The Digital Universe Guide

For Partiview

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Overview

1.1   What is the Digital Universe?

The Digital Universe, developed by the American Museum of Natural History's Hayden Planetarium with support from NASA, 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.

1.2 Getting Help

The Hayden Planetarium staff welcomes your questions and comments about the Digital Universe via our email support line: **du@haydenplanetarium.org**. While we are not particularly staffed for this level of service, we do try to answer all email that is sent and we always like hearing from you.

1.3 Digital Universe License

This License is a legal agreement between you (the "User") and the American Museum of Natural History ("AMNH") regarding AMNH's Digital Universe Atlas (the "Atlas").

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1.4   About This Book

This book is designed for the reader who wants to be an expert on the ways of the Digital Universe with Partiview. Inside these pages, in gross detail, are the specifics of each data set, how it may be used to tell stories about the Universe, and how to manipulate these data to illustrate scientific concepts.

The guide was designed to be read electronically rather than on paper. A paper version will not take advantage of richly distributed, documentwide links. Also, it is impossible to search a paper document other than by eye, and this process leaves a lot to be desired. If you're not convinced, think of the trees.

We use the following conventions in this book:

1.5   Acknowledgments

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Getting Started

If you're new to the Digital Universe, you will want to read this chapter for an introduction to the Digital Universe data and Partiview, the software used to explore the Atlas. In this chapter we cover:

- Installing the Digital Universe.

- Launching the Digital Universe.

- Working with Partiview's user interface.

- Flying and navigation.

2.1 Installing the Digital Universe

Installing the Digital Universe is easy, just follow the instructions below. If you have problems, please email us.

1. Download[1] the installation file for your particular operating system.

2. Unzip the downloaded file if your operating system does not unpack it automatically. (On Mac OS X, the file will appear as a mounted disk on your system.)

3. *Optional:* Move the resulting `Digital Universe` folder to any location in your file system. (The download is completely self-contained and does not rely on files outside the newly created folder. This makes uninstalling a matter of throwing out this one folder.)

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[1]http://www.haydenplanetarium.org/universe/download/

2.2   Launching the Milky Way Atlas

Let's begin a quick orientation to the Digital Universe by launching the Milky Way Atlas. Follow these instructions for your operating system:

For...	Double-click or run the file...
Windows	`milkyway.bat`
Mac OS X	`milkyway.command`
Linux	`milkyway.sh`

Each file launches Partiview and reads a file called `mw.cf`, which loads and sets the display for the Milky Way Atlas.

Mouse Controls   Partiview is designed to function with a three-button mouse, and we recommend using at least a two-button mouse for navigation. If you're using a Macintosh, be sure the secondary mouse button is enabled in the system preferences. If you're using a trackpad on a Macintosh laptop, use the `Control` key along with the mouse button to emulate the right mouse button. (Using a trackpad to fly is difficult, but doable if you are adroit on trackpads.)

In this guide, we will use these conventions:

left-click   to refer to the left-most mouse button.

right-click   to refer to the right-most mouse button.
(Mac: `Control` + mouse button, or enable secondary button).

middle-click   to refer to the middle mouse button on a three-button mouse.

Beginning to Fly   The Milky Way Atlas opens with a view toward the constellation Orion and the bright stars Sirius and Procyon. If you move the mouse in the Graphics Window (where the stars are) while pressing the left mouse button, you will look around the sky (moving your head without moving your feet).

Turn the stars off by pressing the `g1=stars` group button in the upper left and turn on the open clusters (the `oc` button) and the globular clusters (the `gc` button). Also turn on the constellation connectivity lines (`constel` button) so that you know where you are in the sky.

Increasing the Window Size   If you are able to fly around with ease, try enlarging the window. You may want to do this slowly in case the graphics demand is pushed too high for your machine (at which point your computer will grind to a halt). If your machine freezes, either shrink the window or close it (press ESC) and wait for your computer to catch up.

Activating Data Groups   In order to alter the properties of a data group (brightness, color, label size), you must make the data group active. By default, the stars are the active group when the Milky Way Atlas is launched. You can verify that by inspecting the active group indicator below the Groups Menu. It is located next to the More Menu in the upper left and should say [g1] to indicate that group 1 (stars) is the active group.

Let's make the open clusters the active group by either right-clicking on the oc group button or selecting g6=oc from the Groups Menu. Now the active-group indicator below the Groups Menu should read [g6].

Brightening the Open Clusters   Now that the open clusters are activated, you can change their appearance. Start by making them brighter. Use the slider in the upper-right corner of the window.

This is a multipurpose slider that, by default, comes up as the Slum Slider. The slum command sets the scaling factor on the luminosity in Partiview. If you put your mouse on the value adjuster and move it back and forth, you will notice the open clusters becoming bright and dim.

Below the Slider Menu is the word slum, indicating that the slider is set to change the slum value. Set the group's brightness to the maximum value, then select alpha in the Slider Menu. Alpha acts as a fader and sets the transparency of the green polygons that represent the open clusters.

Moving the slider up and down, you can see that this is another way to effectively set the brightness of the polygons.

Leaving Earth   When the Milky Way Atlas is launched, you are sitting on the Sun and viewing the night sky as seen from Earth. With the left mouse button pressed, you can pan around the sky to your heart's content. How do you move away from the Sun, though, and begin flying around the stars? Turn on the stars and turn off the open clusters and globular clusters (click on their group buttons).

Beside the Groups Menu is the Flight Mode Menu. Partiview launches with Orbit Flight Mode as the default active flight mode, as indicated by the word [o]rbit below the menu.

To leave the Sun, choose the Fly Flight Mode from the Flight Modes Menu. Now, with the right button pressed, move the mouse toward the left. You're moving in reverse, flying away from the Sun.

Once you move away from the Sun, switch back to Orbit Mode by selecting it from the Flight Mode Menu or by typing a lowercase o, for orbit, in the Graphics Window (where the stars are displayed). This is a keyboard shortcut (see the *Partiview User's Guide*[2] for a list of keyboard shortcuts). Now use the left mouse button to orbit the Sun and the right button to move forward or backward.

With this brief introduction to Partiview and the Digital Universe, let's look at Partiview's flight modes and mouse functionality in the next section.

2.3   Learning to Fly Partiview

Partiview has four flight modes. Each has two kinds of flight (forward/backward, orbit, etc.), one for each mouse button.

Flight Scale   Moving forward or backward presents difficulties when you are traversing the large scales of the Universe. If your speed were constant everywhere, it would take forever to get outside the Galaxy. For this reason, Partiview has two flight scales in the forward and backward direction, *linear* and *logarithmic*, described in Table 2.1.

Table 2.1 – Flight scales in Partiview. The distance, *d*, is measured from the Point of Interest, which, by default, is the Sun.

Scale	If $d = 0$...	If $d = \infty$...	Description
Linear	v = constant	v = constant	Constant scale everywhere; useful for exploring an object near the Point of Interest.
Logarithmic	$v = 0$	$v = \infty$	The scale increases radially away from the Point of Interest, resulting in higher speeds as your distance increases from the Point of Interest.

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[2]http://haydenplanetarium.org/universe/partiviewguide/

Flight Modes   Partiview has four flight modes, listed in Table 2.2. With each mode come two types of flight. These are discussed in Table 2.3.

Table 2.2 – Flight Control with the Mouse in Partiview.   Shortcut keys are shown in square brackets and are used in the Graphics Window.

