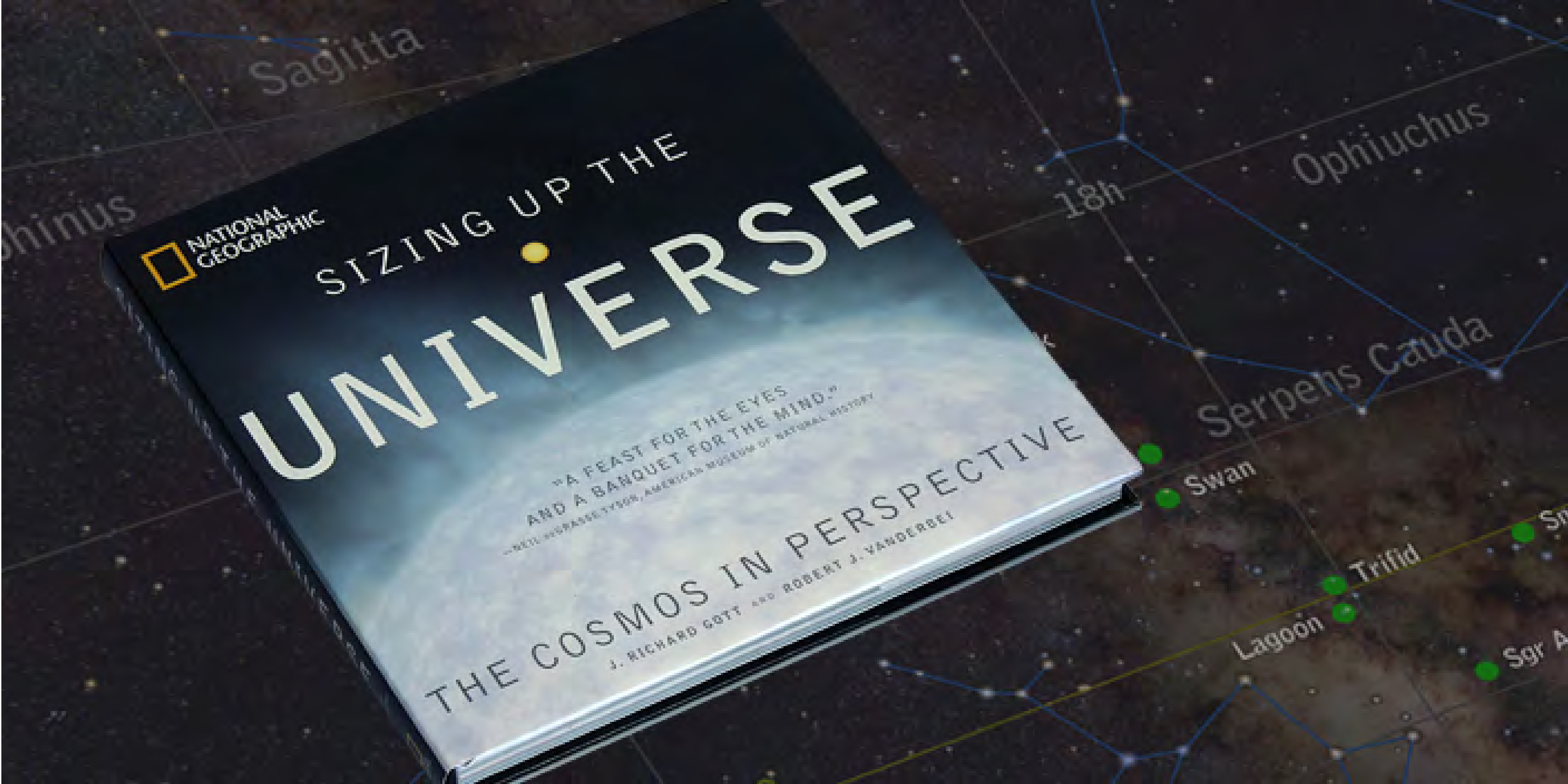
Sizing Up The Universe

Robert J. Vanderbei

September 6, 2012

S*T*A*R Astronomy
Lincroft NJ

http://www.sizinguptheuniverse.com


NATIONAL GEOGRAPHIC
SIZING UP THE
UNIVERSE
"A FEAST FOR THE EYES
AND A BANQUET FOR THE MIND."
—NEIL DEGRASSE TYSON, AMERICAN MUSEUM OF NATURAL HISTORY
THE COSMOS IN PERSPECTIVE
J. RICHARD GOTT AND ROBERT J. VANDERBEI
Sagitta
hinus
18h
Ophiuchus
Serpens Cauda
Swan
Trifid
Lagoon
Sgr A
Sn

As Jupiter's moon Io transits in front of Jupiter, it can be seen against the upper layer of Jupiter's dense clouds below.

CONTENTS

PREFACE BY J. RICHARD GOTT 12

INTRODUCTION 16

CHAPTER ONE
APPARENT SIZES 20

CHAPTER TWO
MAPPING THE SKY 44

CHAPTER THREE
DISTANCES 80

CHAPTER FOUR
MAP OF THE UNIVERSE 110

CHAPTER FIVE
SIZES IN THE SOLAR SYSTEM 136

CHAPTER SIX
TO INFINITY AND BEYOND 184

AFTERWORD BY ROBERT J. VANDERBEI 238

ILLUSTRATIONS CREDITS 242

INDEX 244

INTRODUCTION

HOW BIG ARE THINGS in the sky? It's a child's question, really, but one that has altered the course of civilization. When Aristarchus of Samos first figured out that the sun was bigger than Earth, in about 260 B.C., he correctly deduced that Earth must be orbiting the larger sun, rather than the sun circling tiny Earth. But people didn't believe him. They followed Aristotle's idea that Earth was at the center of the universe. It wasn't until Copernicus published the same idea in 1543 that the concept began to be taken seriously. If people had believed Aristarchus in the first place, science would have been pushed forward by more than 1,700 years. Where might our civilization and technology be by now if people had just listened?

One of the exciting things about astronomy is just *how big* those things in the sky really are. The sun is so big that a million Earths could fit inside. And yet there are stars much larger than the sun. The distances between the stars and between the galaxies are truly humbling. Our tiny Earth is just a speck in the vastness of space. It tends to put things into perspective.

In Chapter 1 we start by showing how big things *look* in the sky. The sun and the moon are the same apparent size in the sky—each about one-half degree across. As they set, you can cover each of them with your thumb held at arm's length. If you know how big something looks and how far away it is, you can figure out its real size. Multiplying an object's apparent size by its distance gives its actual size. Although the sun and the moon appear to be the same size in the sky, the sun is actually 400 times farther away, so its actual size is 400 times larger than the moon—a simple concept but an important one.

Astronomers typically learn how big an object looks by taking its picture through a telescope of known power. Then when we learn how far away it is, we can determine its actual size. Thus, we begin with side-by-side pictures of the sun and moon, showing how big they look. Then we show a series of ever more magnified views of objects through ever more powerful telescopes. As we continue our observing tour, we will show you how big things would look through the Hubble Space Telescope.

Then, in Chapters 2-4, we show where things are in the sky and how far away they are, keyed to discoveries by the ancient thinkers who were not as far off in their calculations as one might expect. Some of their methods are still in use today. And, in Chapter 4, with the conceptual framework firmly established, we offer a "map" of the universe, showing everything from satellites in Earth's orbit to distant stars and galaxies, all on one fold-out section almost 40 inches tall.

Once we know how big things *look*, and how *far away* they are, we can show the *actual sizes* of things in Chapters 5 and 6. Chapter 5 shows sizes of things in the solar system. Hurricane Katrina is compared with a centuries-old storm on Jupiter called the Great Red Spot. In Chapter 6 we start with an actual-size picture of Buzz Aldrin's footprint on the moon and end with the largest known object in the cosmos. If you are someone who likes to peek at the last page of a mystery novel to find out the answer, and you want to know about the real sizes of things, you can skip directly to Chapters 5 and 6.

Photograph of the Horsehead Nebula taken by Bob Vanderbei with his 10-inch-diameter reflecting telescope. Glowing gas in the background is obscured by dust to make the horse's head.

In cosmology, we are dealing with curved space-time, and there are several distance measures we might use. In most circumstances, we want to use a distance based on the look-back time. The universe is 13.7 billion years old. If we imagine galaxies having alarm clocks on them, each measuring the time elapsed since the big bang, a galaxy we see now with an alarm clock reading 12.7 billion years since the big bang would have a look-back time of 1 billion years. That's because light from it has been traveling through curved space for a billion years on its way to us. The distance derived from look-back time shows us where the galaxy was at the time we are seeing it—in the past. But by now it has moved farther away. How far away? We call that distance the co-moving distance.

We can measure a galaxy's look-back-time distance (how far away it is at the epoch when we see it) or its co-moving distance (how far away it has gotten to by now) by observing the redshift in its spectral lines and knowing the cosmological model. The redshift tells us how fast the galaxy is moving away from us because of the expansion of the universe. If we know the dynamic history of the universe, the galaxy's redshift can tell us its look-back-time distance or its co-moving distance today.

The Wilkinson Microwave Anisotropy Probe (WMAP) satellite has measured the cosmic microwave background in exquisite detail and combined these data with other data to produce an accurate cosmological model. If we take a snapshot of the universe at the present epoch, 13.7 billion years after the big bang, WMAP tells us that its geometry is approximately flat. That means we could make a good scale map of a slice of it extending out from Earth's Equator using a huge, flat sheet of paper. According to Einstein's equations of general relativity, the dynamic history of the universe depends on its energy content. The WMAP satellite data show the universe is currently composed of 4.6 percent normal matter; 0.01 percent thermal radiation left over from the big bang (cosmic microwave background radiation); 23 percent dark matter, made of unknown elementary particles, which cluster like the galaxies and provide the mass to bind clusters such as the Coma Cluster together; and 72 percent dark energy.

Dark energy is a quantum vacuum energy state, which gives the vacuum of empty space a constant energy density and a negative pressure. Since the negative pressure is uniform, it exerts no forces. In much the same way, the air pressure in the room where you are sitting is almost 15 pounds per square inch, but you don't notice it because it is nearly uniform.

