

SIZING UP THE UNIVERSE



THE COSMOS IN PERSPECTIVE

J. Richard Gott / Robert J. Vanderbei

<http://www.sizinguptheuniverse.com>



NATIONAL GEOGRAPHIC

WASHINGTON, D.C.

■ 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.

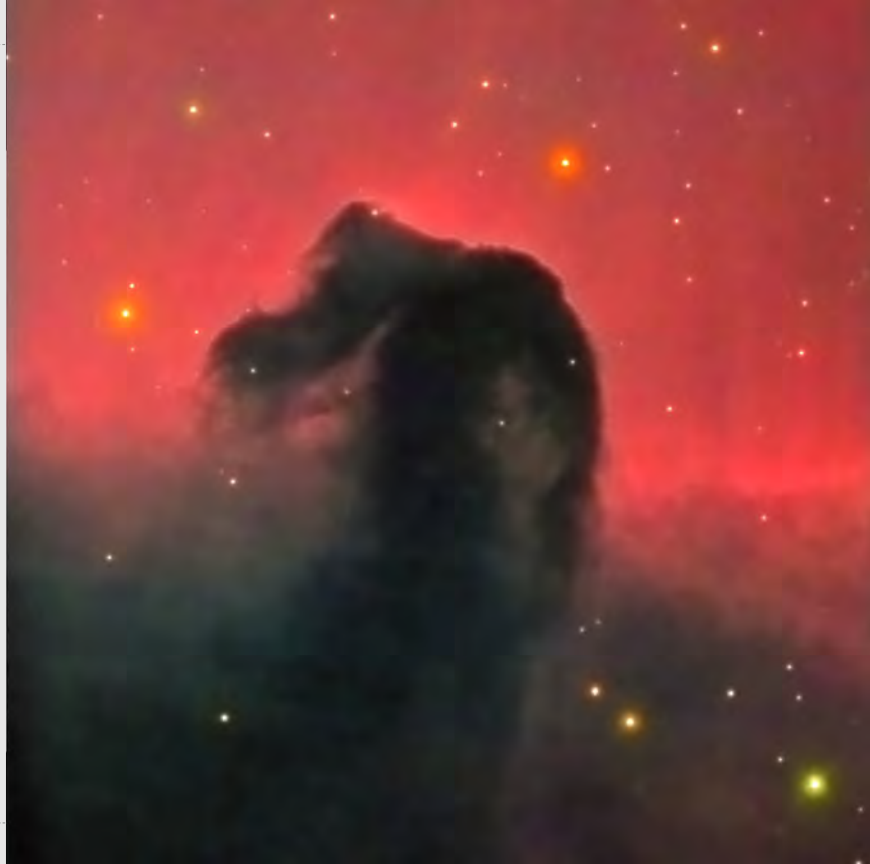
Astronomers typically learn how big an object looks by taking its picture through a telescope of known power.

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.



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

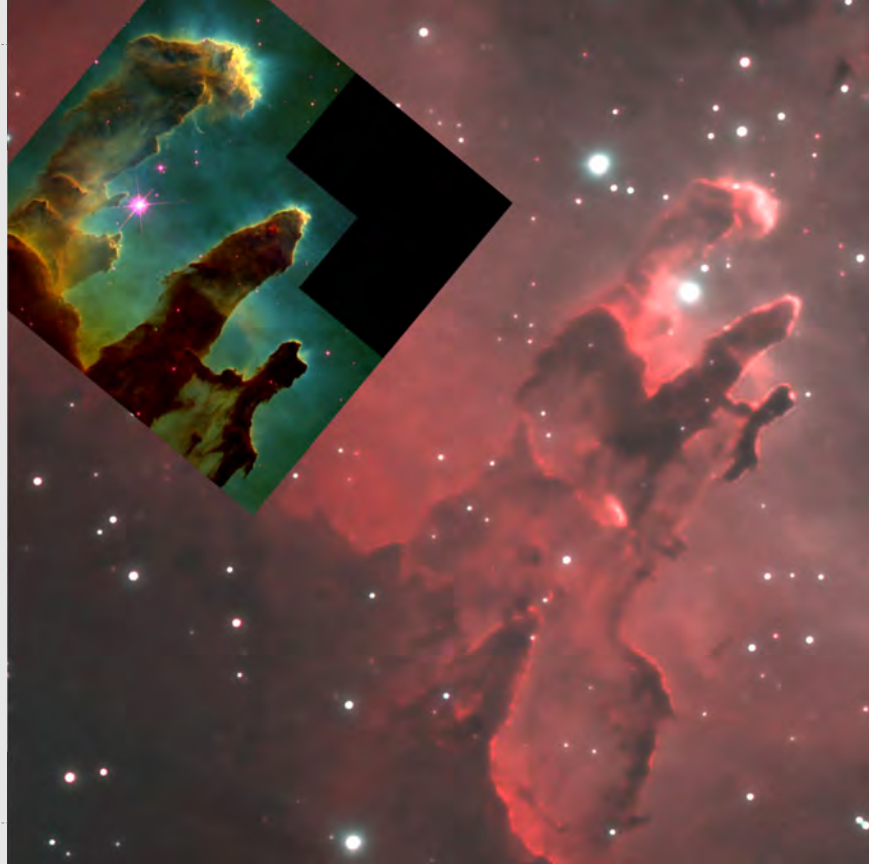
the wonders of the universe without ever leaving home. Vanderbei sets his telescope tracking a galaxy for an hour exposure and goes inside to watch television while it takes the picture. He can then download the picture to his computer and sharpen its image with software or combine it with other exposures 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.

