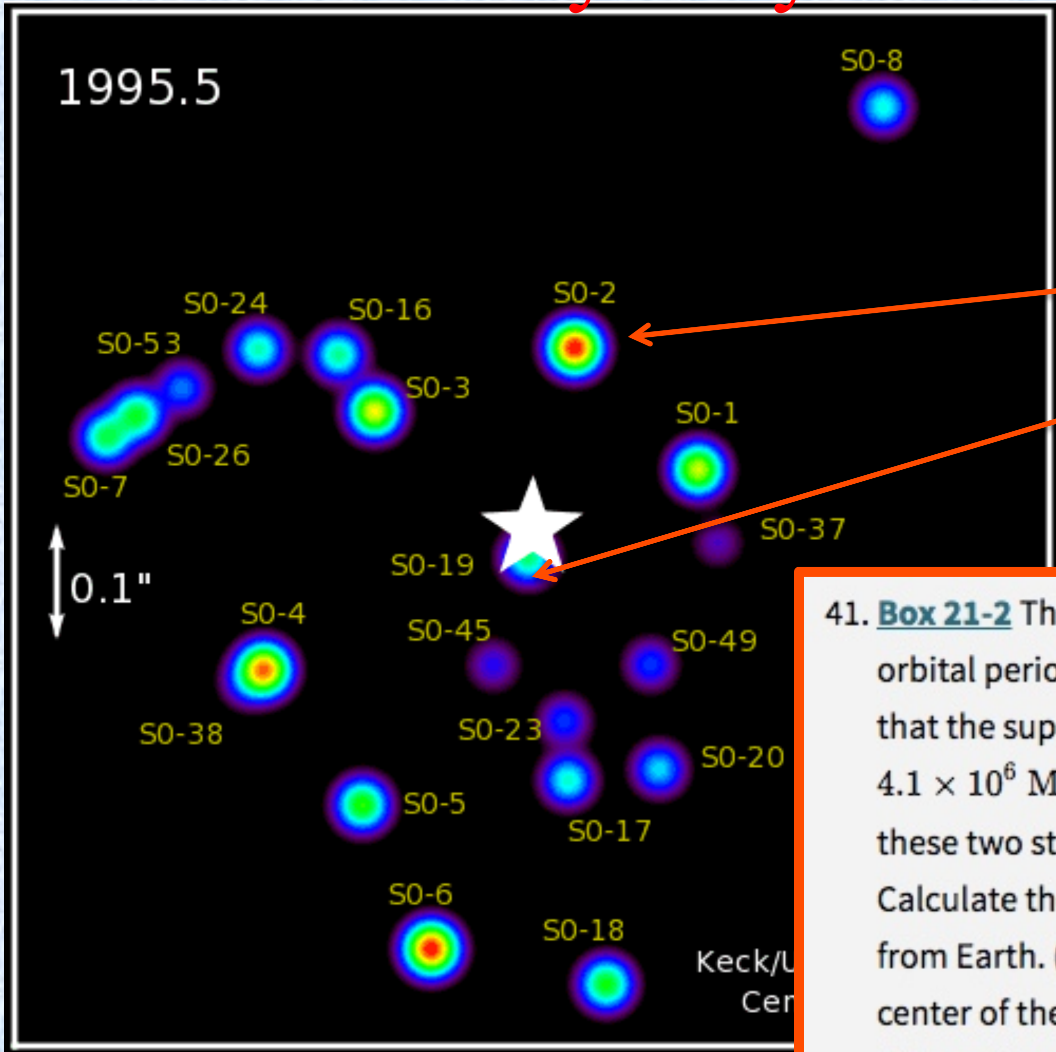
What is Dark Matter?

- Some options are ruled out.
  - Remnant stars (white dwarfs, brown dwarfs, etc.)
  - Cold gas

- So *dark* really means some type of sub-atomic particle that does not interact with light.
  - Weakly interacting massive particles (WIMPS)
  - Neutrinos
  - Axions
  - ...?

