Introduction to
Scale of the Universe

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Introduction

The James Webb Space Telescope (JWST) has begun its mission to shed "new light" on the scale (size) and history (time) of our Universe. To understand the results, we must remember that space and time are linked. In everyday life, we don't care that the far side of a room is seen at a different time than the table in front of us, because light travels across the room in billionths of a second. However, across astronomical distances, light can take billions of years to arrive from distant galaxies, so we see them in the past when they were billions of years younger. In addition, the Universe is expanding, so we see those objects ***where they were then***, not ***where they are now; the age they were then, not how old they are now.*** For example, the JWST has recorded a young galaxy whose light traveled 13.5 billion years to reach us. The Universe has expanded ~17x wider during that time and that galaxy would now be 35 billion light-years away.

Today, our Universe is expanding at a rate of ~7% every billion years. As light from distant galaxies journeys to us, it travels an ever-increasing distance, like walking against a moving walkway in an airport or swimming against a current. To illustrate that concept, a fun video (below) shows a slinky "walking" a treadmill—pretend that the slinky represents a light wave moving towards Earth. By itself, that number (7%) doesn't seem large, yet it causes large changes in distance between objects and even causes the wavelength of light emitted by stars in distant galaxies to lengthen from the visible to the non-visible ("infrared")—an effect called "redshift." (In other words, the slinky should stretch over time.) For this reason, the JWST is optimized to detect infrared light (i.e., high redshifts like Z~20*) to see the farthest back in space and time.

Clearly, our Universe is huge and hard to appreciate with numbers alone. We can better comprehend both its size, and how it is structured, when we compare its dimensions to more familiar objects. For example, ~100 Earths would fit side-by-side across the Sun and ~100 Suns would fit between Earth-Sun, yet ~30 million Suns would be needed to reach the next nearest star, Proxima Centauri. So, despite being large in an absolute sense, the space between stars is relatively empty in comparison. Similarly, a typical distance between galaxies (a few million light-years) is large but galaxies are also large, so only ~20 Milky Way galaxies would fit between us and our nearest neighbor galaxy, Andromeda. In that sense, the space between galaxies is more crowded than the distances between stars; therefore, galaxies can collide more easily, yet the stars that comprise them are too small and separated to collide in the process. As Philip Morrison demonstrates in the video below, our Universe shows periodic patterns of organization from relative emptiness to crowdedness caused by gravity pulling objects together over time.

*****z is used by astronomers as a measure of redshift or blueshift. A z>0 implies that the object is moving away from us, a redshift, and a z<0 implies that the object is moving toward us, a blueshift. The formula is: 1 + z = wavelength (observed spectral line) divided by wavelength (emitted spectral line; rest wavelength). So, a z = 1 implies that the observed wavelength is 2 times its rest wavelength and a z = 13 (GL-z13, for example) implies that the observed wavelength is 14 times its rest wavelength.

Scale Model of the Universe:
Creating a scale model is challenging. A timeline for the history of the Universe can be represented either as a one-page table or as a walk through time. If you want to "scale" the age of the Universe, 13.8 billion years, into one year, you can create a timeline where one second of time (scaled) equals 438 years in the age of the Universe, something that we can fairly easily picture in our minds. Likewise, if 1 millimeter represented 10,000 years, a walk through time would be 1.38 kilometers. A scale model for distance is much harder. Even within the Solar System, if the distance from the Sun to Neptune is scaled to 1000 meters, the Sun would be a 30-cm ball and the Earth would be 2.8 mm in diameter. How does that compare to the size of the Universe? 13.8 billion years is 4.4 x 10^{17} seconds (that is how I got 1 second = 438 years). Compare this to the distance to one of the farthest galaxies that have been observed by JWST, GL-z13. It took light 13.5 billion years to reach us from GL-z13 and it is now 33.2 billion light-years away! That comes out to 3.1 x 10^{26} meters, or 2.5 x 10^{19} times the diameter of the Earth (a lot of pony beads)! If the Universe were scaled to 1 kilometer, the Earth would be 1/3,000,000 the diameter of a hydrogen atom or 1/50 the diameter of a hydrogen nucleus (a proton).

On the next few pages, we attempt to create a scale model of the Universe in 11 steps, from the Earth-Moon distance to the distance of the farthest galaxy observed by JWST. This is an ideal model to have your girls/students assemble and present at a family science night.

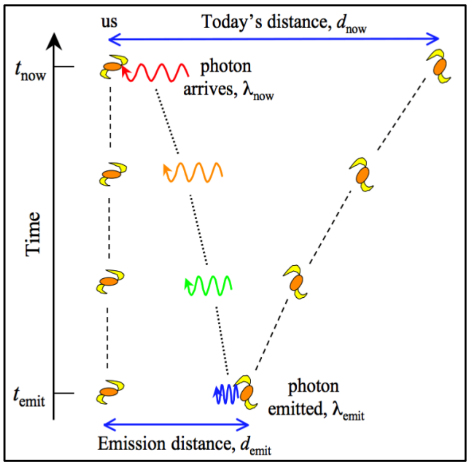
Supplemental Material:
Slinky on a treadmill video
https://www.youtube.com/watch?v=711bZ_pLusQ)

NIRCam and GSUSA Education and Outreach Web site "Light and Lookback Time"
https://lavinia.as.arizona.edu/~dmccarthy/GSUSA/light.html

An Atlas of the Universe
http://www.atlasoftheuniverse.com/

The original *Powers of Ten* video narrated by Philip Morrison
https://www.youtube.com/watch?v=0fKBhvDjuy0

"Distances in Cosmology" (from Max Planck Institute for Astrophysics)



https://wwwmpa.mpa-garching.mpg.de/~gamk/TUM_Lectures/Lecture3.pdf