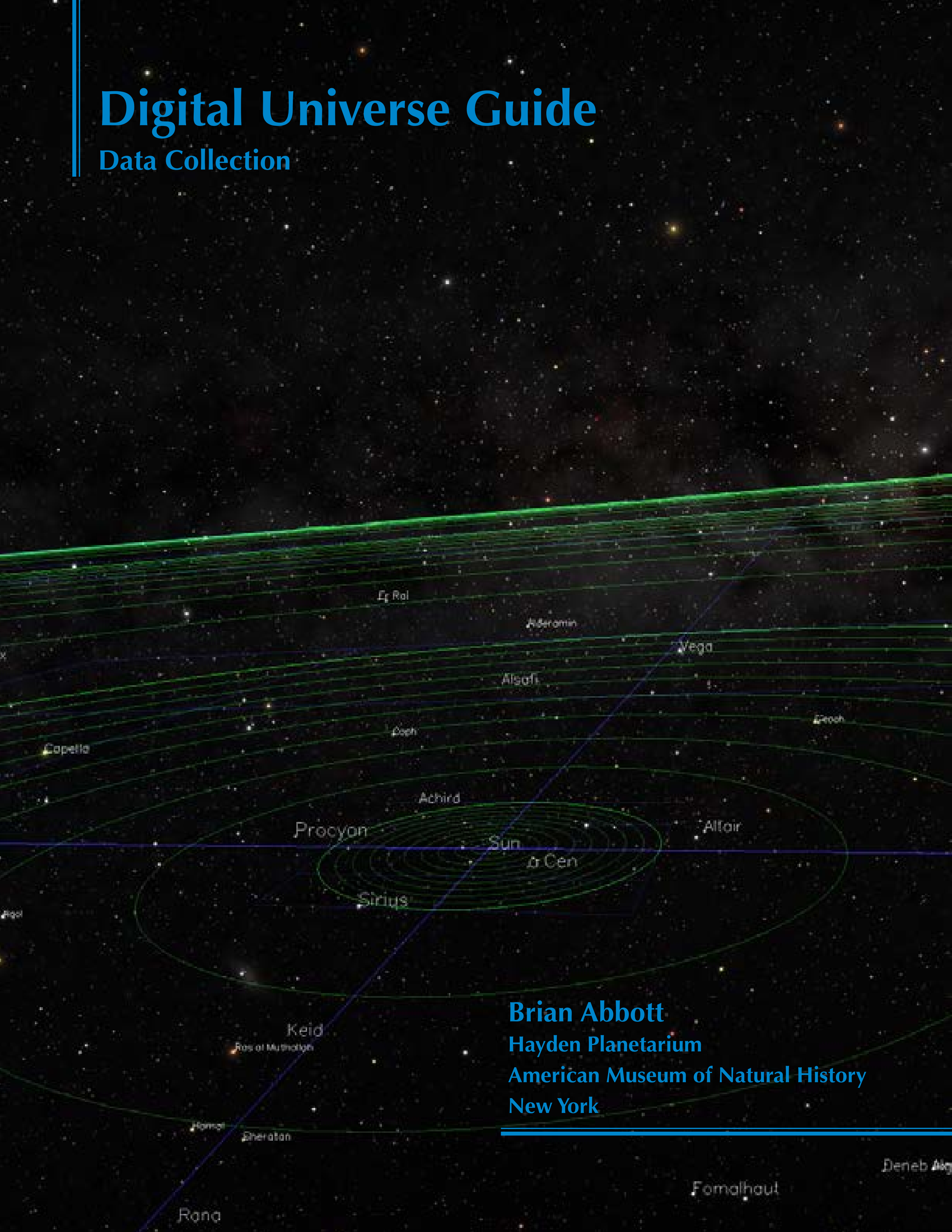
Digital Universe Guide
Data Collection



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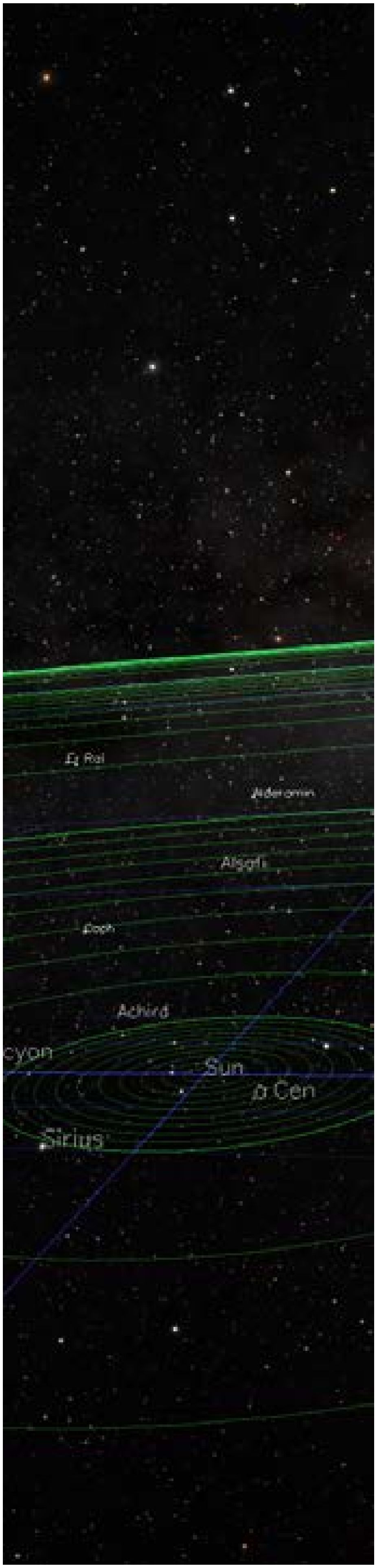

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See the Digital Universe website for more information.

About

The Digital Universe, developed by the American Museum of Natural History's Hayden Planetarium, incorporates data from dozens of organizations worldwide to create the most complete and accurate 3-D atlas of the Universe from the local solar neighborhood out to the edge of the observable Universe.

In preparation for the reopening of the Hayden Planetarium in 2000, the American Museum of Natural History embarked on the creation of a 3-D astronomical atlas to provide a framework for teaching about the discoveries of modern astrophysics. While the Rose Center for Earth and Space was constructed outside the Museum, a digital model of the universe was constructed inside. The atlas grew out of a convergence of two great streams of technical achievement: celestial mapmaking, which incorporates centuries of observation and scientific breakthroughs, combined with hardware and software engineering, which enables sophisticated data visualization. As new data are gathered, and new tools developed, the Digital Universe will continue to expand, filling in more details of our universe as our understanding evolves.

Install

Installing Digital Universe for Partiview is straightforward.

Download the package for your operating system, unzip the downloaded file if necessary, and move the resulting folder wherever you like on your computer.

The install does not move files outside of this folder, so the package is self-contained and may be placed wherever you like.

Open the Milky Way Atlas

To launch the Milky Way portion of the Digital Universe, open:

For...	Open the file...
Windows	`milkyway.bat`
Mac	`milkyway.command`
UNIX	`milkyway.sh`

Opening the file will launch a terminal and then the Partiview software. The terminal will echo the commands it executes from the configuration file, which is `milkyway.cf` for the Milky Way. We will describe this later in this guide.

Point of Interest

The point of interest in the Digital Universe is the Sun.

The point of interest in Partiview is the point about which navigation is based. It is the point about which orbital motion is based.

Mouse Controls

Partiview is designed to function with a two- or three-button mouse. If you use a trackpad, it is possible to navigate in Partiview, but it is not as easy.

If you're using a single-button mouse on a Mac, you'll want to activate the right mouse button in the system preferences.

Flight Modes

Partiview has four flight modes: Fly, Orbit, Rotate, and Translate.

Orbit is the default mode, and allows you to orbit around the center of interest with the left button pressed. It also enables flying forward or backward with the right button pressed. The scale for this motion is logarithmic, so your speed increases the farther you are from the point of interest.

Fly mode allows you to pan your view, that is, move your head without moving your feet with the left button. The right button enables the forward and backward motion, but on a linear speed scale.

The types of motion in Partiview include:

orbit	Revolve around the point of interest. If the point of interest is not in the display but off to the side, then you will orbit the point of interest but look forward, akin to looking away from the center of a carousel as you revolve around its center.
forward/reverse	With eyes forward (looking at the center of the display), moving forward or backward along your line of sight.
pan	Change your view without moving from your position.
rotate	Rotate the view about the point of interest. When the point of interest is in view, this produces a twisting motion parallel to your screen. If the point of interest is out of view, then the data will appear to approach from an angle, similar to the carousel analogy for orbit.
translate	Move in a direction parallel to the display, thereby moving the data across the display in the direction of mouse motion. This is equivalent to moving your feet sideways while keeping your eyes looking straight ahead.

To quickly change your flight mode quickly, use the keys `f`, `o`, `r`, or `t`.

Fly [f]	pan	select [p]	forward	linear
Orbit [o]	orbit		forward	log
Rotate [r]	orbit		rotate	
Translate [t]	translate		forward	linear

To change the flight mode, use the Flight Mode Menu at the top-left, or use the keyboard shortcuts listed in the table.

When you're located on the point of interest, you will not move forward or backward in Orbit Mode. To move, switch to Fly Mode, then move with the right mouse button.

The linear and logarithmic speed scales solve the long-distance problem. In a linear flight mode, your forward and backward speed is constant. In a log more, the forward and backward motion speeds up as your distance from the point of interest increases. This allows you to traverse the large scales of the universe.

Select allows you to choose an object in the foreground. Selecting an object will return information about that object in the Console Window.

Active Data Group

Partiview can handle up to 47 data groups, each controlled by a button on the Group Buttons row in the interface.

Set the active data group by right-clicking on its group button.

In order to change the properties of a data set (brightness, color, etc.), it must be the active data group. The active data group is set by either right-clicking on the group button, or choosing the group from the Groups Menu. We find the former is easiest.

Milky Way Atlas

The Milky Way portion of the Digital Universe covers everything from the solar neighborhood to the outskirts of the Galaxy. It does not include the Solar System.

The Milky Way is a large spiral galaxy and consists of gas, dust, and a few hundred billion stars. The Sun is one of those stars.

Active star formation occurs in the disk of the galaxy, while the halo, a large spherical component is filled with older stars.

We can probe the structure of the Galaxy by examining these various data sets in concert with one another. Star forming regions trace the spiral arms, open star clusters help define the disk of the Milky Way, while globular star clusters indicate the size of the halo.

In this way, we can learn repeat history and come to understand the structure of our galaxy just as astronomers did a century ago for the first time.

Data Groups

The data groups follow the Partiview naming convention and order. Page numbers refer to detailed descriptions later in the text.

The data sets fall into a few categories. One is 3-D data, like stars, exoplanets, and star clusters. We also include all-sky data that spans the electromagnetic spectrum, form radio up to gamma rays. Finally, we include some models and grids that describe the Milky Way and enhance the scale of these data.

`Stars`	The observed stars
`AltLbl`	Bayer and Flamsteed star names
`Err`	Select stellar distance uncertainty
`Constel`	Constellation connectivity lines
`HPMstars`	High Proper motion stars
`Dwarfs`	L, T, and Y dwarfs
`Expl`	Exoplanets
`Kepler`	Kepler exoplanet candidate stars
`OC`	Open star clusters
`OBassoc`	OB associations
`GC`	Globular Clusters
`Pul`	Pulsars
`PN`	Planetary nebulae
`SNR`	Supernova Remnants
`H2`	Star-forming regions (HII Regions)
`OriNeb`	Orion Nebula and star cluster
`Oort`	Oort Cloud sphere
`RaDec`	Equatorial (RA/Dec) coordinates sphere & Radio sphere
`Eclip`	Ecliptic coordinates sphere
`Galac`	Galactic coordinates sphere
`mwRadio`	408 MHz (synchrotron) all-sky survey
`mwH`	21 cm (atomic hydrogen) all-sky survey
`mwCO`	115 GHz (Carbon Monoxide) all-sky survey
`mwFIR`	100-micron Far-infrared all-sky survey
`mcIRASc`	IRAS composite infrared all-sky survey
`mwWISE`	WISE composite infrared all-sky survey
`mw2MASS`	2MASS infrared all-sky survey
`mwVis`	Visible all-sky survey
`mwHalpha`	Hydrogen alpha all-sky survey
`mwFUV`	Far ultraviolet all-sky survey (incomplete)
`mwXray`	MAXI x-ray all-sky survey
`mwGamma`	Fermi gamma ray all-sky survey
`DSO`	Deep sky objects (Messier images)

Milky Way Data Groups		
Partiview Group Name	**Page**	**Description**
`Galaxy`		Milky galaxy image representation
`Arms`		Spiral arm labels
`SunOrbit`		Billion-year solar orbital trajectory (and other stars)
`Bar`		The Galactic bar model
`Halo`		The Milky Way's halo model
`1ly`		Sun-centered, 1-light-year grid
`10ly`		Sun-centered, 10-light-year grid
`100ly`		Sun-centered, 100-light-year grid
`1kly`		Sun-centered, 1,000-light-year grid
`10kly`		Sun-centered, 10,000-light-year grid
`GalGrid`		Galaxy-centered, 100,000 light year grid

AMNH Stars

Group Name	`Stars`
Reference	Gaia DR1 (Gaia Collaboraiton 2016) XHIP: Extended Hipparcos Compilation (Anderson+ 2012) Hipparcos, New Reduction (van Leeuwen 2007) Tycho-2 Catalogue (Hog+ 2000) Hipparcos Catalog (European Space Agency 1997) Third Catalog of Nearby Stars (Gliese+ 1991)
Prepared By	Brian Abbott (AMNH) David R. Rodriguez (AMNH) Ron Drimmel (U Torino, Italy) Carter Emmart (AMNH) Stuart Levy (NCSA/UIUC) James Adams (AMNH)
Labels	Yes. Common star names (see also Alternate Star Names)
Files	`stars.speck` `stars.label`
Dependencies	`halo.pbm` `colorbv.cmap`
Census	1,062,281 total stars 232 star name labels

The stars are among the richest, most complex data group in the atlas. Calculating the distance to stars is exceedingly difficult unless they are very close. For the AMNH star catalog, we set tolerances on the amount of acceptable uncertainty in a star's distance, which then determines the size of our final catalog.

Astronomers use something called the trigonometric parallax to determine a star's distance. We discuss this technique in detail in "Parallax and Distance." The short version is that for nearby stars, astronomers observe a small apparent motion visible only through telescopes. This motion results from Earth's orbit around the Sun, and the angle formed from this motion is called the parallax angle. With a simple geometric argument, the distance to the star can be calculated as one side of a triangle.

Source catalogs. The AMNH catalog is derived from several catalogs, but the bulk of our stars come from the Gaia and Hipparcos catalog. The Hipparcos satellite was launched from French Guyana by the European Space Agency in August 1989. It collected data for four years before it was shut down in August 1993, having fulfilled its mission goals. The satellite still orbits Earth at a very high altitude.

Hipparcos was named after the Greek astronomer Hipparchus, who lived in the 2nd century BCE and who is credited with creating the first star catalog (and inventing trigonometry, among other things). The Hipparcos mission's goal was to measure the trigonometric parallax of more than 100,000 stars and the photometric properties (brightness) of half a million stars. The mission was successful, measuring parallaxes for 118,218 stars and photometric data for more than 1 million stars.

Hipparcos was a "targeted mission," meaning the target stars were determined before the satellite was launched into space. For this reason, Hipparcos did not observe all the nearby stars, as they already had good parallax measurements. Since 1838, astronomers have been measuring parallaxes from ground-based telescopes. The data from these telescopes were compiled in 1969 by Wilhelm Gliese (1915–1993) from the Astronomisches Rechen-Institut, in Heidelberg, Germany, and updated in 1991 by Gliese and Hartmut Jahriess for the third edition of the Gliese Catalog.

The Gliese Catalog contains all known stars (as of 1991) within 25 parsecs (81.5 light-years) of the Sun. The catalog contains more than 3,800 stars and has many that Hipparcos did not observe. We have over 200 such stars from Gliese in our AMNH star catalog.

Many of the stars have velocity information. Astronomers can measure the star's proper motion, how it appears to move in the sky, and its radial velocity, it's motion toward or away from Earth. Combining this information yields the 3-D motion of the star in space. For fast-moving stars, we can see a shift in the star's position over the course of years. The fastest star in the sky is Barnard's Star. The fourth-closest star, Barnard's is about 6 light-years away and moves 10.3 arcseconds/year (1 degree across the sky every 350 years).

The Hipparcos catalog has been revised over the years, including a major revision in 2007 as well as in 2012, when a collation of various catalogs including photometric properties, spectral types, and velocity information resulted in the XHIP: An Extended Hipparcos Compilation.

The AMNH catalog. We call our catalog the AMNH Catalog because we use a unique method for computing the stellar distance, setting it apart from distances used in other star catalogs.

Distances in the AMNH Catalog result from precomputed catalog distances, trigonometric parallax measurements, photometric parallaxes, and a weighted mean of the previous two. (Photometric parallax uses a star's brightness and luminosity to derive its distance.) If the star has catalog distance, we use it first. If we have a trigonometric parallax percent error under some value, we compute the distance using the parallax and use that distance. For stars over the error tolerance, we compute the photometric parallax and distance, as well as a weighted mean distance from the trig parallax and the photometric parallax.

The distance determination method is traced for each star via the dcalc data variable. If dcalc = 0, the star's distance was given in the catalog. If dcalc = 1, the star's distance is derived purely from its trigonometric parallax. If dcalc = 2, the distance is calculated with the weighted mean value of the trigonometric and photometric parallaxes. And, when dcalc = 3, the distance is derived purely from the photometric information.

All the data variables for the stars data group are listed below. As always, the first three columns of any Partiview file are x, y, and z. Column 4 in the file corresponds to data variable zero, column 5 is data variable 1, and so on. Partiview will generate a report of all data variables for the active data group with the command data-var or the shortened dv command.

Metadata for the Stars			
Metadata Number	Name	Description	Units
0	BVcolor	(B – V) color	—
1	lum	Luminosity scaling (calculated)	—
2	Vabsmag	Absolute V magnitude	mag
3	Vappmag	Apparent V magnitude	mag
4	distly	Distance (calculated)	ly
5	distpcPctErr	Parallax percent error	percent
6	U	U-component velocity unit vector	km/s
7	V	V-component velocity unit vector	km/s
8	W	W-component velocity unit vector	km/s
9	speed	Speed of the star	km/s
10	sptypeindex	Index value for spectral type	—
11	lumclassindex	Index value for luminosity class	—
12	catsource	Index value for source catalog	—
13	texture	Texture number	—

Labels for the stars include the star names, which are often Arabic in origin. Names like Betelgeuse, Rigel, and Aldebaran are found in the label file that accompanies this data group. We also provide Bayer and Flamsteed labels in the alternate star labels (AltLbl) data group.