Flight Mode	Button			Scale
	Left (1)	Middle (2)	Right (3)	
Fly [f]	pan	select [p]	forward	linear
Orbit [o]	orbit	select [p]	forward	log
Rotate [r]	orbit	select [p]	rotate	not applicable
Translate [t]	translate	select [p]	forward	linear

Changing the Flight Mode   Change the flight mode by selecting a mode from the Flight Mode Menu or by typing one of the shortcut keys (f, o, r, or t) in the Graphics Window. The active flight mode appears below the Flight Mode Menu.

Table 2.3 – Motion Control in Partiview

Motion	Description
pan	Shift your view without moving from your current position, equivalent to looking around by moving your head but not your feet.
forward, reverse	With eyes forward (looking at the center of the display), moving toward or away (backward) along your line of sight.
orbit	Orbit about the Point of Interest. If the Point of Interest is in view, this is a simple orbit around that point. 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 "orbit" its center.
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 (above).
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.

Table 2.4 – Additional Mouse Functionality in Partiview

Function	Mouse Button	Keyboard Shortcut	Description
select	middle	p	With the mouse on an object, click the middle mouse button to produce a report on that object in the Console Window. If you don't have a middle mouse button, place the cursor on an object and use the p key.
Changing the Point of Interest	Shift + middle	Shift + p	Select a data point near the mouse and move the Point of Interest to that location.

2.4   Partiview's User Interface

Partiview's graphical user interface (GUI) was written to be simple and compact. However, for a new user, parts of the interface may seem cryptic. The buttons, sliders, and menus are designed to make navigation, data manipulation, and data group toggling effortless, but they result in an interface that looks foreign to most experienced computer users.

Most of Partiview's rich command set is not represented in the GUI. We recommend consulting the *Partiview User's Guide*[3] for a list of commands and keyboard shortcuts.

Using the screen shot below or the Partiview session you just launched, let's investigate the GUI elements one by one.

Figure 2.1 – Partiview's graphical user interface (GUI). Consult the tables and
images below to learn how to use the GUI buttons and sliders.

Partiview Menus		
▽ More	▽ [g1]	▽ [o]rbit
▽ More	**More Menu**	More contains two items that are rarely used. Inertia toggles the "drift" feature on and off when you are flying. H-R Diagram invokes a separate window where an H-R Diagram will be displayed (this is not implemented in the Digital Universe).
▽ [g1]	**Groups Menu**	Choose the active data group. The active data group is displayed below the menu (here it is group 1, indicated by [g1]).
▽ [o]rbit	**Flight Mode Menu**	Choose your flight mode (Orbit, Fly, Rotate, Translate). Orbit is the default flight mode and is indicated below the menu by [o]rbit. [See "Learning to Fly Partiview" for information on Partiview's four flight modes.]

Toggle Buttons		
point poly lbl tex box home		
point	**Point**	Turn the points on and off for the active group.
poly	**Polygon**	Turn the polygons on and off for the active group.
lbl	**Label**	Turn the labels on and off for the active group.
tex	**Texture**	Turn the textures (images) on and off for the active group.
box	**Box**	Turn the boxes on and off for the active group.
home	**Home Button**	Return to the 'home' position set by the home command in the config file. (In the Milky Way Atlas, home is roughly Earth's position.)
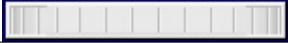
The Partiview Slider		
	Slider Scale Button	A toggle button between the logarithmic or linear scale (if available) for the active slider. See the following table for the range on each slider in the log and linear modes.
	Slider	Use the blue value adjuster to alter the value of the active slider. The logarithmic or linear value is indicated to the left of the Slider. Below the slider you'll see the active data group and the linear value of the slider (except for the Slum Slider, which has no value shown).
	Slider Menu	A drop-down menu to select the slider function. The active slider appears below the menu (the Slum Slider is shown). Slider functions are described in the table below.

Slider Menu	
Alpha	Sets the opaqueness of an object or image.
FOV	Adjusts the field of view. We typically use values near $60°$; "telescopic" views may be achieved with small values for the field of view.
Censize	The size of the Cartesian Point of Interest marker. Values are in the units of the particular data you are viewing. For the Milky Way Atlas, the units of distance are parsecs (1 parsec = 3.26 light-years). In the Extragalactic Atlas, the units are megaparsecs.
Labelmin	Set the minimum pixel height before a label will be drawn. This is useful if you want only the nearby labels displayed. Set this value to 0 pixels for all labels to be drawn. Setting $labelmin$ to 20 will draw labels only when they are more than 20 pixels high.
Labelsize	Set the height of the labels in pixels.
Polysides	Adjust the number of sides of the polygons in the active group.
Polysize	Set the size of the polygons.
Slum	Scale the luminosity of the particles, increasing or decreasing their brightness.
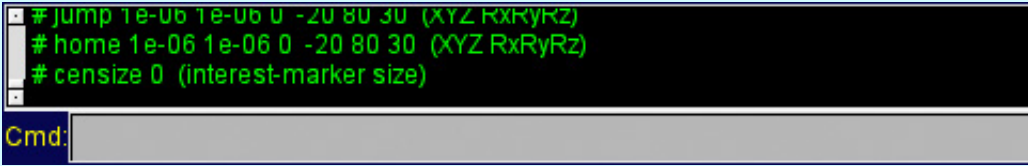
Table 2.5 – Range on the sliders in the linear and logarithmic scales (if available).

Slider	Linear Range	Logarithmic Range	Default Range
Alpha	0–1	not available	linear
FOV	0–180	not available	linear
Censize	0–10,000	0.001–10,000	log
Labelmin	0–20	not available	linear
Labelsize	0.01–1,000	0.001–1,000	log
Polysides	3–16	not available	linear
Polysize	0–10	0.001–10	log
Slum	not available	0.001–31,623	log

Group Buttons	
Note: Group Buttons appear only if two or more data groups are defined.	
Left Mouse Button	Turn the active group on or off.
Right Mouse Button	Activate a data group (a data group must be active for you to change its display properties).

Time Controls	
NOTE: The time controls appear in the GUI only when time-evolving data are loaded.	

	Time Display	Black text box displays the current time. If an offset has been set using the Trip Button, this shows the offset from the tripmeter. The absolute time is the sum of the T and + text boxes.
	Reference Time Display	If the Trip Button is pressed, this blue text box shows the reference time.
	Trip Button	Marks a reference in time. Sets the Time to zero and the Reference Time to the current time.
	Back Button	Sets Time to zero. If the Trip Button has been set, this will return the time to the Reference Time.
	Time Dial	Fine-control time adjuster.
	Time Control Buttons	Adjust time by $(0.1 \times speed)$ data time units.
	Speed Slider	Logarithmic control of the speed.
	Speed Toggle Buttons	Toggle time forward or backward.
	Feed Button	This button has no effect and was built into the GUI for future use.