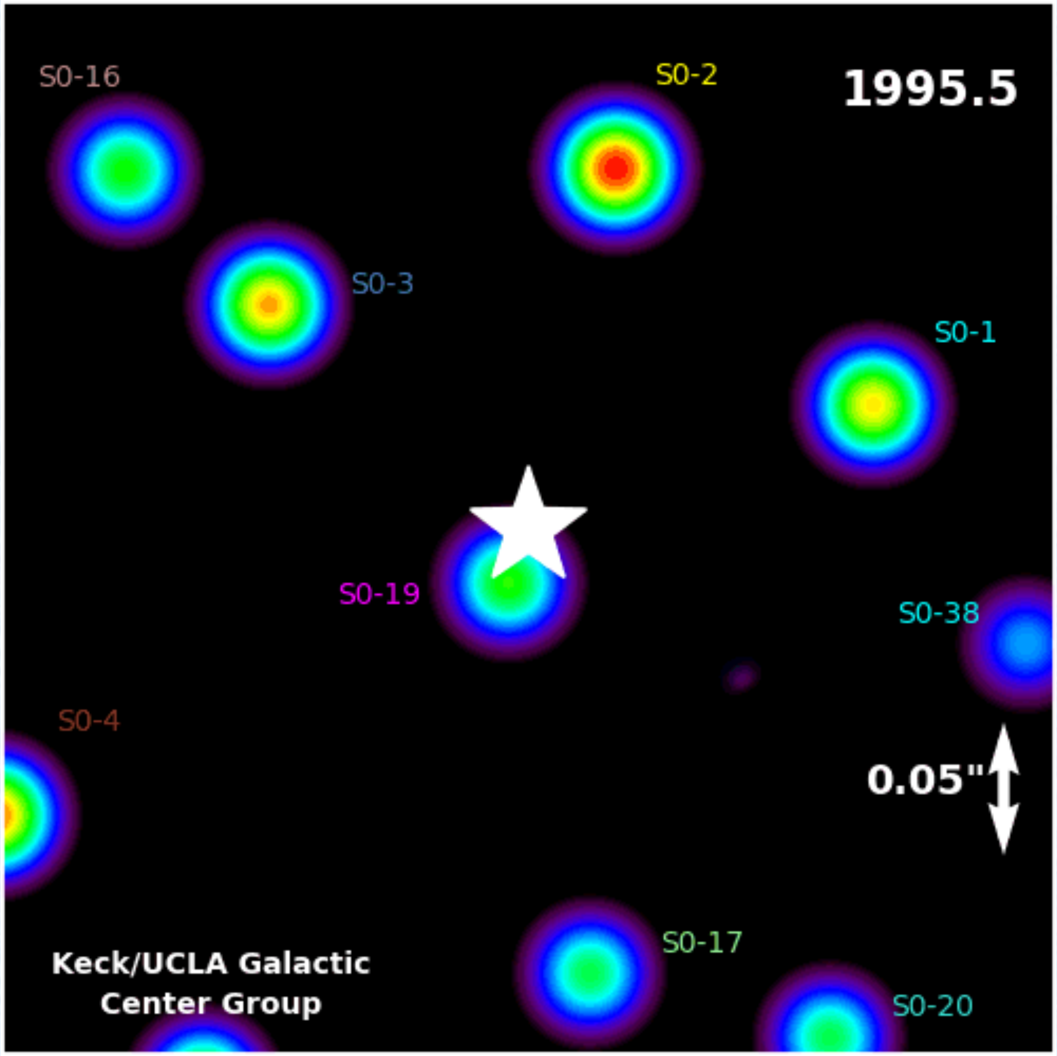
Supermassive black holes

Stars Near the Center of the Milky Way Galaxy Move Fast



41. Box 21-2 The stars S0-2 and S0-19 orbit Sagittarius A* with orbital periods of 14.5 and 37.3 years, respectively. (**a**) Assuming that the supermassive black hole in Sagittarius A* has a mass of $4.1 \times 10^6\ M_\odot$, determine the semimajor axes of the orbits of these two stars. Give your answers in astronomical units (au). (**b**) Calculate the angular size of each orbit's semimajor axis as seen from Earth. (See Section 22-1 for the distance from Earth to the center of the galaxy.) Explain why extremely high-resolution infrared images are required to observe the motions of these stars.

Galactic Center (Ghez Group/UCLA)



- Their motions on the sky are measured using high-resolution imaging.
- Remember, astronomers use adaptive optics to reach the diffraction limit of a telescope.
- Could the shadow of this black be resolved?

iClicker Question

Calculate the Schwarzschild radius (*R_S* = 2GM/c$^{2)}$ of the 4 million solar mass black hole at the center of the Milky Way Galaxy.

[Hint: G = 6.67E-11 m^2/kg^2)

A. 1.2 X 10^{10} m (or 17 R_0)

B. 1.2 cm

C. 10 kpc (the size of the galaxy)

D. 10^{-10} m (the size of an atom)

E. 1.2 Mpc (the distance to Andromeda Galaxy)

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Angular Size of the Event Horizon

- Small angle formula:

  $R_S = d\ \theta$ (radians), or

  $R_S = 4.85 \times 10^{-6}\ d\ \theta$ (arcseconds)

