28.E: The Evolution and Distribution of Galaxies (Exercises)

For Further Exploration

Articles

Andrews, B. “What Are Galaxies Trying to Tell Us?” *Astronomy* (February 2011): 24. Introduction to our understanding of the shapes and evolution of different types of galaxies.

Barger, A. “The Midlife Crisis of the Cosmos.” *Scientific American* (January 2005): 46. On how our time differs from the early universe in terms of what galaxies are doing, and what role supermassive black holes play.

Berman, B. “The Missing Universe.” *Astronomy* (April 2014): 24. Brief review of dark matter, what it could be, and modified theories of gravity that can also explain it.

Faber, S., et al. “Staring Back to Cosmic Dawn.” *Sky & Telescope* (June 2014): 18. Program to see the most distant and earliest galaxies with the Hubble.

Geller, M., & Huchra, J. “Mapping the Universe.” *Sky & Telescope* (August 1991): 134. On their project mapping the location of galaxies in three dimensions.

Hooper, D. “Dark Matter in the Discovery Age.” *Sky & Telescope* (January 2013): 26. On experiments looking for the nature of dark matter.

James, C. R. “The Hubble Deep Field: The Picture Worth a Trillion Stars.” *Astronomy* (November 2015): 44. Detailed history and results, plus the Hubble Ultra-Deep Field.

Kaufmann, G., & van den Bosch, F. “The Life Cycle of Galaxies.” *Scientific American* (June 2002): 46. On the evolution of galaxies and how the different shapes of galaxies develop.

Knapp, G. “Mining the Heavens: The Sloan Digital Sky Survey.” *Sky & Telescope* (August 1997): 40.

Kron, R., & Butler, S. “Stars and Strips Forever.” *Astronomy* (February 1999): 48. On the Sloan Digital Survey.

Kruesi, L. “What Do We Really Know about Dark Matter?” *Astronomy* (November 2009): 28. Focuses on what dark matter could be and experiments to find out.

Larson, R., & Bromm, V. “The First Stars in the Universe.” *Scientific American* (December 2001): 64. On the dark ages and the birth of the first stars.

Nadis, S. “Exploring the Galaxy-Black Hole Connection.” *Astronomy* (May 2010): 28. About the role of massive black holes in the evolution of galaxies.

Nadis, S. “Astronomers Reveal the Universe’s Hidden Structure.” *Astronomy* (September 2013): 44. How dark matter is the scaffolding on which the visible universe rests.

Schilling, G. “Hubble Goes the Distance.” *Sky & Telescope* (January 2015): 20. Using gravitational lensing with HST to see the most distant galaxies.

Strauss, M. “Reading the Blueprints of Creation.” *Scientific American* (February 2004): 54. On large-scale surveys of galaxies and what they tell us about the organization of the early universe.

Tytell, D. “A Wide Deep Field: Getting the Big Picture.” *Sky & Telescope* (September 2001): 42. On the NOAO survey of deep sky objects.

Villard, R. “How Gravity’s Grand Illusion Reveals the Universe.” *Astronomy* (January 2013): 44. On gravitational lensing and what it teaches us.

Websites

Assembly of Galaxies: http://jwst.nasa.gov/galaxies.html. Introductory background information about galaxies: what we know and what we want to learn.

Brief History of Gravitational Lensing: www.einstein-online.info/spot...ensing_history. From Einstein OnLine.

Cosmic Structures: skyserver.sdss.org/dr1/en/ast...structures.asp. Brief review page on how galaxies are organized, from the Sloan Survey.

Discovery of the First Gravitational Lens: astrosociety.org/wp-content/u.../ab2009-33.pdf. By Ray Weymann, 2009.

Gravitational Lensing Discoveries from the Hubble Space Telescope: http://hubblesite.org/newscenter/arc...tational-lens/. A chronological list of news releases and images.

Local Group of Galaxies: http://www.atlasoftheuniverse.com/localgr.html. Clickable map from the Atlas of the Universe project. See also their Virgo Cluster page: http://www.atlasoftheuniverse.com/galgrps/vir.html.

