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.

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*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 4.4×10^{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 3.1×10^{26} meters, or 2.5×10^{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"
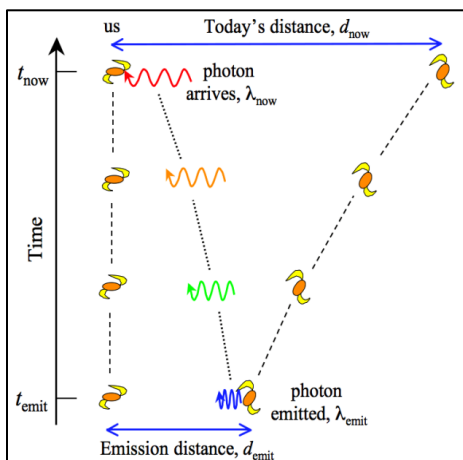   https://lavinia.as.arizona.edu/~dmccarthy/GSUSA/light.html

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)

us — Today's distance, d_{now}
t_{now} — photon arrives, λ_{now}
Time
t_{emit} — photon emitted, λ_{emit}
Emission distance, d_{emit}

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

SCALE OF THE UNIVERSE

Larry Lebofsky
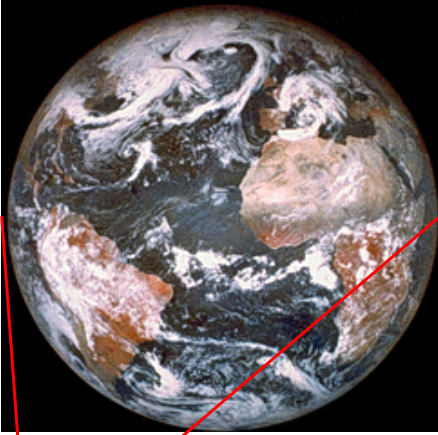
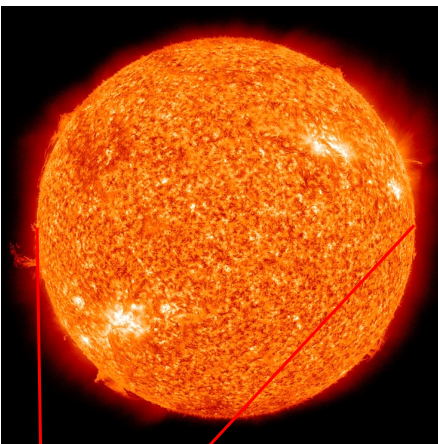Earth diameter = 12,756 km
3.7 times diameter of Moon

Moon diameter = 3,475 km

Earth-Moon (mean distance) = 384,400 km

30.1 times Earth diameter

Earth and Moon to scale

Earth and Moon to scale

Sun diameter = 1,391,000 km
109 times diameter of Earth
3.6 times Earth-Moon distance

Sun-Earth (mean distance) = 149,600,000 km

= 8.3 light-minutes
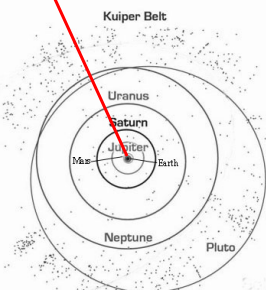= 1 Astronomical Unit (AU)