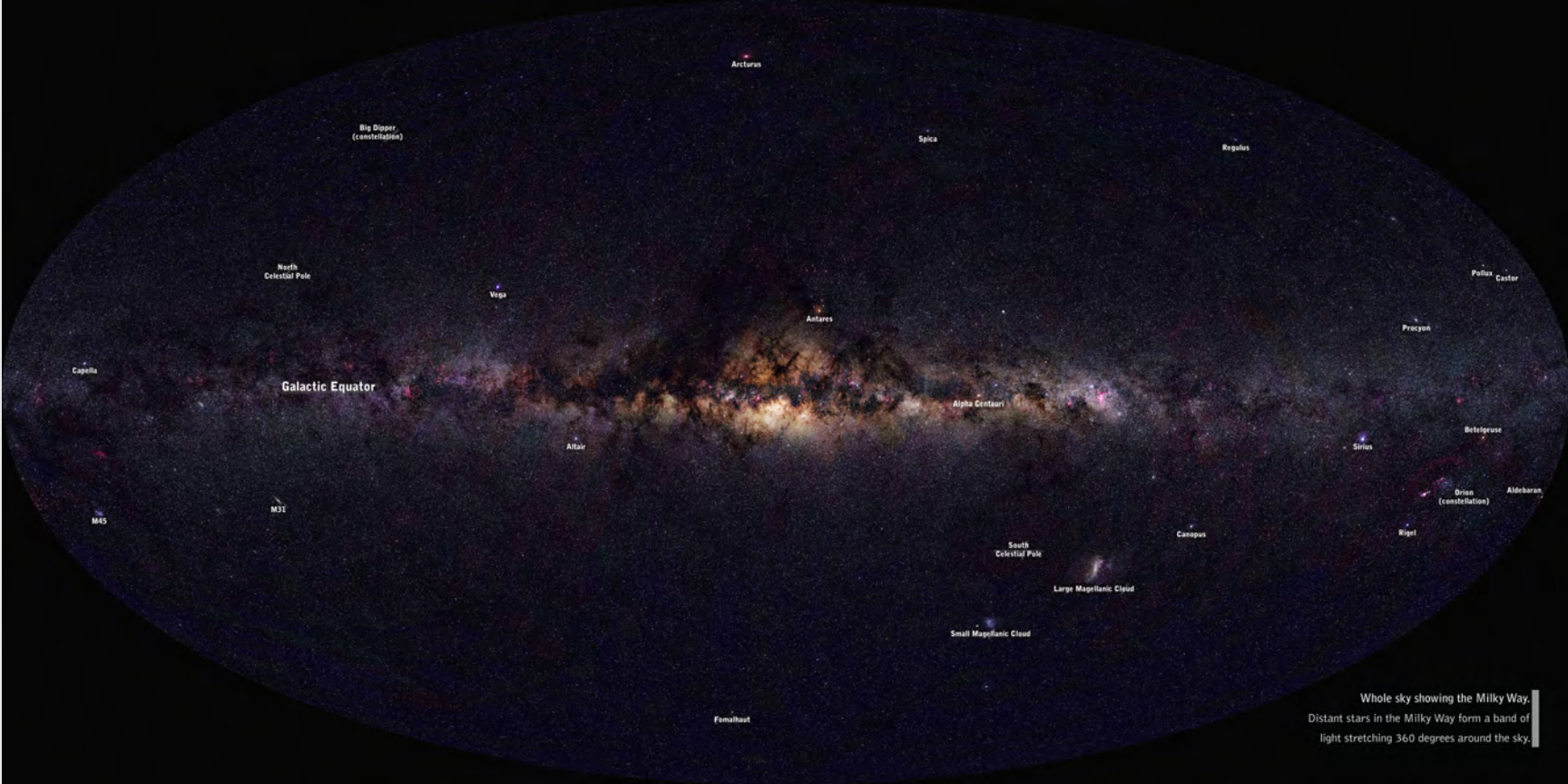
—J. Richard Gott

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.





The Orion Nebula is an enormous cloud of gas and dust that is slowly condensing (over the course of millions of years) into stars. The stars we see are young. Come back in a few million years, and there will be more.