Selection expressions. Using Partiview selection expressions, we have preset some "scenes" in the milkyway.cf file. Selection expressions allow you to display data based on some selection criteria. For example, if you want to see only those stars within 100 light-years, you could write a selection expression to remove all the stars outside this radius using Partiview's thresh, only, and sel commands.

In the following table, we list our preset selection expressions. To use these expressions, type `see [alias]` at the Partiview Command Line (e.g., `see blue`).

Selection Expressions for the Stars		
Alias	**Partiview Command**	**Description**
`blue`	`thresh BVcolor -2 0`	Select the bluer stars
`red`	`thresh BVcolor 0 4`	See the redder stars
`eye`	`thresh appmag -30 6.5`	See stars that have an apparent magnitude brighter than 6.5 (stars visible to the naked eye)
`m75`	`thresh appmag < 7.5`	Show all stars with an apparent magnitude brighter than 7.5
`bright`	`thresh absmag -10 -3`	Show the intrinsically bright stars
`faint`	`thresh absmag 0 10`	Show the intrinsically faint stars
`100ly`	`thresh distly < 100`	Display all stars within 100 light years
`speed`	`thresh speed < 0.0001`	Display all stars with velocity data
`Ostars`	`thresh sptypeindex 10 19`	Display all the O stars
`Bstars`	`thresh sptypeindex 20 29`	Display all the B stars
`Astars`	`thresh sptypeindex 30 39`	Display all the A stars
`Fstars`	`thresh sptypeindex 40 49`	Display all the F stars
`Gstars`	`thresh sptypeindex 50 59`	Display all the G stars
`Kstars`	`thresh sptypeindex 60 69`	Display all the K stars
`Mstars`	`thresh sptypeindex 70 79`	Display all the M stars
`lumclass1`	`thresh lumclassindex 1`	Stars with luminosity class I
`lumclass2`	`thresh lumclassindex 2`	Stars with luminosity class II
`lumclass3`	`thresh lumclassindex 3`	Stars with luminosity class III
`lumclass4`	`thresh lumclassindex 4`	Stars with luminosity class IV
`lumclass5`	`thresh lumclassindex 5`	Stars with luminosity class V

Boxes. In addition to the selection statements, we have defined two sets of boxes. Yellow boxes show open star clusters that are present in the star catalog. These are each 15 light-years on a side, encompassing over 3,000 cubic light years. The aqua boxes surround OB associations within the stellar data and are 130 light years on a side.

Pressing the Box Toggle Button in Partiview will show all the boxes associated with the stellar data set. If you wish to show or hide one of the two sets, you can use the `showbox` and `hidebox` commands. The open cluster boxes (yellow) are level 1, while the OB association boxes (aqua) are level 2. Using `hidebox 2` will remove the aqua boxes, while `showbox 2` will bring them back in view.

Alternate Star Names

Group Name	`AltLbl`
Reference	Various
Prepared By	Brian Abbott (AMNH)
Labels	Yes, but no specks. Use with `Stars`
Files	`stars-altlbl.label`
Dependencies	none
Census	3,119 labels

In addition to the Arabic star names in the `stars.label` file, we include another data group with additional star labels. These are derived from the Bayer Catalog (Greek star names) and the Flamsteed Catalog. (The Bayer names take precedence).

For each constellation, the brightest star is usually designated by the Greek letter α (alpha), the second-brightest is β (beta), and so on to ω (omega), provided there are enough stars in the constellation. These letters were first assigned to the stars in Johann Bayer's sky atlas of 1603. For our catalog, we use a three-letter abbreviation for the Greek letter along with the standard three-letter constellation abbreviation.

Flamsteed numbers run from 1 to N for each constellation and come from John Flamsteed's catalog of 1725. The number 1 star in a constellation has the lowest right ascension, and the numbers increase with increasing right ascension. 61 Cygni is a good example. The subject of the first trigonometric parallax measurement, 61 Cygni led to the first accurate distance determination by Friedrich Bessel in 1838.

Label sizes. These labels are initialized in the `milkyway.cf` file such that they will appear only when you're very close to them. The Partiview command that controls this is `labelminpixels`. This command sets a minimum pixel height before a label will be drawn. If you want to see more of these labels from your position, set `labelminpixels` to a lower value (using the Labelmin Slider, or enter the command at the Command Line). To see what these labels look like after you fly outside the stellar data, type `labelminpixels 0`, then increase their label size. Using the `labelminpixels` command along with the `labelsize` command provides a balanced amount of information without cluttering your view with labels. Such design choices lead to a good "map."

Stellar Distance Uncertainty

Group Name	`Err`
Reference	Hipparcos, the New Reduction (van Leeuwen, 2007) The Hipparcos and Tycho Catalogues (ESA 1997)
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`stars-err.speck` `stars-err.label`
Dependencies	none
Census	9 stars with uncertainty data

The position of each object in the Digital Universe has an uncertainty associated with it. To illustrate this, we demonstrate distance uncertainty with several stars of various distances and luminosities.

From Earth, we can measure a star's two-dimensional position in the sky to great accuracy. However, the star's distance remains elusive. Our most accurate distances come from the measurement of an angle in the sky that is imperceptible to the naked eye. This angle is called the trigonometric parallax (see "Parallax and Distance" for more information), and the uncertainties and errors in the measurement of this angle translate into uncertainties in the star's distance.

Representing uncertainty. In the atlas, uncertainties are represented by red lines. These lines consist of a series of points that, when viewed from a distance, appear as a line. Each point is spaced 1 light year from the next. We leave a space in this line for the published parallax distance. More often than not, the star will be found in this gap, but there are some stars that have a weighted mean distance and are placed elsewhere along the line of sight. Betelgeuse and Antares are good examples. Both are placed closer than their trigonometric parallax distance because of the large error in the parallax measurement.

Labels, in light years, denote the near distance uncertainty, the published distance (from the parallax angle), and the far distance uncertainty.

Ain	ε Tauri	146	145 – 148	3
Bellatrix	γ Orionis	251	242 – 261	19
Spica	α Virginis	248	236 – 261	25
Betelgeuse	α Orionis	488	432 – 544	112
Pleione	28 Tauri	398	385 – 412	27
Polaris	α Ursae Minoris	432	426 – 438	12
Antares	α Scorpii	535	454 – 615	161
Rigel	β Orionis	854	783 – 925	142
Deneb	α Cygni	1,379	1,207 – 1,551	344

The star Ain in the Hyades star cluster in Taurus is the closest star in this sample. At 146 light years away, it has a small uncertainty, only 3 light years. Compare that with Pleione in the Pleiades, a star cluster that is nearby in the sky but lies about 250 light years beyond the Hyades. Pleione has an 27-light-year uncertainty. As you view the atlas of stars, nebulae, and galaxies, consider that there is uncertainty associated with each of these objects and often the uncertainty for nonstellar objects is far greater.

Constellations

Group Name	`Constel`
Reference	—
Prepared By	Brian Abbott, Carter Emmart (AMNH)
Labels	Yes
Files	`constellations.speck` `constellations.label`
Dependencies	none
Census	88 constellations and labels

Astronomers divide the sky into eighty-eight regions called constellations. Today we know the stars in any given constellation do not necessarily have any physical relationship with one another. One star may be nearby, while an adjacent star may be far away. These regions were defined around preexisting figures invented by our ancient ancestors. Stars in the shape of a man, woman, beast, or the occasional inanimate object were part of an oral tradition that was passed from generation to generation.

Throughout history, and across all cultures, artists have drawn pictures over star maps to represent these figures—a bull for Taurus, a dragon for Draco, and a bear for Ursa Major. More often, though, we see “stick figures,” or lines connecting stars, that form the constellation figures.

History of the constellations. While many civilizations interpreted the heavens independently of one another, today the International Astronomical Union defines eighty-eight constellations, based mainly on Babylonian and Greek mythology and lore. More than half of the eighty-eight constellations that became official in 1930 were known to the ancients.

Some of the Greek constellations appear in the poetry of Homer from the 9th century BCE. Around the 5th century BCE, the Babylonians identified the ecliptic—the path that the Sun, Moon, and planets appear to follow throughout the course of the year—and divided it into the twelve parts of the zodiac.

In the 2nd century BCE, the Egyptian astronomer Ptolemy cataloged information on 1,022 stars grouped into 48 constellations. His work, the Almagest, remained the authority on the constellations until the 16th century, when European explorers voyaged into southern latitudes.

Once exploration of the Southern Hemisphere sky began, constellations were added quickly. In 1603, Johann Bayer published the first star atlas, which included twelve new constellations in the southern sky. Throughout the 17th century, an effort to depaganize the heavens led to the creation of the constellation Crux from bright stars that Ptoloemy had considered to be part of Centaur. Additionally, Ptolemy's grand constellation Argo Navis (Argo the Ship) was divided into the ship's keel (Carina), its stern (Puppis), and its sails (Vela).

Changes were made throughout the 18th century and into the 19th century. In 1875, boundary lines for the constellations were drawn along lines of right ascension and declination. These boundaries and the constellations themselves were adopted by the International Astronomical Union in 1930 and provide great simplification to the night sky. Now each star, planet, comet, and nebula—all objects in the night sky—belongs in one of these eighty-eight regions.

Constellation connectivity lines. In the Atlas, we represent the constellations by connecting the main stars that make up the constellation "stick figures," as seen from Earth. We generate the lines by connecting a series of (x, y, z) points using Partiview's mesh command. To avoid some lines appearing twice as bright, some constellations are formed with several meshes so that lines do not overlap.

While there are many philosophies on how to connect the stars—some people swear by the constellation art by author H. A. Rey (famous for the Curious George children's books), others by their favorite star atlas—we have chosen configurations that we are comfortable with.

Each constellation has a label that is positioned within the constellation and arbitrarily placed 65 light years from Earth.

Configuring the lines and labels. The constellation lines and labels can be configured if their colors or brightnesses do not suit you. The colors are set in the `milkyway.cf` file with these commands:

```
eval cment 1 0.6 0.4 0.4
eval cment 2 0.8 0.0 0.0
eval cment 3 0.0 0.3 0.8
eval textcment 1 0.6 0.2 0.2
eval alpha 0.4
```

The `cment` command sets the red-green-blue colors of color indexes 1, 2, and 3. The `textcment` command sets the color of the labels. If you would like to change these colors, simply edit `milkyway.cf` or change them interactively at the Partiview Command Line (where you don't need the `eval` prefix).

The brightness of the lines is set with the `alpha` command. An alpha of 1 sets the transparency of an object to be completely opaque (brightest), while a value of zero sets complete transparency (invisible). You can use the Alpha Slider to adjust this interactively. We don't recommend setting the alpha value to 0 or 1, as the lines are invisible at 0 and completely opaque at 1, often producing unwanted graphics effects.

If you would like to see only one or several constellations, consider forming a new group and pulling out those constellation meshes you want to see into a new file. You can also set the color for a color index to (R, G, B) = (0, 0, 0) (black), rendering those constellations invisible.

High Proper Motion Stars

Group Name	`HPMstars`
Reference	Lépine-Shara Proper Motion Catalog (Lépine+ 2013)
Prepared By	Sébastien Lépine (AMNH)
Labels	No
Files	`SUPERBLINK_NORTH_100pc_Mdwarfs.speck` `SUPERBLINK_SOUTH_100pc_Mdwarfs.speck`
Dependencies	`halo.pbm` `colorbv.cmap`
Census	164,640 stars

Critical toward our understanding of the Galaxy and the Universe are the stars that surround the Sun. If our knowledge of the local stellar population is inaccurate, then astronomer's theories on stellar evolution are unsound. Furthermore, the locations of all stars, even the size and scale of objects in the Universe, rests upon the accuracy of the local stellar neighborhood.

The Lépine-Shara Proper Motion Catalog (LSPM) contains the most complete sample of stars within 100 light years, with over 3,000 newly discovered stars. These stars have high proper motions, that is, they move across the night sky, as seen from Earth, relatively quickly. Of course, we do not see stars streaming across the sky: the fastest star in the sky, Barnard's Star, moves only one-quarter of one degree (about half the width of the full Moon) per century. However, if we observe the same spot over a span of decades with a telescope, we will see the stars shift in the sky.

All stars are in motion within the Galaxy; the Sun orbits the center of the Milky Way galaxy at approximately 800,000 km/hour (500,000 miles/hour). Some stars move alongside the Sun and appear to have little motion in the sky, other stars are moving at angles perpendicular the Sun, giving them higher proper motions. Barnard's Star will be the closest star to the Sun around the year 11,700 CE, when it will be only 3.8 light years distant.

The new stars in this catalog were discovered by comparing images of the sky from two epochs. When astronomers analyze two images from the same patch of sky taken 50 years apart, the light from each pixel should match between the two images. If there is a bright spot in one image that is not in the other, then it is scrutinized to see if it's a fast-moving star.

Revealing the unseen. Most of the stars in this catalog are below the brightness limit of our eye, so how do we see them in the Digital Universe? We must represent them conceptually rather than photo-realistically. To see the dimmer stars, which represent the majority, we must increase their luminosity scale in the Digital Universe. By default, the stars in this data set are 200,000 times their normal brightness and the halo on each star has an upper size limit of 20 pixels, so that the few bright stars in the 100-light-year-radius volume, like Sirius, do not overpower the rest of the stars with their brightness. To return these stars to their true brightness, use the commands `slum /200000` and `polymin 1 1e8` (in this order), then they will be on equal footing with the normal stars.

Dwarf Catalog

Group Name	`Dwarfs`
Reference	Private communication (Faherty, 2017)
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`dwarfs.speck` `dwarfs.label`
Dependencies	`dwarfs.cmap`
Census	23 M dwarfs, 1144 L dwarfs, 491 T dwarfs, 17 Y dwarfs

In astronomy, there are dwarf stars—red, white, and brown—dwarf novae, and even dwarf galaxies. As you might imagine, astronomers use the term when they refer to the smaller objects in any given class.

For decades it was believed that M stars were the coolest stars in the Universe. Some M stars, called red dwarfs, make up 70% of the stars in the Galaxy, including our nearest known neighbor, Proxima Centauri. However, a new class of objects, even cooler than M stars, was recently discovered and given the name L dwarf. The L-class dwarfs include normal stars, or red dwarfs, and brown dwarfs, which are not massive enough to ignite the nuclear processes necessary for it to shine as a star.

Also included in this catalog are objects, called T dwarfs. These are even cooler than L dwarfs and are also called brown dwarfs. They resemble large, massive, Jupiter-like objects, too large to be planets and too small to be stars. Brown dwarfs are extremely difficult to see, mainly because they are so dim in optical light. However, they appear brighter in infrared light.

Using infrared surveys, such as the Wide-field Infrared Survey Explorer (WISE), astronomers compared data from infrared images to optical images. If an object appeared bright in the infrared, but was dim or nonexistent in optical light, it was targeted for further observation to confirm its identity as a dwarf.

Representing what we cannot see. In the Digital Universe, we cannot represent these objects accurately since it is not possible to see them with the unaided eye. Instead, we represent them conceptually with oversized points. The M dwarfs are orange, the L dwarfs appear bright red, the T dwarfs are a dimmer red-purple color, and the Y dwarfs are deeper violet. It is important to note that the brightness for these objects is grossly exaggerated relative to the stars. Also, their brightness, or size, is not proportional to their intrinsic brightness, but to distance. Of course, if you want to see these dwarfs sized according to their intrinsic luminosity, just type `lum lum`. To change back to constant luminosity, type `lum const`.

Selection expressions. To see the various types of dwarfs we have predefined selection expressions.

`Mdwarfs`	`thresh sptypeidx 0 9.9`	See the M dwarfs
`Ldwarfs`	`thresh sptypeidx 10 19.9`	See the L dwarfs
`Tdwarfs`	`thresh sptypeidx 20 29.9`	See the T dwarfs
`Ydwarfs`	`thresh sptypeidx 30 39.9`	See the Y dwarfs

Exoplanets

Group Name	`Expl`
Reference	NASA Exoplanet Archive (CalTech/NASA)
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`expl.speck` `expl.label`
Dependencies	`target-blue.pbm`
Census	2,517 systems with 3,397 planets 89 systems have no distance

Extrasolar planets, or exoplanets, are a relatively new phenomenon in astronomy. While many astronomers believed in their existence, no observational evidence was available until 1995. Since that time, we have discovered thousands of systems consisting of one or more planets around a host star, by way of several detection methods.

Lost in starlight—detecting exoplanets. To the eye, exoplanets are lost in the glare of their host star. Unconventional techniques are required to infer or observe them. The most common method, thanks to the Kepler Mission, is using the transit of the planet in front of its host star. This, of course, requires the alignment of the orbit is edge-on from our vantage point, which is not terribly probable. However, this method can detect planets a few thousand light years away. Projects include Kepler, Wide Angle Search for Planets (WASP), the Kilodegree Extremely Little Telescope (KELT), the Hungarian Automated Telescope (HAT), and the Convection Rotation and planetary Transits (CoRoT).

The radial velocity method is the next most common. A variation in the star's radial velocity is observed in the spectrum and results from the planet's motion around the star. While we think the Sun is stationary, it actually moves, or wobbles, because of the planets that orbit around it. The larger the planet, the larger the wobble. This is because the center of the orbit is actually located at a point called the center of mass of the system. So, for example, the Sun-Jupiter system's center of mass is more than 778,000 kilometers (483,000 miles) from the Sun's center. This point, along the line connecting the two bodies, lies just outside the Sun's photosphere, or "surface," which has a radius of about 696,000 km (432,000 miles). While we do not perceive it, the Sun is orbiting this point and would be observed to wobble from a point of view outside the Solar System. Some projects detecting radial velocities include High Accuracy Radial Velocity Planet Searcher (HARPS) and the High Resolution Echelle Spectrometer (HIRES) on the Keck Telescope.

The next most common method for exoplanet discovery uses gravitational microlensing to detect a planet. Lensing occurs when the light of a distant star is magnified by a foreground star. When the foreground star has a planet, its gravitational influence is seen in the lensed light from the background star. This requires two stars to align with one another, which only happens for a short time, given earth is in motion, along with the two stars in question. This requires continuous monitoring to catch one of these lensing events. The Optical Gravitational Lensing Experiment (OGLE) developed a technique for observing such events. The benefit of this technique is that lensing can reveal low-mass planets with smaller orbits. The drawback is that the observation cannot be repeated, and science likes reproducibility.