107.5 times Sun diameter

Sun to scale, Earth and Moon 10x

Solar System diameter (to Neptune's orbit)
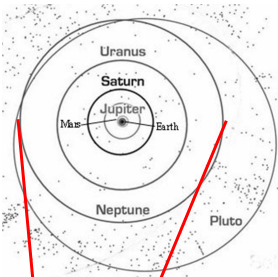= 9,000,000,000 km
= 60.1 AU
= 8.3 light-hours
= 0.00095 light-years
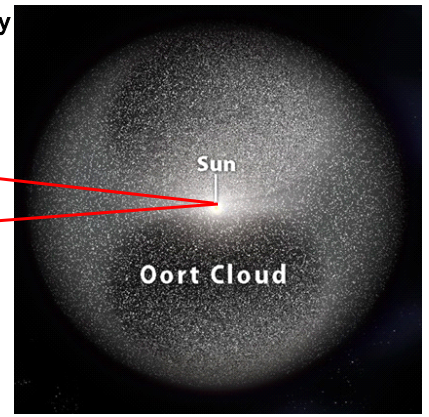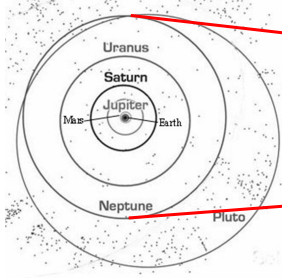
Inner Oort Cloud Torus, 2,000 to 20,000 AU;
   Outer Oort Cloud Sphere, 20,000 to 50,000+ AU
   (both theorized based on comet orbits)
    about 700 times the Solar System (to Neptune) diameter at the Inner/Outer boundary

Proxima Centauri b, c, d
   Star system (known) to d orbit
         = 1.5 AU

enlarged 20X
Star not visible

Distance to nearest star (other than the Sun),
   Proxima Centauri = 268,500 AU
                  = 4.25 light-years
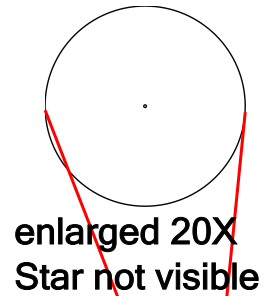
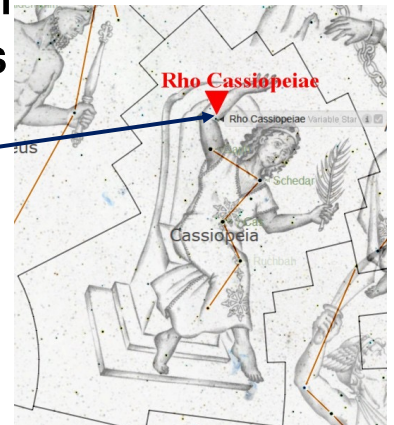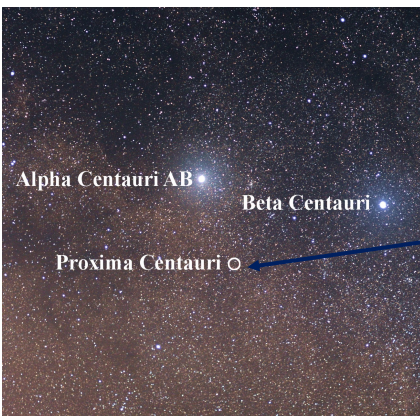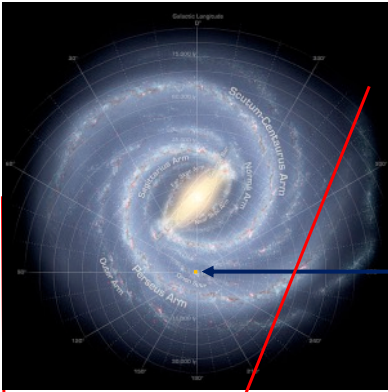about 8,800 times distance to Neptune
about 13 times distance to Oort Cloud

Solar System enlarged 100X
Sun enlarged 10,000 x

Star System enlarged 2,000X
Star enlarged 50,000 x

Distance to farthest star visible to the unaided eye,
   Rho Cassiopeiae, magnitude 4.1
               = 3,400 light-years