The negative pressure produced by dark energy does have a gravitational effect, however, according to Einstein's theory of gravity—general relativity. Since it is a negative pressure (or suction), it exerts a negative gravitational effect, and since it operates in three directions (up-down, left-right, front-back), it has three times as large a gravitational impact as the positive gravitational effect of the energy supplied by the dark energy. Thus, dark energy produces an overall gravitational repulsion, causing the universe's expansion to be accelerating today.

Einstein first proposed this effect in 1917, calling it the cosmological constant. Adam Riess, Saul Perlmutter, Brian Schmidt, Bob Kirshner, Alex Filippenko, and their colleagues discovered it in 1997 when they carefully measured the expansion of the universe over time by measuring the distances to distant supernovae; they found that the universe's expansion is accelerating.

Vanderbei took a picture of M51 in May 2005. In June, a star in M51 exploded and became a supernova—so he took another picture.


2005


2011

Years ago, when I started astronomy, many young people were discovering it as a backyard hobby. You could see the wonders of the universe—from planets to galaxies—all from your backyard. But our increasingly bright city lights over the years have brightened the sky so much that the galaxies have faded from view. We call this phenomenon light pollution. To see anything but the brightest objects in the night sky you now have to go to a dark site. The backyard hobby became one where you needed to drive to a remote location and stay all night. As a result, it became a hobby for adults. Like skiing, it had cool equipment, but while better skis might make you only a slightly better skier, a bigger and more expensive telescope would allow you to see a lot more. So Vanderbei caught the wave of adults becoming amateur astronomers.

Vanderbei is also part of the making of a new hobby—astrophotography. The new digital cameras available today allow you to take long-exposure photographs and use filters to overcome light pollution. You can take photographs from your backyard that will show things you would never be able to see through the telescope. The galaxies are back! For the moon and planets, a simple webcam attached to a small telescope allows you to take videos of these objects and select the best frames (those least affected by atmospheric distortion) for producing your picture.

Vanderbei has taken all of his photographs from his backyard in light-polluted New Jersey. He took a beautiful picture of the lunar crater Plato using only a 3.5-inch-diameter telescope and a simple webcam. His photographs appear throughout this book along with the best NASA photographs, as noted in the illustrations credits.

I have had the good fortune to travel around the world and see a number of its wonders, from the Taj Mahal to the Great Pyramid, and one of my joys was taking pictures along the way. But Vanderbei can take pictures of the wonders of the universe without ever leaving home. Vanderbei sets his telescope tracking a galaxy for an hour exposure and goes inside to watch television while it takes the picture. He can then download the picture to his computer and sharpen its image with software or combine it with other exposures to make a brighter image.

Astronomy has become a computer hobby. Young people today are experts at downloading digital photographs onto their computers. We hope that this book, by showing what can be done from the backyard with a digital camera and a telescope, will help lure young astronomers back, for it has once again become a backyard hobby. With that in mind, Vanderbei has written an afterword with some of his thoughts on astrophotography, hoping that some of our readers will be encouraged to size up the universe for themselves.

Whether this is your first book on astronomy or you have read many, there should be some surprises here. (For example, I myself was surprised to see just how big the Ring Nebula is—I had thought it was about 25 times smaller.) Whether you are 16 years old or 60, whether you enjoy looking through a telescope or are just a curious armchair astronomer who has heard of black holes and wants to know more, this book was made for you. I hope you will find learning about sizes in the universe just as fascinating as I did once, so long ago.

—J. Richard Gott

Vanderbei captured this photo of the Eagle Nebula (opposite) with a 10-inch-diameter telescope from his backyard. For comparison, the famous Hubble Space Telescope picture of the Eagle Nebula is shown inset. The Hubble picture has more detail, having been taken from the vacuum of space, but the colors in Vanderbei's photograph are more realistic—the nebula is actually red.

APPARENT SIZES

CHAPTER 1

JUXTAPOSITIONS

IN THE NEXT FEW PAGES, we show a sequence of ever more magnified views of the sky with the moon arbitrarily placed as a template in each picture for comparison. In this way we can illustrate the angular sizes of various objects as seen from Earth. We begin by showing you how the moon would look if it ever wandered up near the Big Dipper, which it doesn't. The moon is just one-half degree in diameter. In contrast, the pointer stars of the Big Dipper (the two rightmost stars in this picture) are five degrees apart, or about ten lunar diameters.

FYI The fraction of the celestial sphere taken up by the Big Dipper is almost as large as the fraction of the surface of Earth taken up by the continental United States.

The apparent sizes of objects in the sky are measured by the angles they span in our field of view. A full circle spans 360 degrees. The horizon is a full circle on the celestial sphere, so a complete panorama around the horizon spans 360 degrees. You have to turn in a complete circle to view the entire horizon.

It was the ancient Babylonians who first divided the circle into 360 degrees. Since the sun has an angular size of half a degree (that's 1/720th of a full circle), it takes up just 1/720th of the horizon when it sets. Each day, the sun moves about one degree in the sky relative to the stars. As Earth circles the sun each year, the sun appears to circle the sphere of stars once a year. While a year is actually about 365.25 days, the Babylonians chose to divide the circle into 360 degrees because it is conveniently divisible by many numbers. Their definition of the degree stuck.

The moon may look large when seen setting against distant houses and trees along the horizon, but at arm's length, your thumb will still completely cover it. Half a degree is not very large. A typical digital camera in snapshot mode without zoom has an angular field of view of about 45 degrees. That means that it takes about eight pictures to stitch together a complete 360-degree panorama of the horizon. At a half degree wide, the moon takes up only 1/90th of the width of a typical digital camera field of view. That's why the moon may appear surprisingly small in your snapshots.

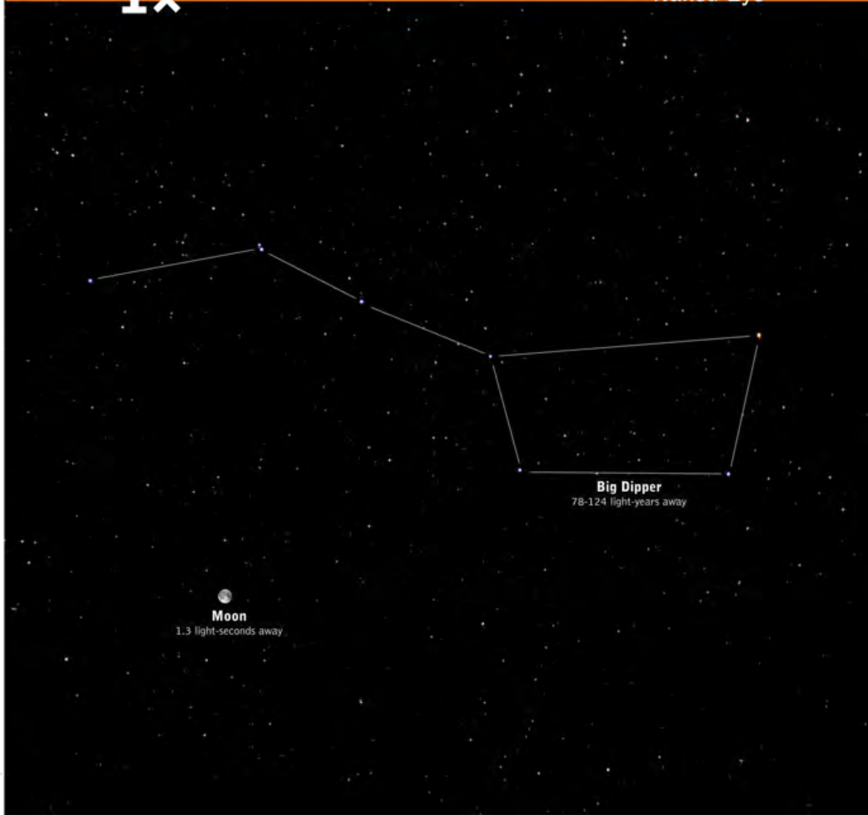
The moon is the astronomical object closest to Earth. Astronomers measure distances by how long it takes light, traveling at 300,000 kilometers (or 186,000 miles) per second, to cross those distances. The distance to the moon is 1.3 light-seconds.

When Apollo astronauts on the moon talked to President Richard M. Nixon, you could hear 2.6-second delays in the conversation. That is, it took the radio signals carrying Nixon's voice 1.3 seconds to travel to the moon and 1.3 seconds for the astronauts' replies to get back.

The stars in the Big Dipper are much, much farther away. Their distances range from 78 light-years to 124 light-years. That means that we are seeing these stars not as they appear today, but rather as they appeared 78 to 124 years ago.

The illustration opposite shows how the moon would look if it ever wandered up near the Big Dipper (which it doesn't). Viewed from a reading distance of about 17 inches, the angular scale is that of a normal naked-eye view from a dark site. The magnification is 1×, in other words, one times the magnification you see with the naked eye.