Arcturus

Big Dipper
(constellation)

Spica

Regulus

North
Celestial Pole

Vega

Antares

Pollux Castor

Procyon

Capella

Galactic Equator

Alpha Centauri

Betelgeuse

Airair

Sirius

Orion
(constellation)

Aldebaran

M45

M31

Canopus

Rigel

South
Celestial Pole

Large Magellanic Cloud

Small Magellanic Cloud

Fomalhaut

Whole sky showing the Milky Way.
Distant stars in the Milky Way form a band of
light stretching 360 degrees around the sky.

Apparent Sizes

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.

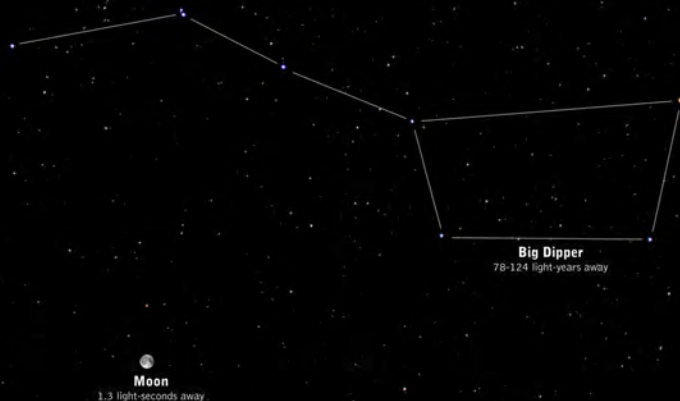
The moon may look large when seen setting against distant houses and trees along the horizon, but at arm's length, your thumb will still completely cover it. Half a degree is not very large. A typical digital camera in snapshot mode without zoom has an angular field of view of about 45 degrees. That 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 1x, in other words, one times the magnification you see with the naked eye.





Moon

1.3 light-seconds away

Andromeda Galaxy
2.5 million light-years away

17 arc-minutes



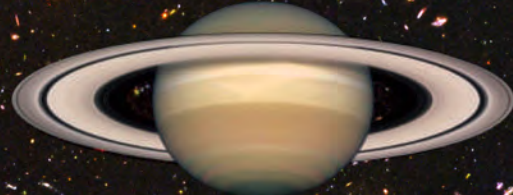
1,500x

Hubble Telescope

Hubble Ultra Deep Field
most distant galaxies 13 billion light-years away



Mars
3.1 light-minutes away



Saturn
71.2 light-minutes away

APPARENT SIZES 38

Moon
1.3 light-seconds away

15.5 arc-seconds

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 **14,000,000x** 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

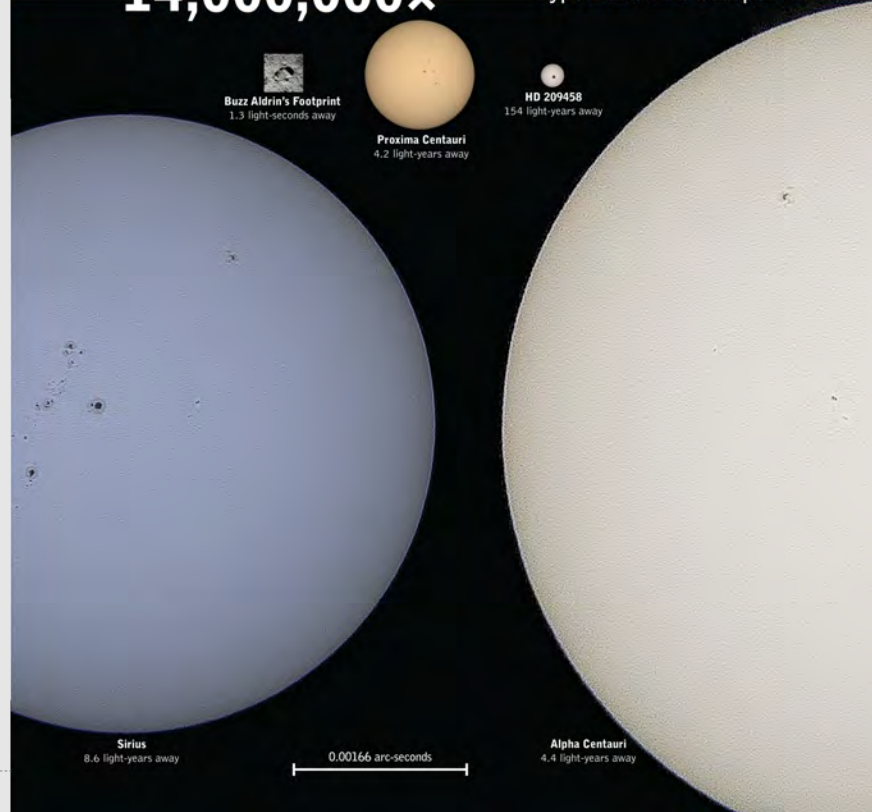
each be 56 kilometers (35 miles) across, about the size of a large metropolitan city. Jupiter's image would be seven-eighths of a mile across. Alpha Centauri's image would be only 25 centimeters (10 inches) across, and Proxima Centauri's image would be 3.0 centimeters (1.2 inches) across.