about 800 times distance to
Proxima Centauri

Alpha Centauri AB

Beta Centauri

Proxima Centauri

Rho Cassiopeiae

Rho Cassiopeiae Variable Star
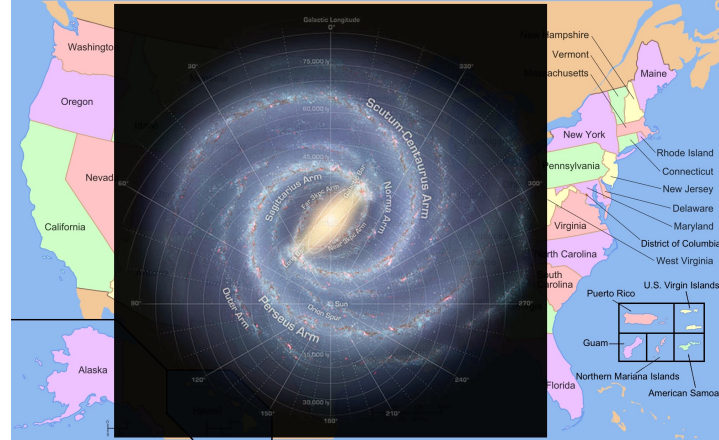
Schedar

Cassiopeia

Artist's sketch
of Milky Way

Milky Way Galaxy diameter = 120,000 light-years
about 125,000,000 times Solar System diameter
about 35 times the distance to Rho Cassiopeiae

Solar System
enlarged 1,000,000 times

If the Solar System were
the size of a quarter, this
would be the relative size
of the Milky Way Galaxy

# Milky Way Galaxy to Andromeda Galaxy,
distance = 2,500,000 light-years

20 times Milky Way diameter

Andromeda Galaxy
about 1.8 times diameter
of Milky Way Galaxy

# Virgo Supercluster of Galaxies,
diameter = 110,000,000 light-years

1,000 times Milky Way diameter
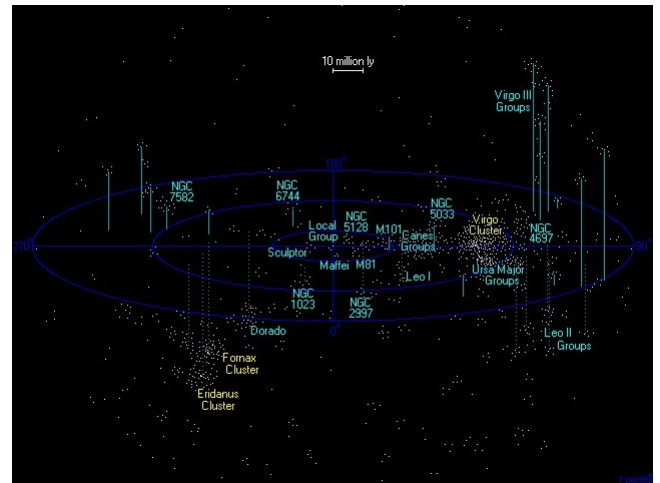
Milky Way enlarged
about 100x

Milky Way to Andromeda
enlarged about 10x

If the Milky Way Galaxy were the size of the Sun, the Virgo Supercluster would extend nearly
to the orbit of Jupiter and contain 100 to 150 galaxies the size of the Milky Way (some larger)
and thousands of dwarf galaxies

Milky Way
enlarged
about 1000x

Milky Way Galaxy to farthest observed galaxy =
about 13,500,000,000 light-years

more than 110,000 times Milky Way diameter
more than 120 times the diameter of the Virgo Supercluster
(the time for its light to reach us, its present distance is greater)

GL-z13
enlarged
about 10000x

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VATICAN OBSERVATORY

1 Earth-Moon Distance*: 30.1 Earths (30 blue pony beads and light blue string; pony bead = Earth's diameter)
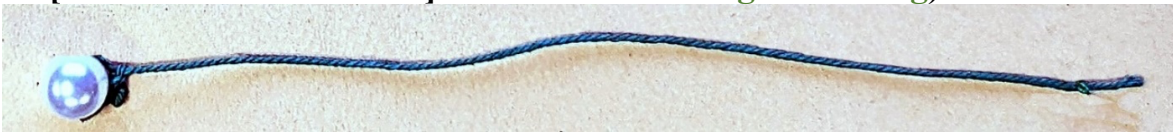
2 Earth Diameter vs. Sun Diameter: 109 Earths (109 blue pony beads and dark blue string; pony bead = Earth's diameter)

3 Sun-Earth Distance*: 107.5 Suns (108 yellow pony beads and yellow string; pony bead = Sun's diameter)

4 Earth Orbit to Neptune (Sun's planetary system): 30.1 AU (20-mm bead [true radius** = 10 mm] and 30.1-cm dark green string)