Flight Path Controls		
NOTE: Partiview is not capable of recording a flight path.		
	Path Button	Opens a file explorer to choose a flight path file to load.
	Play [Stop] Button	Toggle the path animation on and off. Right-click on this button to adjust the play speed. `Play 0.5` will play the path at half speed; `play 5` will play the path 5 times as fast. `Play 5f` increases the frame rate 5 times.
	att Button	This button appears to have no function.
	Frame Controls	The frame number is displayed in the white text box. Use the ◀ or ▶ buttons to advance the path by 1 frame. Use the ◀◀ or ▶▶ buttons to advance the path by 10 frames.
	Flight Path Slider	Manually adjust time and position on the path. Wall-clock time is shown in the black text box to the left of the slider.

|	
Console Window and Command Line	
Console Window	Shows the input and output to and from Partiview. Some commands issued by the user are echoed here in yellow along with Partiview's response (if any) to them in green.
Command Line (`Cmd:`)	Use the Command Line to enter Partiview commands interactively. To type in this line, focus must be given to this narrow window. You can do this by either placing the mouse in this small space (and hope it stays there) or use the `Tab` key to move the cursor to the Command Line. Use the up and down arrow keys to scroll through the history of commands issued.

2.5   Digital Universe Files

Once the Digital Universe is installed, you will find all the necessary files in one folder (called `Digital Universe` in the figure below). Inside that folder you will find the following:

Figure 2.2 – The hierarchy of files and folders in the Digital Universe Atlas.
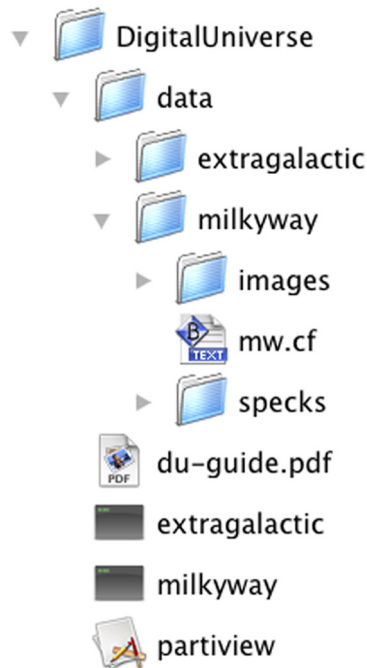
Within the `Digital Universe` folder are the Partiview application, several start scripts, and the data folder. Within the data folder are the `milkyway`, `extragalactic`, and possibly other data folders. Down one more level within `milkyway` and you'll find the config file `mw.cf` for the Milky Way Atlas and the `speck` and `images` folders for the Milky Way Atlas. A similar file structure is found in the `extragalactic` folder.

You will find several file types in the Digital Universe distribution. Table 2.6 lists these file types by group.

Table 2.6 – Digital Universe file types and definitions

File Type	File extension	Description
Launcher file	`*.bat` `*.command` `*.sh`	Double-click on these files to launch the Milky Way Atlas or the Extragalactic Atlas. (You will have only one of these, depending on your operating system.)
Data Files	`*.speck` `*.label` `*.cmap` `*.obj`	Data and data variable commands Labels for the data Color map data Surface data
Images	`*.sgi`	Image files
Configuration	`*.cf`	Initialization commands and configure options. Customize the atlas with these files.

Customizing the Digital Universe   You can use the `*.cf` files to customize the initial look of the Milky Way Atlas and Extragalactic Atlas. These files are simply a listing of Partiview commands that are read by Partiview and executed. If an object is too bright or you want to change its color, for example, set the desired brightness or color in Partiview, then open the config file in a text editor and make the change to the appropriate command under the correct data group.

Of course, it is necessary to have some familiarity with the Partiview commands. Information on these can be found in the *Partiview User's Guide*[4] or from information on the Partiview website.

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[4] http://haydenplanetarium.org/universe/partiviewguide/

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The Milky Way Atlas

The Milky Way, our home Galaxy, is a large concentration of gas, dust, and a few hundred billion stars. Our star, the Sun, is one among them. The Milky Way is called a spiral galaxy for its spiral arms, where much of the gas is concentrated.

After an overview of the data groups, we will lead you through the Milky Way Atlas in a series of self-guided tutorials, then provide a reference for each data group.

end figure.

3.1 Milky Way Atlas Overview

The Milky Way Atlas represents, in two and three dimensions, scientific information spanning everything from the presence of infrared radiation to the locations of exoplanets (stars that have planetary systems).

Each of these elements is represented by a single data group in Partiview, defined and given a name by the `object` command in the `mw.cf` file. These names are then displayed in the Group Menu and on the Group Buttons in the Partiview user interface.

Table 3.1 – Milky Way Atlas data groups. Refer to the associated page
number for a detailed description for each group.

Group Name	See Page	Description
stars	66	The observed stars
altLbl	72	Greek (Bayer) and Flamsteed star names
err	73	Stellar distance uncertainty
constel	75	Constellation connectivity lines
nearstars	78	Lépine-Shara proper motion star catalog
dwarfs	80	L and T dwarf catalog
expl	82	Extrasolar planets
oc	84	Open star clusters
ob	86	OB associations
gc	88	Globular star clusters
pul	91	Pulsars
pn	94	Planetary nebulae
h2	96	Star-forming clouds (a.k.a. H II Regions)
snr	99	Supernova remnants
oricl	101	Orion Nebula star cluster
orineb	102	Orion Nebula model
oort	105	Oort Cloud sphere
radec	106	Equatorial (RA/Dec) coordinates sphere & Radio sphere
eclip	108	Ecliptic coordinates sphere
galac	110	Galactic coordinates sphere
		Continued on next page.

(Table Continued)

Group Name	See Page	Description
mwVis	111	Visible all-sky survey
mwH	113	Atomic hydrogen all-sky survey
mwCO	114	Carbon monoxide all-sky survey
mwFIR	115	The far-infrared all-sky survey
mwIRASc	117	The IRAS composite all-sky survey
mw2MASS	119	The 2MASS all-sky survey
mwHa	120	The hydrogen-alpha all-sky survey
mwGamma	122	Gamma-ray all-sky survey
dso	124	"Deep-sky" images
sloanstars	140	Sloan Digital Sky Survey Stars
galaxy	127	An exterior image for the Milky Way
starorbits	142	One-billion-year stellar orbits
bar	129	The Galactic bar
bulge	130	The central bulge of the Galaxy
halo	131	The Galactic halo
lgrp	132	Local Group of galaxies
solsys	133	Planetary orbits of the Solar System
probes	135	Pioneer and Voyager spacecraft trajectories
1lmo	137	Grid centered on the Sun extending to 1 light-month
1ly	137	Grid centered on the Sun extending to 1 light-year
10ly	137	Grid centered on the Sun extending to 10 light-years
100ly	137	Grid centered on the Sun extending to 100 light-years
1kly	137	Grid centered on the Sun extending to 1,000 light-years
10kly	137	Grid centered on the Sun extending to 10,000 light-years
galGrid	139	100,000-light-year grid centered on the Milky Way

3.2 Milky Way Atlas Tutorial

The Milky Way tutorial is designed to introduce you to the Milky Way in segments that lend themselves to the scale and structure of our Galaxy. Each tutorial covers the science, the data, and Partiview's user interface and selected commands. Complete information on each data group can be found in "Milky Way Data Groups."

Each tutorial will tell you what to turn on before starting and what data groups and commands you will use in the tutorial. Let's start with the view from Earth.

3.2.1 The View from Earth

We begin with what may be familiar: the night sky. Each tutorial in this section focuses on how to view the Atlas from one place, Earth. In reality, the Earth-Sun distance is negligibly small in the parsec-scaled Milky Way Atlas (the Earth-Sun distance is about 93 million miles, or 0.00000485 parsecs), so the Earth and Sun are synonymous with one another when we discuss their position in the Atlas.