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.

14,000,000x

Hypothetical Telescope



Actual Sizes

Sizes in our Solar System

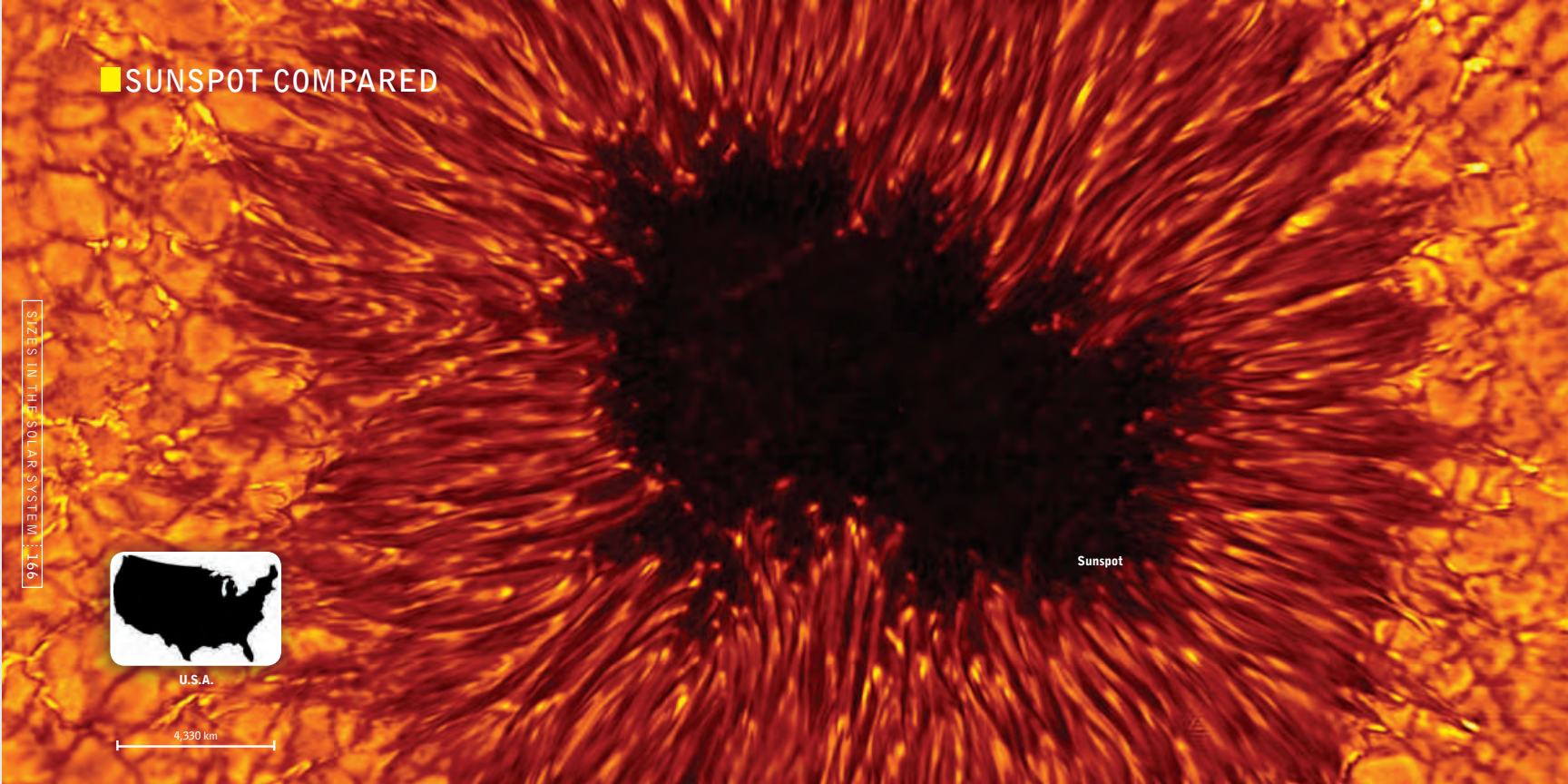
SUNSPOT COMPARED



U.S.A.

4,330 km

Sunspot



CANYONS COMPARED

Valles Marineris



Grand Canyon

189 km

SIZES IN THE SOLAR SYSTEM 154

STORMS COMPARED

SIZES IN THE SOLAR SYSTEM :: 170



Hurricane Katrina

4,370 km

Great Red Spot

SIZES IN THE SOLAR SYSTEM : 178

Earth and Moon

for comparison



Kuiper Belt Objects



5,080 km

Moons

Neptune



Triton

Uranus



Titania



Oberon



Ariel



Umbriel

Saturn



Enceladus



Tethys



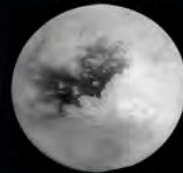
Dione



Rhea



Lapetus



Titan

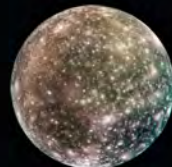
Jupiter



Europa



Io



Callisto



Ganymede

Asteroids



Ceres



Pallas



Vesta



Hygiea

Note: This comparison contains all remaining known objects in the solar system that are larger than 500 kilometers in diameter.

