Module 8: The Cosmos in Motion

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Objectives/Key Points

1. Differentiate between classical motions across space (peculiar velocities) and cosmological motions with space (cosmic flow velocities). By analogy, distinguish Doppler redshifts from cosmological redshifts.
2. Interpret distance-velocity relations in terms of universe models. Link the Hubble Law to the expanding universe and the Big Bang.
3. Differentiate the real Big Bang from a standard explosion. Explain how the universe can have no center and no edge.
4. Enrichment: Estimate the time since the Big Bang (age of the Universe). Note that the Hubble constant (the slope for the real Universe) is 1/age.
5. Enrichment: Examine data for an accelerating Universe, determine what it implies, and discuss recent research on dark energy.

Unit Home

After Waves and Newton's Laws.

Prerequisites

Students should have completed modules 1-7 or equivalent material introducing the idea of galaxies, the finite speed of light, Doppler shifts, and Einstein's concept of spacetime.

Time: 60 min (main lesson can be split at either of two check-in points)

Materials

balloons (make sure they are easy to blow up)
small stickers to represent galaxies (or students can draw galaxies on balloons with pen/marker)
worksheet

Sticking Points

1. Students have trouble mentally "subtracting out" the overall average motion and seeing the scatter around the line as the local orbital motion.

Warm-Up (5 min.)

[Mandatory: need reminder of Doppler shift.] Ask the students: "What is a Doppler shift? If two galaxies are orbiting each other, when will the Doppler shifts be maximal: (a) when their orbital plane is in the plane of the sky (b) when their orbital plane is edge on?"

In discussing the correct answer to the warm-up (choice b), have everyone use their hands to trace the orbits in the air, and ask the students if the Doppler shift is always the same. (Correct answer is no, it reaches minimum and maximum as the two galaxies orbit each other.) The pictures at the bottom of page 1 of the worksheet tutorial can also be used as a visual aid.

Main Lesson (40 min.)

Students work in groups through attached worksheet tutorial, with teacher circulating to assist groups and periodically checking answers up to the check-in points. Check-in points 1 & 2 should occur after 15 minutes and then after another 15 minutes – if students fall behind, they can be given the answers up to that point and then move on with the next sections. [Note on check-in point 2: if class is going smoothly, teacher can take time to discuss the fact that cosmological redshifts can seem to imply velocities faster than the speed of light, but since those velocities represent motion with space rather than across space, laws of physics are not violated.] The final section should be allotted 10 minutes – it will generate a lot of discussion!

Answers:

1. toward us; negative; peculiar
2. zero because no net motion in a static universe; deviations due to peculiar velocities from galaxies orbiting each other, which are larger/smaller depending on random inclination to line of sight as well as strength of gravitational interaction
3. L: peculiar random, cosmic zero; R: peculiar random, cosmic rushing inward (collapse) ** Teacher can help students to this answer by having them draw a fit or trend line, then a box at a particular distance (analogous to #2).
4. in an infinite size, static universe, gravity would pull equally in every direction so the universe would not collapse
5. L: i R: ii
6. the Big Bang was an explosion like scenario ii, expanding everywhere with no center
7. L: Doppler shift – stretch across spacetime; R: cosmological redshift – stretch of spacetime itself
8. the 2D creature perceives no true center, but sees the expansion centered on him/herself; the 2D creature perceives no physical boundary/edge (2D spacetime expands into the 3rd dimension, which this creature cannot perceive) but may perceive a maximum light travel distance boundary; a 3D creature can see the center of the expansion (in the middle inside the balloon) and that the 2D spacetime is expanding its radius, thus creating an expanding spherical boundary/edge in 3D

Summarizer (5 min.)

Ask students to confer with a partner and answer on a sheet of paper they turn in:
"How does the Hubble Law show that the Universe is expanding? What is it expanding into?"

Enrichment

Not yet available.

Post-Lesson

None.

Worksheet for the Cosmos in Motion

I. Universes Governed by Gravity

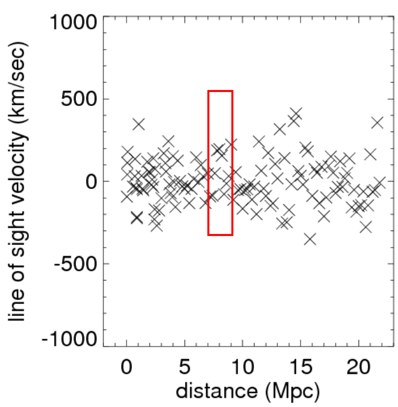
We've seen that galaxies have internal motion like rotation, and they can also move through space as they orbit each other, so even a "static" universe is always in motion ("static" here means space itself doesn't change). For the moment, let's ignore the internal motions of galaxies and focus on their overall velocities through space. We cannot measure their motions across the sky (which are too slow on human timescales), but only along the line of sight, using redshifts and blueshifts. Normally the portion of a galaxy's motion due to local orbits of galaxies around each other is called its "peculiar" motion and the rest of its motion is considered "cosmic flow."