  Where

  $R_S = 1.2 \times 10^{10}$ m

  $d = 8$ kpc $= 2.47 \times 10^{20}$ m

- Gives $\theta = 1.00 \times 10^{-5}$ arcseconds

  = 10 micro-arcseconds

Theoretical Prediction of Black Hole *Shadow*

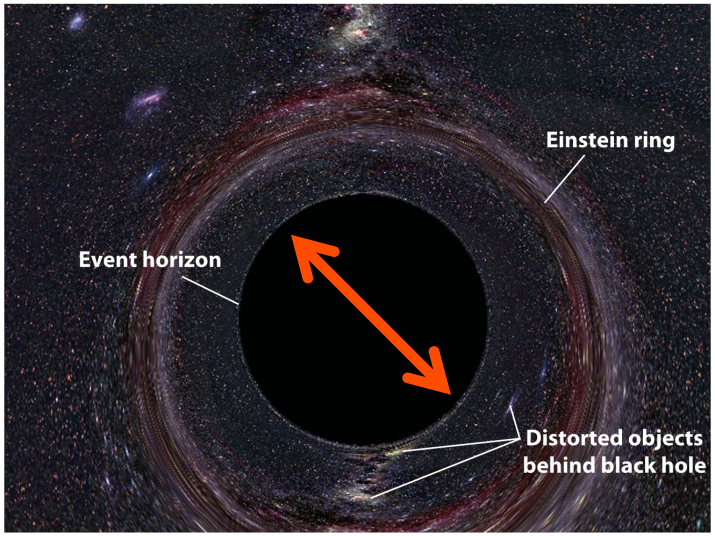

Figure 21-20
Universe, Tenth Edition
Andrew J. S. Hamilton/University of Colorado, Boulder

iClicker Question

How large a telescope would you need to resolve the shadow of the event horizon of the black hole at the center of the Milky Way galaxy?

Assume you observe at a wavelength of 1.3mm to see through the dust. [Hint: Angular radius of 10 micro-arcseconds and diffraction limit is $\theta = 2.5E5\ \lambda/D$)