At the bleeding edge of exoplanet science is direct imaging. Planets that orbit far from their host star and can be resolved, tend to reflect less starlight and so we can detect their thermal energy. This method is only really beneficial for systems near the sun, and for large planets that orbit far from their star. But, it is a burgeoning field and about one percent of these planets were found by direct imaging.

Less than one percent of the known systems were discovered using other methods, including pulsar timings, measuring the periodic variation in the light arrival time.

Planetary hosts. Most planetary systems are hosted by main-sequence stars. These systems take the names of their host star. Some of these stars have Bayer names, like Upsilon Andromedae, some have Flamsteed names, like 51 Pegasi, the first system detected in 1995, and others have HD numbers from the Henry Draper star catalog. Two pulsars host planets and are labeled with “PSR.” The detection method used for pulsars allows their planets to be found at greater distances.

Planets visualized. The exoplanet systems are represented by a blue ring centered on each host star. The ring is not intended to signify an orbit; the various sizes relate their distance from you. The labels list the host star name, and if there is more than one planet, will list the number of planets in parentheses.

0	`distance`	Distance of the system	light years
1	`numplanets`	Number of planets in the system	—
2	`year`	Year of discovery	years
3	`method`	Discovery method	—
4	`distmethod`	Distance source	—

The `method` metadata specify the method, via the method number, for detection of the exoplanet.

Discovery Method for Exoplanets		
Method Number	Number of Systems	Description
1	462	Radial velocity
2	1970	Transit
3	35	Imaging
4	2	Pulsar timing
5	43	Microlensing
6	1	Astrometry
7	2	Orbital brightness modulation
8	1	Pulsar timing variations
9	1	Eclipse timing variations

The `distsource` metadata specifies the source catalog used for the distance to the system. When possible, we match the distance to our AMNH star catalog so the two data sets correlate with one another. If it's a Kepler planet, we pull the distance from the Kepler candidates data set. And, if the host star is not in either of these catalogs, we use the distance provided in the original exoplanet catalog from the source.

Distance Source for the Exoplanetary Systems		
Source Number	Number of Systems	Source
1	454	AMNH star catalog
2	1704	Kepler candidates star catalog
3	359	NASA exoplanet archive

Kepler Candidates

Group Name	`Kepler`
Reference	NASA Exoplanet Archive (CalTech/NASA)
Prepared By	Brian Abbott, Emily Rice, Jason No (AMNH)
Labels	No
Files	`kepler.speck` `kepler.label`
Dependencies	`halo.pbm`
Census	4,269 Kepler candidate stars

The Kepler candidate stars are likely targets for exoplanets. These are stars plucked from NASA's Kepler space telescope. The Kepler mission was designed to stare at one spot, roughly twelve degrees across, in the constellation Cygnus. By staring at one spot, the spacecraft could monitor over 100,000 stars in that field for subtle variations in brightness.

These slight difference in brightness signify the transit of the star's planet, so we must view the planetary orbit edge-on for Kepler to detect a planet. In order to be considered a candidate for exoplanets, the observations must pass several tests to rule out other factors that could affect the brightness.

In July 2012, Kepler lost control of four of its reaction wheels that provide attitude control of the spacecraft. And, less than one year later, one of the two remaining reaction wheels failed, threatening the entire mission. In response to this, the K2 mission was accepted as an extension of the original mission. The spacecraft was limited to searching along the plane of Earth's revolution around the Sun, called the ecliptic. In addition to the field of data in Cygnus, fewer K2 candidates appear in batches along the ecliptic.

Visualization. The data included here are the stars that are considered good candidates to host planets. Rather than represent them photo-realistically, with accurate colors, we choose to visualize them as generic, pure yellow stars. The nature of these stars is not important, it is their distribution that concerns is.

Exoplanets and Kepler. The crucial aspect of these data are seeing just how many have been confirmed to host planets. By viewing these in concert with the Exoplanets group, we can see just how many in the original Kepler field are confirmed. To see the exoplanets far out into the Kepler field, you will need to brighten them up a lot. Select `Expl` as the active group, and use the Slum Slider to make them larger.

Open Star Clusters

Group Name	OC
Reference	Optically Visible Open Clusters & Candidates (Dias+ 2015) XHIP: Extended Hipparcos Compilation (Anderson+ 2012)
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`oc.speck` `oc.label`
Dependencies	None
Census	2,040 clusters with labels

An open star cluster is a loose assemblage of stars numbering from hundreds to thousands. Unlike in an OB association, the stars in an open cluster are bound by their mutual gravitation. Astronomers know from the stellar spectra that stars in open clusters are typically young. (With a star's spectrum, we can determine the spectral type and the luminosity class, revealing the age of the star.)

Because these are young stars, we expect to see them in the star-forming regions of our Galaxy, namely in the spiral arms. For this reason, open clusters exist, for the most part, in the plane of the Galaxy, where we view the arms edge-on as that band of light in the night sky. Because of this, open clusters were originally known as Galactic clusters, but this term fell out of favor once astronomers began to understand that the Galaxy includes objects beyond the Milky Way's disk.

Source catalog. The open cluster catalog was compiled by Wilton Dias and collaborators in Brazil and Portugal. It is a comprehensive collection of data from other catalogs coupled with the latest science and data from ground- and space-based observatories.

0	`diam`	Angular diameter of the cluster	arcminutes
1	`logage`	Log of the cluster's age	log years
2	`distance`	Distance to the cluster	light years

Exploring the data. Open clusters are good tracers of local spiral structure. We have included a parameter in the data file to emphasize this point visually. The `logage` metadata is an indication of where the most recent clusters are forming. A preset selection expression (in `milkyway.cf`), called `young`, will remove the older clusters from view, leaving those clusters younger than 20 million years. To see this, type `see young` at the Partiview Command Line (be sure `OC` is the active group).

From outside the Galaxy, the remaining clusters vaguely trace out the local spiral structure, which form three distinct arms: the Sagittarius Arm toward Galactic center; the Orion Spur, where we live;

and the Perseus Arm, toward the outer edge of the Galactic disk. To emphasize the point further, turn on the OB associations (`OB`). These are in exact agreement with the open clusters, each providing a measure of the Galactic structure in our part of the Galaxy. The spiral structure is also visible in the pulsars (`Pul`) and the star-forming regions (`H2`). Type `see all` to return all clusters to view.

OB Associations

Group Name	`OBassoc`
Reference	New List of OB Associations (Melnick+ 1995)
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`ob.speck` `ob.label`
Dependencies	`ob.cmap`
Census	61 OB associations
Notes	Blue = Sagittarius Arm Purple = Orion Spur Orange = Perseus Arm

OB associations are young groups of stars that were formed within a giant molecular cloud, but have dispersed after the original gas and dust from the cloud is blown away by the star's radiation pressure. Although an association's stars are no longer gravitationally bound to one another, they share a common motion in space because they were formed from the same cloud. This allows astronomers to easily determine OB association membership stars.

Associations typically have anywhere from 10 to 100 massive stars (O and B stars), and hundreds or thousands of lower-mass stars. The short-lived O stars will explode via supernova in roughly a million years, so they do not move far from their birthplace.

O and B stars are quite luminous, making OB associations visible to great distances. And since O and B stars are young stars, we know they form in the regions of the Galaxy where star formation occurs: the spiral arms. Therefore, OB associations are good tracers for spiral structure.

In the Atlas, seven-sided polygons of different colors represent the these data. The colors denote spiral arm membership. All the associations in this data set lie within 10,000 light-years, close enough to see our neighboring arms: the Sagittarius Arm toward Galactic center (blue), the Perseus Arm opposite Galactic center (orange), and the Orion Spur (purple). The Sun and Earth are located just on the inner edge of the Orion Spur, whose bright stars are scattered throughout Orion, Cygnus, and Centaurus.

Color and size. There are two settings for the color and luminosity of the OB associations. The default has colors set to the color data variable in the `ob.speck` file. This produces blue (Sagittarius Arm), purple (Orion Spur), and orange (Perseus Arm) markers. The luminosity of each point is set to the association's diameter (in parsecs), rendering markers whose size no longer decreases with distance but is set to a scaling of the association's physical size.

0	`diameter`	Diameter (used for luminosity/size)	parsecs
1	`distance`	Distance to association	light years
2	`arm`	Spiral arm index: 1 = Sagittarius Arm 2 = Orion Spur 3 = Perseus Arm	—

If you want to use a constant sizing, type `lum const 50`. Now, as with other data groups, the larger the marker is, the closer it is to you. If you would like a constant color as well, type `color const 0.4 0.5 1.0`, and the polygons will all be blue. To return to the settings based on the metadata color and luminosity, type `color color` and `lum diameter` at Partiview's Command Line.

Globular Star Clusters

Group Name	GC
Reference	Properties of Galactic Globular Clusters (Francis+ 2014)
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`gc.speck` `gc.label`
Dependencies	None
Census	157 clusters with labels

Globular star clusters are gravitationally bound groups of 100,000 to 1 million stars. They are compact, spherical "balls" of stars with very high stellar densities in their centers (stars near their center are within a light year of one another). These clusters are typically 30 to 100 light years in diameter. If Earth were located inside one of these clusters, our sky would be lit by thousands of stars brighter than the brightest stars we currently see.

Size of our star system. Globular clusters were paramount to our understanding of the structure of our Galaxy. The story began in 1912, when Henrietta Leavitt (1868–1921), a "computer" for astronomers at the Harvard College Observatory, discovered a relationship between the period of Cepheid variable stars and their intrinsic luminosity (absolute magnitude). She found that the longer the period of variability, the more luminous the star. By observing the period of variation, Leavitt then knew the star's absolute magnitude, or intrinsic luminosity, and with the observed apparent brightness, she was able to find the distance to these stars.

In 1918, the astronomer Harlow Shapley (1885–1972) noted that the open clusters were mainly in the plane of the Milky Way, while more than half the globular clusters were in or near the constellation Sagittarius. He deduced that these clusters must be distributed around the center of our star system, the Milky Way, and that we were viewing that point from afar. If he found the distances to these clusters, he would find the distance to the center of our Galaxy, overthrowing the long-held belief that Earth was at the center of the Universe.

Shapley observed the presence of RR Lyrae stars in these clusters. RR Lyrae stars vary in brightness over periods of less than a day, so they are easy to observe provided they are bright enough. While the intrinsic brightness of Cepheids was known, the period-luminosity relationship had not yet been established for RR Lyrae stars. Shapley was able to calibrate these variable stars to the intrinsic brightness scale and was then able to find the distances to the clusters. Jan Oort, a Dutch astronomer, confirmed this result by studying the motions of stars, showing that they are orbiting about a distant center.

We know today that Shapley overestimated their distances by about a factor of three, making the Galaxy about 300,000 light-years in diameter. Shapley was a proponent of the Milky Way Universe cosmology, believing that all that we see is part of our Galaxy and that our Galaxy is the entire Universe. In April 1920, Shapley and the astronomer H. D. Curtis met at the National Academy of Sciences to debate this cosmology in what is now called The Great Debate. This question would be answered within five years by Edwin Hubble (1889–1953) when, in 1923, he discovered Cepheid variables in the Andromeda Nebula. He found the distance to the Andromeda and M33 to be about 300 kiloparsecs (just less than 1 million light-years). An underestimation, but these results set the scale. Now the Andromeda Nebula could be considered a galaxy in its own right and the Universe was now known to be far larger than the Milky Way.

Exploring the catalog. The globular clusters form one of the most complete data sets in the Atlas. Data for the clusters represent almost all the clusters in our Galaxy—several on the opposite side of Galactic center may be invisible to us.

In Partiview, it's easy to see what Shapley observed a century ago: that most of the clusters are located around the constellation Sagittarius. The closer the marker, the closer the cluster. One of the nearest clusters to us is Messier 4 (M4), in the constellation Scorpius. It is about 6,100 light-years away. Some of the farthest clusters lie at the edge of the Galactic halo and perhaps even beyond it.

Cluster ages. The age of a globular cluster is directly related to something called metallicity. (In astronomy, all atomic elements heavier than helium are called metals, and the metallicity is the fractional abundance of these elements in an object.) Clusters with stellar populations that have higher metallicities (more metal-rich stars) are younger, and are typically found near the Galactic center. Clusters that are deficient in metals are older, and found in the Galactic halo. Use the Partiview commands `see young` and `see old` to invoke preset selection expressions to see these data subsets. Remember `see all` returns all data to view.

Globular clusters are among the oldest objects in the Galaxy. They were around when the Galaxy formed 12-13 billion years ago, perhaps even before the disk evolved to the shape it is today. Some of the oldest stars in the entire Galaxy are found in these clusters.

The metal-rich clusters are several billion years younger than the metal-poor clusters. This may be a reflection of galaxy interaction and tidal captures from other small galaxies. In fact, astronomers are now studying whether some of the globular clusters previously thought to belong to the Milky Way are bound to other small satellite galaxies.

Pulsars

Group Name	`Pul`
Reference	ATNF Pulsar Catalogue (Manchester+ 2017)
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`pulsar.speck` `pulsar.label`
Dependencies	None
Census	2,498 pulsars and labels

Upon death, stars leave behind one of three possible remnants: a white dwarf, a neutron star, or a black hole. Stars that are more massive than the sun will often become neutron stars in a violent explosion called a supernova. During a supernova, the core of the star collapses under such high pressure that the electrons, which normally remain outside the atomic nucleus, are forced to combine with the protons in the nucleus. Atomic nuclei break apart, producing what is called a degenerate state of matter. The collapse is halted when the material cannot be packed any tighter. At this point, the star has a radius of about 10–15 kilometers. The density of this material is so high that a teaspoonful would weigh about 100 million tons on Earth.

Just as ice skaters spin faster as they pull their arms in, dying stars rotate faster as they collapse. If the Sun were to suddenly collapse to a radius of 10 km, its rotation period would increase from its current 25 days to 1,000 times per second. Similarly, after a supernova, the neutron star is spinning fast from the rapid collapse, but it slows over time as it converts rotational energy into radiation.

Astronomers now know that pulsars are not pulsing but are spinning neutron stars whose beams of radiation point toward Earth just as a lighthouse sweeps the horizon. Pulsars have strong magnetic fields that funnel beams of light from its magnetic poles. When these beams point to Earth, we see a strong radio signal.

Observing pulsars. The first pulsar was discovered in November 1967 by Jocelyn Bell, who was then a graduate student at the University of Cambridge. Bell and Anthony Hewish investigated further and found the repeating signal had a period of 1.3373 seconds and originated from the same spot in the sky, night after night (Hewish won the 1974 Nobel Prize in physics for this discovery). The regularity of the signal led them to consider calling these objects LGMs—Little Green Men—implying these regular signals must come from intelligent beings. However, more were soon found in other parts of the sky flashing at different periods and the LGM name was dropped in favor of “pulsar.”

Pulsars are observed primarily in the radio spectrum, although some are seen in the visible, x-rays, and gamma rays. (The Crab Nebula Pulsar, the Vela Pulsar, and a few others are seen in the visible spectrum.) Pulsar signals are detected with radio telescopes including those at Green Bank, West Virginia (US); Arecibo, Puerto Rico; Jodrell Bank in the UK; and the Parkes Observatory and the Molonglo Observatory in Australia. The observing frequencies range from 400 MHz to 1520 MHz. The periods of most pulsars are between 0.03 and 0.3 seconds. This corresponds to a flashing between 3 and 30 times each second, a rate our eye cannot detect.

The basis for this catalog was compiled by Joe Taylor (Princeton), Richard Manchester (Australia Telescope National Facility), and Andrew Lyne (University of Manchester) and published in 1993. The Australia Telescope National Facility (ATNF) has taken this catalog and added many more pulsars which were mainly discovered by the ATNF. The labels take the form of right ascension in hours and arcminutes and declination in degrees and minutes. For example, PSR0334+2356 is a pulsar that lies at 3 hours, 34 arcminutes right ascension and +23°, 56 minutes declination.

Pulsars and supernova remnants. Many pulsars are found in the `SNR` group. Since supernova remnants have short lifetimes, we can assume that the pulsars seen in them are quite young. Once the supernova remnant disappears, the pulsar's rotation period continues to slow, and after about 1 million years the pulsar is no longer visible. Therefore, all the pulsars we see today must be the remnants of stars that have died over the previous 100,000 to 1 million years.

Pulsars in globular clusters. Pulsars result from the supernova explosions of stars that live only a few tens of millions of years after their formation. Why, then, do astronomers see so many pulsars in globular clusters that are more than 10 billion years old? The answer seems to be that these pulsars are drawing in material from a nearby companion star. This matter causes the star to spin faster, re-energizing the system. These are called millisecond pulsars for their periods, which can be as short as 0.002 seconds (2 milliseconds). More than 30 of these have been found and are easily seen to line up with the globular clusters in the atlas. (Note that the distances can differ between the pulsar data and the globular cluster data, since they use different distance determination techniques.) Some examples include the globular clusters 47 Tuc, M5, and M13.

Spiral structure. The pulsar catalog clearly shows the nearby spiral arms. The Sagittarius Arm is prominent in the direction of galactic center, and the Perseus Arm is anticenter. Traces of the arms interior to Sagittarius, the Scutum-Centaurus Arm and even the Norma Arm are visible.

Planetary Nebulae

Group Name	PN
Reference	Strasbourg-ESO Catalogue of Galactic Planetary Nebulae (Acker+ 1992)
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	pn.speck pn.label
Dependencies	None
Census	778 nebulae and labels

A planetary nebula is an expanding shell of gas ejected from a star late in its life cycle. Appearing like greenish disks to a telescopic observer, planetary nebulae received their name from their resemblance to the gaseous planets of our solar system. In no way are they related to planets, rather, they are products of dying stars.

As an intermediate-mass star exhausts its core hydrogen fuel, its helium core contracts and heats to meet the energy needs of the star. The core contraction releases gravitational energy, which has two effects. First, hydrogen just outside the core begins to burn, producing a more massive helium core over time. Second, the expansion of the star's envelope, or its outer layers, occurs. The star becomes a red giant.

For stars of less than about two solar masses, the core continues to condense until the temperature and density become sufficient to burn helium into carbon. The ignition of helium occurs rapidly, producing a flash of light, and the star's outer shells expand, leaving a bright core that soon becomes a white dwarf star. These expanding shells become the planetary nebula.

Planetary nebulae are often spherical. As the gas from the star expands, it sweeps up the cooler gas like a snowplow. The gas glows because of the ultraviolet light from the stellar remnant at the center.