1× Naked Eye



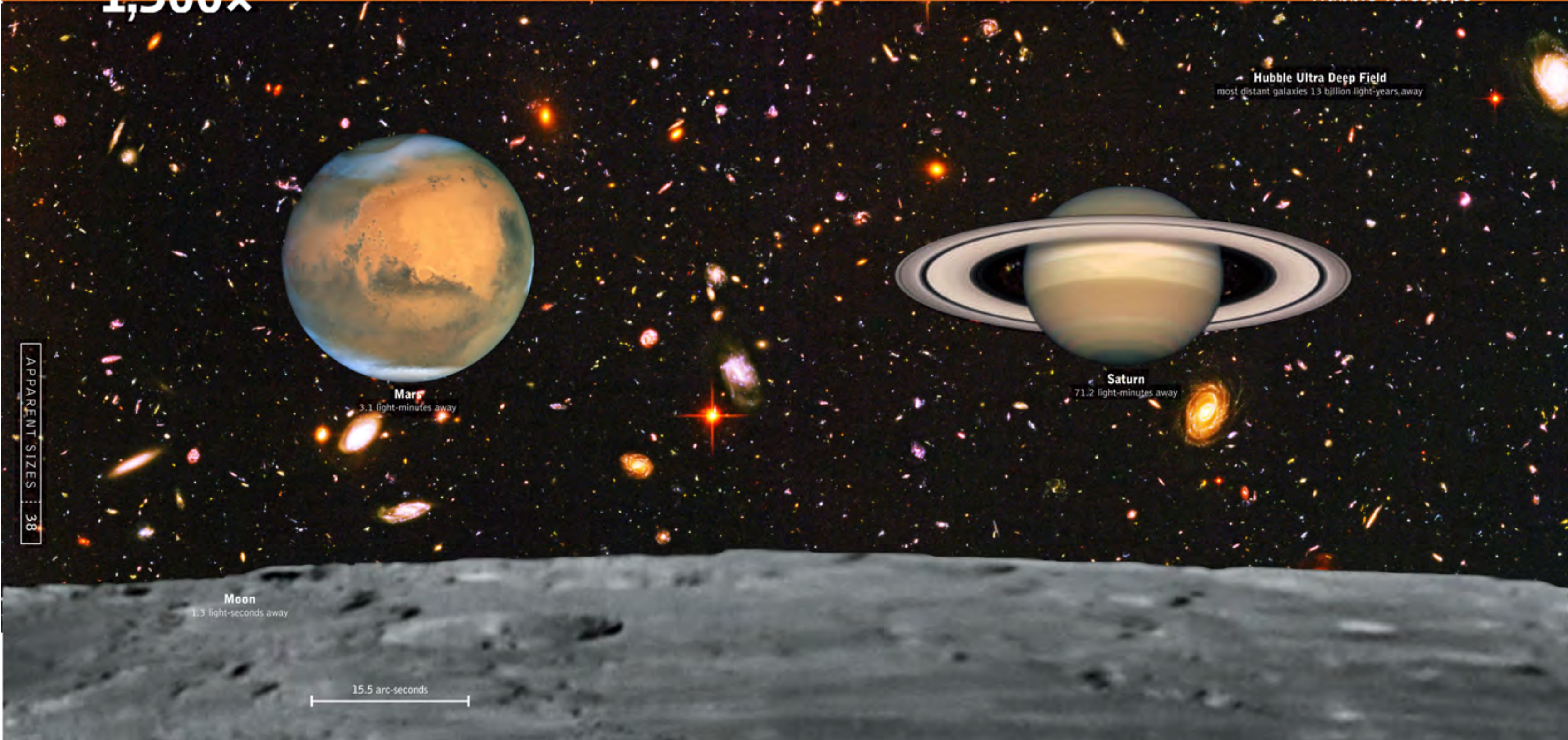
March 19, 2011

December 19, 2010


Andromeda Galaxy
2.5 million light-years away
Moon
1.3 light-seconds away
17 arc-minutes

1,500×

Hubble Telescope



Aldrin's Footprint

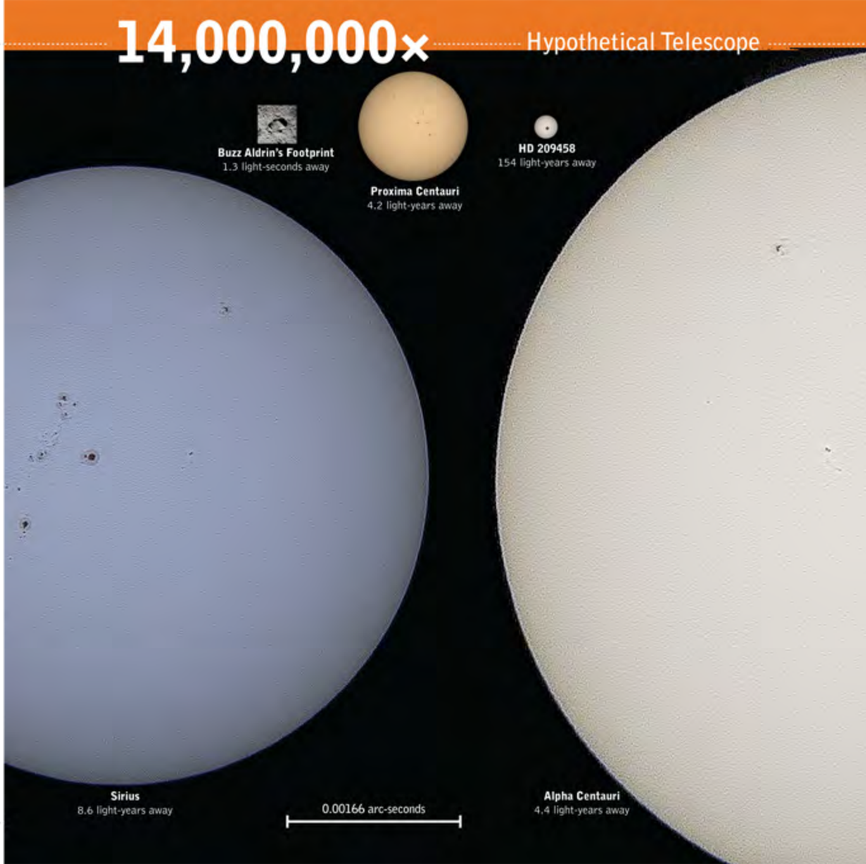
FOR OBJECTS OF EVEN SMALLER angular size, we show an even more magnified view. Alpha Centauri can be seen peeking in at the side. Proxima Centauri, its companion, and the closest star to Earth, is also shown. It is a red dwarf star. The star HD 209458 is a star similar to our sun but considerably farther away than Alpha Centauri. It has a Jupiter-like planet that transits in front of it, which we show in the illustration opposite. Astronomers measured that planet's size by observing how much the luminosity of the star was dimmed as the planet passed in front of it.

FYI A telescope with a magnification of 14,000,000× would be able to give you as good a view of a quarter from a distance of 4,000 miles as you get from holding it in your hand.

Finally, we can see Buzz Aldrin's footprint on the moon. It should still be there to observe. If we could get above the perturbing effects of Earth's atmosphere and if we had a telescope about 40 kilometers (25 miles) wide, we could see it this well.

We have now had a look at the entire sky. One way to put it all in perspective is to think of the celestial sphere as it might be mapped onto or overlaid on a globe of Earth. In this projection, the band of light we call the Milky Way would encircle it, tracing a circumference of some 40,000 kilometers (25,000 miles). The Big Dipper would be almost as large as the continental United States. The image of the Andromeda galaxy would be about the size of New Jersey. The images of the sun and moon would each be 56 kilometers (35 miles) across, about the size of a large metropolitan city. Jupiter's image would be seven-eighths of a mile across. Alpha Centauri's image would be only 25 centimeters (10 inches) across, and Proxima Centauri's image would be 3.0 centimeters (1.2 inches) across.

Now that we understand the apparent sizes of objects in the universe as seen from Earth, we are on a better footing to discover their actual sizes, which we will come to in Chapters 5 and 6. But first, in the following chapter, we will show how and where one can find these objects in the night sky.

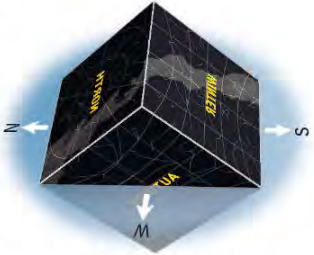


With 14,000,000-power magnification provided by a hypothetical supertelescope, we would be able to see dramatic views of nearby stars as well as the footprint Buzz Aldrin left behind on the moon.

MAPPING THE SKY

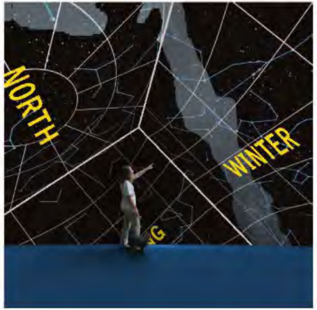
CHAPTER 2

What's Above the Horizon?

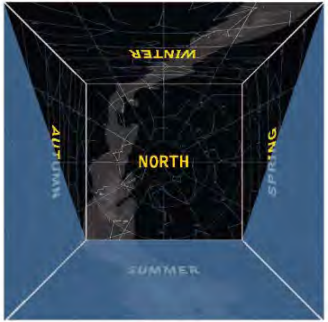


HALF THE CELESTIAL CUBE is always above the horizon. If you are at mid-northern latitudes (approximately 45° north) and you go out at midnight on December 21, here is what you will see: Toward the north you will see the north circumpolar stars. The north celestial pole with Polaris, the North Star, will be about 45° above the northern horizon. The north circumpolar stars will extend from the northern horizon to the zenith (overhead). The winter stars will extend from the southern horizon to the zenith. The bottom of the winter star chart will sit on the southern horizon. The celestial cube will hang over you like a pup tent (below, and right). On the next page, in the top-left perspective drawing looking into the cube, as in the big diagram on the previous page, the part of the sky seen in winter at midnight is the black area enclosed in the trapezoid. Areas below the horizon are blue. The north and winter stars can be seen, as can half of the autumn and spring stars. The four sides of the trapezoid represent the northern, western, southern, and eastern horizons, clockwise from bottom.

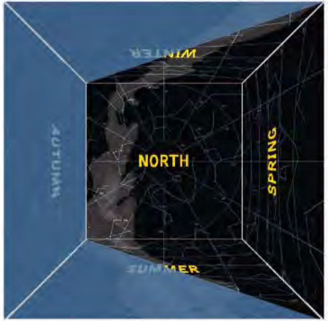
Similar effects occur in the other seasons as indicated opposite. The visible part of the sky rotates during the year. March 21 at midnight shows the north and spring stars, June 21 at midnight shows the north and summer stars. September 21 at midnight shows the north and autumn stars. The north circumpolar stars are always visible bordering the northern horizon.



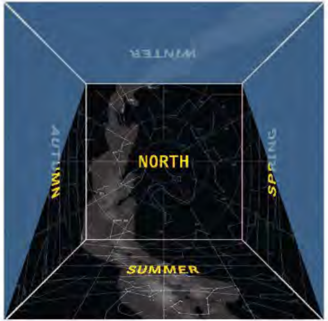
A celestial cube oriented for winter observing from mid-northern latitudes (left) hangs like a pup tent over the observer, who is inside the tent on the ground at the center of it looking up. Half of the cube is "below the horizon" and so not visible. Black regions (opposite) represent parts of the celestial cube visible at different times of the year from 45° north latitude on Earth. The blue areas are below the horizon. In each case, as on the previous page, the perspective view is looking into the cube.