Of course, there is no daytime sky in the Digital Universe—Partiview is not a planetarium simulator. Partiview cannot show you when stars rise and set or where the planets are. Rather, its strength lies in giving context to the objects that make up our Galaxy, tapping into its data visualization roots.

Now, let's begin by launching the Digital Universe's Milky Way Atlas.

Tutorial: Learning to Fly

Goals: To learn basic functions and review navigation.

Before starting, turn on: `stars`, `mwVis`

You will be using: no additional groups

Your Initial Location   When you launch the Milky Way Atlas, the preset position has you looking toward the constellation Orion, with the stars Sirius and Procyon in the foreground. The size of their labels is proportional to their distance from you, so you can gauge the distance of objects based on their label size. But from where are you viewing these stars?

When you start the Milky Way Atlas, you are on a unique point. In Partiview it is called the Point of Interest. The Point of Interest is the point about which rotations and orbiting take place. In the Milky Way Atlas, it is set to the Sun's location at $(x, y, z) = (0, 0, 0)$. (You are actually positioned a negligible distance from the Point of Interest for reasons we'll discuss later in this section.)

Panning Around the Sky   With the left mouse button pressed, move the mouse inside the Graphics Window to pan around the sky. You will notice the stars, a few star labels, and the band of the Milky Way. The stars resemble those in the sky in luminosity and color. We place a texture, or image, on each, giving depth to the star field. If you don't care for these textures, you can click the Polygon Toggle Button to turn off the star's polygons (the textures are drawn on polygons). Remember, for this change to take effect, stars must be the active group. (A group becomes active when you right-click on its Group Button or select it from the Group Menu.) Of course, once you turn the textures off, the stars will all look similar to one another, so we prefer to have the polygons on.

Moving Off the Point of Interest   Let's exercise our navigational skills. Partiview starts in the Orbit Flight Mode. You can confirm this by looking at the active flight mode printed below the Flight Mode Menu, which should read [o]rbit.

You've seen what the left button does from this position; it moves your head without moving your position in space. If you try holding the right button down, you won't see too much happen. Because Orbit Mode is a logarithmic flight mode, you will have zero speed when sitting on the Point of Interest. Because you're not exactly on the Point of Interest, you are likely to begin moving backward or forward after some time, but who wants to wait?

Now, using the Flight Mode Menu, switch the flight mode to [f]ly. With the right button, fly backward away from the Sun. Fly is a linear flight mode, so it remains the same speed no matter where you are in the Atlas. Using the left button in Fly Mode, pan around a bit, keeping the Sun in view. Here you're moving your head but not your position.

Using the Keyboard to Switch Flight Modes   Now switch back to Orbit Flight Mode. With the left button, you will now orbit the Point of Interest, in this case the Sun. The bracketed first letter in each flight mode may be used in the Graphics Window to switch flight modes.

To test this, activate the Rotate Flight Mode by pressing r (must be lowercase) in the Graphics

Window. You should see [r]ot appear below the Flight Mode Menu. You'll quickly notice that the left button is the same as Orbit Flight Mode, orbiting the Point of Interest. The right button twists the view about the Point of Interest, in a plane parallel to your screen.

Translate Flight Mode Finally, switch to Translate Flight Mode using the t key and, with the left button pressed, move the mouse. Here you move your position but always keep your eyes forward. The data always move parallel to your screen in the direction of mouse motion. The right button moves you forward or backward.

Now switch to Orbit Mode and press the Home Button to bring you back to the Earth's view. You're ready to continue to the next tutorial.

Tutorial: Constellations

> **Goals:** To become familiar with the constellations data set; altering the transparency and color values for objects and labels.
>
> **Before starting, turn on:** stars, mwVis, constel
>
> **You will be using:** alpha, cment, and the textcment commands

Much as we might spot a cloud in the sky and imagine what it resembles, ancient astronomers looked to the stars and dreamed of the heroes and cowards, animals and monsters, or kings and queens of their lore. Given this task today, perhaps we would see star patterns in the form of Gandhi, a computer, or an airplane. The constellations adopted by astronomers include those from ancient Greek times as well as several modern constellations, mostly in the sky as seen from the Southern Hemisphere. For more information on their origin, see "Constellation Connectivity Lines."

We represent these celestial beings as "stick figures" connecting the bright stars that form their shapes. There are three colors assigned to the constellations in the mw.cf file. Most constellations have a dark pink shade. The zodiacal constellations are bright red and Orion and Ursa Major are given a blue color. The data also have labels associated with them. These labels are placed at an arbitrary distance of 65 light-years.

Brightening the Lines If you want to brighten or dim the constellation lines, you must use the alpha command. (The slum command that scales the luminosity works only on points.) Use the Alpha

Slider (choose `alpha` from the Slider Menu) to increase or decrease the opaqueness. If `alpha` = 0, the lines are completely transparent (invisible); if `alpha` = 1, the lines are opaque. We don't recommend using an `alpha` of 1, as it will produce unwanted graphics effects. Use `alpha` = 0.99 if you want really bright lines.

You may also use the Partiview Command Line to set an alpha value. For example, type `alpha 0.5` to bring the lines to half transparency.

Changing Their Color   If you're unhappy with the colors we've chosen, you are free to change it. In Partiview, particles are assigned a color set by the color command; however, objects and labels are assigned color using the cment and textcment commands. Well, it's actually more complicated than that. cment assigns a red-green-blue color to a reference number called a color index, and this color index is then assigned to the object.

In the Digital Universe, we try to use color indexes of 1 when possible. Occasionally, a data group has more than one object or more than one color assigned to an object (as is the case for the constellations), making it necessary to use more than one color index.

For the constellations, we use a color index of 3 for Orion and Ursa Major, a color index of 2 for the zodiacal constellations, and a color index of 1 for the remaining constellations. Partiview will report the color assigned to color index 1 when you type

```
cment 1
```

and so on, replacing "1" for the remaining color indexes. Remember, the colors are expressed in red, green, blue values, which range from 0–1. A color value of 0 means there is no color present, while a value of 1 is color saturation.

For a pure red color we have $(R, G, B) = (1, 0, 0)$. White is $(R, G, B) = (1, 1, 1)$, black is $(R, G, B) = (0, 0, 0)$, and pure yellow is $(R, G, B) = (1, 1, 0)$. To make the lines a nice greenish color, type `cment 1 .2 .7 .2`.

Changing the Label Color   Similarly, the label color may be changed with the textcment command:

```
textcment 1 .2 .7 .2
```

You may notice that the labels appear much brighter than the lines. This is because the lines have an alpha channel factored into their display. Bring the alpha up to 0.9 and the lines and labels will resemble one another. This is not the best solution, though, as the lines dominate the view. Better to bring the alpha down so that the lines are subtle, then desaturate the label color. For example, the commands

```
alpha 0.4
textcment 1 0.05 0.4 0.05
```

will bring the color of the lines and labels into general agreement.

If you like these changes and wish to preserve them, open the `mw.cf` file and change the values for these commands in the constellation section.

Tutorial: Coordinates in the Sky

> **Goals:** Familiarize yourself with the different coordinate systems; discover what these systems tell us about the Galaxy and our position in it.
>
> **Before starting, turn on:** `stars`, `mwVis`
>
> **You will be using:** `radec`, `eclip`, `galac`, `altLbl`, cment and fov commands

Coordinate systems are used primarily to locate objects in the sky. There are several Earth-based systems that astronomers use to describe the position of an object. One is based on Earth's system of longitude and latitude, while another is based on the plane of the Solar System. Yet another is based on the plane of our Galaxy.