A. Diameter of 3×10^7 m (earth size)

B. Diameter of the size of the galaxy

C. Diameter of 10^{-10} m (the size of an atom)

D. Diameter of 10 m (like the Keck telescopes)

E. The size of the solar system.

iClicker Question

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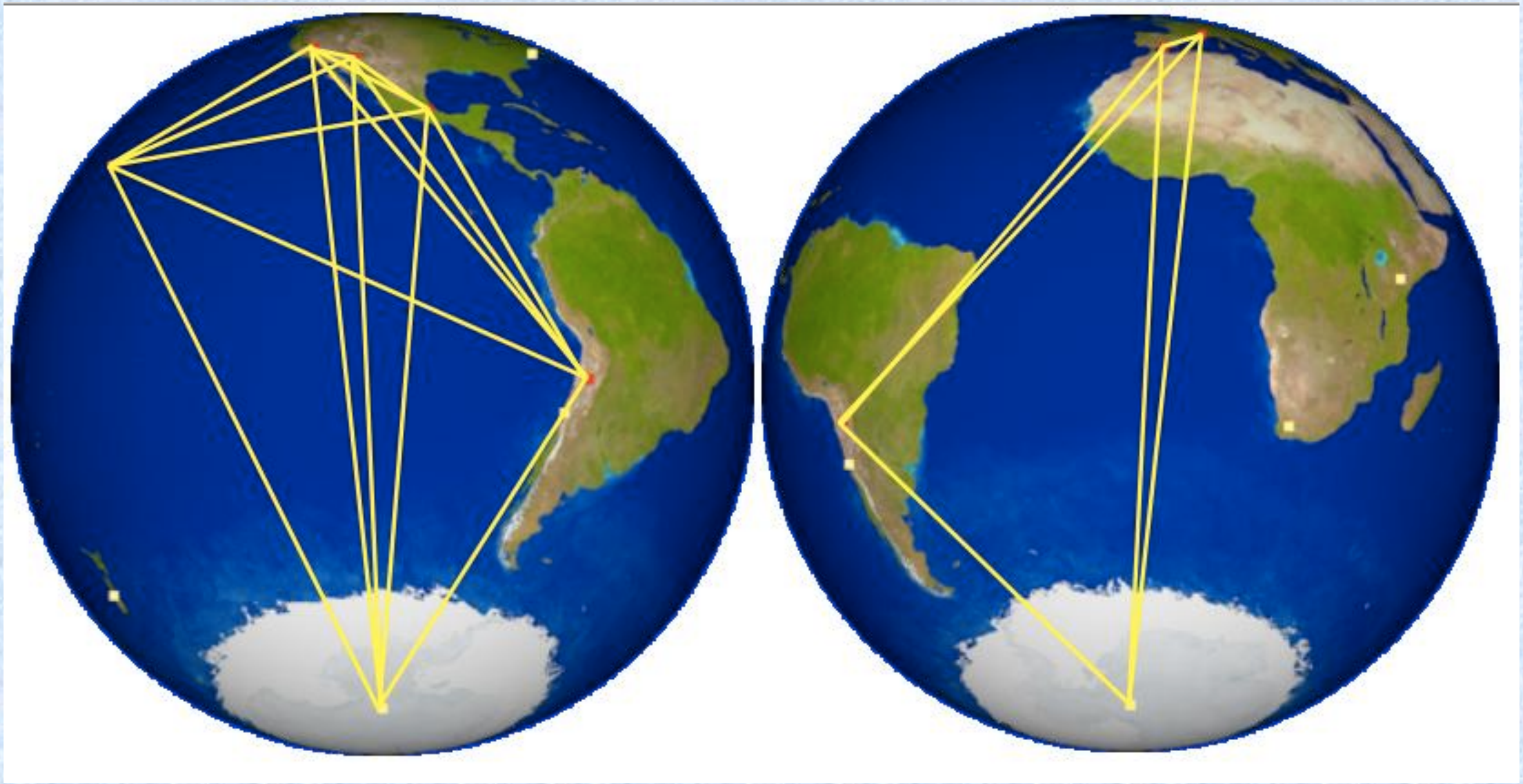
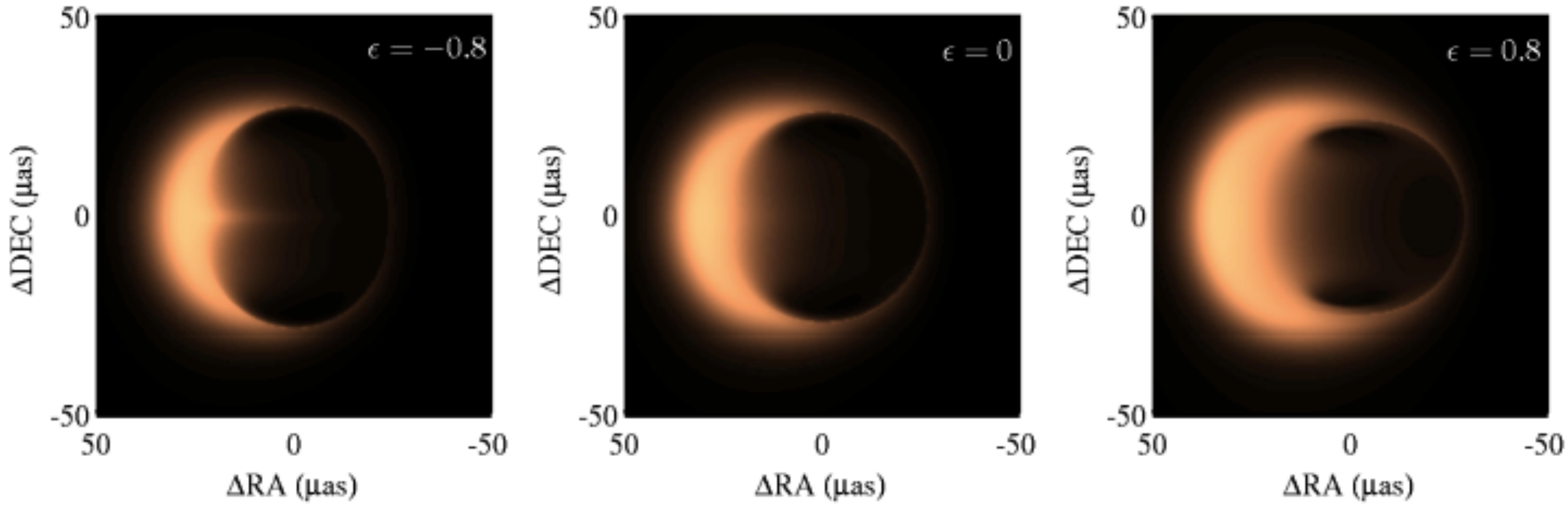
Event Horizon Telescope



Simulation: Event Horizon Telescope Picture of Sagittarius A*



Summary

- The Milky Way Galaxy
  - Contains ~2×10^{11} stars
  - Sun is in a nearly circular orbit 8 kpc from the center
  - Stars (Pop I) in disk are young and metal rich
  - Stars in halo (Pop II) are older and metal poor
  - The central bulge has a radius of 1 kpc and a mass about 1000 times larger than the supermassive BH.
- Spiral arms are density waves
- The velocities of the stars in a galaxy determine its mass
  - This mass is much higher than the mass of the stars and gas
  - That the Universe as whole contains about 5 times more "dark matter" than normal matter.
- The Milky Way will collide with the Andromeda galaxy in about 4 Gyr.