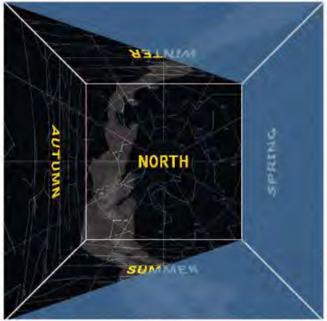
Winter



Spring



Summer



Autumn

Summer

AT MIDNIGHT ON JUNE 21 from mid-northern latitudes these stars are visible above the southern horizon. The **ECLIPTIC** is the yellow line passing through **SAGITTARIUS** and **SCORPIUS**. **THE MILKY WAY** is prominent in the summer. **THE RING NEBULA**, the double star **ALBIREO**, and the **DUMBBELL NEBULA** are great objects to view with small telescopes.

ALBIREO: A beautiful binary star, one star orange, the other blue.
19h30.7m, +27°58′

ALTAIR: Visual magnitude 0.8. Period of rotation is 6.5 hours. Diameter at its equator is 14 percent larger than its pole-to-pole diameter.
19h50.8m, +08°52′ See pp. 26, 209

ANTARES: Visual magnitude 1.1. A class M supergiant, about 800 times the diameter of our sun.
16h29.4m, -26°26′ See pp. 27, 41, 209

COAT HANGER: An asterism (random superposition of stars) reminiscent of a coat hanger.
Brocchi's Cluster or Collinder 399
19h25.4m, +20°11′

CRESCENT: An emission nebula.
NGC 6888
20h12.0m, +38°21′ See p. 221

DUMBBELL: A bright planetary nebula about 1,360 light-years away.
M27
20h59.6m, +22°43′ See pp. 57, 132, 216, 219

EAGLE: Open cluster of stars in a diffuse emission nebula, about 7,000 light-years away.
M16
18h18.8m, -13°49′ See pp. 15, 216, 219

HERCULES CLUSTER: Best globular cluster in northern hemisphere, about 25,000 light-years away.
M13
16h41.7m, +36°28′ See pp. 216, 218, 220

LAGOON: A giant, bright interstellar cloud, emission nebula, and star cluster.
M8
18h03.8m, -24°23′

M5: Globular cluster. Distance is 24,500 light-years. Very old cluster with age of 13 billion years.
15h19.0m, +02°05′

RHO OPHIUCHI: Triple star embedded in a large blue reflection nebula.
IC 4604
16h25.6m, -23°28′

RING: One of the brightest planetary nebulae visible from the northern hemisphere.
M57
18h53.6m, +33°02′ See pp. 216, 222

SEYFERT'S SEXTET: Misnumbered group of four foreground galaxies and one background galaxy.
NGC 6027
15h59.2m, +20°45′

SGR A: Black hole in Sagittarius at the galactic center. Not directly observable.
17h45.7m, -29°00′

SWAN: An emission nebula glowing like a neon sign.
M17 or Omega Nebula
18h20.8m, -16°11′

SNAKE NEBULA: A dark S-shaped dust lane obscuring the dense star clouds of the Milky Way.
B72 or S Nebula
17h23.5m, -23°38′

TRIFID: A three-petaled emission nebula.
M20
18h02.3m, -23°02′

VEGA: The fifth brightest star in the night sky at visual magnitude 0.0. Distance from Earth is 25.3 light-years.
18h36.9m, +38°47′ See pp. 41, 55, 210, 214

VEIL NEBULA: A remnant from a supernova explosion 5,000 to 8,000 years ago. Entire loop spans 3°.
NGC 6992
20h57.1m, +31°13′ See p. 221

WILD DUCK CLUSTER: A rich and compact open cluster containing about 2,900 stars.
M11
18h51.1m, -06°16′

Map Key ⬬ Galaxy -●- Planetary Nebula ● Nebula (other than planetary) ⊕ Globular Cluster ● Open Cluster

DISTANCES

CHAPTER 3

Robert J. Vanderbei

The Earth Is Not Flat

An Analysis of a Sunset Photo

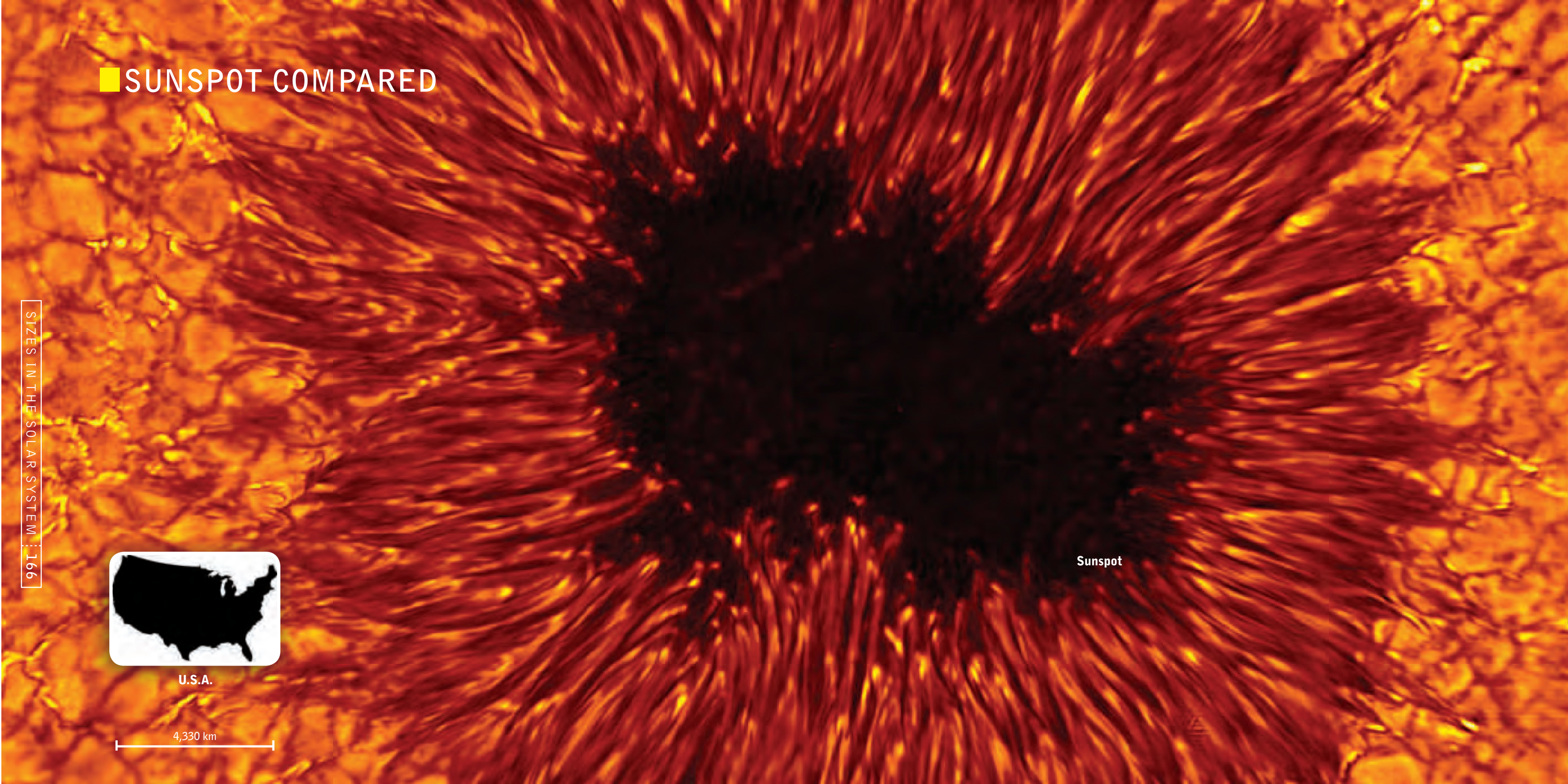
Can a photo of the sunset
over Lake Michigan reveal the
shape of our planet?