RotCurve: burro.astr.cwru.edu/JavaLab/R...eWeb/main.html. Try your hand at using real galaxy rotation curve data to measure dark matter halos using this Java applet simulation.

Sloan Digital Sky Survey Website: http://classic.sdss.org/. Includes nontechnical and technical parts.

Spyglasses into the Universe: www.spacetelescope.org/scienc...ional_lensing/. Hubble page on gravitational lensing; includes links to videos.

Virgo Cluster of Galaxies: http://messier.seds.org/more/virgo.html. A page with brief information and links to maps, images, etc.

Videos

Cosmic Simulations: www.tapir.caltech.edu/~phopki...ies_cosmo.html. Beautiful videos with computer simulations of how galaxies form, from the FIRE group.

Cosmology of the Local Universe: http://irfu.cea.fr/cosmography. Narrated flythrough of maps of galaxies showing the closer regions of the universe (17:35).

Gravitational Lensing: https://www.youtube.com/watch?v=4Z71RtwoOas. Video from Fermilab, with Dr. Don Lincoln (7:14).

How Galaxies Were Cooked from the Primordial Soup: https://www.youtube.com/watch?v=wqNNCm7SNyw. A 2013 public talk by Dr. Sandra Faber of Lick Observatory about the evolution of galaxies; part of the Silicon Valley Astronomy Lecture Series (1:19:33).

Hubble Extreme Deep Field Pushes Back Frontiers of Time and Space: https://www.youtube.com/watch?v=gu_VhzhlqGw. Brief 2012 video (2:42).

Looking Deeply into the Universe in 3-D: https://www.eso.org/public/videos/eso1507a/. 2015 ESOCast video on how the Very Large Telescopes are used to explore the Hubble Ultra-Deep Field and learn more about the faintest and most distant galaxies (5:12).

Millennium Simulation: wwwmpa.mpa-garching.mpg.de/ga...rgo/millennium. A supercomputer in Germany follows the evolution of a representative large box as the universe evolves.

Movies of flying through the large-scale local structure: www.ifa.hawaii.edu/~tully/. By Brent Tully.

Shedding Light on Dark Matter: https://www.youtube.com/watch?v=bZW_B9CC-gI. 2008 TED talk on galaxies and dark matter by physicist Patricia Burchat (17:08).

Sloan Digital Sky Survey overview movies: astro.uchicago.edu/cosmus/projects/sloanmovie/.

Virtual Universe: https://www.youtube.com/watch?v=SY0bKE10ZDM. An MIT model of a section of universe evolving, with dark matter included (4:11).

When Two Galaxies Collide: www.openculture.com/2009/04/w...s_collide.html. Computer simulation, which stops at various points and shows a Hubble image of just such a system in nature (1:37).

Collaborative Group Activities

1. Suppose you developed a theory to account for the evolution of New York City. Have your group discuss whether it would resemble the development of structure in the universe (as we have described it in this chapter). What elements of your model for NYC resemble the astronomers' model for the growth of structure in the universe? Which elements do not match?
2. Most astronomers believe that dark matter exists and is a large fraction of the total matter in the universe. At the same time, most astronomers do not believe that UFOs are evidence that we are being visited by aliens from another world. Yet

astronomers have never actually seen either dark matter or a UFO. Why do you think one idea is widely accepted by scientists and the other is not? Which idea do you think is more believable? Give your reasoning.