Equatorial Coordinates Resemble Earth's Coordinates in the Sky   With the Milky Way Atlas running and from the home position, turn on the `radec` group. These are the equatorial coordinates. This system is based on Earth's longitude and latitude; the brighter blue line is the celestial equator, the line projected on the sky from our equator on Earth. Pan around and you will see the north and south celestial poles, those points directly above the North and South poles on Earth.

In the sky, the equivalent to Earth's latitude is called declination (Dec) and is measured from $+90°$ at the north celestial pole to $-90°$ at the south celestial pole. Longitude is called right ascension (RA) and is measured from 0 to 24 hours. You can find more information on this system in "Equatorial Coordinates Sphere." The coordinates are labeled in 10-degree increments for declination and every hour for right ascension.

You will notice Polaris, the pole star, is right beside the north celestial pole, just where you probably expect it to be. Orion's belt, three stars in a line, is just below the celestial equator.

Ecliptic Coordinates are Based on the Solar System   Turn off `radec`, then turn on ecliptic coordinates group `eclip`. The ecliptic coordinates are in red and have a brighter line for the "equator." What is the physical significance of this coordinate system, though?

The equator in this coordinate system is called the ecliptic. It is the path the Sun makes in the sky and, therefore, is the plane shared by the Sun and Earth, generally the plane of the Solar System. In this system, we measure an object in ecliptic longitude and latitude.

Because ecliptic coordinates describe the Sun's path in the sky throughout the year, the ecliptic passes through all the zodiacal constellations. If you turn on the `radec` group once again, you can see the effect of Earth's obliquity. The obliquity refers to the degree to which Earth is tipped on its axis of rotation. If it weren't tipped, the ecliptic (bright red line) would coincide exactly with the celestial equator (bright blue line) and the Sun would always be directly over Earth's equator, resulting in an Earth with no seasonal climate changes. The amount of "tip" can be seen in the angles between these two systems. Find where the celestial equator and the ecliptic cross. The angle between them is $23\overset{\circ}{.}5$. Now look toward either of the poles. The angle between the celestial pole and the ecliptic pole is also $23\overset{\circ}{.}5$. Also, the maximum distance between the ecliptic and the celestial equator is. . . you guessed it, $23\overset{\circ}{.}5$. This number appears many times on Earth's coordinates too. The angle between the equator and the Tropic of Cancer or Capricorn, the angle between the North Pole and the Arctic Circle, are all $23\overset{\circ}{.}5$. Let's keep to the sky, though.

Galactic Coordinates Trace the Galactic Plane   Now turn off the ecliptic and equatorial coordinates and turn on the Galactic coordinates with the `galac` button. In Galactic coordinates, objects are expressed in terms of Galactic longitude and Galactic latitude, which are measured in degrees. The Galactic equator (bright green line) coincides with the band of the Milky Way in the sky. When you look toward the equator, you are looking right into the disk of the Galaxy. Therefore, when we look to the Galactic poles, we are looking directly out of the disk of our Galaxy. These areas are windows out of the Galaxy—with little gas and dust along these lines of sight, we can see much farther into the Universe.

Now turn on the ecliptic coordinates and find where the ecliptic meets the Galactic equator. Once you find their crossing, switch to Rotate Fly Mode and rotate the view with the right mouse button such

that the Galactic equator is level (parallel to your tabletop). The angle between these two lines demonstrates the inclination of the plane of our Solar System with respect to the Galaxy. At about 62°, the planets revolve around the Sun steeply inclined to the Galactic disk. Of course, the planetary orbits are so small that they are lost in the Galactic disk along with the Sun, but it is fascinating to think we are not orbiting the Sun in the same plane that we orbit the Galaxy. One often thinks of the plane of the Solar System as a cardinal plane, defining how we think of up and down in space, but now we have a new horizon, the Galactic plane.

Tutorial: The Milky Way from Earth

> **Goals:** Understand how the band of light in the sky relates to the 3-D picture of the Galaxy.
>
> **Before starting, turn on:** nothing
>
> **You will be using:** gall command, stars, mwVis, alpha command, radec, gc

If you're coming from the previous tour, let's clear the board. In Partiview's command line, type the command

```
gall off
```

This command tells Partiview to act on all groups with the off command. Of course, you can use this command to increase the brightness of all groups (gall slum *4) or turn them all red (gall color const 1 0 0) if you desire.

The Band of the Milky Way   Now turn on the stars and the mwVis groups. The mwVis data group is the band of light across the sky that, for thousands of years, we have called the Milky Way. That band is the disk of our Galaxy, bright toward Sagittarius, dimmer toward Orion.

Brighten up the Galaxy by increasing its alpha value. You can either use the Alpha Slider (choose alpha from the Slider Menu) or use the Command Line by entering alpha 0.8, for example. (Recall that the alpha value ranges from 0–1.)

Now you see some details that would not normally be seen. The bright clouds and the dark dust lanes reveal themselves when we brighten up the image. Upon scanning the entire band, you will notice a clear distinction between the bright areas toward the center of the Galaxy and the dim regions opposite the center.

Relate this to Earth by turning on the equatorial coordinates, `radec`. These are Earth's coordinates projected onto the sky. The bright line is the celestial equator, and the poles (where the lines converge) are those parts of the sky directly over the poles on Earth. From mid-northern latitudes, we see from about $-40°$ to $+90°$ declination throughout the course of the year. Notice the difference between the Milky Way visible in the Northern Hemisphere and that part visible at southern latitudes. The southern Milky Way is much brighter and more beautiful.

Globular Clusters Are Mostly Near Galactic Center   Let's perform the same experiment that the astronomer Harlow Shapley did 80 years ago. Born in 1885, Shapley was studying the sky at Mount Wilson Observatory outside Los Angeles when the country was involved in World War I. Wartime blackouts in the city provided astronomers an opportunity to see the sky without the lights of the city below.

Shapley had been looking at the globular clusters in the sky for some time. Turn on the globular clusters, `gc`, scan the sky, and see if you notice anything odd about where they are located. See anything strange? Look toward the star Sirius, then look toward the opposite side of the sky along the Milky Way. It's easy to see that most of the clusters are found around the bright part of the Milky Way.

From this, Shapley deduced that the center of our star system must be in this direction. By estimating the distance to these clusters, he put to rest the debate about the size and structure of our Galaxy. We'll revisit this in three dimensions later in these tutorials.

Earth lies within the disk of the Galaxy, making it difficult for astronomers to understand the structure of our star system. Not until astronomers began seeing the Milky Way in wavelengths outside the visible spectrum did the structure of the Galaxy become apparent.

Tutorial: Two-Dimensional Distributions

> **Goals:** View various data sets from Earth's perspective to see what they reveal about the Galaxy.
>
> **Before starting, turn on:** `stars`, `mwVis`, `gc`
>
> **You will be using:** `oc`, `ob`, `pul`, `pn`, `h2`, `snr`

You've seen the distribution of the globular clusters in "The Milky Way from Earth," now let's investigate other data sets for similar trends.