PRINCETON
P
EOS DIGITAL

SIZES IN THE SOLAR SYSTEM

CHAPTER 5

SUNSPOT COMPARED

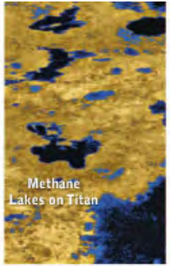


CANYONS COMPARED

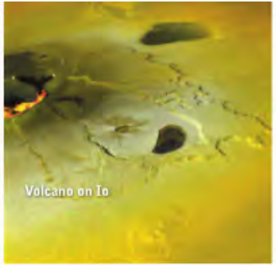
STORMS COMPARED

LAKES AND VOLCANOES COMPARED

Lake Michigan

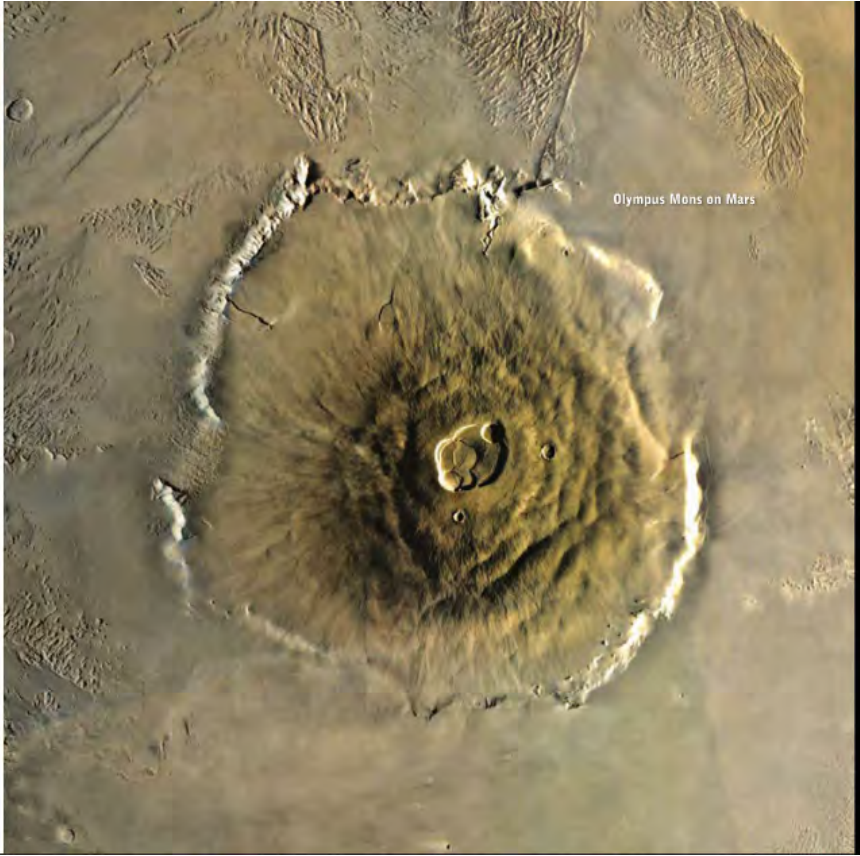


Methane Lakes on Titan



Volcano on Io

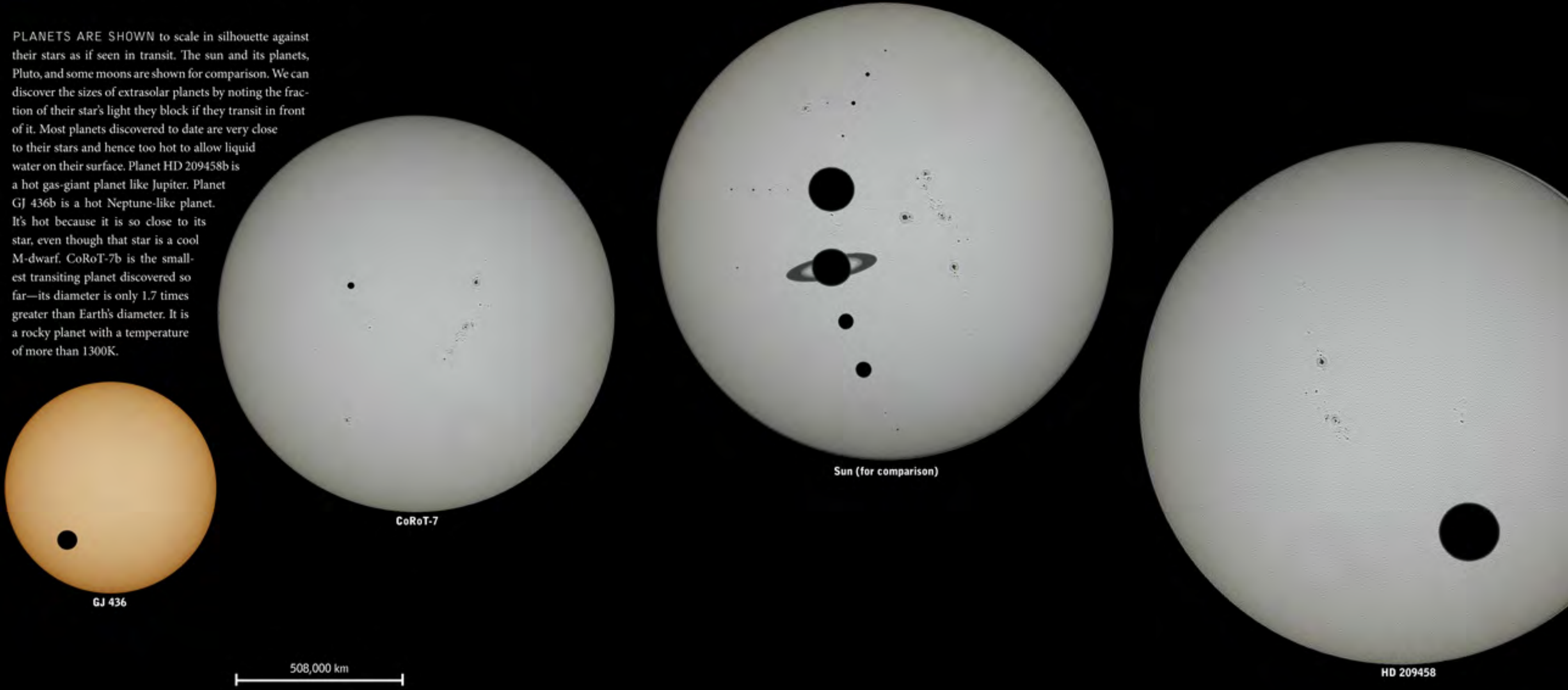
Hawaiian Islands



Olympus Mons on Mars

EXOPLANETS COMPARED

PLANETS ARE SHOWN to scale in silhouette against their stars as if seen in transit. The sun and its planets, Pluto, and some moons are shown for comparison. We can discover the sizes of extrasolar planets by noting the fraction of their star's light they block if they transit in front of it. Most planets discovered to date are very close to their stars and hence too hot to allow liquid water on their surface. Planet HD 209458b is a hot gas-giant planet like Jupiter. Planet GJ 436b is a hot Neptune-like planet. It's hot because it is so close to its star, even though that star is a cool M-dwarf. CoRoT-7b is the smallest transiting planet discovered so far—its diameter is only 1.7 times greater than Earth's diameter. It is a rocky planet with a temperature of more than 1300K.