Planetary nebulae in the Galaxy. The Milky Way consists of two major star populations: the older halo population and the younger disk population. Because the planetary nebula phase of a star's evolution is relatively short, we observe only those that have occurred recently in the younger stellar population. Therefore, we expect to see planetary nebulae in the disk of the Galaxy. Moreover, the inner disk of the Galaxy has a higher star density and a higher ratio of young stars to old. For these reasons, we expect to see planetaries in or near the Galactic disk and we expect to see an increased number toward the Galactic center.

The stars that will evolve into planetary nebulae also typically have relatively eccentric orbits around the Galaxy and, therefore, a wider range of distances above and below the Galactic disk. Thus we also expect to see increased numbers of nebulae above and below the Galactic plane.

In the Digital Universe, we see all of these trends. While the data are observationally biased, we do in fact see the planetaries trending toward the disk, with less correlation to the plane than, say, the HII regions. We also see more planetaries toward the Galactic center, as well as an increased amount above and below the plane at Galactic center.

Supernovae Remnants

Group Name	`SNR`
Reference	The First Fermi LAT SNR Catalog (Acero+, 2016)
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`sn.speck` `sn.label`
Dependencies	None
Census	112 supernovae remnants

A supernova remnant is the nebulous gas left over from a supernova explosion. During a supernova, one-fifth the mass of the original star may be expelled. This gas expands at great speeds, 10,000 to 20,000 km/sec, and rams into the surrounding interstellar gas. The expanding gas excites the surrounding gas, causing it to glow, producing the nebulous cloud we observe from Earth.

A supernova remnant contains a neutron star or pulsar at its center, the core of the dying star. The cloud that enshrouds the core does not last long, though. After about 50,000 years, the gas mixes into the interstellar medium and no longer glows. Astronomically, this is a very short time, so the supernova remnants we see must be left from explosions that have occurred very recently.

The most recent supernova occurred in the Large Magellanic Cloud in 1987. The most studied supernova in history, SN 1987A is the latest in a series of explosions observed by astronomers. In 1054, the Chinese recorded the appearance of a “guest star” in Taurus. Bright enough to see in the daytime, the star brightened rapidly, then faded from sight over the next two years. Modern astronomers pointed their telescopes to the star and found a gas cloud about 4.4 light years in radius expanding at a rate of 1,400 km/sec. Projecting this expansion back in time, they found that the explosion began about

900 years ago, confirming the Chinese records. We call the object Messier 1 (M1), or the Crab Nebula.

In the past 2,000 years, only 14 supernovae (SN) have been recorded in our own Galaxy. Aside from SN 1054, Arab and Chinese astronomers observed one in 1006 and European astronomers observed SN 1572 (Tycho's supernova Cassiopeia A) and SN 1604 (Kepler's supernova in Serpens). For the next 383 years, no supernovae were seen, until February 23, 1987, when a "new star," SN 1987A, appeared in the Large Magellanic Cloud.

Location in the Galaxy. Similar to pulsars, supernova remnants are found in the disk of the Galaxy. These remnants are short-lived nebulae and will be visible only in areas of active star formation. Because they have such short lifetimes, you would expect them to be tightly correlated with the Galactic disk and, relative to the pulsars, lie very close to the plane of the Galaxy.

Labels. The labels are a hodgepodge of different catalog source names. A few are in "English," such as the Cygnus Loop (the Veil Nebula region). Some have names from the Third Cambridge Radio Survey Catalog that begin with 3C, while others have a W number, from the Westerlund catalog. And there are others, too numerous to discuss here.

HII Regions

Group Name	`H2`
Reference	The WISE catalog of Galactic HII regions (Anderson+, 2014)
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`h2.speck` `h2.label`
Dependencies	None
Census	1,546 star-forming regions and labels

HII (pronounced "H-two") regions are stellar nurseries for newborn stars. Stars are born from condensing clouds of hydrogen gas. As these clouds condense, the densities become high enough to form stars.

Typical gas clouds in the interstellar medium have densities too low to form stars. They need an outside stimulus or perturbation, like a nearby supernova, to compress parts of the cloud. If this occurs, small fragments are compressed, and heat up the gas. If the cloud densities continue to increase, the cloud will collapse into a protostar. This protostar will contract under its own gravity, causing it to heat up. Eventually the protostar is hot enough to clear away the gas and dust that enshroud it. When the core temperature is hot enough for hydrogen fusion, the star is born.

HII regions are the surrounding clouds of hydrogen that glow from the stars born within them. It takes ultraviolet light to ionize hydrogen, light that can come only from hot, luminous stars (like O stars). When the star "turns on," the electrons in the surrounding hydrogen are stripped away. The hotter the star, the farther the ionization radius, creating what astronomers called a Strömgren sphere. An O5 star can excite hydrogen up to 65 light years from the star. (Ionized hydrogen is typically written as H^+, but in astrophysics, the convention is to use roman numerals, so HI is neutral hydrogen, and HII is ionized hydrogen.)

The result is a bright, glowing nebula which is seen to great distances. One local celebrity among HII regions is the Orion Nebula (M42). About 1,500 light-years away, the wispy cloud is visible to the naked eye in Orion's sword and resembles a hazy star. At its center are four bright stars that form an asterism called the Trapezium. These stars are surrounded by the cloud, which is about 25 light years across. The largest of these stars, θ^1 Orionis C, is 40 solar masses and has a surface temperature around 30,000 Kelvin (compared that with the Sun's 6,000 K), and is about 300,000 times more luminous than the Sun. The cloud, however, is heated only to about 70 K and has a very low density of 600 atoms per cubic centimeter. Compare this with air at sea level that has 1,019 atoms per cubic centimeter.

Tracing Galactic structure. From Earth's perspective, you'll notice that the HII regions all lie close to the Galactic plane. This is not an accident of nature. These star-forming regions lie in the plane of the Galaxy because that is where star formation occurs in spiral galaxies such as our Milky Way.

Radio astronomy was born in the 1950s, but it was not until the late '60s that astronomers began using these observations to trace the spiral arms of our Galaxy, forming a picture of the Galaxy we live in. Only 40 years earlier, we were debating the very existence of galaxies, and now we were mapping our Galaxy's spiral arms using radio observations of the CO molecule found in HII regions.

These data clearly delineate the spiral arms of the galaxy. Strands of these nebula arc along the Sagittarius Arm and the Perseus Arm, and one side of the Norma, and Outer Arms. You may also notice a nearby cluster toward Cygnus. These correspond with the Cygnus OB Associations, where there is ongoing star formation.

Orion Nebula

Group Name	`OriNeb`
Reference	Model: Wen & O'Dell, The Astrophysical Journal, v438, p784 Image: NASA, ESA, M. Robberto (STScI/ESA), Hubble Space Telescope Orion Treasury Project Team Stars: Orion Nebula Cluster Population (Hillenbrand 1997)
Prepared By	Carter Emmart, Erik Wesselak, Brian Abbott, Ryan Wyatt (AMNH)
Labels	No
Files	`orion_nebula.obj`, `orishocks.obj`, `proplyds.obj` `oricluster.speck`
Dependencies	`halo.bpm`, `colorbv.cmap`, `heic0601a_masked.pbm`
Census	813 stars, 1 3-D nebula model with shocks and proplyds
Notes	Star distances are statistically generated

The Orion Nebula, at about 1,500 light years, is one of the closest star-forming regions to us. Ultraviolet light from its young, hot stars causes the surrounding hydrogen gas to glow. Astronomers call this an HII region (HII is the astronomical symbol for ionized hydrogen).

To view the Orion Nebula up close, use the Field of View Slider, and with the nebula centered, reduce the field of view until the nebula is sufficiently large.

Also known as M42, the Orion Nebula shows up in the HII regions and its associated stars are represented in the Orion Nebula star cluster, the open clusters, and the OB associations, but it receives special treatment here as a three-dimensional model recreated from Hubble Space Telescope observations of the nebula.

To visit and explore the Orion Nebula, fly out to the object, place your mouse over one of the stars in the cluster, and hit shift-p. This changes your origin to the chosen object. To return the origin to the Sun, pick the Sun in the same manner, or type `center 0 0 0` *at Partiview's Command Line.*

The hot, young stars at the center of the Orion Nebula ionize the surrounding gas—ultraviolet radiation strips electrons from their parent atoms—and when the electrons get reabsorbed by other atoms, light is emitted. Radiation from the hot stars doesn't ionize all that gas instantaneously; it takes time for the ultraviolet light to penetrate the dense gas clouds in which stars form. The radiation eats into the surrounding cloud, carving out a vast, electrically charged volume of space. Astronomers call the transition region from neutral to ionized gas the "ionization front." Most of the light we see comes from the ionization front.

Furthermore, the emission of light occurs at very specific wavelengths, so astronomers can tune their observations to capture exactly these parts of the electromagnetic spectrum. Although the nebula contains primarily hydrogen and helium, astronomers also study light emitted by oxygen, sodium, sulfur, and other atoms that exist in much smaller quantities. As it turns out, these trace elements allow astronomers to determine many characteristics of the nebula—its density and temperature, for example. Based on the assumption that most of the ionizing radiation comes from a particular star in the nebula, θ^1 Orionis C, astronomers have reconstructed the three-dimensional shape of the ionization front.

Most HII regions that we see lie close to the edge of dense clouds of molecular hydrogen (HII regions embedded inside such clouds remain invisible at optical wavelengths). The Orion Nebula has entered what some call the “champagne phase” of an HII region, when the young stars’ radiation has heated enough of the surrounding gas for it to expand and burst out of the dense molecular cloud in which it formed. We view the nebula from an angle that allows us to see the “far wall” of the ionization front, in front of which (from our perspective) lie the bright young stars of the Trapezium and the heated gas moving toward us at about 10 km/sec. We actually see through the veil of gas to the ionization front in large part because we are observing the finely-tuned emission from trace elements, which passes through hydrogen and helium without being absorbed.

The ionizing radiation comes primarily from a single star, θ^1 Orionis C, which allowed the astronomers Zheng Wen and C. Robert O’Dell to reconstruct the three-dimensional form of the ionization front. Assuming a constant thickness for the emitting layer, one can actually determine its distance from the nebula’s brightest star. We know the spectrum of the light coming from the star, and we know how the atoms in the nebula respond to the star’s radiation—each atom acts like an electromagnetic tuning fork, ringing with a particular frequency of light. Thus, the shape of a nebula can be determined through careful observation and a knowledge of the laws of atomic physics.

The model. In the Digital Universe model of the Orion Nebula, we depict the ionization front effectively as a terrain, with a flat Hubble image of the nebula mapped on the undulating surface. In reality, the ionization front has a slight thickness to it—about a third of a light year—but is quite thin compared to the overall size of the nebula, which stretches about ten light years from side to side.

The first American Museum of Natural History space show, *Passport to the Universe*, used this same model, rendered into a digital movie using advanced volumetric techniques, to voyage through the Orion Nebula. A limitation of the way Partiview displays the model causes parts of it to appear deceptively bright—when the surface folds over on itself, for example, the additive brightness results in a region that appears excessively bright.

Close into the center, near θ^1 Orionis C, we see small teardrop-shaped structures with their narrow ends pointing away from the bright star: these are protoplanetary disks (or “proplyds”) of dense gas and dust surrounding young stars. The sides of the proplyds that face θ^1 Orionis C form tiny ionization fronts of their own, which end up shielding the far side of the proplyds to form tails. Proplyds near θ^1 Orionis C have long, slender tails whereas the ones farther away have short, stubby tails.

The larger formations that one sees farther away from the center of the nebula take on a cup-like shape, with the narrow end pointing away from the nebula's center. These enormous structures are "bow shocks" that delineate the region where high-speed winds from the central star slow from supersonic to subsonic speeds. (There may be no sound in space, but there is a speed of sound—the velocity at which a compression wave naturally travels given the temperature and density of the tenuous medium. "Supersonic" is a speed faster than that, "subsonic" is slower than that.) You can think of an HII region as a sort of tremendous explosion, taking place over millennia, and the bow shocks are part of the outward rush of material.

Both the bow shocks and the proplyds suffer from a problem similar to the aforementioned issue with the surface folding over on itself. When seen with the ionization front model behind them, they appear brighter than normal. Furthermore, the bow shocks consist of a front and back side, which can look slightly odd when viewed from some angles.

Overall, the Orion Model represents a triumph of our understanding of the dynamics and detailed structure of HII regions. Not only can we admire the beauty of the Orion Nebula as seen through a telescope, we can measure particular characteristics of the nebula and reconstruct it in three dimensions.

The star cluster. In order to have an accurate depiction of the Orion nebula, we needed to include the star cluster that was birthed from it. We turned to a study of the cluster's stellar population by Lynne Hillenbrand, who was working at the University of California, Berkeley at the time.

The catalog from her paper contains more than 1,500 stars, about half the stars in the actual cluster. The cluster is very crowded, with a peak density of 10,000 stars per cubic parsec over a wide range of masses from a tenth the sun's mass up to 50 times its mass. We were presented with one problem: there are no distances.

For the stellar distances, we needed to deduce them by statistical methods. Knowing the size of the cluster and approximating the shape to be roughly spherical, we placed each star along a line of sight through this imaginary sphere centered on the cluster. In this sense, these data are observed data, for the view from Earth is accurate. But the distance of each star has been derived from this educated-guess approach for the cluster distribution.

Oort Cloud

Group Name	`Oort`
Reference	—
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`oort.speck`
Dependencies	none

The Oort cloud is a region of space surrounding the Sun where comets are believed to originate. Proposed by Jan Oort in the 1950s, the Oort cloud is believed to extend from 20,000–100,000 AU, or Astronomical Units, with its greatest concentration around 50,000 AU (1 AU is the average Earth-Sun distance, which equals 149 million kilometers, or 93 million miles).

Comets are small, icy bodies that orbit the Sun. Perhaps the most famous is Halley's Comet, which travels around the Sun in an eccentric orbit every 76 years. Comets were likely ejected from the solar system once the planets formed. Jupiter, Saturn, Uranus, and Neptune's strong gravitational field likely ejected many comet-sized bodies out of the solar system in random directions, where they settled into a cloud.

Occasionally, one comet in the cloud interacts with another or is perturbed by a passing star or a passing star's comet cloud. This could send the comet toward the Sun and planets, where it may enter into an eccentric, long-period orbit.

We represent the Oort cloud with a 50,000-AU-radius, wire-frame sphere representing the location of the central concentration. Fifty thousand astronomical units is equal to about 10 light months, which is 0.8 light years, or 4.8 trillion miles. Keep in mind, though, that the Oort cloud is 80,000 AU thick and imagine a similar sphere around each star in the atlas. Would any two overlap? Of course, stars of different luminosities would have Oort clouds of differing size, or even no Oort cloud at all, but visualizing the Oort cloud allows us to see the possibility of stars interacting.

The Oort cloud is the last outpost of our solar system. Beyond it is the gas of the interstellar medium through which the Sun, planets, and comets move as they orbit the Galaxy once every 225 million years.

Equatorial Coordinates aka Radio Sphere

Group Name	`RaDec`
Reference	—
Prepared By	Carter Emmart, Brian Abbott (AMNH)
Labels	Yes
Files	`radec.speck`
Dependencies	none
Notes	Also represents Earth's radio sphere, with R = 75 light years

The equatorial coordinate system is a projection of our Earth-based coordinate system of latitude and longitude onto the "celestial sphere." The celestial sphere is an imaginary shell that surrounds Earth upon which all objects in the sky lie. Astronomers describe an object's position in the sky by its right ascension (RA) and declination (Dec). Declination is simply a projection of our latitude on Earth. The point directly above the North Pole (the zenith point) is the north celestial pole and is located at +90° declination. If you're standing on Earth's equator, your zenith—that point directly overhead—would lie on the celestial equator.

Right ascension is based on Earth's longitude but is expressed in hours instead of degrees. Astronomers have split the sky into 24 hours (15° per hour) measured from the vernal equinox. An object's location is then described in hours, arcminutes, and arcseconds. For example, the star Sirius in the constellation Canis Major, the brightest star in the sky as seen from Earth, is located at right ascension 6 hours, 46 arcminutes, and −16° 45 minutes declination.

We use arcminutes and arcseconds for right ascension to remind ourselves that the length of these units depends on your declination. Close to the pole, an hour of right ascension will be quite small, while at the equator, it will be at its maximum. As with lines of longitude on Earth, lines of right ascension are not parallel with one another.

The radio sphere. We have not chosen the radius of this sphere arbitrarily. The RA/Dec coordinate sphere takes on another role when you're away from the Sun. We call it the radio sphere.

The radio sphere describes the theoretical extent of Earth's radio signals in space. In the early 20th century, radio began to take hold after the discovery that certain radio waves bounce, or reflect, from Earth's ionosphere, a region in the upper atmosphere where gases are ionized by incoming solar particles. However, early broadcasts were not powerful enough to penetrate the ionospheric layers and remained confined to Earth.

Before television carrier waves, early-warning radar first used in

World War II, and the detonation of atomic weapons, Earth was radio-quiet to the Universe. After the use of these and other radio emitters began, in the late 1930s and early 1940s, signals were able to escape the atmosphere and travel into space at the speed of light (300,000 km/sec or 186,000 miles/sec). Since then, we have been broadcasting to the Universe.

As we look farther into space, we look further back in time. Turn on the 1 light year grid (1ly) and imagine what happened one year ago. Broadcasts from that time, traveling at the speed of light, are now reaching the 1 light year mark, 5.89 trillion miles from Earth. They will take an additional three years to reach the nearest star to the Sun. At the edge of the sphere are those transmissions of the 1940s: atomic testing and the echoes of World War II. Turn this principle around and consider the light from distant sources, and we see now why looking into space means we are looking back in time to a younger universe.

However, we mention earlier that this is the *theoretical* extent of these signals. In reality, these signals will dissipate rapidly into the ambient cosmic noise of the universe. All light falls off as $1/r^2$, and radio waves are no different. The signals that emanate from Earth are likely lost in the noise at the edge of the solar system, but the radio sphere remains a visually compelling astronomical concept.

Subdivisions. The current grid is subdivided every hour in right ascension and every 10° in declination. If you need further subdivisions, the data are there, but we've colored them black. To show them, use the `cment` command with the third color index, then specify a color. For example, `cment 3 0.2 0.2 0.2` will show the lines as a dim gray.

Ecliptic Coordinates

Group Name	`Eclip`
Reference	—
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`eclip.speck`
Dependencies	none
Notes	R = 500 light years

Ecliptic coordinates are based on the imaginary line in the sky traced by the Sun throughout the year. This line is called the ecliptic and, in three dimensions, also defines the plane that contains the Sun and Earth.