1. We observe that our nearest large neighbor galaxy, Andromeda, has a significant blueshift.

What is its direction of motion along the line of sight? ___________________________________

What is the sign (positive or negative) of its measured velocity? __________________________

Is this a peculiar or a cosmic flow motion? ____



Consider all galaxies viewed at a particular distance from a particular galaxy in a static universe, for example those in the red box.

2. What is their average velocity according to this graph, and why should this be so?

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What causes the deviations from the average, and why are some bigger and some smaller? (Hint: think about how peculiar motions are measured for the systems shown below.)

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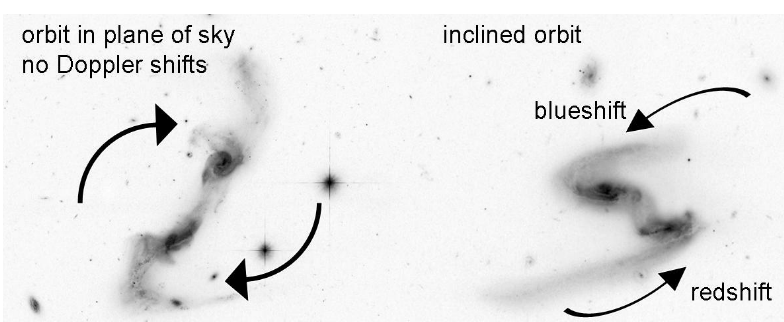
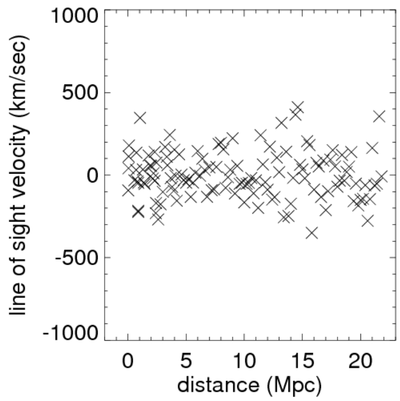
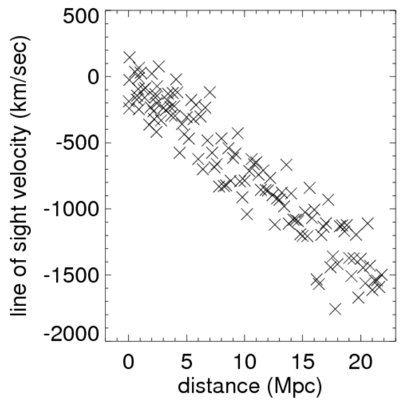


Now imagine two universes in which galaxies at different distances from us have line-of-sight velocities as shown in the plots below (each X is a galaxy).





3. For each universe, describe the typical peculiar and cosmic flow motions seen in the plots.

Left:____

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Right:____

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Newton realized gravity attracts everything in the Universe to everything else. Yet the Universe didn't seem to have collapsed into a single mass. He concluded we must live in an *infinite* static universe like the one at left.

4. How would the infinite size of such a universe prevent the situation at right? Hint: think about the combined pull of gravity in every direction.

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Check-In Point 1: Confirm your answers with your teacher and get materials for the next activity.

II. Universes Where Gravity Isn't the Whole Story

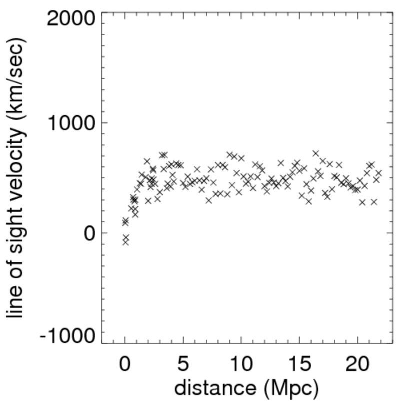
You've probably heard the term "Big Bang" used to describe the first moments of our (real!) Universe, in which most galaxies are, surprisingly, rushing *away* from us. Use a balloon and a pen to think about two ways this can happen. First, draw a lot of small galaxies on the surface of your balloon, spaced roughly 0.5 cm apart. Now blow up the balloon and watch how the galaxies move away from each other. Note that although your balloon galaxies look like they stretch, in the real Universe gravity would hold them together, so they would not expand.