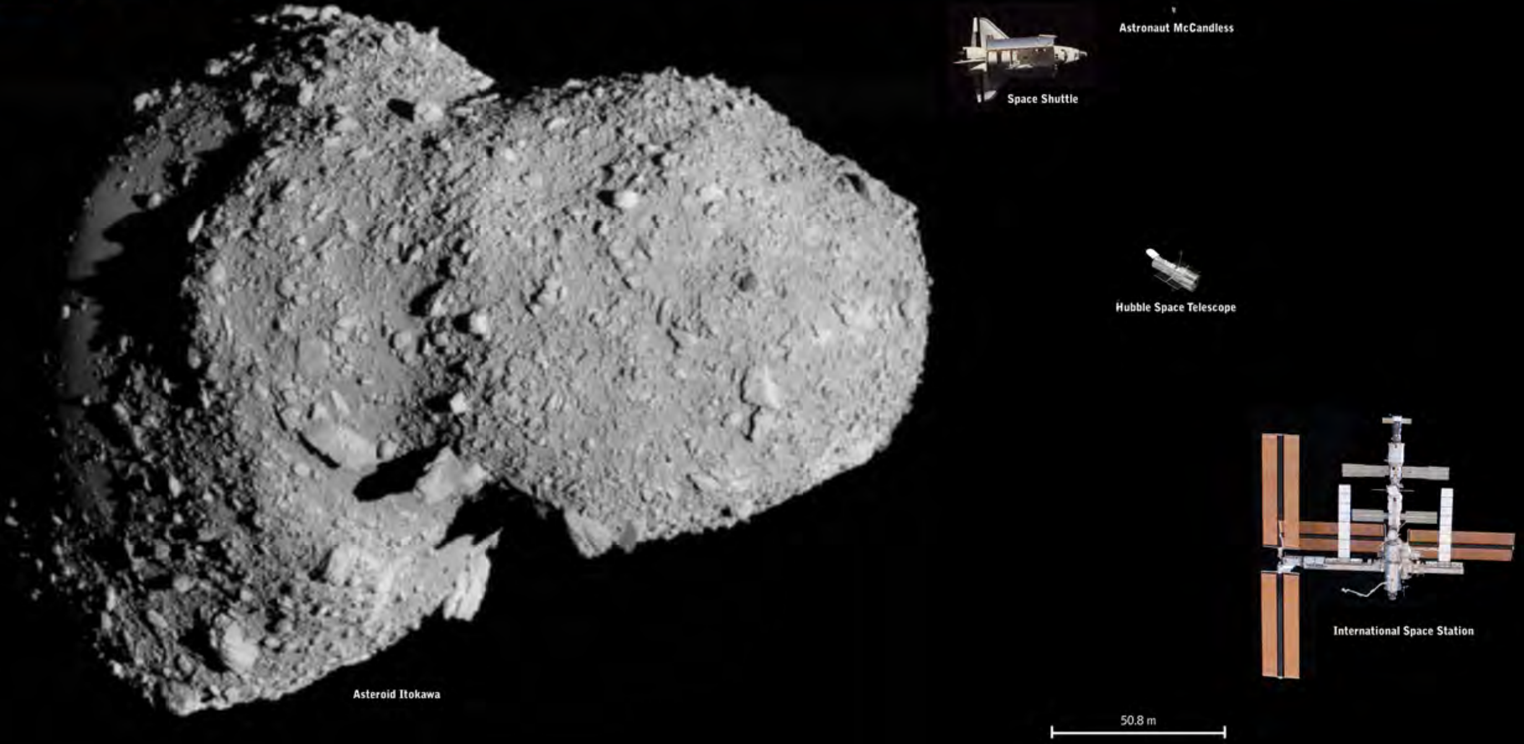
CHAPTER 6

TO INFINITY AND BEYOND

Buzz Aldrin's Footprint

1:1 Thousand

« Size of previous step

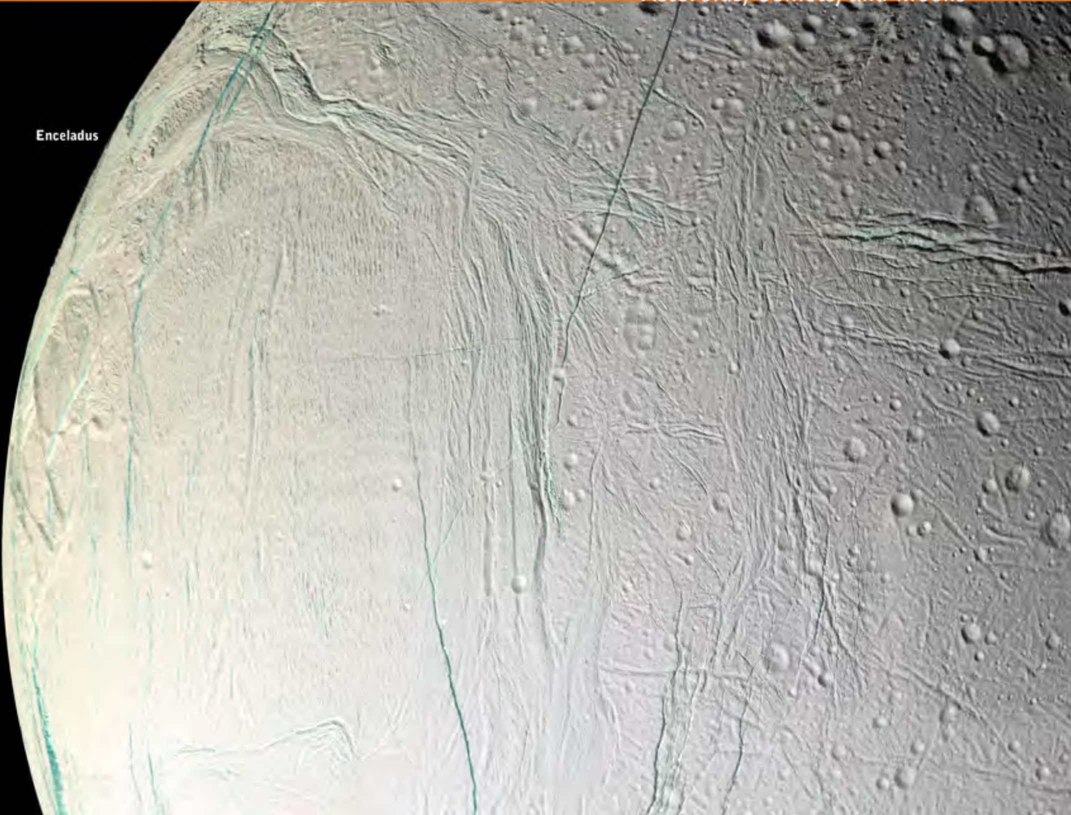


1:1 Million

« Size of previous step


Comet Wild 2


Halley's Comet


Enceladus


951 Gaspra


Phobos


Deimos


Dactyl


Eros


Ida

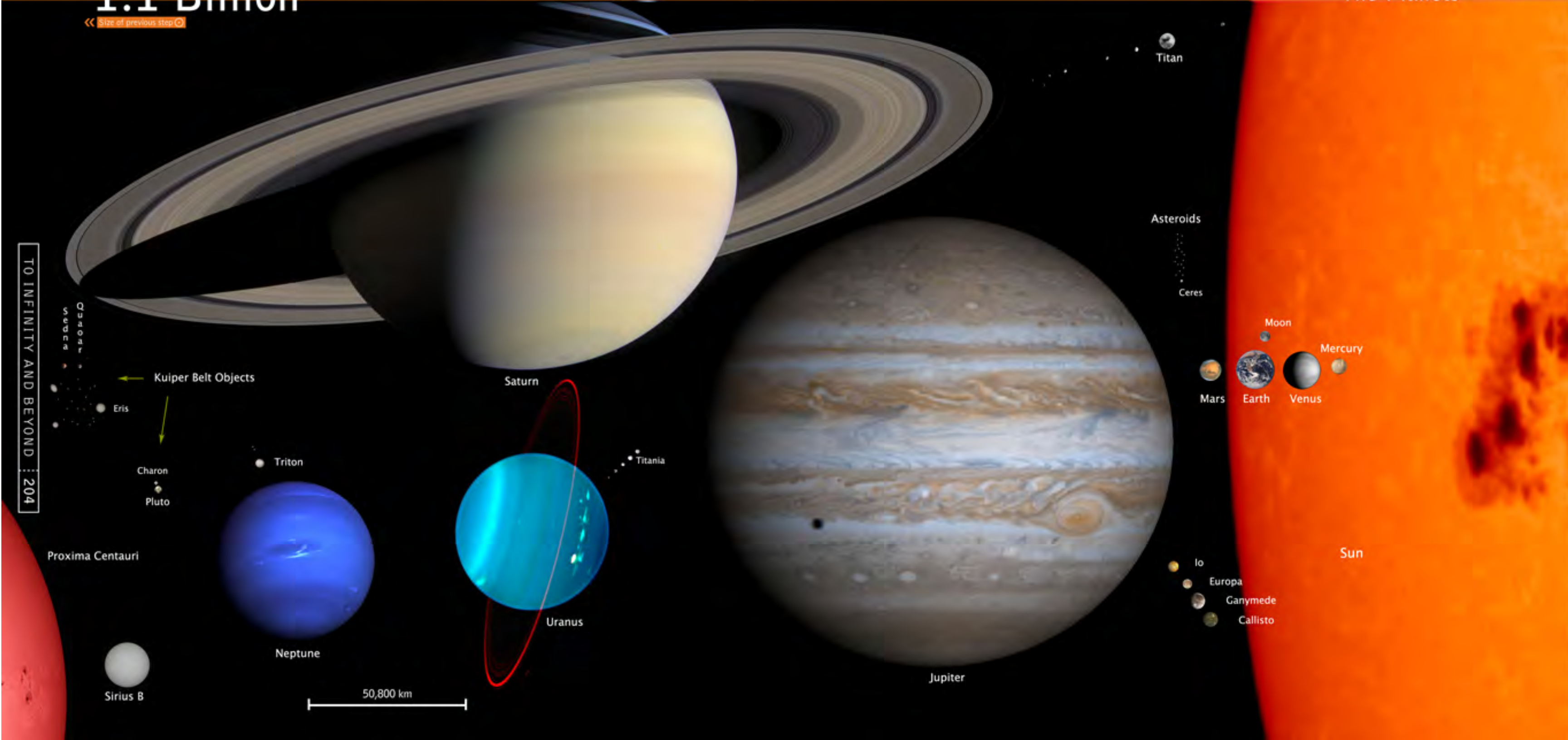

Cygnus X-1 Black Hole


Neutron Star

50.8 km

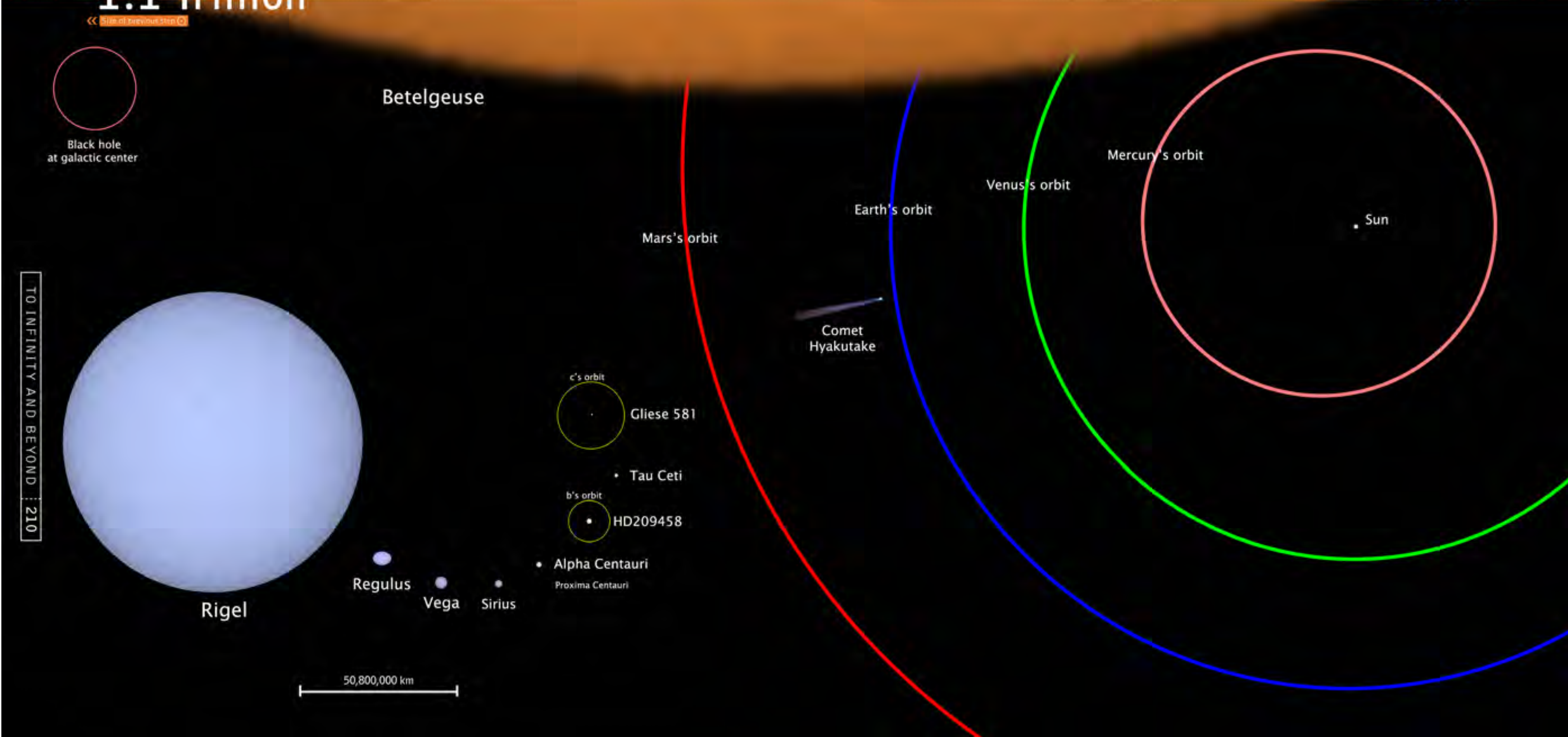
1:1 Billion

« Size of previous step



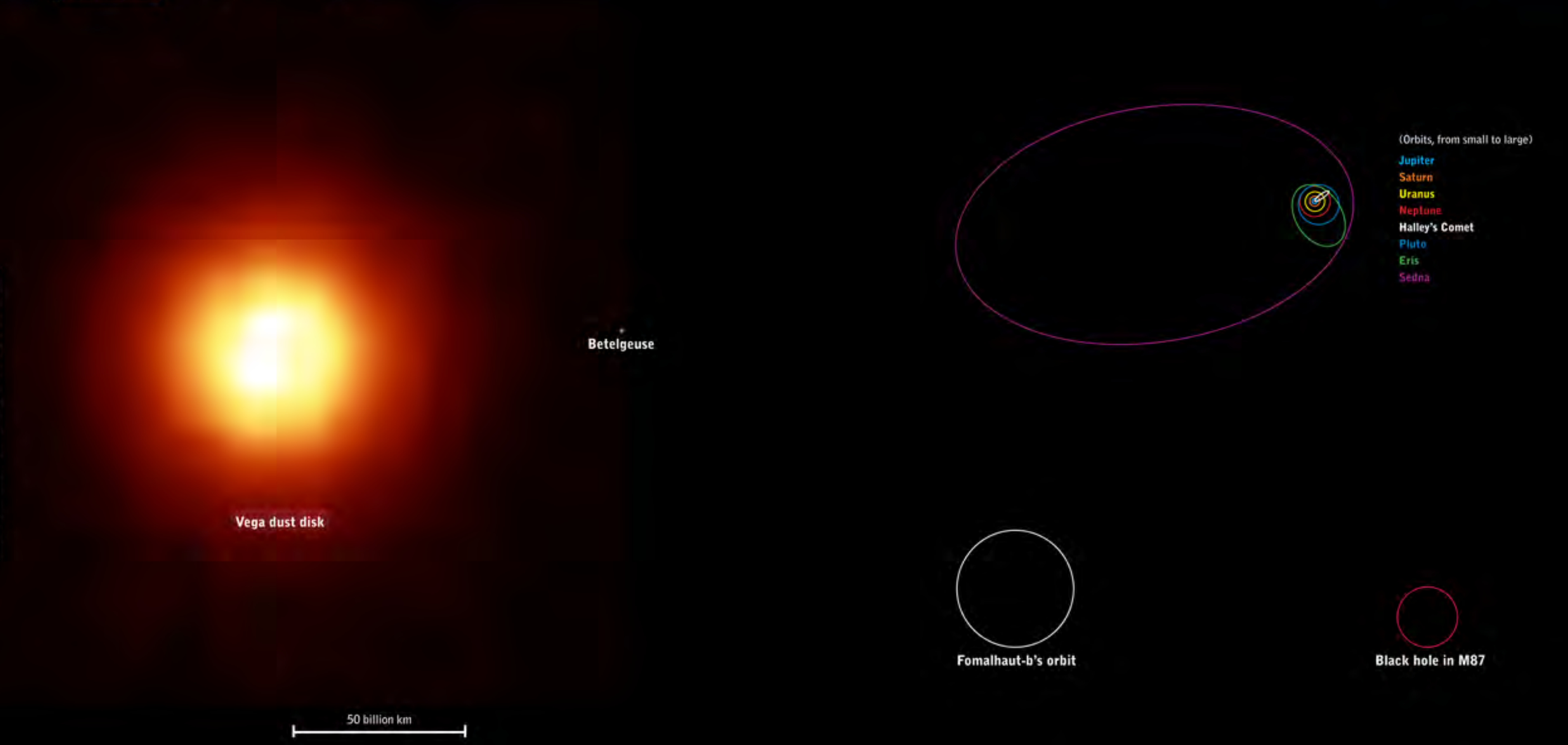
1:1 Trillion

« Size of previous step



1:1 Quadrillion

« Size of previous step ⊙



1:1 Quintillion

« Size of previous step

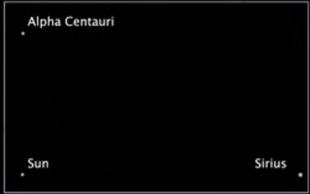

Dumbbell


SN 1987a

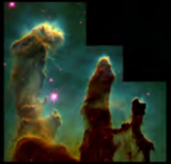

Ring


Eskimo


Horsehead




Orion


Eagle


Crab

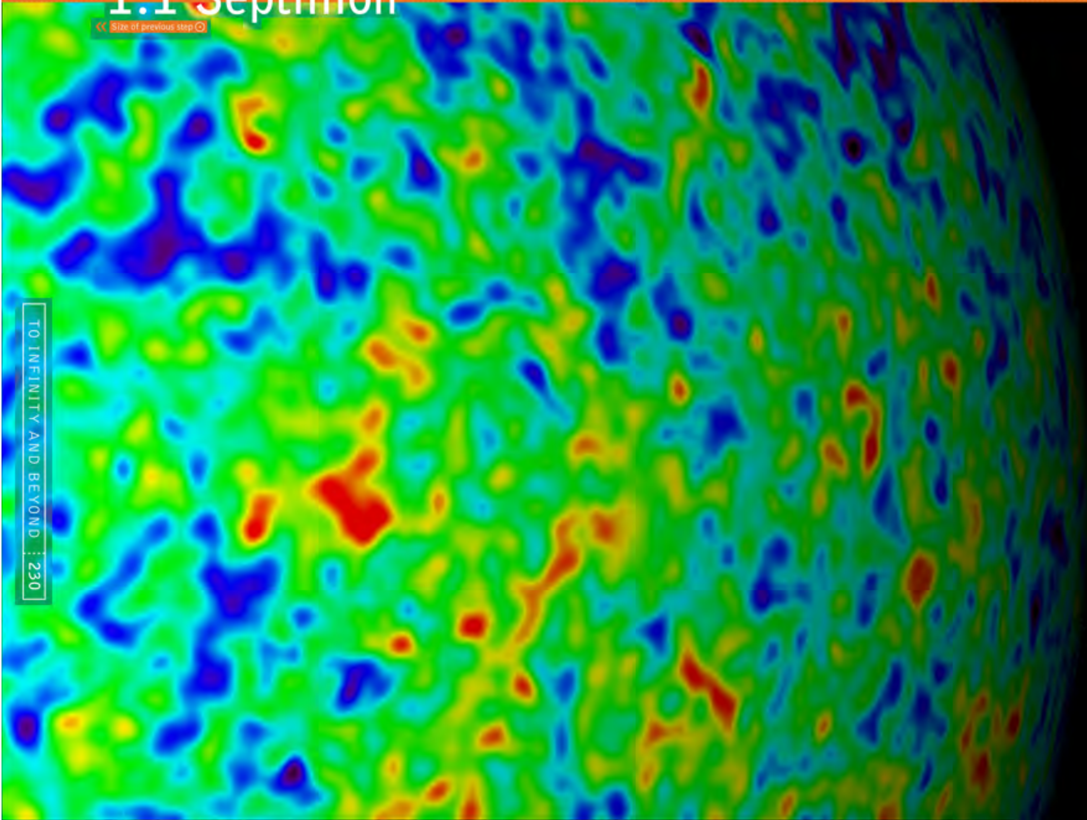
1:1 Sextillion

« Size of previous step

1:1 Septillion

Galaxy Clusters

« Size of previous step ⊙



Cosmic Microwave Background

Perseus Cluster

Coma Cluster

Local Group

Bullet Cluster

5.37 million ly

Step Ten

ONE LAST JUMP by a factor of a thousand, and we can see the extent of the entire visible universe—everything we can see. We are looking here at the equatorial slice of the Sloan Survey containing 126,594 galaxies and quasars. It is a cross-sectional slice of the universe extending outward from Earth's Equator. Earth is in the center of the picture. Galaxies are shown as green dots, and quasars as orange dots. The two large, blank regions are zones of avoidance, where our galaxy blocks the distant view. The scale shows the look-back-time distance in billions of light-years.

When we look out in space, because of the finite velocity of light, we look back in time. A galaxy five billion light-years away we see as it was five billion years ago. We can see out to a radius of just 13.7 billion light-years in any direction, because the universe began in a big bang explosion 13.7 billion years ago. The farthest thing we can see is the cosmic microwave background radiation left over after the big bang, which encircles the visible universe.