Open Clusters Are Found in the Band of the Milky Way   With the globular clusters on (`gc`), turn on the open clusters with the `oc` button. Open clusters are less dense, younger star clusters. In the Atlas, they are represented by green points. By turning off the `stars` group, you have a clear view of the two types of clusters. You can make things even clearer by turning off the clusters' labels. Make `oc` the active data group and press the Label Toggle Button. Once you've turned off the labels for both data groups, it becomes apparent that the open clusters are concentrated in the Galactic disk, while the globulars are found mainly in one part of the sky.

This concentration of open clusters in the disk led astronomers to call them *Galactic clusters.* Since gaining a wider perspective on our Galaxy and the surrounding Universe, astronomers have since turned to calling them open clusters, a name that refers to the more spread-out nature of the stars within them.

Open Clusters Are Younger Than Globular Clusters   This spatial distinction between open and globular clusters reveals a story of Galactic structure and evolution. Open clusters are filled with younger stars and, therefore, are found in regions of the Galaxy where star formation occurs. Globular clusters are filled with older stars that formed very soon after the Galaxy was born.

In our Galaxy, star formation occurs in the spiral arms within the disk. The gas in the disk condenses to form stars, some of which are massive enough to explode in supernovae, thereby triggering new stars to form by compressing the surrounding gas. The older stellar population is found in the spherical component of the Galaxy, often called the halo. Most of the stars in the halo are cool, dim stars that are spherically distributed around the Galactic center.

What Do Other Data Sets Tell Us About the Galaxy?   Let's turn on another data set, `ob`, that shows the locations of bunches of stars called OB associations. These contain from tens to hundreds of stars and, as you can see, lie in the plane of the Galaxy. Again, these are filled with younger stars, as the associations last only a few tens of millions of years before drifting apart into individual stars.

Turn on the rest of the 3-D data groups: pulsars, `pul`, planetary nebulae, `pn`, star-forming regions, `h2`, and supernova remnants, `snr`. Aside from the star-forming regions (called H II regions), which signal stellar birth, the rest of these signify stellar death. H II regions, in a sense, are at the beginning of the stellar life cycle. These give birth to open clusters and OB associations, which eventually die to become planetary nebulae, pulsars, or supernova remnants. Because these are connected to the stellar

life cycle, you would expect them to lie in or near the Galactic plane. For the most part, they do. You may see some pulsars or planetary nebulae up toward the Galactic poles [turn on the Galactic coordinates, `galac`, to see], but these are typically nearby, just above or below us in the Galactic disk.

As you scan the sky, you now see the clutter that is our Galaxy. The disk appears to be a disordered mess. This view is akin to looking at a map with too much information. One would never look at a map that contained every town and village. Cartographers must choose which towns to display and typically choose population as a filter. But they also base it on the scale of the map. In the Digital Universe, this is equivalent to changing the field of view. Center the disk of the Galaxy in the Graphics Window and use the FOV Slider to "zoom in" so that the map becomes clear. Some of the polygons may be too large, but you get the idea. By decreasing your field of view, you effectively increase your resolution, clarifying the view.

You have explored the Atlas from Earth's point of view. Now it's time to leave our home planet and fly into the solar neighborhood.

3.2.2 The Solar Neighborhood

In this section of tutorials, you will leave Earth's view behind and begin to explore that part of the Galaxy near the Sun and Solar System. We will look at the nearest stars, stars with planetary systems, and the extent of Earth's radio signals. But first let's leave the Sun behind and explore our surroundings.

Tutorial: The Solar System

> **Goals:** Seeing the size and scale of the Solar System and the extent of the farthest spacecraft; understand light-travel time and distance.
>
> **Before starting, turn on:** `stars`, `mwVis`
>
> **You will be using:** `solsys`, `probes`, `1lmo`, `constel`, `1ly`, **clip** command

Turn on the Solar System's planetary orbits with the `solsys` button. Because the orbits are so close to the Sun in the parsec-scaled Milky Way Atlas, you need to perform some maintenance in Partiview to view them.

Adjust the Clipping Planes to See Objects Right Next to You   In computer graphics, programs regulate what the computer must draw and keep track of to improve their performance. If you think of your view as a pyramid in which you are looking through the apex, the sides of the pyramid are defined by the field of view. Set the field of view to small values and less information is drawn, your pyramid is narrow. What about the sides parallel to your screen? These boundaries are set by the near and far clipping planes.

When you start the Milky Way Atlas, the near clipping plane, which sets where the apex of the pyramid is located, is set to 0.1 parsec (0.326 light-years). Objects closer than this will not be drawn. Similarly, the far clipping plane, the base of the pyramid, is that distance beyond which nothing is drawn. In the Milky Way Atlas this value is set to 1 million parsecs (3.26 million light-years). To see these current values, type `clip` in the Partiview Command Line and it will return # `clip 0.1 1e+06`.

Let's alter the planes to bring those objects right in front of us into view. Type the command

    clip 0.0001 1e5

setting the near and far clipping planes to 0.0001 and 100,000 parsecs, respectively. (Note that some systems cannot handle a near clipping plane of less than 1, so this may not work on your computer. You

may need to adjust the clipping plane values to remove unwanted flashing.)

Now you should see the orbits of the planets drawn on the sky.

Viewing the Solar System in the Milky Way Atlas   Pull back slowly (hold the right mouse button down and move the mouse to the left) until the Sun pops into view, then stop (click the mouse). Turn off the glare of the Sun by selecting `stars` as the active group and pressing the Polygon Toggle Button.

In this group you will find the orbits of the rocky, inner planets huddled around the Sun: Mercury, Venus, Earth in blue, and Mars in red. Beyond these are the gaseous planets Jupiter, Saturn, Uranus in green, and Neptune in blue. Finally, we have Pluto, the small, dwarf planet that's smaller than our Moon and whose orbit is inclined to the plane of the Solar System by $17°$.

The Farthest Man-Made Objects   Turn on the space probes (`probes` button). These four trajectories show the paths of the Pioneer and Voyager spacecraft from their launch date to the year 2050. Voyager 1 was launched in 1977 and explored Jupiter and Saturn before it was shot out of the plane of the Solar System by Saturn's gravity. Voyager 2 explored Jupiter (1979), Saturn (1981), Uranus (1986), and Neptune (1989) before leaving the plane.

Labels on the trajectories mark the years as well as the light-travel time. You may be familiar with the light-year, the distance light travels in one year. Similarly, a light-day is the distance light travels in one day. At 300,000 km/sec (186,000 miles/sec) and with 86,400 seconds in one day, that distance equals 26 billion kilometers (16 billion miles). A table of the relationship between light-travel time and distance can be found in "Light-Travel Time and Distance."

Let's get some perspective. Turn on the 1-light-month grid, `1lmo`, and pull back from the Solar System a bit. This group consists of green rings and faint blue lines. These form a grid that is aligned with the Galactic plane and is a measure of light-travel time. The first ring out from the Solar System is 1 light-day from the Sun. The Voyager and Pioneer space probes are the farthest objects we have sent into space. Launched nearly 30 years ago, they will reach this 1-light-day mark in another 40 years.

While you're here, you can see the inclination of the Solar System to the grid and, therefore, to the Galactic plane. You saw this before with the coordinate grids; now you can see the Solar System orientation in relation to that plane.

Continuing to fly away from the Sun, you now see the entire light-month grid split into 4 light-weeks. Restore the stellar polygons so the stars' luminosity is represented accurately. Also turn on the

constellations, `constel`, and return to more reasonable clipping planes with the command

```
clip 0.1 1e6
```

Turn on the 1-light-year grid, `1ly`, and now you see the light-months stretch across space. You also begin to see the constellation lines distort, revealing those stars that are nearby. You will explore these nearby stars in the next tutorial.