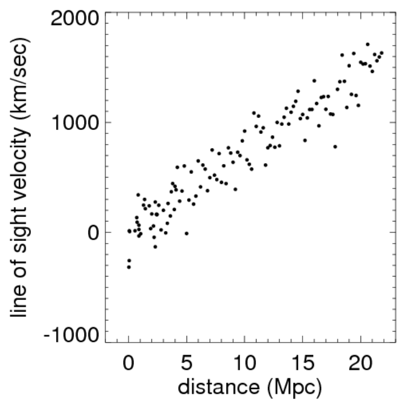
Think about two scenarios:

i. You can imagine the balloon as just one layer of a spherical universe, like an onion layer, in which all the galaxies are moving at the same speed away from the center of the balloon.

Another layer of galaxies, like another layer of onion, will expand away from the center just outside or inside the first layer at roughly the same speed. This is like a firecracker explosion.

ii. Alternatively, you can imagine the surface of the balloon as the entire universe that is known to a species of two-dimensional creatures who cannot perceive the third dimension. From their perspective, every galaxy is rushing away from every other galaxy. In 3D, this is like the raisins in a loaf of raisin bread expanding in the oven. Note that in the balloon/raisin-bread case galaxies are not really moving *across* space. Rather, space itself is expanding, causing all galaxies to move apart from each other.

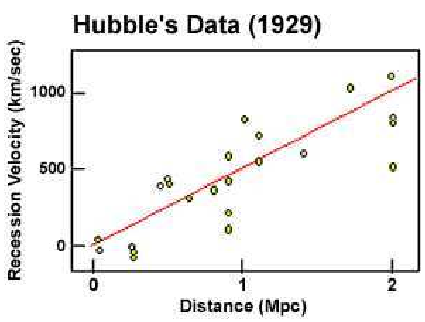




5. Study the two graphs above. Which one best describes each scenario above?

Left:____

Right:____



In the 1920s Edwin Hubble discovered that our Universe has a relation like the plot at right, which is referred to as the Hubble Law.

6. What does this discovery tell us about the nature of the Big Bang and the expansion of our Universe?

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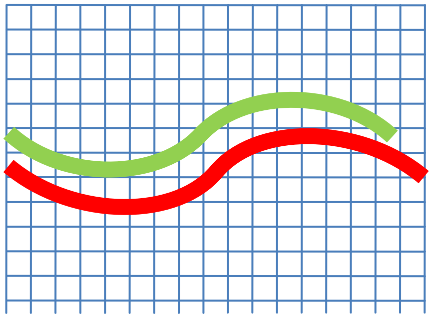
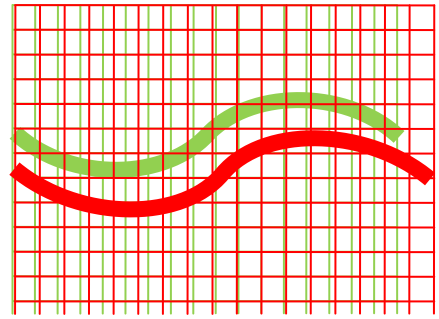
In the early 20^{th} century, Einstein predicted that if spacetime could curve and stretch like it does around black holes, all of spacetime in the entire Universe could expand or contract. When Hubble published his results, they were seen as proof that our Universe is expanding as envisioned by Einstein. By the way, this interpretation of Hubble's plot means that the redshifts of galaxies are primarily "cosmological" redshifts and not truly Doppler redshifts. A cosmological redshift occurs when a galaxy moves *with* spacetime as it expands rather than *across* spacetime grid lines.



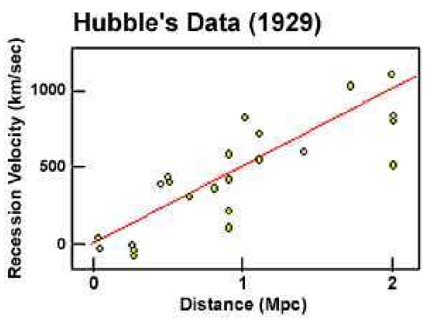
7. Which is which type of redshift in these cartoons? [Upper/lower waves are original/ observed.] Explain the difference.



Left:____

Right:____

Check-In Point 2: Confirm your answers with your teacher before going on.



Perhaps surprisingly, there is no significance to the (0,0) point on Hubble's graph. To prove this to yourself, go back to the balloon. Choose a galaxy to be your "home" and watch how all the galaxies on the balloon move relative to it as you blow up the balloon. Now change your home to a different galaxy, and watch how the galaxies move relative to this new home.

8. As a 2D balloon creature, where would you perceive the "center" to your universe?

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As a 2D balloon creature, would you perceive your universe expanding into a boundary (an "edge of the universe")?

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As a 3D creature "outside" the 2D creatures' universe, how do you perceive things differently?

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The meaninglessness of (0,0) proves our galaxy is not at the center of the universe. Most astronomers believe our universe is infinite, unlike the 2D balloon world. Whether finite or infinite, the Universe is expanding everywhere with no center and no 3D boundary. The *perceived* edge of the universe is just how far we can see given how far light has traveled since the Big Bang (i.e., in the age of the Universe).