Earth is at the center of the visible universe. This does not mean that we are in a special location. If you look out from the top of the Empire State Building in New York City, the region you can see, out to the horizon, is circular and centered on the Empire State Building. Looking out from the top of a different building, you would see a different circular region—one centered on it. An observer in a distant galaxy would see a different visible region of the universe, one centered on his galaxy instead of ours. Most of the galaxies visible are less than 5 billion light-years away, while most of the quasars are between 5 and 12 billion light-years away. Near Earth, many voids and walls of galaxies are visible. These also appear in the Map of the Universe shown on pages 123-126.

The Sloan Great Wall (highlighted by a detailed, same-size inset that points to its location in the map) is the largest structure we have found in the universe so far. Its length stretches 1.37 billion light-years, one-tenth the radius of the visible universe.

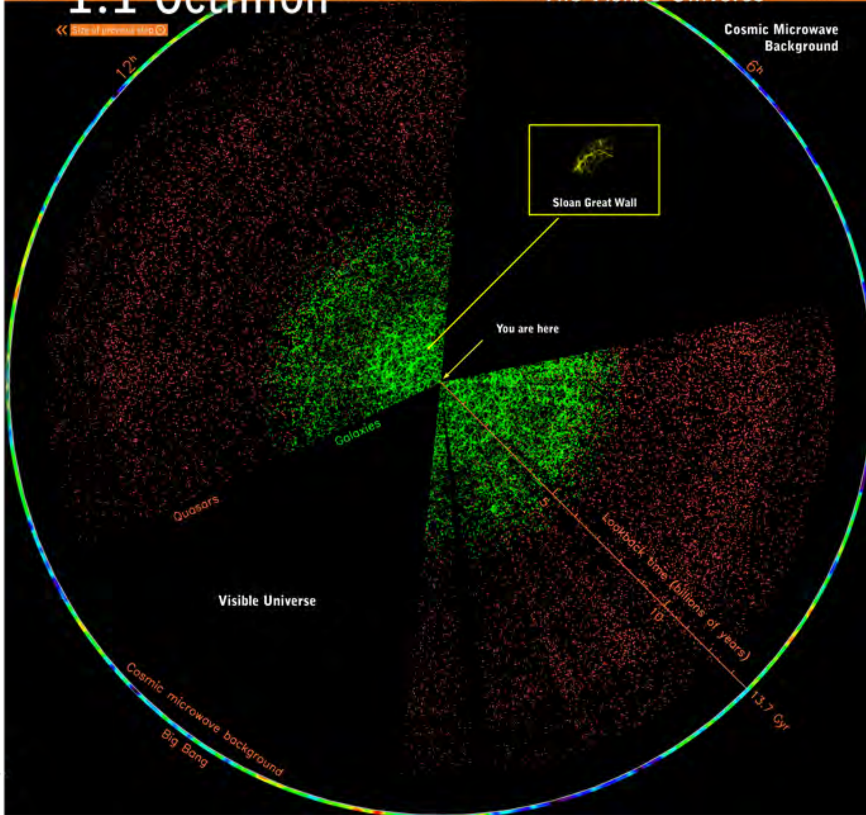
The visible universe is very large because gravity is such a weak force. In 1961, physicist Robert Dicke pointed out that it is no accident we live about one stellar main-sequence lifetime after the big bang—after some stars have died (to make the carbon needed for life) but before all the stars have burned out, making it too cold for life. If gravity were stronger, main-sequence lifetimes of stars would be shorter, we would live closer in time to the big bang, and the radius of the visible universe would be smaller. Since gravity is weak, we carbon-based life-forms, orbiting our main-sequence star, are treated to a truly grand view.