3. Someone in your group describes the redshift surveys of galaxies to a friend, who says he's never heard of a bigger waste of effort. Who cares, he asks, about the large-scale structure of the universe? What is your group's reaction, and what reasons could you come up with for putting money into figuring out how the universe is organized?
4. The leader of a small but very wealthy country is obsessed by maps. She has put together a fabulous collection of Earth maps, purchased all the maps of other planets that astronomers have assembled, and now wants to commission the best possible map of the entire universe. Your group is selected to advise her. What sort of instruments and surveys should she invest in to produce a good map of the cosmos? Be as specific as you can.
5. Download a high-resolution image of a rich galaxy cluster from the Hubble Space Telescope (see the list of gravitational lens news stories in the "For Further Exploration" section). See if your group can work together to identify gravitational arcs, the images of distant background galaxies distorted by the mass of the cluster. How many can you find? Can you identify any multiple images of the same background galaxy? (If anyone in the group gets really interested, there is a Citizen Science project called Spacewarps, where you can help astronomers identify gravitational lenses on their images: https://spacewarps.org.)
6. You get so excited about gravitational lensing that you begin to talk about it with an intelligent friend who has not yet taken an astronomy course. After hearing you out, this friend starts to worry. He says, "If gravitational lenses can distort quasar images, sometimes creating multiple, or ghost, images of the same object, then how can we trust any point of light in the sky to be real? Maybe many of the stars we see are just ghost images or lensed images too!" Have your group discuss how to respond. (Hint: Think about the path that the light of a quasar took on its way to us and the path the light of a typical star takes.)
7. The 8.4-meter Large Synoptic Survey Telescope (LSST), currently under construction atop Cerro Pachón, a mountain in northern Chile, will survey the entire sky with its 3.2-gigapixel camera every few days, looking for transient, or temporary, objects that make a brief appearance in the sky before fading from view, including asteroids and Kuiper belt objects in our solar system, and supernovae and other explosive high-energy events in the distant universe. When it's fully operating sometime after 2021, the LSST will produce up to 30 terabytes of data *every night.* (A terabyte is 1000 gigabytes, which is the unit you probably use to rate your computer or memory stick capacity.) With your group, consider what you think might be some challenges of dealing with that quantity of data every night in a scientifically productive but efficient way. Can you propose any solutions to those challenges?
8. Quasars are rare now but were much more numerous when the universe was about one-quarter of its current age. The total star formation taking place in galaxies across the universe peaked at about the same redshift. Does your group think this is a coincidence? Why or why not?
9. One way to see how well the ideas in astronomy (like those in this chapter) have penetrated popular culture is to see whether you can find astronomical words in the marketplace. A short web search for the term "dark matter" turns up both a brand of coffee and a brand of "muscle growth accelerator" with that name. How many other terms used in this chapter can your group find in the world of products? (What's a really popular type of Android cell phone, for example?)
10. What's your complete address in the universe? Group members should write out their full address, based on the information in this chapter (and the rest of the book). After your postal code and country, you may want to add continent, planet, planetary system, galaxy, etc. Then each group member should explain this address to a family member or student not taking astronomy.

Review Questions

1. How are distant (young) galaxies different from the galaxies that we see in the universe today?
2. What is the evidence that star formation began when the universe was only a few hundred million years old?
3. Describe the evolution of an elliptical galaxy. How does the evolution of a spiral galaxy differ from that of an elliptical?
4. Explain what we mean when we call the universe homogeneous and isotropic. Would you say that the distribution of elephants on Earth is homogeneous and isotropic? Why?
5. Describe the organization of galaxies into groupings, from the Local Group to superclusters.
6. What is the evidence that a large fraction of the matter in the universe is invisible?
7. When astronomers make maps of the structure of the universe on the largest scales, how do they find the superclusters of galaxies to be arranged?
8. How does the presence of an active galactic nucleus in a starburst galaxy affect the starburst process?