Because Earth is tilted on its axis 23.5° to this plane, the Sun appears to move in declination throughout the year. Two days a year, on the vernal equinox around March 21, and on the autumnal equinox around September 21, the Sun crosses the celestial equator. Around June 21, it lies over the Tropic of Cancer (the summer solstice in the Northern Hemisphere), and around December 21, it lies over the Tropic of Capricorn (winter solstice for the Northern Hemisphere). Coincidentally, the Tropics of Cancer and Capricorn are at 23.5° north and 23.5° south latitude, respectively.

Ecliptic coordinates are described by ecliptic longitude and latitude measured in degrees (labels provided every 10°). Longitude is measured from the vernal equinox [(RA, Dec) = (0h, 0°)] and the ecliptic north pole is in the constellation Draco (23.5° from the celestial north pole and the north star, Polaris). The ecliptic north pole is the point perpendicular to the plane of the solar system and would be the north celestial pole if Earth were not tilted 23.5°.

A new horizon. In the atlas, the ecliptic sphere is similar to the celestial sphere but is given a radius of 500 light years. Turn on the Milky Way all-sky image (`mwVis`) and notice the tilt of the ecliptic to the band of the Milky Way. These two planes, the plane of the solar system and the plane of the Galaxy, are tilted about 60° to each other (62.87° to be precise).

Many of us are used to thinking of the solar system plane as our cosmic horizon line. All the planets lie roughly within this plane, so it makes sense that this should be the plane from which we measure up, down, over, and under. However, the Milky Way band tells us otherwise. The Sun and all its planets are orbiting the center of the Galaxy once every 225 million years, and doing so while tipped 60° to the Galactic plane. We now see there's a more significant horizon to obey—that of our home Galaxy. Are there any horizons beyond this?

Galactic Coordinates

Group Name	`Galac`
Reference	—
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`galac.speck`
Dependencies	none
Notes	R = 1,000 light years

Once astronomers understood the structure of our Galaxy in the early part of the 20th century, it was necessary to devise a coordinate system based on that structure. Galactic coordinates are defined by galactic longitude, l, and galactic latitude, b, measured in degrees. The "equator" coincides with the plane of the Galaxy. Galactic longitude is measured from Galactic center, which is generally in the direction of Sagittarius A*, a compact radio source that astronomers now know to be about 5 arcminutes from the Galactic nucleus.

The north galactic pole (b = +90°) lies in the constellation Coma Berenices, while the south galactic pole (b = –90°) is in the constellation Sculptor. These points are perpendicular to the plane of the Galaxy. If you look toward these points in the sky, you are looking directly out of the Galactic plane. Because there are not as many stars or much gas and dust in this direction, we can see objects to greater distances when we look toward the Galactic poles. Other galaxies and clusters of galaxies are easier to find in these regions of the sky.

In the atlas, we have given the galactic coordinates a greenish color. Labels appear every 10° in both l and b. The sphere has a radius of 1,000 light years.

Radio All-sky Survey

Group Name	`mwRadio`
Reference	Reprocessed Haslam 408 MHz All-Sky Map (Remazeilles+, 2014)
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`mwRadio408MHz.speck, mwRadio408MHz.label`
Dependencies	`lrg_haslam408_dsds_Remazeilles2014.pbm`
Wavelength	73.4785 cm
Frequency	408 MHz

The 408 MHz all-sky map is one of the most complete radio maps of the sky and remains critical to our understanding of the universe.

At this frequency, the radio continuum is mainly showing hot, ionized interstellar gas. More specifically, observations at this wavelength show light from the scattering of free electrons in interstellar plasmas. This hot gas is typically the result of a supernova explosions that compress and heat interstellar gas.

The most striking feature of the map is the sweeping arc of light in the northern sky. This is called the North Polar Spur, and was thought to be a hot interstellar bubble of gas associated with a nearby supernova that occurred thousands of years ago, or associated with the Sco-Cen star-forming region around 500 light years from earth. However, it is not thought that this emission is associated with the outflows of hot gas from the inner Galaxy. This phenomenon remains a hot topic of study, decades after its discovery.

Other objects in the map include the Orion nebula, the Crab Nebula, the Large and Small Magellanic Clouds, the Andronmeda Galaxy, and the Vela and Cassiopeia A supernova remnants.

The false colors represent intensity, with reds and yellows representing higher intensity than aqua and blue.

Atomic Hydrogen All-sky Survey

Group Name	`mwH`
Reference	HI4PI: A full-sky HI survey based on EBHIS and GASS (AIfA, MPIfR, and CSIRO; Image: Benjamin Winkel, 2016)
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`mwRadio21cm.speck`, `mwRadio21cm.label`
Dependencies	`hi4pi_composite_nogrid_w_on_k.pbm`
Wavelength	21 cm
Frequency	1.4 GHz

Warm neutral hydrogen radiates in the radio spectrum at a wavelength of 21 centimeters. In the hydrogen atom, the electron and proton are magnetized, giving each a north and south pole just like a bar magnet. Any particular neutral hydrogen atom can exist in two configurations: a lower energy state, in which the north poles of the electron and proton are pointing in the same direction, and a higher energy state, in which they point in opposite directions.

The warm interstellar gas provides the energy to boost the atom into this higher energy state. Once the atom returns to its lower energy state, it gives off energy at a wavelength of 21 cm. The low-energy light in this survey reflects the small difference between these atomic states.

This radiation is important because it penetrates the dust in the interstellar medium, allowing us to see it across the galaxy. The 21-cm light is perhaps the most important tracer we have for determining the structure of our Galaxy.

This map conveys more information than intensity. The brightness is proportional to the intensity on a log scale, or the number of atoms along the line of sight. The color delineates the radial velocity, the speed of the gas along the line of sight. Orange, yellow, and green hues indicate gas that is moving away from us, while blue and violet colors show gas that is moving toward us.

Labels reveal some of the prominent features of the map, including the Large and Small Magellanic Clouds, the Andromeda Galaxy, and M33, and the wispy strands of gas that surround us.

Carbon Monoxide All-sky Survey

Group Name	mwCO
Reference	The Milky Way in Molecular Clouds (Dame+, 2001)
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	mwRadio21cm.speck, mwRadio21cm.label
Dependencies	big_wco_image.pbm
Wavelength	2.6 mm
Frequency	115 GHz

In order to map the large clouds of molecular hydrogen (H_2), we look for carbon monoxide (CO). Carbon monoxide is about 10,000 times less abundant than molecular hydrogen, yet we see traces of CO via its radio signature line at 2.6 millimeters (115 GHz). Using radio telescopes, astronomers observe this portion of the radio spectrum where the atmosphere is semitransparent.

Normally, CO molecules would be broken apart by the ultraviolet radiation from stars. However, the CO molecules remain shielded deep inside dense, dusty molecular clouds of hydrogen from the harmful UV rays in interstellar space. This allows scientists to infer the existence of large molecular clouds by observing CO.

The Orion Nebula is the best example of a nearby giant molecular cloud. The nebula sits on the edge of a much larger cloud that is invisible to us in optical light. However, the cooler atomic hydrogen and CO radiate in this region of the EM spectrum. We observe CO mainly in the Galactic plane, where most of the gas and dust are concentrated in our Galaxy and star formation occurs. If we see CO, we can expect to see new stars.

CO intensity is represented by colors mapped to the intensity of the CO spectral line. The violet and blue regions are less intense and the red and yellow regions are of higher intensity. The survey covers the entire range in galactic longitude but only a narrow band centered on the galactic equator. Because CO is confined to the plane of the Galaxy, this is a reasonable range in galactic latitude.

Labels highlight the some of the objects and structures: the Orion Nebula, the California Nebula in Perseus, and the Rho Ophiuchi Cloud, a structure we'll see in many other all-sky images.

Far Infrared All-sky Survey

Group Name	`mwFIR`
Reference	IRAS Sky Survey Atlas Explanatory Supplement (Wheelock+, 1994)
Prepared By	Ryan Wyatt (AMNH)
Labels	No
Files	`mwIRiras100.speck`
Dependencies	`iras-100um.pbm`
Wavelength	100 microns
Frequency	3,000 GHz

IRAS (InfraRed Astronomy Satellite) was launched in January 1983 and orbited 900 km above Earth, observing the infrared sky for much of that year. With its 56-centimeter (22-inch) mirror, IRAS observed in the near and far infrared at 12, 25, 60, and 100 micron wavelengths. (1 micron = 1 μm = 0.001 mm.)

Infrared light comes from cooler objects in the universe: planets, comets, asteroids, cool stars, and dust in space. When astronomers talk about dust, they do not mean those pesky particles that settle on your tabletops. Astrophysical dust refers to microscopic particles. Dust was once thought to be particles composed of 10,000 atoms or more, but thanks to IRAS and other space telescopes, we now understand that it can include smaller particles of just 100 atoms. These microscopic particles are normally quite cold, close to absolute zero even, but when ultraviolet light shines on them, they can increase in temperature by 1000 Kelvin (1300°F).

IRAS's most important discovery was the extent to which dust pervades the Galaxy. IRAS provided us with the most detailed map of interstellar dust to date. Dust is created when stars explode and, therefore, is present where stars are forming. For this reason, dust is abundant within interacting galaxies where mergers trigger new stars to form.

This image is the 100-micron far infrared (FIR) survey. This corresponds to objects with temperatures of about 15 Kelvin to about 120 Kelvin and includes cold dust particles and cold molecular clouds. In some of these clouds, new stars are forming and glow in FIR light. The center of our Galaxy glows brightly in FIR light, where dense clouds of dust are heated by the stars within them. This results in the bright band of light toward Galactic center. The survey is rich in detail, with bright glows in areas of star formation, like the Orion complex and Rho Ophiuchi. Bright extragalactic sources are visible too, like the Andromeda Galaxy and the Small and Large Magellanic Clouds.

IRAS Composite All-sky Survey

Group Name	`mwIRASc`
Reference	IRAS Sky Survey Atlas Explanatory Supplement (Wheelock+, 1994) IRIS: A New Generation of IRAS Maps (Miville-Deschênes+, 2005)
Prepared By	Carter Emmart, Brian Abbott (AMNH)
Labels	No
Files	`mwIRirasComposite.speck`
Dependencies	`iris_3color_2048.pbm`
Wavelength	25, 60, and 100 microns
Frequency	12, 5, and 3 THz,

IRAS (InfraRed Astronomy Satellite) was one of the most successful astronomical missions, increasing the number of known cataloged objects by 70%. The orbiting telescope observed in the mid- and far infrared, and this map is a composite of the 25, 60, and 100 micron observations. This map is a re-reduction of the original image.

The map is bright across the Galactic plane, as we might expect. Toward the center of the Galaxy, in the direction of Sagittarius, the infrared light is tightly constrained to the plane. In the opposite direction, toward Orion, the band of light seems to break up, becoming more clumpy as we look away from the center of the Galaxy.

Many objects glow in this part of the sky. The Orion Nebula and the Rosette Nebula, two nearby star-forming regions, are bright. The Andromeda Galaxy is visible but faint, and the Rho Ophiuchi cloud is visible above Scorpius. There is a faint glow over the Pleiades star cluster, and a bright glow due to Rho Ophiuchi.

WISE Composite All-sky Survey

Group Name	`mwWISE`
Reference	Wide-field Infrared Survey Explorer (NASA/JPL-Caltech/UCLA, 2012)
Prepared By	Brian Abbott (AMNH)
Labels	No
Files	`mwIRwise.speck`
Dependencies	`630315main_pia15482c-full_full.pbm`
Wavelength	3.4, 4.6, 12, and 22 microns
Frequency	88, 65, 25, 14 THz

The Wide-field Infrared Survey Explorer (WISE) was designed to observe the entire sky at four infrared wavelengths over a ten-month period. Probing the sky in the mid-infrared spectrum yielded new findings as the telescope peered through dust clouds to see star-forming regions and star clusters.

The blue regions are the 3.4-micron band, which is sensitive to stars and galaxies, and the 4.6-micron band, which is more sensitive to substellar sources like brown dwarfs. At 12 microns, the telescope will be more sensitive to thermal energy from asteroids and is colored green. And, the 22-micron band will pick up the glow from dust in star-forming regions and is colored red in this map.

The composite map shows, in higher resolution, the infrared sky. The Orion Nebula, the Pleiades, the Andromeda Galaxy, the Rho Ophiuchi complex, and the Small and Large Magellanic Clouds are easily visible.

Also, you may notice a ring around a star near Orion's head. The star at the center of this ring is Lambda Orionis, an O star that gives off a lot of radiation. In later wavelengths, we'll see the glow around this star, but in this bandpass, we only see the outer ring of what is really a glowing bubble of hydrogen gas. We see the outer edge of the glow, which is cooler than the inner part of the bubble.

WISE filled in our knowledge in this part of the infrared spectrum, and is a precursor to the next major space telescope, the James Webb Space Telescope, the successor to Hubble.

2MASS Composite All-sky Survey

Group Name	`mw2MASS`
Reference	Two Micron All-Sky Survey (UMass, IPAC/CalTech, NASA, NSF, 2003)
Prepared By	Brian Abbott (AMNH)
Labels	No
Files	`mwIR2mass.speck`
Dependencies	`allsky-2mass.pbm`
Wavelength	1.24, 1.66, and 2.16 microns
Frequency	242, 181, 139 THz

The Two Micron All-Sky Survey (2MASS) is an infrared survey of the sky. Because it is looking in the infrared, and this is a composite of the 2MASS point-source catalog, most of the light from this survey is starlight. In visible light, clouds of gas and dust obscure our view. However, in infrared, the longer wavelengths of light can penetrate these clouds without being scattered, thereby revealing stars that would normally be hidden to our eye.

The 2MASS data were taken over 1,400 nights from 1997 to 2001 with two, 1.3-meter telescopes located on Mt. Hopkins, Arizona, and Cerro Tololo, Chile. Each telescope had identical detectors that observed light at 1.24, 1.66, and 2.16 micron wavelengths. The 2MASS Image Atlas contains more than 4 million images in these wavelengths that cover 99.998% of the sky.

The 2MASS image contains many point sources. If you turn up the image's brightness (using the Alpha Slider) and turn off the stars, you will see many of the stars in the image align with the constellation outlines. Many of the stars, particularly cooler stars, shine in the infrared. If you look toward Orion, you'll see many of the hotter stars in that constellation are not visible or as bright. Conversely, Betelgeuse, the red giant, is bright, radiating much of its light in the infrared.

The Galaxy itself is quite prominent, with the bright disk and the Galactic bulge toward the center of the Milky Way and virtually no disk showing toward Orion, away from Galactic center. Clouds of gas and dust are also apparent and are a brownish color, correlating exactly with the carbon monoxide all-sky survey (`mwCO` group).

Few features pop out as they do on other surveys. The Large and Small Magellanic Clouds are visible, as is the glow of the Pleiades star cluster, but beyond these, the survey is mainly starlight.

Visible All-sky Survey

Group Name	`mwVis`
Reference	Axel Mellinger (Universitaet Potsdam)
Prepared By	Ryan Wyatt (AMNH/Hayden)
Labels	No
Files	`mwVisible.speck`
Dependencies	`mwpan_nostars8_modified.pbm`
Wavelength	400 nm – 700 nm
Frequency	750 THz – 430 THz

In ancient times, our ancestors knew of the stars, the wandering stars (planets), and the Milky Way. Aside from the occasional comet, guest star (supernova), or aurora, these were the only cosmic features visible to them.

The Milky Way has been the subject of many myths and legends. The Greeks believed it to be a river of milk pouring from the breast of Hera, the wife of Zeus, and called it a "galaxy," from the Greek word for milk. The Romans called it the Via Lactea, or the Milky Way. But it was not until 1610 that Galileo first observed this faint band of light with his telescope, discovering that it was composed of innumerable faint stars.

In the past 400 years, astronomers and philosophers have speculated about the nature of this band of light, but it was not until the 20th century that astronomers began to understand the nature and structure of our Galaxy.

Several features of this band of light become obvious upon inspection (particularly if you increase its alpha value using the Alpha Slider). You will see the brightest part of the Galaxy if you look toward Galactic center [turn on the Galactic coordinates (`Galac`) and bring (l, b) = (0, 0)° to center screen] toward Scorpius and Sagittarius. The bright haze is the light from millions of stars; the dark lanes are foreground dust, obscuring our view. Relative to the rest of the Milky Way band, the center forms what astronomers call a "bulge" of light, whereas the rest of the band appears thinner.

If you turn to look in the opposite direction, toward Orion [(l, b) = (180, 0)°], you will see that the Milky Way is not too bright on this side of the sky. Here we look out of the Galaxy through what remains of the Galactic disk between the Sun and its outer edge.

This image is composed of many photographs of the sky, carefully knitted together in this giant mosaic. The stars have been removed for the most part, but the bright stars show some residual light.

H-alpha All-sky Survey

Group Name	`mwHalpha`
Reference	Doug Finkbeiner (Princeton)
Prepared By	Brian Abbott (AMNH)
Labels	No
Files	`mwHalpha.speck`
Dependencies	`mwHalpha.pbm`
Wavelength	656 nm
Frequency	457 THz

Hydrogen-alpha, or H-alpha, is a term that describes light from the ground state of the hydrogen atom. When an electron in an atom moves from one energy level to a higher one, we say the atom is excited. But the electron does not move to this higher energy level without the atom absorbing energy from either another atom or a passing photon (packet of light).

Once the atom is excited, it cannot remain in that state for long before it wants to return to its ground state. When the electron moves back down to the lower energy level, a photon is released at a wavelength commensurate with the energy between the two levels. For the H-alpha line, this energy difference translates to a wavelength of 656 nanometers (nm) and is in the extreme red end of the visible spectrum.

This survey of the sky is a snapshot of light from this wavelength. We can see this light with our eyes, but we also see the integrated light from the entire visible spectrum. If we could block the rest of that light so that we could see only light at 656 nm, we would see this picture of the Milky Way in the night sky.

Image features. One element of the sky at this wavelength is the presence of large, spherical bubbles surrounding hot stars. One of the most prominent is the bubble around Lambda Orionis. This is an O star and is among the hottest we see. It lies around 1,000 light years away and is so hot that it ionizes the surrounding hydrogen gas, causing it to glow.

We can perform a crude size determination on the ionization cloud. If the star is 1,000 light years away and the cloud has about a 3-degree radius in the sky, then, using a simple triangle, we can determine that the cloud extends about 60 light years in radius. Zeta Ophiuchi is another hot star, about 400 light-years away, near Scorpius.