■ EXOPLANETS COMPARED

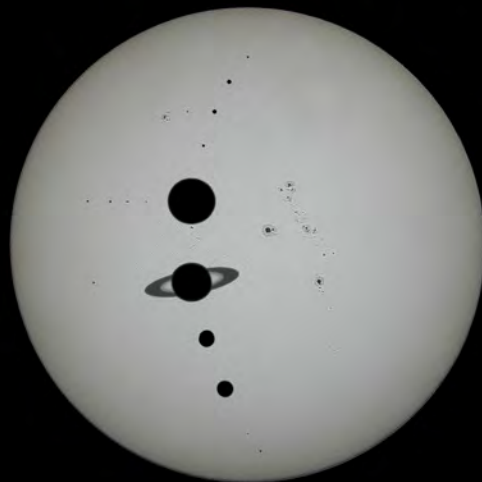
PLANETS ARE SHOWN to scale in silhouette against their stars as if seen in transit. The sun and its planets, Pluto, and some moons are shown for comparison. We can discover the sizes of extrasolar planets by noting the fraction of their star's light they block if they transit in front of it. Most planets 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.



GJ 436



CoRoT-7



Sun (for comparison)



HD 209458



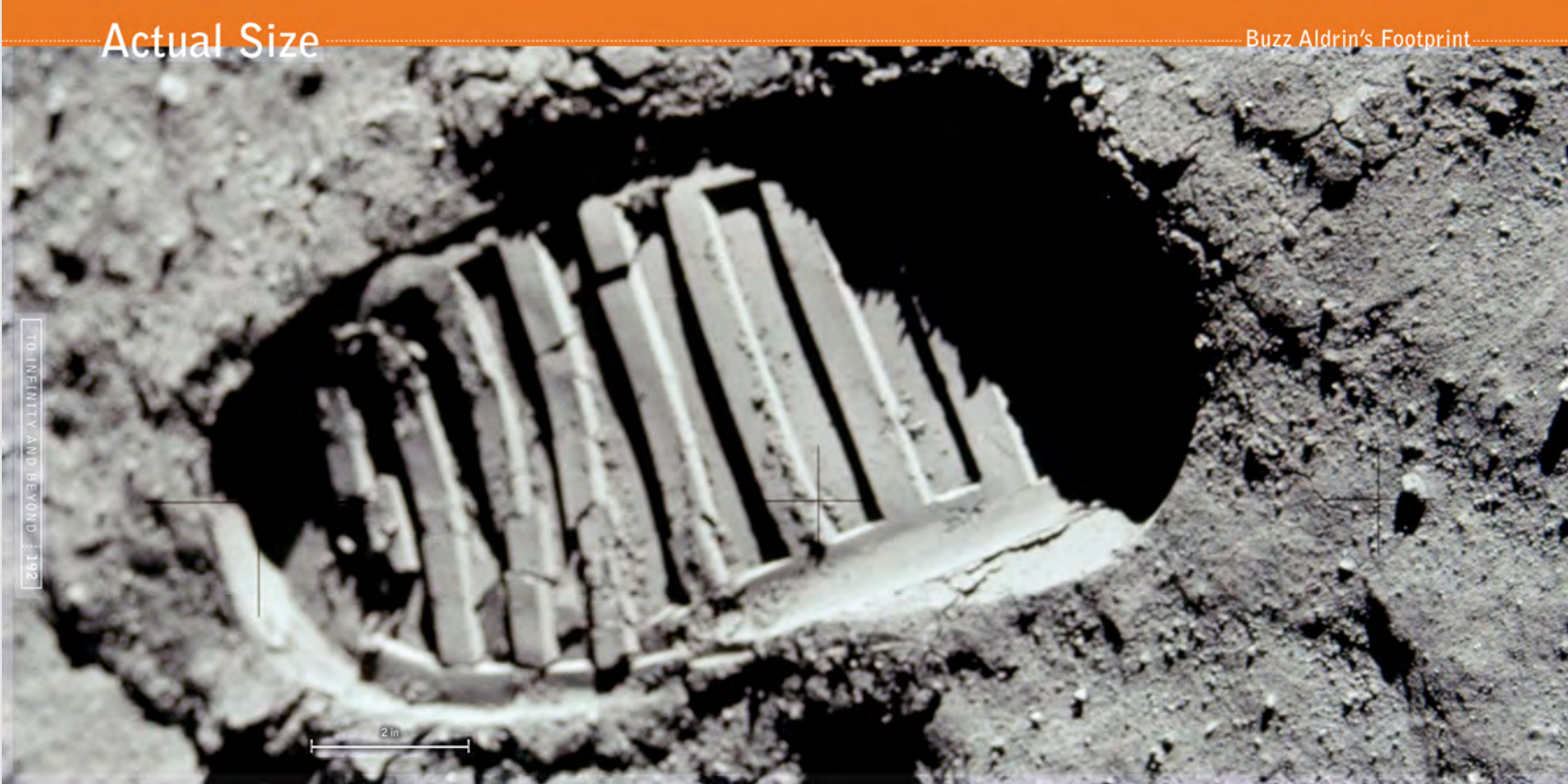


TO INFINITY AND BEYOND

CHAPTER 6

Actual Size

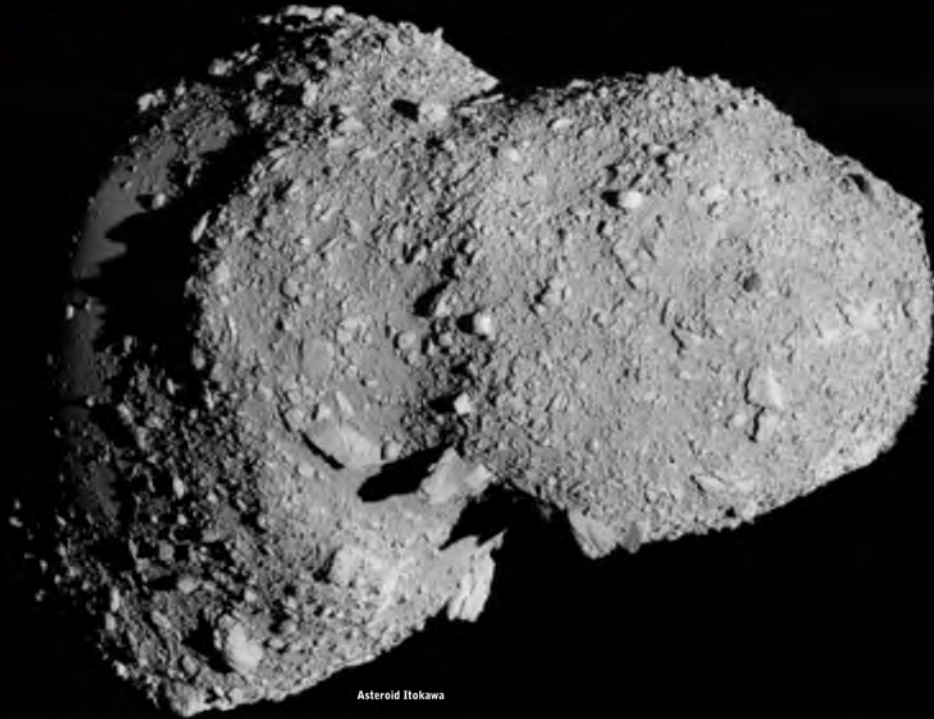
Buzz Aldrin's Footprint



TO INFINITY AND BEYOND 1992

2 in

[← Back to previous slide](#)