Thought Questions

1. Describe how you might use the color of a galaxy to determine something about what kinds of stars it contains.
2. Suppose a galaxy formed stars for a few million years and then stopped (and no other galaxy merged or collided with it). What would be the most massive stars on the main sequence after 500 million years? After 10 billion years? How would the color of the galaxy change over this time span? (Refer to Evolution from the Main Sequence to Red Giants.)
3. Given the ideas presented here about how galaxies form, would you expect to find a giant elliptical galaxy in the Local Group? Why or why not? Is there in fact a giant elliptical in the Local Group?
4. Can an elliptical galaxy evolve into a spiral? Explain your answer. Can a spiral turn into an elliptical? How?
5. If we see a double image of a quasar produced by a gravitational lens and can obtain a spectrum of the galaxy that is acting as the gravitational lens, we can then put limits on the distance to the quasar. Explain how.
6. The left panel of the thumbnail photo of Chapter 27 shows a cluster of yellow galaxies that produces several images of blue galaxies through gravitational lensing. Which are more distant—the blue galaxies or the yellow galaxies? The light in the galaxies comes from stars. How do the temperatures of the stars that dominate the light of the cluster galaxies differ from the temperatures of the stars that dominate the light of the blue-lensed galaxy? Which galaxy's light is dominated by young stars?
7. Suppose you are standing in the center of a large, densely populated city that is exactly circular, surrounded by a ring of suburbs with lower-density population, surrounded in turn by a ring of farmland. From this specific location, would you say the population distribution is isotropic? Homogeneous?
8. Astronomers have been making maps by observing a slice of the universe and seeing where the galaxies lie within that slice. If the universe is isotropic and homogeneous, why do they need more than one slice? Suppose they now want to make each slice extend farther into the universe. What do they need to do?
9. Human civilization is about 10,000 years old as measured by the development of agriculture. If your telescope collects starlight tonight that has been traveling for 10,000 years, is that star inside or outside our Milky Way Galaxy? Is it likely that the star has changed much during that time?
10. Given that only about 5% of the galaxies visible in the Hubble Deep Field are bright enough for astronomers to study spectroscopically, they need to make the most of the other 95%. One technique is to use their colors and apparent brightnesses to try to roughly estimate their redshift. How do you think the inaccuracy of this redshift estimation technique (compared to actually measuring the redshift from a spectrum) might affect our ability to make maps of large-scale structures such as the filaments and voids shown in Figure $28.3.8$ in Section 28.3?

Figuring for Yourself

1. Using the information from Example $28.3.1$ in Section 28.3, how much fainter an object will you have to be able to measure in order to include the same kinds of galaxies in your second survey? Remember that the brightness of an object varies as the inverse square of the distance.
2. Using the information from Example $28.3.1$ in Section 28.3, if galaxies are distributed homogeneously, how many times more of them would you expect to count on your second survey?
3. Using the information from Example $28.3.1$ in Section 28.3, how much longer will it take you to do your second survey?
4. Galaxies are found in the "walls" of huge voids; very few galaxies are found in the voids themselves. The text says that the structure of filaments and voids has been present in the universe since shortly after the expansion began 13.8 billion years ago. In science, we always have to check to see whether some conclusion is contradicted by any other information we have. In this case, we can ask whether the voids would have filled up with galaxies in roughly 14 billion years. Observations show that in addition to the motion associated with the expansion of the universe, the galaxies in the walls of the voids are moving in random directions at typical speeds of 300 km/s. At least some of them will be moving into the voids. How far into the void will a galaxy move in 14 billion years? Is it a reasonable hypothesis that the voids have existed for 14 billion years?
5. Calculate the velocity, the distance, and the look-back time of the most distant galaxies in Figure $28.3.8$ in Section 28.3 using the Hubble constant given in this text and the redshift given in the diagram. Remember the Doppler formula for velocity $\left(v = c \times \frac{\Delta\lambda}{\lambda}\right)$ and the Hubble law ($v = H \times d$, where d is the distance to a galaxy). For these low velocities, you can neglect relativistic effects.
6. Assume that dark matter is uniformly distributed throughout the Milky Way, not just in the outer halo but also throughout the bulge and in the disk, where the solar system lives. How much dark matter would you expect there to be inside the solar system? Would you expect that to be easily detectable? Hint: For the radius of the Milky Way's dark matter halo, use R = 300,000 light-years; for the solar system's radius, use 100 AU; and start by calculating the ratio of the two volumes.

7. The simulated box of galaxy filaments and superclusters shown in Figure $28.5.3$ in Section 28.5 stretches across 1 billion light-years. If you were to make a scale model where that box covered the core of a university campus, say 1 km, then how big would the Milky Way Galaxy be? How far away would the Andromeda galaxy be in the scale model?
8. The first objects to collapse gravitationally after the Big Bang might have been globular cluster-size galaxy pieces, with masses around 10^6 solar masses. Suppose you merge two of those together, then merge two larger pieces together, and so on, Lego-style, until you reach a Milky Way mass, about 10^{12} solar masses. How many merger generations would that take, and how many original pieces? (Hint: Think in powers of 2.)