Tutorial: The Nearest Stars

> **Goals:** To understand the distance scale between the Solar System, Oort cloud, and the nearest stars.
>
> **Before starting, turn on:** `stars`, `constel`, `mwVis`, `1lmo`, `1ly`
>
> **You will be using:** `oort`, `10ly`, **jump** command

Let's continue exploring the solar neighborhood from the previous tutorial. If you're starting a new session in the Milky Way Atlas, be sure to turn on the data groups listed above and use the **jump** command

```
jump 0.05 0.6 0.3 -60 10 170
```

to go to $(x, y, z) = (0.05, 0.6, 0.3)$ parsecs with the viewing angles $(R_x, R_y, R_z) = (-60, 10, 170)°$.

From this position, the star labels are a bit large. Decrease their size using the Labelsize Slider and orbit the Sun using the left mouse button in Orbit Flight Mode. Set it drifting and observe the constellation lines. A few of them appear as though they're being pulled in toward the Sun. Stars like Alpha Centauri (marked `a Cen`), Sirius, Procyon, and, to a lesser extent, Vega.

The Oort Cloud Shows the Most Distant Parts of Our Solar System Before we discover the nearby stars, let's look at the outermost reaches of the Solar System. When the planets were forming, the larger, outer planets likely swept the Solar System clean of smaller bodies like comets. These were ejected from the inner regions by the strong gravitational influence of the planets, relegating the comets to an area called the Oort cloud. This "cloud" is where the comets have settled, and it ranges from 20,000 AU to about 100,000 AU (recall that 1 AU = 149 million km = 93 million miles and is the average Earth-Sun distance).

Turn on the Oort cloud with the `oort` button. It's a wire-frame sphere, but how far does it extend? Because the highest concentration of comets lies around 50,000 AU, we place the sphere at this distance. While the Oort cloud is not a perfect sphere, we use the sphere as a representational model that provides us with the size and scale of the cloud. If you still have the 1-light-year grid (`1ly`) on, you will notice that 50,000 AU equals about 0.8 light-years. Remember, the planets are lost in the glare of the Sun; Neptune is a little more than 4 light-hours away from the Sun.

The Nearest Stars Are More Than Four Light-Years Away   Pull away from the Oort cloud and turn on the 10-light-year grid, `10ly`, increasing the star label size as necessary. Now the cloud is a small sphere and the nearby stars are beginning to reveal themselves. Try to approximate their distances.

In the Graphics Window, type the keys `cw`. This resets the camera location, transporting you to a location that is 3 units up the +z-axis looking back toward the origin. Now back straight out from this position. By resetting the camera, you can be sure that you're looking at the grid face-on from a position perpendicular to the plane. Can you see the nearest star? Orbit a bit to regain some depth.

Alpha Centauri Is the Closest Star   Proxima, a cool, dim star in the Alpha Centauri triple system, is the closest star to the Sun. Aptly named, this star lies close to the Galactic plane too, allowing you to read off its distance from the 10-light-year grid (`10ly`). From here, it looks to be about 4.5 light-years away (it's actually 4.24 light-years from the Sun). Now see if you can maneuver yourself so that you're looking at Sirius and Procyon edge-on to the grid. Sirius will be on one side, Procyon on the other. See how far from the plane these stars are. Place your mouse on top of Sirius and either press the middle mouse button or type the `p` key. Partiview should report back to you one of the following:

```
# [g1]Picked -1.7693 -1.9125 -0.4074 @2.86269 (of 32) "Sirius"
```

or

```
# [g1]Picked -1.7693 -1.9125 -0.4074 "HIP32349 HD48915 Gli244a Alp CMa
Sirius" @2.86269 (of 30); colorb_v 0.021 lum 20.3348 absmag 1.45 appmag
-1.44 txno 1 dist 8.6 dcalc 2 plx 379.21 hipno 32349
```

The first is a report of the label, located at $(x, y, z) = (-1.7693, -1.9125, -0.4074)$ parsecs. The '@2.86269' is the distance (in parsecs) from which we are viewing the chosen object (your distance will

likely be different). In the second report, Partiview reports from the stellar data set, printing the location information, names, and all the parameters defined in the data file, such as the star's luminosity, its absolute and apparent magnitude, and other information found in the `stars.speck` file.

We want to know how far off the plane of the Galaxy, and hence the grids, the star is. The Milky Way Atlas is a Cartesian coordinate system expressed in x, y, and z parsecs. The x axis points toward Galactic center; the y axis is in the direction of Deneb, which is the direction of our rotation around the Galaxy; and z axis points perpendicular to the plane. So Sirius is 0.4074 parsecs from the Galactic plane, or (0.4074 pc) $\times$ (3.26 ly/pc) = 1.328 light-years. From above, Sirius appears to be about 9 to 10 light-years away (it's actually 8.6 light-years away).

Now move on to the next tutorial, in which we discuss other planetary systems outside the Solar System.

Tutorial: Extrasolar Planetary Systems

 Goals: Discuss the discovery and distribution of extrasolar planets.

 Before starting, turn on: `stars`, `mwVis`, `constel`, `10ly`

 You will be using: `expl`, `textcment` command

Last we left you, your were orbiting the Sun from about 20 light-years away. Now let's explore those stars that have confirmed planetary systems, the extrasolar planets, or exoplanets (`expl` group). The first exoplanet was discovered around 51 Pegasi in 1995. Since then, astronomers have been uncovering planetary systems all over the sky. For more on how these are found, please see our description of this data group in "Extrasolar Planets."

Turn on the `expl` group and pull out a bit to see them in perspective. Each of these blue rings encircles a star that is host to one or more planets. If you orbit the Sun, you will notice that they are all huddled around the Sun. This is an observational bias since, for the majority of exoplanetary systems, we see the effects of the planets only on nearby stars. For a few detection techniques like pulsar timing and lensing, astronomers can actually see planetary systems to great distances. But mostly they are seeing the wobbling of the star from its spectrum and do not actually see the planets themselves. Now that you've flown from the Solar System to about 100 light-years away, perhaps you have a better appreciation for the challenges involved in seeing planets from such distances.

If you see the exoplanets fading from view, feel free to "slum" them up using the Slum Slider. The

rings will grow as you increase the luminosity scale factor. If you find the labels are fading from view or prefer a stronger color to the blue, you may change the label color by using the textcment command. Change the labels to a gray color by using the command

```
textcment 1 .3 .3 .3
```

This changes color index 1 to a red-green-blue color of 0.3.

Next we'll see how many of these exoplanets have heard from us when we discuss the extent of Earth's radio signals in space.

Tutorial: Earth's Radio Sphere

> **Goals:** Understand the relationship between light-travel time and distance in the Universe; see the extent of Earth's radio signals in the Galaxy.
>
> **Before starting, turn on:** stars, mwVis, expl
>
> **You will be using:** radec, 1ly

With the stars (stars group) and exoplanets (expl group) on, let's turn on a marker showing where Earth's earliest radio transmissions have reached in space. Turn on the equatorial coordinates (radec). From this perspective, this group no longer acts like a coordinate system but rather doubles as Earth's radio sphere.