Many nebulae and HII regions are visible, like the California Nebula, and what could be called the Orion nebluplex. Among the sights in the lower part of Orion, the Great Nebula of Orion is among the most beautiful star-forming regions in our neighborhood. Just above it is the Horsehead Nebula, an emission nebula with a small, obscuring dust cloud in the shape of a horse's head. Surrounding this is the extended supernova remnant called Barnard's Loop.

We also see galaxies that emit in H-alpha, including the Andromeda Galaxy and the faint M33, the large face-on spiral in Triangulum. In the southern sky are the Large and Small Magellanic Clouds (LMC and SMC), two nearby (about 130,000 light-years) satellite galaxies that have collided with our Galaxy.

This H-alpha view of our sky reveals where the hot, ionized hydrogen is. For the most part, it lies in the plane of the Galaxy but is above or below the plane when objects are relatively nearby in the Galactic foreground.

Ultraviolet All-sky Survey

Group Name	`mwNUV`
Reference	GALEX Diffuse Observations of the Sky: The Data (Murthy, 2014)
Prepared By	Brian Abbott (AMNH)
Labels	No
Files	`mwNUVgalex.speck`
Dependencies	`hlsp_uv-bkgd_galex_map_allsky_nuv_v1_sky-map.pbm`
Wavelength	231.6 nm
Frequency	1,295 THz

One of the last major regions of the electromagnetic spectrum without an all-sky map is in the ultraviolet. The map we include in this data group is, in fact, not complete. But, we include it as the best data we have for the ultraviolet sky.

These data are from the Galaxy Evolution Explorer (GALEX), an orbiting UV telescope launched in 2003. This is the near ultraviolet map of the diffuse light in the sky. Ultraviolet light stems mainly from hot plasma between about 1,000 K and 10,000 K, which can be found in nearly all corners of the universe: around stars, nebulae, planetary atmospheres, in the interstellar gas, nuclei of galaxies, near black holes, and the intergalactic medium.

While this all-sky map does not show detailed structure, we feel there's value in seeing the best we have for UV light.

X-ray All-sky Survey

Group Name	`mwXray`
Reference	ROSAT Soft W-ray All-sky Survey (Digel & Snowden (GSFC), ROSAT, MPE, NASA, 1995)
Prepared By	Brian Abbott (AMNH)
Labels	No
Files	`mwXray.speck`
Dependencies	`rass_m.pbm`
Wavelength	1.65 nm
Energy	0.75 keV

The only all-sky survey of the x-ray continuum was taken with the Röntgen Satellite, or ROSAT, and was published in 1995. While the resolution is fairly low, it remains the best all-sky picture of the x-ray sky.

This particular map is the 0.75 keV, or 1.65 nm, soft x-ray band and shows local, Galactic, and extragalactic x-ray emission. These emissions are mainly from hot, tenuous gas. But, x-rays at lower energies are absorbed by cold, interstellar gas, indicated by the darker areas of the map.

Many objects are visible in this map. Perhaps the most prominent is the large glow of the Vela pulsar. Many other supernova remnants appear in this map, including the SN 1006, the Cygnus Loop (which includes the Veil Nebula), Cassiopeia A, Tycho, the Crab Nebula, and Puppis A.

There are also fainter wisps of x-ray gas around some other objects like the Orion Nebula, the Pleiades, and other young, hot clouds.

Also, there are some extragalactic sources that appear in this map, including the Large and Small Magellanic Clouds, the Virgo Cluster, the Perseus Cluster, and wisps around some of the other nearby galaxy clusters. The galaxy M87, in the Virgo Cluster, was the first x-ray source detected outside the Milky Way in 1966. These sources are attributed to the hot gas that exists throughout and around each cluster.

Gamma-ray All-sky Survey

Group Name	`mwGamma`
Reference	Fermi Gamma-ray Space Telescope (NASA/DOE/Fermi LAT Collaboration, 2013)
Prepared By	Brian Abbott (AMNH)
Labels	No
Files	`mwGammaRay.speck`
Dependencies	`Femri_5_year_11000x6189.pbm`
Wavelength	< 0.0000000012 nm
Energy	> 1 GeV

Gamma rays are the most energetic light in the universe. This radiation arises from radioactive decay of the atomic nucleus. In the cosmos, gamma rays are produced when cosmic rays interact with the atmosphere, or when high-energy electrons are produced and interact with other particles. Mostly, in this map, we're seeing energetic particles accelerated in the shock waves of supernova remnants collide with atoms and even light in interstellar gas.

Gamma radiation can ionize other atoms and is, therefore, not the sort of light we want to be around. As the light passes through our body, it will do real damage to our cells. The only real protection is shielding from a large, thick layer of concrete or other solid material. Luckily, Earth's atmosphere protects us from natural gamma ray radiation.

This all-sky view was collected by the Fermi Space Telescope and is an improvement over the first gamma ray telescope called Compton. The map shows sources of gamma rays, and these include supernova remnants, pulsars, active galaxies, and even a globular cluster or two. And, we see radiation from all scales: local, Galactic, and extragalactic.

Among the pulsars that appear in Fermi, Vela glows bright in the disk of the Milky Way. Geminga, in Gemini, and the Crab Nebula are also very bright. A handful of supernova remnants, including the Cygnus Loop, Cassiopeia A, Tycho SN 1572, and IC 443, shine brightly in the map. The Orion Nebula and associated diffuse gas is also present, along with a few dozen active galaxies, like M87, NGC 1275, and Centaurus A. And, a few normal galaxies, the Small and Large Magellanic Clouds, the Andromeda Galaxy, and the starburst galaxies M82 and NGC 253, also appear, albeit dimmer.

Deep Sky Images

Group Name	DSO
Reference	NOAO, see dso.speck file for image credits
Prepared By	Nate Greenstein, Matt Everhart, Ryan Wyatt, Brian Abbott (AMNH)
Labels	Yes
Files	dso.speck dso.label
Dependencies	Various images
Census	65 images

"Deep-sky object" is a term familiar to avid sky watchers as an object in the sky that is not a star or planet. These include open and globular star clusters, nebulae, supernova remnants, and even galaxies. Often invisible to the unaided eye, they require binoculars or a telescope to view them.

The first list of such objects was compiled by Charles Messier (1730–1817), a French astronomer who was searching for comets. Comets resemble diffuse, fuzzy objects, and with the low-power optics of the day, star clusters, nebulae, and galaxies looked like diffuse comets too. In order to distinguish these static nebulae, clusters, and galaxies from the comets that move in the sky, Messier created a list of the stationary diffuse objects so he would not confuse them with the comets he was searching for. The resulting list contains 110 objects beginning with Messier object 1, or M1, also known as the Crab Nebula, and ending with M110, a small satellite galaxy of the Andromeda Galaxy, which itself is called M31.

The DSO data are 2-D images of Messier objects placed in 3-D space. Not only do we place our images at the proper location and give them the correct orientation, we also size them accurately so that you can fly to the globular cluster M13, for example, and see just how small the cluster of hundreds of thousands of stars is relative to the rest of the Galaxy.

The group consists mainly of open star clusters, globular clusters, diffuse nebulae, and planetary nebulae. All together, sixty-seven of the Messier objects are represented in 65 images (M32 and M110 appear in the image for M31). We do not include galaxies outside the Local Group or objects for which we have 3-D data, which is often superior to a 2-D image. For example, you will not see the Orion Nebula (M42 and M43) because we have a 3-D Orion Nebula model (OriNeb group) in the atlas. Similarly, we have 3-D stars in place for M45 (Pleiades), M44, and a few other open star clusters. Below we list the Messier objects included in the DSO group.

Messier Objects in the DSO Group	
Object Type	**Messier Object Number**
Open star clusters	6, 7, 11, 16, 18, 21, 23–26, 29, 34–39, 41, 46– 48, 50, 52, 67, 93, 103
Globular star clusters	2–5, 9, 10, 12–15, 19, 22, 28, 30, 53–56, 68–72, 75, 79, 80, 92, 107
Planetary nebulae	27, 57, 76, 97
Diffuse nebulae	8, 17, 20, 78
Supernova remnants	1
Galaxies	31, 32, 33, 110

You may know some of these objects by their common names:

M1	Crab Nebula	M31	Andromeda Galaxy
M8	Lagoon Nebula	M42	Orion Nebula
M16	Eagle Nebula	M44	Beehive star cluster
M17	Omega Nebula	M45	Pleiades star cluster
M20	Trifid Nebula	M57	Ring Nebula
M27	Dumbbell Nebula	M97	Owl Nebula

I don’t see any images. By default, the `DSO` data group is on when you launch the Milky Way atlas, but you are not likely to notice them just as you don’t typically see these objects in the night sky. This is due to their size, which in most cases is quite small. One way to pick them out is to turn on the labels for the group. To see the image, you can either zoom in from your current location on Earth, or fly out to the object.

To view the images from Earth’s position, use Partiview to simulate how we see these objects in the night sky when looking through binoculars or a telescope. Center one of the objects in your view and select `fov` from the Slider Menu. The default value for the Digital Universe is 60°. To zoom in, decrease the field of view by moving the slider to the left. You may need to center the object as you zoom in. The value under the slider is the vertical field of view (in degrees) of your window. A value of 5–10° might simulate a pair of binoculars while a value less than 0.5° replicates a telescopic view.

Image credits. For information such as credits, place your mouse over an image and hit the `p` key. This picks an object in your view, although this can be challenging if you have a lot of data in your view. Doing so will return some information about the object (the group number, the x,y,z position, and, for `DSO`, will list the image credit.

Galaxy

Group Name	Galaxy
Reference	European Southern Observatory
Prepared By	Carter Emmart, Brian Abbott (AMNH)
Labels	No
Files	galaxy.speck
Dependencies	eso9845d-processed.pbm

A problem that continues to baffle astronomers today is defining the structure of our star system, the Milky Way. Because we reside within our Galaxy, we cannot see the larger picture of what the Galaxy actually looks like. Astronomers continue to debate the structure of the Milky Way with more uncertainty than that of other galaxies that are millions of light years away.

In 1918 and 1919, a series of papers by Harlow Shapley were published that described the dimensions of our Galaxy. Using the distribution of globular clusters in the sky, Shapley deduced that the center of our star system was in the direction of Sagittarius and that the distance to those clusters was greater than anyone had ever proposed.

A great debate had taken the astronomical world by storm. Was the Andromeda Nebula inside our own Galaxy, or was it a distant extragalactic object similar to our Galaxy? Within five years, Edwin Hubble solved the debate by observing Cepheid variable stars in the Andromeda Nebula, which allowed him to measure the distance to the star system, now called a galaxy with confidence. With other galaxies as examples, it soon became clear that we were inside a spiral galaxy like Andromeda.

The Galaxy image. The exterior view of the Milky Way is simply a two-dimensional image. The image is that of NGC 1232, a galaxy thought to resemble our Milky Way. The image has been properly sized and functions as a placeholder, allowing one to gauge the scale of the Galactic disk relative to other data sets in the atlas.

The features you see in the image, of course, do not represent our Galaxy, per se, but resemble similar features found in our Galaxy. The Sun is just on the inside of the smaller Orion Arm, sometimes called the Orion Spur, which might connect the Sagittarius and Perseus arms. The features seen in this image should be used as a guide only, since they only reflect the structure of NGC 1232.

Spiral Arms

Group Name	`Arms`
Reference	—
Prepared By	Brian Abbott (AMNH)
Labels	No
Files	`galaxyArmLabels.speck`
Dependencies	`eso9845d-processed-labels.pbm`

The `Arms` data group is an image that contains labels for the Milky Way's spiral arms. We label them in this manner ("hard coding" the labels into an image rather than having native Partiview labels) so that they can retain their size, shape, and location as they overlay the galaxy.

We reiterate that these are guides and not based in reality, because we never have this view of the Milky Way and can only infer it's structure. The labels in this data group build upon the scientifically informed positioning of the galaxy image, and these arm labels are anchored in those presumptions.

The sun is located in the Orion Spur, a subarm that's likely an offshoot from a major spiral arm. As we look away from the center of the Galaxy, we look toward the Perseus Arm, and beyond that is the Outer Arm. If we look toward the center of the Galaxy, we are beside the Sagittarius-Carina Arm, and inside that is the Scutum-Centaurus Arm, and inside that is the Norma Arm and the 3 kiloparsec arms that surround the Galactic center.

Galactic Bar

Group Name	`Bar`
Reference	Merrifield, M. & Binney, J. 1998, Galactic Astronomy (Princeton: Princeton University Press)
Prepared By	Carter Emmart, Brian Abbott (AMNH)
Labels	No
Files	`bar.speck`
Dependencies	`halo.pbm`

The Milky Way has two main structural elements: the disk and the spherical component. The disk is a thin layer of stars, gas, and dust that contains the Galaxy's spiral arms. The spherical component includes the Galactic bulge and the Galactic halo. The bulge, at the center of the Galaxy, contains both old and young stars with some gas and dust.

Most of the mass and luminosity of the Galaxy are contained in the Galactic bar, an oblate spheroid located at the center of the Galaxy. The bar is shaped like an American football, with axes of (a_x, a_y, a_z) = (5500, 2050, 1370) light years. Because we are located on the outskirts of the Galactic disk, we cannot see directly to the center of the Galaxy with all the gas and dust in our way. How do we know there is a bar if we cannot see it in the visible spectrum?

The main evidence for the existence of a bar is the infrared luminosity differences around the Galactic center. Because dust obscures our view of the Galaxy, we must turn to the near infrared (around 2–4 microns) to peer through it. At these wavelengths, the intensity on one side of the Galactic center is higher than it is on the opposite side. Astronomers deduced that there must be a triaxial bar present, with the bright side of Galaxy center corresponding to the end of the bar that is closest to us. Currently, the long axis of the bar (which is parallel to the Galactic plane) is believed to be inclined 30° to the line connecting the Sun and the center of the Galaxy.

We represent the bar as a yellow ellipsoid with a glow texture at its center. The glow is composed of three polygons that lie in the x, y, and z planes, respectively. The glow can be turned off with the Polygon Toggle Button.

Galactic Halo

Group Name	`Halo`
Reference	Merrifield & Binney 1998, Galactic Astronomy (Princeton: Princeton University Press)
Prepared By	Brian Abbott (AMNH)
Labels	No
Files	`halo.speck`
Dependencies	none

Surrounding the disk of the Milky Way is the spherical Galactic halo. Unlike the population of the disk, where stars continue to form, the halo population is devoid of gas and dust and, therefore, star formation. It contains cooler, dimmer stars left over from an era of star formation in the Galaxy's early history. There are no young, luminous stars in this population.

The main player in the Galactic halo is the system of globular clusters (turn them on with the `GC` button). Numbering about 150, the Milky Way's globulars are spherically distributed about the Galactic center, and most are within the halo. The stars in the halo are so intrinsically dim that it is difficult to see them unless they are close to the Sun. These stars travel in elliptical orbits about the center of the Galaxy that are not confined to the disk but are distributed throughout the spherical halo.

Many properties of the halo are still under consideration by astronomers. With the introduction of dark matter and the discovery of more small satellite galaxies around the Milky Way, the halo seems to come under continual scrutiny. We place the radius of the halo at about 134,000 light years (41 kpc); however, some astronomers believe it to be far larger, perhaps as much as 300,000 – 800,000 light years in radius.

Sun-centered Grids

Group Name	`1ly, 10ly, 100ly, 1kly, 10kly`
Reference	—
Prepared By	Brian Abbott (AMNH)
Labels	Yes

Files	`target1ly.speck, grid1ly.speck`
	`target10ly.speck, grid10ly.speck`
	`target100ly.speck, grid100ly.speck`
	`target1kly.speck, grid1kly.speck`
	`target10kly.speck, grid10kly.speck`

Dependencies	none

The Sun-centered coordinate grids consist of two superimposed meshes. One mesh is a square coordinate grid with lines through the origin and lines appearing halfway along the grid's length. For example, if the grid is 1 light year, then grid lines would cross the origin, mark the 0.5-light-year (6 light-month) point, and mark the edge of the grid. The other mesh forms lines of constant radius. These are rings around the Sun (not to be confused with orbits) that mark where these distances lie in space.

The grids in each of these data groups are nested within one another and range from the light year scale (in `1ly`) to the 10,000-light-year scale (in `10kly`). The grids are placed in the Galactic plane. Each grid is centered on the Sun and covers a size scale that is well suited for particular data sets in the atlas.

`1ly`	The 1-light-year grid consists of lines of constant radius for each light-month and an overlying grid in increments of 6 light months. Displaying the Oort cloud (oort) along with this grid provides a good measure for the Oort cloud sphere (about 10.5 light months).
`10ly`	A 10-light-year grid with lines of constant radius every light year. Viewing the grid along with the stars, one is able to see the locations of those nearby stars close to the plane. It's easy to see that Alpha Centauri is around 4 light years and Sirius is around 9 light years.
`100ly`	A 100-light-year grid with lines of constant radius every 10 light years. Here we can see the radio sphere's edge (`RaDec`) at 75 light-years with many of the exoplanets (`Expl`).
`1kly`	A 1-kilo-light-year (1,000-light-year) grid with lines every 500 light years and lines of constant radius every 100 light years. On this scale we see several of the local OB associations (`OB`) that lie in the Orion Spur, as well as a few of the nearest open clusters (`OC`).
`10kly`	The 10 kly (10,000-light-year) grid is large enough to view those nearby data sets that are confined to the plane of the Galaxy, more or less. All the OB associations are found within the grid, as are data from the open clusters, supernova remnants (`SNR`), and the star-forming regions (`H2`).

Galaxy-centered Grid

Group Name	`GalGrid`
Reference	—
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`galgrid.speck`
Dependencies	none

The Galaxy grid spans the Galactic disk. It is 100,000 light-years on each side, and its center is at the Galactic center. The grid lies in the plane of the Galaxy, which is about 50 light years “below” the Solar System (the sun is currently about 50 light years above the Galactic plane). Labels appear every 10,000 light years and are in units of kilo light years (kly).

All of the 3-D data sets lie within this grid except for a handful of globular clusters (`GC`), and some pulsars (`Pul`). The grid is complemented by the Milky Way image (`Galaxy`), the spiral arm labels (`Arms`), the Galactic bar (`Bar`), and the Galactic halo (`Halo`), which diagrammatically highlight some of the Galaxy’s structural features.

Extragalactic Atlas

The Extragalactic portion of the Digital Universe is less diverse than the Milky Way's data sets merely because the scales are so huge that we no longer can see the level of detail at such great distances. What we do see are the biggest, brightest objects out there—galaxies and quasars.

We include a few contextual data sets up front, then begin with galaxy surveys, pointing out some of the local galaxy groups and clusters. Beyond the local galactic neighborhood lie larger surveys which peer deeper into the universe, but do not cover the entire night sky and, therefore, take on a bow tie shape.