Asteroid Itokawa



Space Shuttle

Astronaut McCandless



Hubble Space Telescope



International Space Station

50.8 m

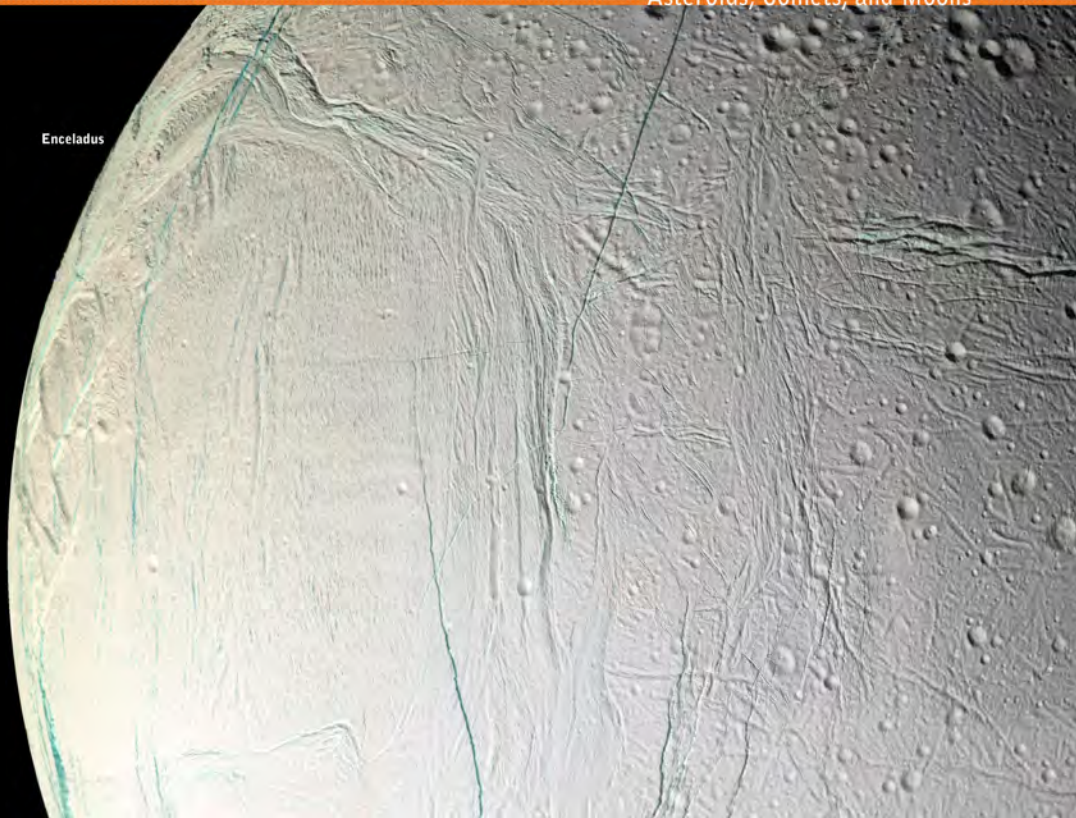
1:1 Million

Asteroids, Comets, and Moons

[Back of previous step](#)