FYI We are now observing a scale a billion, billion, billion times larger than Buzz Aldrin's footprint. And that footprint is a billion times larger than a hydrogen atom.

Just think: After the end of inflation, the process that produced the big bang explosion 13.7 billion years ago, all the matter we can see in the visible universe today was still inside a region smaller than Buzz Aldrin's footprint.

1:1 Octillion

The Visible Universe



A computer-generated representation of the visible universe. Sloan Survey galaxies (green) and quasars (orange) are plotted at their look-back-time distances—black wedges are regions obscured by our galaxy and not covered by the Sloan Survey. Around the perimeter is the cosmic microwave background.

And Beyond

WHAT'S BEYOND the visible universe? Galaxies and more galaxies for a long way beyond the boundary of what we can see. Measurements of the cosmic microwave background by the WMAP satellite have enabled us to survey accurately the visible universe. The results tell us that a slice through the universe at the present epoch appears flat, like a sheet of paper. Keep extending a flat sheet of paper, and it forms an infinite flat plane. That might suggest the universe is infinite, with an infinite number of galaxies. Actually, it just means that the universe is much larger than the part we can see. Manhattan looks flat but actually is part of the finite, but large, curved surface of Earth. The universe could be almost any shape, but if it is large enough, any piece of it will look flat. All we really know for sure is that the true size of the universe is much larger than 13.7 billion light-years. Alan Guth's theory of inflation predicts this, but how much bigger is it?

Physicist Andrei Linde's theory of chaotic inflation suggests that our universe today may be $10^{40,000}$ times larger than the part we can see. Our universe forms in a high-density inflationary sea of dark energy. This dark energy has a very large negative pressure, and the repulsive gravitational effects of this pressure start a runaway expansion. This sea doubles in size every 10^{-37} seconds. Such a sequence (1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, . . .) blows up quickly. Inflation in our region ends when the dark energy converts into thermal radiation (the hot big bang) and the explosive expansion starts to slow down.

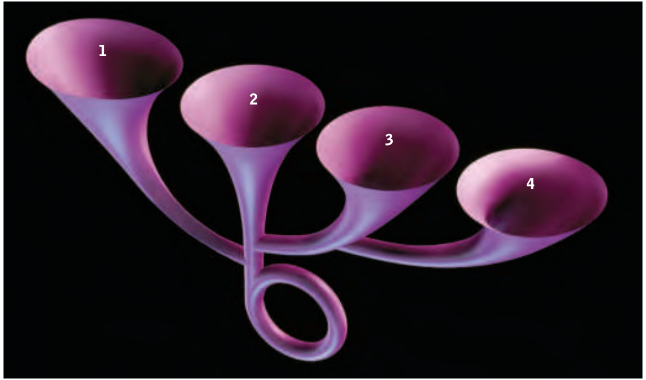
In my (Gott's) theory of bubble universes we are just one bubble in this expanding sea. Our bubble expands at nearly the speed of light and grows to infinite size, eventually creating an infinite number of galaxies inside. Beyond our own bubble universe is the inflating sea, which forms an infinite number of other bubble universes—a *multiverse*.

But there's more. Linde has shown that inflationary regions can give birth to other inflationary regions through quantum fluctuations, like branches growing off a tree. Each branch grows up to be as big as the trunk and sprouts branches of its own. The process, once started, continues forever, producing an infinite fractal tree with an infinite number of branches.

FYI According to Linde's theory, it would take over 10,000 more pictures, each covering a scale a thousand times larger than the one before, to capture our universe in its full glory.

Our universe is just one of many on one of these branches. We will never see these other branches, because the space separating us from them is expanding so fast that light can never cross it. Where did the trunk come from? Perhaps it simply popped into existence by a process called quantum tunneling, as proposed by Alex Vilenkin. Or perhaps it formed from a time loop, as proposed by me (Gott) and Li-Xin Li, when a branch looped back in time to grow up to be the trunk. We simply don't know. Superstring theorists Paul Steinhardt and Neil Turok have suggested that our universe is a three-dimensional membrane floating in a ten-dimensional space and that the big bang occurred when our membrane collided with another.

If our universe is a bubble, it is infinite in extent. Beyond our universe, myriad other universes in the multiverse branch off in the distance, farther than the eye can ever see.



The space-time diagram above shows the Gott-Li model for the creation of multiple universes from a time loop. Each funnel represents an inflating universe that is growing larger with time—we show one dimension of space (the circumference of the funnel) and the dimension of time (running upward out the funnel). We label four universes 1, 2, 3, and 4, from left to right. Universe 2 gives birth to universes 1 and 3—they are its children. Universe 3 gives birth to universe 4. So universe 4 is the grandchild of universe 2. Each branch grows to infinite size and sprouts branches of its own. We live in one of the many branches. Physicist Andrei Linde has shown that, once started, this branching process will continue forever, creating an infinite fractal tree of universes.

But where did the original trunk come from? Alex Vilenkin, Stephen Hawking, and James Hartle suggest it simply pops into existence. But Gott and Li have proposed that universe 2 was its own mother, giving birth to a branch that circled back in time and grew up to be the original trunk.

The Gott-Li model represents just one of a number of speculative possibilities being explored by physicists for the origin of our inflating universe. Studies of the cosmic microwave background suggest that inflation is likely, but details of how it got started have yet to be worked out.

MAP OF THE UNIVERSE

CHAPTER 4

ALL IN ONE

AS WE HAVE SEEN, astronomers mapping the universe are confronted with the challenge of showing a wide variety of scales. What should a map of the universe include? It should show locations of all the famous things in space: the Hubble Space Telescope, satellites orbiting Earth, the moon, the sun, planets, asteroids, Kuiper belt objects, stars such as Alpha Centauri, black holes, galaxies, quasars, and finally the cosmic microwave background radiation itself.

We want our Map of the Universe to display clusters of galaxies, but also stars within our own galaxy and the sun, moon, and planets. Objects close to us may be inconsequential in terms of the whole universe, but they are important to us. This calls to mind the famous *New Yorker* cover of March 29, 1976, “View of the World from 9th Avenue” by Saul Steinberg, which humorously depicts a New Yorker’s view of the world. The traffic, sidewalks, and buildings along Ninth Avenue are visible in the foreground. Behind is the Hudson River, with New Jersey as only a thin strip on the far bank. At even smaller scale, we see the rest of the United States, with the Rocky Mountains sticking up like small hills. In the background, but not much wider than the Hudson River, is the entire Pacific Ocean, with China and Japan in the distance.

This is, of course, a parochial view, but it is just the kind of view that we are looking for. For our Map of the Universe, we would like a single map that would show equally well both interesting objects in the solar system, nearby stars, galaxies in the local group, and large-scale galaxy clustering out to the cosmic microwave background.

Armed with the standard cosmological model from the Wilkinson Microwave Anisotropy Probe (WMAP) data, we can plot the expansion of the universe as a function of time. For the first time, we have fairly accurate knowledge of the geometry of the universe and the distances to individual galaxies and quasars, so we can plot a map of where they will be on a certain date.

In 1972, while I (Gott) was a graduate student, I invented a map projection for the universe and produced small versions of it over the years. Confronted with the task of displaying the galaxy-clustering data from the Sloan Digital Sky Survey, Mario Jurić and I decided that it was time to make a large-scale detailed version of my Map of the Universe to summarize all the exciting new discoveries that had been made recently in astronomy. The map projection I had devised was conformal, preserving local shapes, as the Mercator projection does, while still allowing us to cover the wide range of scales—from Earth’s neighborhood to the cosmic microwave background. We include all objects known within two degrees of the celestial equator—plus famous objects above and below the celestial equator.

FYI This map projection is conformal because on the map of the pizza slice (far right) the pepperoni retain their true round shapes.

The WMAP satellite data tell us that the geometry of such a two-dimensional cross section taken through the universe at the present epoch (using co-moving distances) is flat like a piece of paper. The map of the universe shows a 360-degree panorama from left to right, looking out from Earth’s Equator, while the vertical coordinate shows distance from Earth. Earth’s surface is a horizontal line at the bottom of the map, and the cosmic microwave background is at the top. As you move up the map, you get farther and farther from Earth. The left- and right-hand borders coincide; they could be taped together to display the map as a cylinder. The horizontal coordinate is celestial longitude (which divides the 360-degree view into 24 hours—each hour covering 15 degrees).

Lines fanning out from Earth’s Equator, like edges of a pizza slice, are shown as parallel vertical lines in the map. Imagine a round piece of pepperoni sitting on a slice of pizza just wide enough to span the width of the slice (above left). The slice gets wider the farther it gets from the pie’s center, so if there was another piece of pepperoni farther out that also spanned the pizza slice, it would have to be bigger. Those two pieces of pepperoni would be shown with the same width on the map because they cover the same angle as seen from the center of the pizza. In our pizza slice we show three pieces of pepperoni. The first one, nearest the center, is the smallest. The second one is twice as big as the first, and twice as far away. The third is twice as big as the second and twice as far away. Now, usually a pizza will have pieces of pepperoni that are all the same size, but in our special pizza, the pepperoni pieces get bigger farther out. The strip on the right shows our map projection of the same pizza slice. Radial lines, the edges of the wedge-shaped pizza slice, show up as vertical lines on the map.

If the map is to be conformal, showing local shapes well, then the pepperoni pieces should all be shown as

Saul Steinberg’s famous *New Yorker* cover (opposite) provides an illustration of scale, as does a slice of pepperoni pizza (above left). The same slice after applying a logarithmic conformal map (above right).

Let The Movie Begin

Let The Movie Begin

Let The Movie Begin

Let The Movie Begin