5 Neptune Orbit to Inner Oort Cloud/Outer Oort Cloud Boundary (theory): 20,000 AU [outer edge of Oort cloud 50,000 to 100,000 AU?] (6-mm bead [true radius = 2.7 mm] and 180-cm light green string)
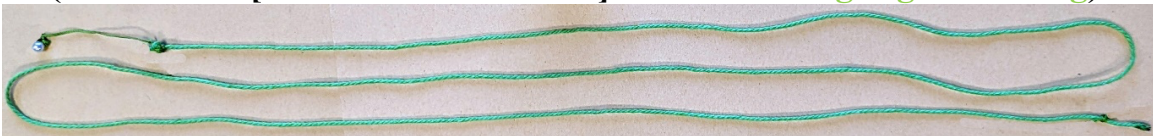
6 Oort Cloud to Proxima Centauri (Nearest Star): 268,500 AU [4.25 light-years] (4.3-cm golf ball [true radius = 2.15 cm] and 29-cm red string)
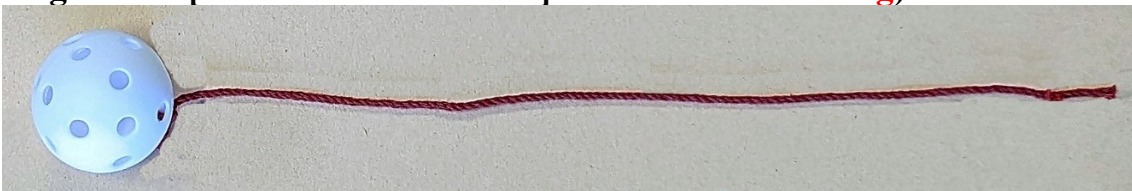
*Earth-Moon mean distance: 384,400 km, 1.3 light-seconds;
Sun-Earth distance: 149.6 million kilometers = 1 Astronomical Unit (AU) = 8.3 light- minutes
**The true radius is based on the actual measured diameter of the bead which is not always the same as what is on the package label.

7 Distance to Proxima Centauri vs. Distance to Rho Cassiopeiae (most distant star visible to naked eye): 4.25 light-years vs. 3,400 light-years (6-mm bead [true radius = 2.7 mm] and 216-cm white string)


8 Distance to Rho Cassiopeiae vs. Diameter of Milky Way Galaxy Disk: 3,400 light-years vs. 120,000 light-years (20-mm bead [true radius = 10 mm] and 35-cm black string)

9 Milky Way Galaxy Disk to Andromeda Galaxy Disk: Milky Way, 120,000 light-years in diameter and Andromeda, 220,000 light-years in diameter, 2,500,000 light-years apart (Milky Way, 10-mm bead and Andromeda, 18-mm bead [true diameter = 9.5 mm and 17.4 mm, respectively] and 19.8-cm orange string)

10 Distance to Andromeda vs. width of Virgo Supercluster (both Milky Way and Andromeda galaxies in it): 2,500,000 light-years vs. 110,000,000 light-years (18-mm bead [true radius = 17.4 mm] and 76.6-cm purple string)
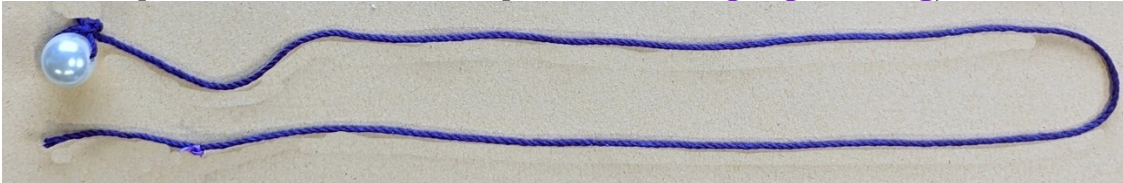
11 Width of Virgo Supercluster to HD 1 or GL-z13 (most distant galaxies): 110,000,000 light-years vs. 13,500,000,000 light-years (10-mm bead [9.5 mm true diameter] and 117-cm pink string)