Enceladus



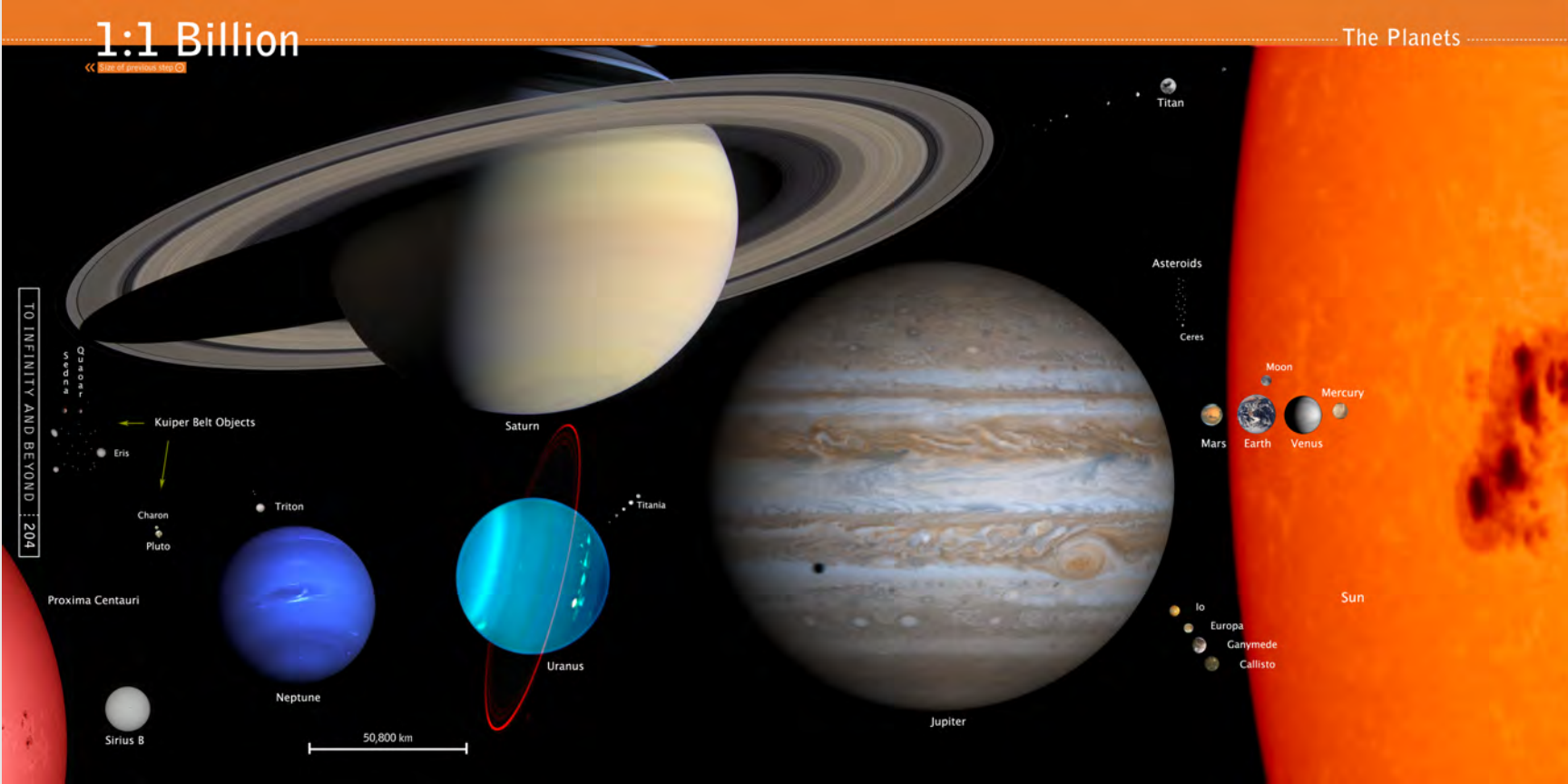
50.8 km

1:1 Billion

The Planets

<< Size of previous step >>

TO INFINITY AND BEYOND 204



1:1 Trillion

Stars

<< Back of previous slide >>



Black hole at galactic center

TO INFINITY AND BEYOND 210



Rigel

Betelgeuse

Regulus

Vega

Sirius

• Alpha Centauri
Proxima Centauri



c's orbit

Gliese 581

• Tau Ceti



b's orbit

HD209458

Mars's orbit

Earth's orbit

Venus's orbit

Mercury's orbit

Sun

Comet Hyakutake

50,800,000 km



1:1 Quadrillion

[← Back at previous step](#)

TO INFINITY AND BEYOND 214



Vega dust disk

Betelgeuse



Fomalhaut-b's orbit



Black hole in M87



(Orbits, from small to large)

Jupiter

Saturn

Uranus

Neptune

Halley's Comet

Pluto

Eris

Sedna

50 billion km



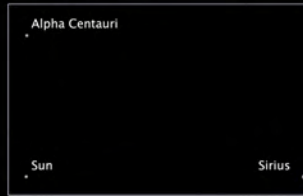
1:1 Quintillion

← Site of previous slide →

COMMUNITY AND BEYOND : 218

M13

5.37 ly



1:1 Sextillion

Galaxies

← Size of previous step

← G76

Andromeda Galaxy (M31)

← G64

5,370 ly

M110

TO INFINITY AND BEYOND 224



1:1 Septillion

Galaxy Clusters