At the edge of the observable universe is our visual limit. We represent this with the cosmic background radiation, which is the earliest light we can see. However, this light is not plastered at the edge of the observable universe, rather, it is ubiquitous throughout the universe, even among the planets of the solar system.

Data Groups

The data groups follow the Partiview naming convention and order. Page numbers refer to detailed descriptions later in the text.

`constel`	Constellation connectivity lines
`mwVis`	Visible all-sky survey
`halo`	The Milky Way's halo
`radec`	Equatorial coordinates (5-million-light-year sphere)
`LocalGroup`	Sphere marking the Local Group of galaxies
`LocalDwarfs`	Dwarf galaxies in the Local Group
`Tully`	The Tully galaxy catalog
`Groups`	Nearby galaxy groups (labels)
`Clusters`	Nearby galaxy clusters (labels)
`Voids`	Nearby voids (labels)
`VirgoScl`	Sphere marking the extent of the Virgo Supercluster
`LaniakeaScl`	Rough outline of the Laniakea Supercluster
`Abell`	Abell galaxy clusters
`Superclusters`	Nearby galaxy superclusters (labels)
`2MASS`	2MASS galaxy catalog
`6dF`	Six-degree Field galaxy survey
`2dF`	Two-degree Field galaxy survey
`Sloan`	Sloan Digital Sky Survey galaxies
`Quasars`	Half Million Quasars catalog
`CMB1965`	Simulation of the CMB at its discovery
`COBE1992`	CMB from COBE mission, 1992
`WMAP2003`	CMB from the WMAP mission, 2003
`Planck2013`	CMB from the Planck mission, 2013
`100kly`	100,000-light-year grid centered on the Sun
`1Mly`	1-million-light-year grid centered on the Sun
`10Mly`	10-million-light-year grid centered on the Sun
`100Mly`	100-million-light-year grid centered on the Sun
`1Gly`	1-billion-light-year grid centered on the Sun
`20Gly`	20-billion-light-year grid centered on the Sun

Constellations

Group Name	`Constel`
Reference	—
Prepared By	Brian Abbott, Carter Emmart (AMNH)
Labels	Yes
Files	`constellations.speck` `constellations.label`
Dependencies	none
Census	88 constellations and labels

We provide the constellation lines in the Extragalactic data sets so that we can have the context of the night sky. In this manner, one can see the galaxy clusters and surveys as they relate to the sky.

They are at a fixed distance of 5 million light years, so you need to be close to the origin for them to appear in the correct place. Issuing the partiview command `jump 0 0 0` will insure you're seeing them in the proper place.

Visible All-sky Survey

Group Name	`mwVis`
Reference	Axel Mellinger (Universitaet Potsdam)
Prepared By	Ryan Wyatt (AMNH/Hayden)
Labels	No
Files	`mwVisibleExgal.speck`
Dependencies	`mwpan_nostars8_modified.pbm`
Wavelength	400 nm – 700 nm
Frequency	750,000 GHz – 430,000 GHz

The visible all-sky survey shows the Milky Way from our night sky perspective. That band of light in the sky reveals the gas and dust in the disk of the Galaxy.

The image is wrapped on a sphere whose radius is arbitrary. In this case, we choose the approximate radius of the Local Group, and display the image there.

Find out more about this survey in it's description in the Milky Way Section.

Galactic Halo

Group Name	`Halo`
Reference	Merrifield & Binney 1998, Galactic Astronomy (Princeton: Princeton University Press)
Prepared By	Brian Abbott (AMNH)
Labels	No
Files	`haloExgal.speck`
Dependencies	none

The Milky Way is surrounded by a large, spherical halo. The most prominent objects in this halo are the globular clusters, the bright, compact star clusters, but the halo is also filled with dimmer, cooler stars, hot gas, and dark matter.

We include the halo here to see its scale among our neighboring galaxies. It is about 300,000 light years in radius, but that is a very rough number and depends upon how we measure it (using stars, gas, etc.).

For more information about our Galactic halo, see "The Galactic Halo" in the Milky Way Atlas chapter.

Equatorial Coordinates

Group Name	`RaDec`
Reference	—
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`radecExgal.speck`
Dependencies	none

The equatorial coordinates trace earth's system of latitude and longitude onto the night sky. The brighter blue line is the celestial equator and lies directly above Earth's equator.

From outside Earth's view, the coordinates are rendered as a sphere. The radius of this sphere is 1 megaparsec, coincident with the sphere of stars, the constellations, and the visible Milky Way.They are at a fixed distance of 5 million light years, so you need to be close to the origin for them to appear in the correct place. Issuing the partiview command `jump 0 0 0` will insure you're seeing them in the proper place.

A detailed description of the equatorial coordinates can be found in "Equatorial Coordinates Sphere" in the Milky Way Atlas.

Local Group

Group Name	`LocalGroup`
Reference	—
Prepared By	Brian Abbott (AMNH)
Labels	No
Files	`localgroup.speck`
Dependencies	none
Census	1 sphere showing the extent of the Local Group

The Local Group is an oblate sphere that outlines the size of the Local Group of galaxies. The sphere contains the approximately 75 galaxies that make up the Local Group, including the Milky Way, Andromeda, and all of their dwarf galaxies.

The long axis is 5 million light years, and roughly indicates the boundary of the Local Group.

Local Dwarf Galaxies

Group Name	`LocalDwarfs`
Reference	—
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`localdwarfs.speck`
Dependencies	none
Census	65 dwarf galaxies; the remaining 9 galaxies that make up the Local Group are in Tully

The Local Dwarf Galaxies group contains all the smaller galaxies in the Local Group. The main galaxies of the Local Group—the Milky Way, Andromeda galaxy, M33, and a few others—are included in the Tully dataset, so these two datasets act in concert with one another.

Dwarf galaxies are small, satellite galaxies composed of hundreds of millions to several billion stars. They are typically under the gravitational influence of a larger galaxy, and are often shredded by them at some point over their lifetime.

To view the entire Local Group, turn on these data along with the Tully galaxies.

The Local Group is composed of these galaxies, plus those in Tully. The data appear in two main batches—the Milky Way and its satellite dwarfs, and Andromeda and its dwarfs. Because these are so small, we cannot see them clearly beyond the Local Group, but it’s safe to assume many galaxies have their own companions.

Tully Galaxy Catalog

Group Name	`Tully`
Reference	Tully 8,000 km/s Galaxy Catalog (Brent Tully, U Hawaii) The Galaxy Catalog (Zsolt Frei and James E. Gunn) National Optical Astronomical Observatory
Prepared By	R. Brent Tully (U Hawaii) Stuart Levy (NCSA/U Illinois)
Labels	Yes
Files	`tully.speck` `tully.label`
Dependencies	`lss.cmap`, various images
Census	28,364 galaxies

The Tully Catalog is the most polished, accurate catalog of nearby galaxies. It includes over 28,000 galaxies in the local universe that surround the Milky Way. This catalog demonstrates the large-scale structure of the universe exceptionally well. And, each galaxy has a representative image reflecting it's morphological type, and is properly sized and inclined.

Size and shape. The data form a cube, which was an arbitrary cut-off based on the completeness of these data. Beyond this, data from these sources are not as reliable, so effort is made to show a complete picture, albeit limited by observations (for example, we cannot see dwarf galaxies much beyond the Local Group).

The size of the cube is roughly 750 million light years per side, or about 1 billion light years on the diagonal.

Because this is all observed data, the Milky Way appears to be at the center of these data, but this is only an observational bias—we are not at the center of the universe.

Colors. The color of the points are based on the local density of galaxies around each point. If a galaxy is in a dense area, like a cluster, it will be colored orange. As the density decreases, the colors will move to yellow, green, aqua, and finally blue for galaxies that are relative loners.

Galaxy images. Each galaxy is represented by an image that represents its morphological type (spiral, elliptical, etc.). Most of these come from The Galaxy Catalog.

A handful of nearby galaxies are represented by their actual images from the national Optical Astronomy Observatory (NOAO). These include the Large and Small Magellanic Clouds (NOAO/AURA/NSF), the Andromeda Galaxy or M31 (Bill Schoening, Vanessa Harvey/REU program/NOAO/AURA/NSF), M33 [T. A. Rector (NRAO/AUI/NSF and NOAO/AURA/NSF) and M. Hanna (NOAO/AURA/

NSF)], M81 (N. A. Sharp/NOAO/AURA/NSF), M101 (George Jacoby, Bruce Bohannan, Mark Hanna/NOAO/AURA/NSF), M51 (Todd Boroson/NOAO/AURA/NSF), and Centaurus A (Eric Peng, Herzberg Institute of Astrophysics and NOAO/AURA/NSF).

Each of these images has been altered from its original state. These images were taken from Earth on some of the world's largest telescopes, so foreground stars from our own Galaxy appear in each image. We are representing galaxies in extragalactic space, where stars would not appear as large, bright objects. So, we have removed the stars from each image from NOAO.

Metadata. The richness of the Tully dataset lies in the metadata associated with each galaxy. These include the brightness, the morphological type, the diameter of the galaxy, etc.

0	`distMly`	Distance in million of light years	Mly
1	`prox5Mpc`	Number of galaxies within 5 Mpc	galaxies
2	`type`	Morphological type	—
3	`diamkpc`	Galaxy diameter	thousands of parsecs
4	`Mblueneg`	Negative absolute B magnitude	mag
5	`lum`	Galaxy luminosity scaled to `Mblueneg`	—
6	`texture`	Texture (image) number	—
7	`cloud`	The cloud (group) number	—
8	`pgcID`	Principal Galaxy Catalog number	—
9	`hicnt`	References for a grouping catalog	—
10–15	`orientation`	Unit vectors for the galaxy orientation	millions of parsecs

Galaxy morphological type. The galaxy morphological type metadata is an integer that reflects the type of galaxy classified first by Edwin Hubble (1889–1953) in the 1930s. The classification scheme has four main groups: elliptical galaxies (E), barred spiral galaxies (SB), unbarred spiral galaxies (S), and irregular galaxies (Irr). The integers assigned to these types are decoded in the table below. In this numbering system, barred and unbarred spiral galaxies (S & SB) are merged, since data on bars are often inconclusive.

-5	E	Elliptical	990
-3	E/SO	Elliptical/Lenticular (class uncertain)	652
-2	SO	Lenticular	1439
0	SO/a	Lenticular/Spiral	9132
1	Sa	Spiral	1314
2	Sab	Spiral	1629
3	Sb	Spiral	2046
4	Sbc	Spiral	2332
5	Sc	Spiral	3323
6	Scd	Spiral	2284
7	Sd	Spiral	581
8	Sdm	Spiral	498
9	Sm	Spiral/Irregular	311
10	Irr	Irregular	481
12	S	Spiral/Irregular (class uncertain)	0
13	P	Peculiar	0

Selection Expressions. A few selections have been predefined. These segregate galaxies by region. Use the `see [alias]` command in Partiview to view these data subsets.

`ga`	Shows the galaxies of the Great Attractor
`gw`	Picks out the Great Wall galaxies
`abell`	Removes all but the galaxies that are members of an Abell cluster

Galaxy Groups

Group Name	`Groups`
Reference	Tully 8,000 km/s Galaxy Catalog (Brent Tully, U Hawaii)
Prepared By	Brian Abbott (AMNH)
Labels	Yes (no data)
Files	`groups.label`
Dependencies	none
Census	62 galaxy group labels

Groups is a set of labels for the nearby galaxy groups. The Milky Way is in the Local Group, and we are surrounded by many other groups, or what were once called clouds.

The Local Group is populated with several large galaxies, and many dwarf galaxies. Of course, only the big, bright galaxies will be visible in more distant groups, so these consist of only a few galaxies each.

Galaxy Clusters

Group Name	`Clusters`
Reference	Tully 8,000 km/s Galaxy Catalog (Brent Tully, U Hawaii)
Prepared By	Brian Abbott (AMNH)
Labels	Yes (no data)
Files	`galclust.label`
Dependencies	none
Census	15 galaxy cluster labels

The Clusters dataset is a series of labels that mark where the large clusters of galaxies are within the local universe.

The nearest large cluster to the Milky Way is the Virgo Cluster, which is about 60 million light years from Earth. Other large clusters within Tully are labeled in this dataset.

Voids

Group Name	`Voids`
Reference	various
Prepared By	Brian Abbott (AMNH)
Labels	Yes (no data)
Files	`voids.label`
Dependencies	none
Census	24 labels for cosmic voids

The Voids dataset labels the voids in the local universe. Cosmic voids are vast, empty spaces where there are either no galaxies, or very few galaxies. They are associated with cold spots in the cosmic background radiation (CMB), the earliest picture we have of the universe. Those cold spots in the CMB evolved into large voids, some as much as 300 million light years in diameter.

Virgo Supercluster

Group Name	`VirgoScl`
Reference	—
Prepared By	Brian Abbott (AMNH)
Labels	No
Files	`virgoScl.speck`
Dependencies	none
Census	1 sphere showing the extent of the Virgo Supercluster

Until 2014, the Milky Way was considered a member of the giant Virgo Supercluster, sometimes called the Local Supercluster. At its heart is the Virgo Cluster of galaxies. But, in 2014 a larger structure was discovered, which we will discuss next.

The Virgo Supercluster is about 110 million light years across, and contains about 50,000 galaxies. However, this is merely a lobe within the larger Laniakea Supercluster.

Laniakea Supercluster

Group Name	`LaniakeaScl`
Reference	Brent Tully+ (U Hawaii)
Prepared By	Brian Abbott (AMNH)
Labels	No
Files	`laniakeaScl.speck`
Dependencies	none
Census	1 sphere showing the extent of the Laniakea Supercluster

The Laniakea Supercluster was discovered in 2014, and supplanted the Virgo as our home supercluster. The oblate spheroid roughly encompasses the galaxies and galaxy clusters that make up the newly discovered structure, of which the Virgo Supercluster is but a small portion.

Laniakea contains approximately 100,000 galaxies and is over 500 million light years across. It's main concentrations include Virgo, the Hydra-Centaurus Supercluster, the Great Attractor, and include the Fornax, Hydra, and Centaurus clusters.

The supercluster was discovered using a new tool: analysis of the motions of the galaxies. By subtracting out the motion from the expanding universe, localized flow can be deduced, and, therefore, galaxies within the same related structure become apparent. But, this method has limitations. We could be part if an even larger structure involving the neighboring Shapley Supercluster.

Abell Clusters

Group Name	`Abell`
Reference	A Catalog of Rich Clusters of Galaxies (Abell+ 1958, 1989) With alterations by R. Brent Tully (U Hawaii)
Prepared By	R. Brent Tully (U Hawaii) Stuart Levy (NCSA/U Illinois)
Labels	Yes
Files	`abell.speck, abell.label`
Dependencies	`abell.cmap`
Census	2,246 galaxy clusters

The Abell catalog includes all the nearby, and not so nearby, galaxy clusters. The northern hemisphere survey, published in 1958, was compiled by George Abell (1927–1983) from the Palomar Sky Survey plates. A subsequent southern hemisphere catalog was published posthumously in 1989. Further analysis by Brent Tully determined their distance and three-dimensional distribution.

Each point in this data set represents a cluster of tens to hundreds (possibly even thousands) of galaxies. You will notice some points are assigned colors while most are gray. The data set also has an arbitrary cut-off, resulting in the rectangular shape of the data set.

Clusters of clusters. Galaxies group together to form the large-scale structure of the Universe. Dense clusters of galaxies are connected by filaments, or strands, of galaxies. Between, vast voids resemble the inside of a bubble and are occupied by less dense material. Beyond these structures, astronomers have found larger-scale constructs called "superclusters."

Larger than a cluster of galaxies, superclusters are made from many galaxy clusters. In the Abell data, the non-gray colors represent these superclusters. These mammoth objects are on the order of 300 million light-years in diameter. Compare that to the size of one cluster, Virgo, which is only 15 million light-years across, or our Galaxy, which is a scant 100,000 light-years across.

Notable clusters. One way to see the superclusters is to filter Abell by the `notable` index. Each Abell cluster has a notable index that is either 1, meaning the cluster is attached to a large supercluster, or zero, meaning it is relatively isolated. Type `see scl`, and 313 galaxy clusters in about two dozen superclusters will remain. Type `see all` to return all the galaxy clusters to view.

Labels. The labels for this group will appear when you're close to an Abell cluster, and will reflect the name of that cluster. However, to see the names of the superclusters, which is more useful, turn on the Superclusters data group, which we describe next.

Superclusters

Group Name	`Superclusters`
Reference	Superclusters of Abell and X-ray Clusters (Einasto+, 2001)
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	`superclust.speck, superclust.label`
Dependencies	none
Census	33 labels for Superclusters

The superclusters dataset is a set of labels that mark the major galaxy superclusters in the local universe. They correspond to, and should be viewed with, the Abell clusters. Astronomers estimate there are 10 million superclusters in the observable universe.

What is a supercluster? A supercluster is a group of smaller galaxy clusters. They are among the largest structures in the universe. However, they are not bound by gravity, so individual galaxy clusters will drift away from one another due to the expansion of the universe. And, this expansion, as well as dark energy, will disperse the superclusters eventually.

Extragalactic survey metadata. The following extragalactic surveys—6dF, 2dF, Sloan, and the quasars—have the same metadata. They are mostly concerned with the distance of these object and allow for one to generate subsets of data to see the universe differently—to ostensibly see the forest through the trees.

0	`redshift`	Object's redshift	—
1	`distMpc`	Distance	millions of parsecs
2	`distGly`	Distance	billions of light years
3	`Tlookback`	Lookback time	billions of years
4	`prox5Mpc`	Number of galaxies within 5 Mpc of a particular galaxy	galaxies

The redshift describes the shift in light due to the Doppler shift from the motion of the galaxy. Galaxies that are receding from us faster, will have a higher redshift in their spectrum. So, the higher the redshift, the farther the object is from Earth. Using redshift, we can determine the distance to the object fairly easily.

The lookback time reflects when the light left the object and how long it took to reach our eyes or telescope. When the light from a distant galaxy reaches our eye, the galaxy was, say, 6 billion light years away, but the lookback time—how long ago the light left the galaxy—was only 5 billion years ago. And, so the galaxy was 5 billion light years away when the light left. Lookback time ranges from 0 to the age of the universe, 13.8 billion years.

The 5 Mpc proximity factor (not included with quasars) is a number we use to determine the local density of the universe. The number reflects the number of other galaxies around a particular galaxy within a 5 megaparsec (16 million light year) sphere. We use this number to apply a color map to the galaxy datasets, using orange for dense regions and blue for lower-density regions. This number may also be used to create subsets. For example, the Sloan galaxies have a prox5Mpc that ranges from 0–511, with an average around 9. If we create a subset of data only showing galaxies with a prox5Mpc between 50–700, we will see only the dense clusters within the data set.

6dF Galaxy Survey

Group Name	`6dF`
Reference	6dF galaxy survey (Jones+, 2009)
Prepared By	Brian Abbott (AMNH)
Labels	No
Files	`6dF.speck`
Dependencies	`lss.cmap`
Census	109,569 galaxies

The Six-degree Field (6dF) Galaxy Survey mapped nearly half the sky form the Anglo-Australian Observatory. Unlike previous datasets, this one is not all-sky, meaning there are patches of sky that are not covered. In this case, the entire northern hemisphere has no coverage at all.

This catalog overlaps with the Tully dataset, and there is a noticeable difference in the quality of these datasets. Tully is much tighter and the structure is more apparent, while the 6dF data are more spread out. This is because of local motions within galaxy clusters.

Fingers of God. Early in the process of mapping the local universe, astronomers noticed that galaxies, when plotted, appeared on lines that pointed radially back to Earth. These lines, dubbed "fingers of god," are a cluster of galaxies spread out radially because of the local motions within the cluster (for example, the galaxies of the Local Group are all moving in seemingly random directions as they gravitationally interact with one another—many are blueshifted, so coming toward us, even as the universe expands. These local motions contaminated the redshift in the spectrum, causing the stretching of the clusters.

Metadata. The redshift for these data range from 0.0016 to 3.79, which corresponds to galaxies within 23 billion light years, though the vast majority are within a 1.3 billion light years. The lookback time for these galaxies extends to 11.8 billion years.

2dF Galaxy Survey

Group Name	2dF
Reference	2dF galaxy redshift survey (Colless+ 2003)
Prepared By	Brian Abbott (AMNH), Eric Gawiser (Rutgers U)
Labels	No
Files	2dF.speck
Dependencies	lss.cmap
Census	229,293 galaxies

The Two-degree Field (2dF) Survey is a project designed to map portions of the extragalactic universe. Mapping the universe's structure provides astronomers with constraints on its formation and evolution.

The 2dF instrument is mounted on the 3.9-meter (12.8-foot) Anglo-Australian Telescope (AAT), located 450 km (280 miles) northwest of Sydney. The telescope has a two-degree field of view on the sky, enabling large parts of the sky to be observed at one time. For each pointing of the telescope, the instrument can acquire up to 400 spectra simultaneously via optical fibers that feed into two spectrographs. The spectrographs see light that is between 350 nm and 800 nm, spanning the visible spectrum.

The survey was conducted from the extended APM Galaxy Survey. This catalog was derived from the Southern Sky Survey, taken by the UK Schmidt Telescope and scanned by the Automated Plate Measuring (APM) Machine. This extended catalog contains more than 5 million galaxies that span the north and south Galactic hemispheres.

The 2dF survey has three main components: the north Galactic pole strip, the south Galactic pole strip, and the random fields that surround the south Galactic pole strip. The galaxy survey is composed of about 230,000 galaxies with brightness and redshift measurements.

Distribution. The 2dF survey covers the same general volume as the 6dF, but 90% of these galaxies are within 2.5 billion light years, so it surveys a little deeper into the universe than 6dF. This corresponds to a lookback time of 2.3 billion years.

Because the observations were along narrow bands, they result in relatively thin sheets of galaxies, which makes it easier to see the large-scale structure. So, clusters, connecting filaments of galaxies, and voids are readily apparent in the 2dF survey.

Sloan Galaxy Survey

Group Name	`Sloan`
Reference	Sloan Digital Sky Survey
Prepared By	Brian Abbott (AMNH), Eric Gawiser (Rutgers U)
Labels	No
Files	`SDSSgals.speck`
Dependencies	`lss.cmap`
Census	2,600,258 galaxies

The Sloan Digital Sky Survey (SDSS) is an ambitious project to map about 35% of the sky, deep into the universe. The survey measured the position and brightness of 500 million objects, and obtained spectra to more than 3 million objects.

The telescope is located at Apache Point Observatory in south-central New Mexico (US) and began operating in June 1998. It is 2.5 meters (8.2 feet) in diameter and was designed specifically for this mapping project. The telescope takes images of the sky as well as spectra for individual objects. Imaging the sky is not too difficult compared with taking individual spectra, so the spectral catalog lags behind the imaging project.

The spectral range for the SDSS is 380 nm–920 nm, stretching from the blue end of the visible spectrum to the red, and barely into the infrared.

The SDSS galaxies are similar to the 2dF data in that they form triangular wedges, revealing those parts of the sky observed by the telescope. If the entire sky were covered, you would see a spherical distribution of galaxies surrounding the Milky Way. With only 35% of the entire sky observed, we see only a few select slices from that sphere.

Distribution. These galaxies appear to extend beyond the 2dF survey to distances that exceed 5 billion light-years. However, the weblike structure of clusters, filaments, and voids seems to fade by about 2 billion light-years. Beyond this distance, the completeness of the survey drops so that only the intrinsically bright galaxies are visible. This is easily seen if you set a threshold on the distance. However, compared to 2dF, where 90% of the galaxies are within 2.5 billion light years, for Sloan 90% of the survey is within 7 billion light years, so Sloan sees farther into the universe.

Quasars

Group Name	`Quasars`
Reference	Half Million Quasars Catalogue (Flesch, 2015)
Prepared By	Brian Abbott (AMNH)
Labels	No
Files	`quasars.speck`
Dependencies	None
Census	418,893 quasars

The Half Million Quasars Catalogue is an aggregate catalog of several surveys, including 2dF and Sloan. So, it should not be surprising that the shape of these data mimic the shape of the Sloan and 2dF galaxy surveys.

Discovering quasars. Radio astronomy was born in 1931, when Karl Jansky of Bell Telephone Laboratories discovered that the Milky Way was radiating its own radio waves. In the years following World War II, hundreds of radio observations were recorded and cataloged in the Third Cambridge (3C) Catalog of radio sources. Many of these sources were identified to have a nebulous optical counterpart, like the Crab Nebula or the nearby galaxy Centaurus A.

However, in 1960, astronomers detected the first object that radiated radio light, but appeared like a faint blue star rather than a nebulous cloud. This object, 3C 48, was mysterious because its spectrum revealed lines that were unfamiliar. Astronomers thought they had discovered a new class of radio-emitting stars.

About two years later, this object was joined by another, 3C 273. Astronomers observed the same spectral features in this object, and, in 1963, Maarten Schmidt of Palomar Observatory discovered that these were not new lines but were the familiar hydrogen lines shifted by 16% into the radio spectrum. This redshift (0.16) was the largest that had been observed to date and meant that the object was receding from us at about 16% the speed of light.

With such large redshifts, these objects were clearly not stars in our Galaxy. Furthermore, their enormous distances implied that they must be incredibly bright. In fact, they are the brightest objects in the universe, comparable in luminosity to 20 trillion suns or 1,000 Milky Way galaxies. But what are these mysterious objects?

What are quasars? Quasars have been observed in all regions of the electromagnetic spectrum, but they emit most of their light in the infrared. They resemble active galaxies but have much higher luminosities. An active galaxy has a supermassive black hole at its center that gobbles up gas from a surrounding accretion disk. This process emits high-energy light that can be seen to great distances. Quasars are simply more intense versions of these active galaxies. The central black hole consumes more material over the same period.

Quasars are our baby pictures of the "normal" galaxies we see nearby. The lookback times for the 2dF quasars range from 1 billion to more than 11 billion years. Consider a quasar with an 11 billion-year lookback time. The light we see from that quasar left 11 billion years ago, when the Universe was very young. By now, the quasar has no doubt evolved into something else, perhaps a calmer, "normal" galaxy, like the Milky Way.

Astronomers believe that quasars are snapshots from the formation stage of galaxies. As a galaxy comes together, it is very active and unsettled. This is the quasar stage. As the object evolves, its central black hole consumes material left over from the galaxy's formation and that rate of consumption slows over time. This is the active, or radio, galaxy phase, when the material around the black hole is emitting a lot of light and energy that is so bright, we can see it even at great distances. Once there is a lack of material for the black hole to feed on, the galaxy becomes less active and enters its normal stage, like our Milky Way. The Milky Way still has a massive black hole at its center, but its rate of consumption has slowed to the point where the energy emitted is much less than that of an active galaxy.

Furthermore, if we could travel instantaneously to a quasar that is 10 billion light years from Earth (and violate all physical laws doing so), we would see that the quasar has evolved into a "normal" galaxy like those in our neighborhood. And looking back to the Milky Way, we would see a galaxy in its quasar stage of evolution.

Distribution. The quasars are the most distant objects we see. The lookback times for the farthest quasars approach the age of the universe itself. The farthest known quasar, ULAS J1120+0641, is among these data. It has a redshift of 7.085, a distance of 28 billion light years, and a lookback time of 12.9 billion years.

Quasars appear to have no obvious signs of large-scale structure. This makes sense since we're only seeing a sparse sampling of the large-scale structure that exists. It's as if we only displayed the bright galaxies at the center of large clusters.

Cosmic Microwave Background

Group Name	`CMB1965, COBE1992, WMAP2003, Planck2013`
Reference	Cosmic Background Explorer (NASA, 1992) Wilkinson Microwave Anisotropy Probe (NASA, 2003-2012) Planck (ESA, 2010)
Prepared By	Brian Abbott (AMNH)
Labels	No
Files	`precobe.speck, cobe.speck, wmap.speck, planck.speck`
Dependencies	Various images
Census	1 all-sky image for each data group

The cosmic microwave background (CMB) radiation is our baby picture of the universe. It is the earliest light that we can see and reveals the primordial conditions in the early universe. For the past century, we have searched for and refined our knowledge of the CMB using space telescopes, but the history of its discovery predates our ventures into space.

Origin of the CMB. In the beginning, the universe was very hot and free electrons (those not attached to any atom) prohibited light from traveling freely, just as fog prevents light from traveling long distances.

As the universe began to expand, the temperature dropped several thousand Kelvin, allowing protons and electrons to combine to form hydrogen atoms. This occurred about 380,000 years after the Big Bang. Once most of the free electrons were bound to hydrogen atoms, the universe became transparent to light, allowing the cooled radiation left over from the Big Bang to travel freely throughout the universe—the fog lifted.

When recombination took place, the light from the Big Bang peaked at about 1 micrometer in the infrared. At that time the gas would have been about 3,000 Kelvin and would have glowed orange-red in the visible spectrum. However, the universe has expanded 1,000 times since, and the light within space has been redshifted to longer and longer wavelengths because of that expansion. Today, the peak wavelength is close to 1 mm (1 micrometer × 1,000 = 1 mm) and corresponds to a gas temperature around 3 Kelvin (3,000 K ÷ 1,000 = 3 K).

History of the CMB. In 1948, the astronomers Ralph Alpher (1921–2007), Hans Bethe (1906–2005), and George Gamow (1904–1968) published their assertion that the gas in the early Universe must have been very hot and dense and that this gas should be present throughout today's Universe, albeit much cooler and far less dense.

Alpher searched for this cool gas, but it would be another 16 years before it was discovered, not by astronomers but by two physicists working at Bell Telephone Laboratories in New Jersey. In 1964, Arno Penzias (b. 1933) and Robert Wilson (b. 1936) were trying to communicate with a recently launched communications satellite and could not remove "noise" from their transmissions. This weak hiss was a constant nuisance that was present during the day, the night, and throughout the year. This fact ruled out possibilities such as equipment interference, atmospheric effects, or even bird droppings on the radio telescope built to communicate with their satellite.

Penzias and Wilson tried their best to remove this noise but were unsuccessful. In the end, they acknowledged that the faint microwave signal must be real and is not from some defect or artificial interference.

In the meantime, researchers down the road at Princeton University were on Alpher's trail, investigating this gas from the early Universe. They maintained that the hot radiation would have been redshifted from gamma rays into x-rays, ultraviolet, visible light, and into the radio range of the EM spectrum. Furthermore, astronomers expected this radiation to be thermal, or what astronomers call blackbody radiation. An object is said to be a blackbody when it emits all the radiation it absorbs. In the early Universe, with only free electrons and nuclei (protons and neutrons), light scattered off electrons just as light travels through a dense fog and would have produced a blackbody spectrum.

If the signal detected at Bell Labs corresponded to a blackbody, it would have a temperature of about 3 Kelvin, which is equivalent to −270°C or −454°F. (In practical terms, most astronomical objects can be approximated by a blackbody spectrum, which has an inverse relation between the object's peak intensity and its temperature, called Wien's Law. Given the wavelength or frequency of the object's peak intensity, Wein's Law tells us the object's temperature.) But the Bell Labs observations could not confirm that the radiation was in fact from a blackbody, and they therefore could not conclude with certainty that this was the radiation left from the Big Bang.

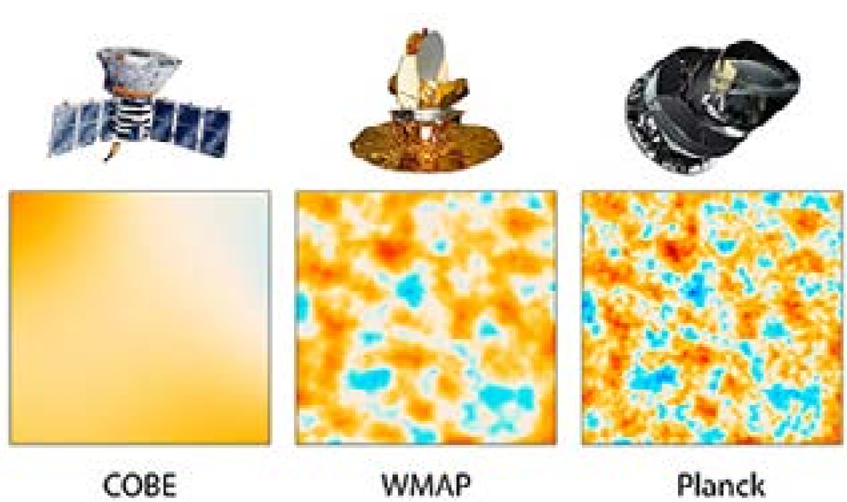
In 1989, the Cosmic Background Explorer (COBE) was launched into orbit to see, once and for all, whether the CMB was a blackbody. COBE observed light in the range from a few microns to about 1 cm, covering a broad swath in the radio spectrum. The results were indisputable. COBE had confirmed decades of theories with observational proof that the CMB was indeed the light left over from the Big Bang.

COBE also confirmed that the light was remarkably uniform. No matter where the telescope looked, it observed radiation equivalent to a 2.73-Kelvin blackbody with deviations on the order of one part in a hundred thousand. While COBE's angular resolution on the sky was about 7°, it was able to see small differences in temperature.

In 1995, a new mission to explore the CMB to greater resolution was proposed to NASA. Called the Microwave Anisotropy Probe (MAP), it was approved by NASA and launched on June 30, 2001, aboard a Delta II rocket. With the death of David Wilkinson, one of the founding members of MAP and COBE, the mission was named in his honor in 2002.

In 2009, the European Space Agency launched the Planck satellite into space. It's first all-sky map of the CMB was released in 2013 and improved upon WMAP's results.

A comparison of the relative sensitivity of each mission is demonstrated in the following image:



NASA/JPL-Caltech/ESA

What the maps reveal. The CMB images map the temperature in the microwave spectrum for the entire sky. The differences in color correspond to small differences in temperature. Those slight differences are on the order 0.00001 Kelvin, or one one-hundred-thousandth Kelvin.

These slight differences in temperature reflect the tiny fluctuations in density in the early universe—the structure of the universe shortly after the Big Bang. These are the seeds that will eventually grow, by gravity, into the large-scale structure we see today.

Group: CMB1965. This idea with this data group is to show that when the CMB was discovered in the 1960s, it essentially appeared the same in every direction. One uniform temperature, which we represent as a green image (green because it signifies the average color in the red-blue spectrum).

Group: COBE1992. COBE was the first real confirmation that the CMB was a blackbody, and that it has slight differences in temperature. These findings resulted in Nobel Prizes for it's principal investigators. The map is in red and blue, with the red patches slightly hotter than the blue patches. Variations in temperature are one part in 100,000.

Group: WMAP2003. WMAP released it's all-sky image in 2003, and it's final nine-year release in 2012. The map shows hotter areas in red, and colder areas in blue, with a temperature variation from the mean of 0.00005 Kelvin.

Group: Planck2013. Planck is the latest map of the CMB and is more sensitive than its predecessors. It can measure the temperature difference to about 2 parts per million. In this image, the orange spots are slightly hotter than average, while the dark blue areas are slightly cooler than average.

Placement. We place the CMB on a sphere that signifies the boundary of our observable universe. This is a bit misleading. While this is the earliest light we can see, it is ubiquitous throughout the universe, even in the Solar System.

Extragalactic Grids

Group Name	100kly, 1Mly, 10Mly, 100Mly, 1Gly, 20Gly
Reference	—
Prepared By	Brian Abbott (AMNH)
Labels	Yes
Files	100kly.speck, 1Mly.speck, 10Mly.speck 100Mly.speck, 1Gly.speck, 20Gly.speck
Dependencies	none

We use grids in the Extragalactic Atlas to provide scale as well as a visual beacon for home. The nested grids in the Extragalactic Atlas are centered on the Sun (or the Milky Way Galaxy) and extend to the farthest reaches of the observable Universe.

The grids are formed with Partiview's mesh command and can be brightened or dimmed with the Alpha Slider. The grids cover these size scales:

100kly	This is our final scale covering the Milky Way. Reaching out to 100,000 light-years, the grid is coplanar with the disk of our Galaxy and centered on the Sun. (All grids after this are in the plane of the celestial equator, since much of the galaxy survey data are in this plane.) This grid highlights the scale of the disk, the Sun's distance from the center of the Galaxy, and reaches out to the vicinity of our nearest neighboring galaxies.
1Mly	The 1 million-light-year grid is tipped with respect to the 100kly. This grid covers many of the Milky Way's satellite galaxies but not the entire Local Group.
10Mly	The next order of magnitude out is the 10 million-light-year grid. It spans the Local Group, and some of the neighboring galaxy groups.
100Mly	The 100 million-light-year grid covers the local universe, including the Virgo Cluster, and begins to reach the 2dF and Sloan galaxy surveys.
1Gly	The 1 billion-light-year grid covers the inner portions of the galaxy surveys, particularly where the large-scale structure is apparent.
20Gly	The largest grid extends to 20 billion light-years from the Sun and spans the majority of the quasars.