← Site of previous slide →



Perseus Cluster



Coma Cluster



Local Group



Bullet Cluster

Cosmic Microwave Background

5.37 million ly

TO INFINITY AND BEYOND 230

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

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.

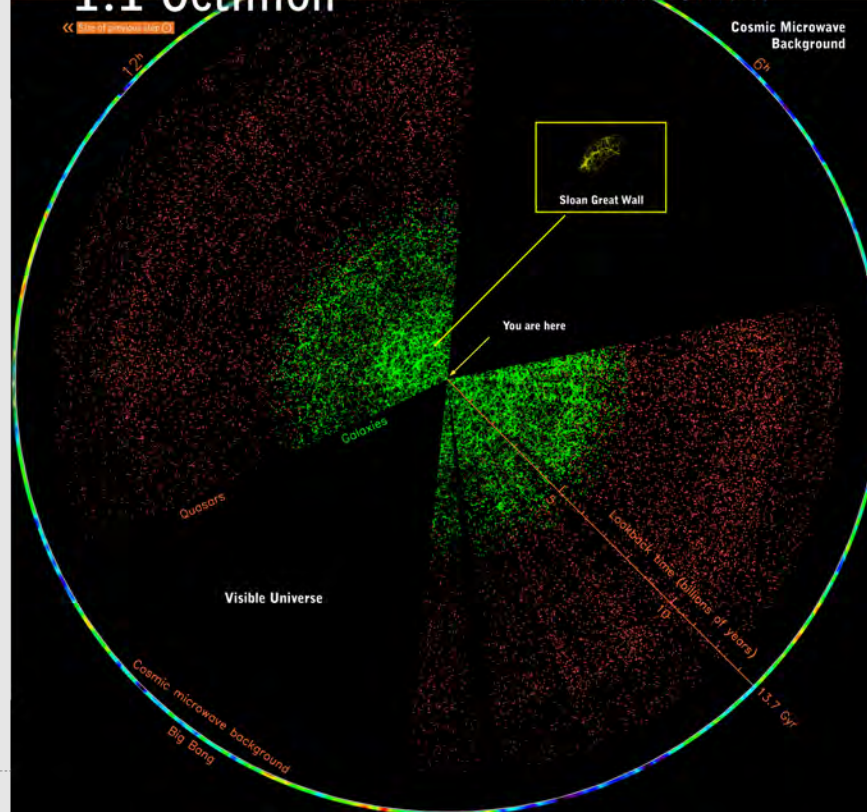
stars have burned out, making it too cold for life. If gravity were stronger, main-sequence lifetimes of stars would be shorter, we would live closer in time to the big bang, and the radius of the visible universe would be smaller. Since gravity is weak, we carbon-based life-forms, orbiting our main-sequence star, are treated to a truly grand view.

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.

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.

1:1 Octillion

The Visible Universe



A vibrant, multi-colored nebula or galaxy core, featuring a bright star on the left. The colors range from deep red and orange to bright blue and cyan, set against a dark, star-filled background.

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).