The radio sphere shows the boundary of Earth's radio signals beginning in the late 1930s and into the early 1940s, when radar, television carrier waves, and atomic testing started sending strong radio signals into space. Strong enough to pass through Earth's ionosphere, these signals travel into interstellar space at the speed of light. A signal that left in 1940 is, as of 2012, 72 light-years away. The radio sphere then contains a history of Earth's signals and implies what you likely know: looking out into space means you're looking back in time. At 57 light-years away, we would detect the broadcast debut of *The Honeymooners*, and at 48 light-years, we would her the Beatles appearance on Ed Sullivan.

With the radio sphere and the exoplanets on, it is now possible to see how many planetary systems have heard from us. How many do you count?

Fly away from the radio sphere so that you see most of the stars. The radio sphere is the farthest extent of mankind's presence in our Galaxy and the Universe, just 72 light-years from Earth. Turn on the 1,000-light-year grid, 1kly, and you begin to see just how small an influence we've had in the Galaxy. In the coming tutorials, we'll explore how much larger the Galaxy is, but let's start with the stars.

3.2.3 The Stellar Catalog

The stellar data set is among the richest in the Atlas, so it is worthy of our attention. In these tutorials, you will explore the different stellar populations in the Galaxy, get an estimate of the uncertainty in their distance, and discover how many more stars there are in the Galaxy whose distances are out of our reach.

Tutorial: Stellar Data Variables

Goals: Explore what data are available within the stellar data group.

Before starting, turn on: `stars`, `mwVis`

You will be using: datavar command

Within the stellar catalog are numerous astronomical stories. Let's begin by looking at the data variables available to you in the `stars` data group. Start the Milky Way Atlas and type the command

    `datavar`

For any data group, this command reports all defined data variables. Data variables can be used to set brightness, size, and any other data attributes. Once you've issued the command, Partiview will report the following:

```
datavar 0 BVcolor -0.63..  2.057 mean 0.534[color]
datavar 1 lum 0.00016..  106732 mean 94.4331[lum]
datavar 2 absmag -7.85..  15.45 mean 1.96288
datavar 3 appmag -1.44..  14.85 mean 8.23806
datavar 4 txno 1..  1 mean 1
datavar 5 dist 4.22..  16041.8 mean 850.625
datavar 6 dcalc 1..  2 mean 1.5451
datavar 7 plx 0.64..  772.33 mean 8.35486
datavar 8 plxerr 0.19..  76.92 mean 24.7276
datavar 9 vx -7933.02..  9534.59 mean -7.38226
datavar 10 vy -9991.64..  1440.02 mean -13.366
datavar 11 vz -8979.18..  3840.21 mean -5.44464
datavar 12 speed 0..  11342.2 mean 40.9835
datavar 13 hipno -99..  120402 mean 58981
```

These variables are discussed in the data group section on the stars. Briefly, each line is a data variable

and reports its number, name, range, and mean value. For example, the first line, data variable 0 called
BVcolor, is the $(B - V)$ color of the star and ranges from -0.63 to $+2.057$ with the mean value of 0.535.

In the tours that follow, we will use these data variables to explore the stars around us and even the
Galaxy we live in.

Tutorial: Stellar Brightness

> **Goals:** Examine a star's brightness as we see it from Earth.
>
> **Before starting, turn on:** stars, constel, mwVis
>
> **You will be using:** thresh and see commands

In this tutorial, we examine the brightness of the stars in our sky. This is described by what
astronomers call the apparent magnitude and what we call the appmag data variable.

We can attribute the system of magnitudes to Hipparchus, the Greek observer from the second
century BC. He developed the first star atlas and set the brightest stars in the sky to first magnitude and
the dimmest stars to sixth magnitude. Now, with more precise scientific methods, we have quantized the
magnitudes, and some stars were found to be brighter than 0 and, therefore, have negative magnitudes.
For example, Sirius has an apparent magnitude of -1.4 and the Sun's is -26.

Beginning from the home position (press the Home Button) and looking toward Orion, you can see
the bright stars that form the hunter as well as Sirius and Procyon, two nearby bright stars. Let's see
how bright they are. Recall from our data variable report that the range in apparent magnitude, m_V, is
$-1.44 < m_V < 14.85$ (not including the Sun). If you wish to see only the bright stars in the sky, you can
select them for display by using the thresh command. To see only stars in the range $-1.4 < m_V < 1$,
type

```
thresh appmag -2 1
```

We simply use -2 instead of -1.44 to take everything from the lower limit to $m_V = +1$. Partiview reports

```
# thresh 3(appmag) min -2 max 1 (15 of 100659 selected)
```

echoing the threshold, then telling you that it found 15 stars in that range. You can confirm that the sky
is empty of stars except for the 15 brightest ones in the sky.

In a dark sky free of light pollution, the human eye can see to about +6.5 magnitude. Let's simulate this by showing only stars in that range. We have defined a selection expression called `eye` in the `mw.cf` file that you can use to display the "naked eye" stars. To use it, type the command

```
see eye
```

This will display the stars according to the Partiview command `thresh appmag -2 6.5`. Partiview reports that there are 8,667 stars in this range. The next time you look toward the sky, remember that there are only about 9,000 stars visible to the human eye in the entire sky (including the northern and southern hemisphere—unless you live near the equator, this number will be less than 9,000) as seen throughout the course of the year.

Finally, we provide a selection expression that is calibrated to the completeness limit of the Hipparcos catalog. Most of the stars in the stellar data are from the Hipparcos mission, and we know that the Hipparcos data are complete down to about $m_V = 7.5$. Beyond this, there are dimmer stars missing from the catalog at these distances. To see a complete stellar catalog, type

```
see m75
```

This displays about 25,000 stars and accurately represents the stellar population around the Sun down to apparent magnitude 7.5.

Return all the stars to view by typing

```
see all
```

We'll explore the intrinsic brightness of the stars in the sky in the next tutorial.

Tutorial: Intrinsic Brightnesses

Goals: Explore the intrinsic brightness of the stars and contrast the intrinsically bright and faint stars.

Before starting, turn on: stars, mwVis

You will be using: lum const, lum $datavar$, and the see commands

We've seen the brighter stars around the Sun, but are they the only stars nearby? If you've scanned the sky, you may have noticed the label `Barnard's` seemingly hanging out in space without a star

beside it. Even if you fly right up to the label, it is exceedingly difficult to see the star itself. Barnard's Star is the fourth-closest star to the Sun. It is a cool star with a very low luminosity, making it difficult to see. How many more stars like this lie in our cosmic backyard but are too dim to see? Let's find out.

Setting the Stars to the Same Luminosity   Let's leave reality for a moment and set the intrinsic brightness of each star to one constant value using this command:

```
lum const 0.003
```

Now all stars are on an equal footing—the brighter the star, the closer it is to us.

Sirius and Procyon look normal because they are among the closest stars, but Orion has disappeared. Most of the stars in Orion are far away. The Hyades, the star cluster in the face of Taurus the bull (turn on `oc` briefly to see where the cluster is), appears above Orion. Turn off the constellation lines and see if anything recognizable remains. In a universe where all stars had the same intrinsic brightness, we would have to invent new constellations.

Restore the stars to read the intrinsic luminosity from the `stars.speck` by using the **lum** *datavar* command. In `stars.speck`, the data variable that sets the luminosity of each star is called `lum`. Use it in place of the *datavar* argument by typing

```
lum lum
```

Now the familiar night sky is back. (If nothing appeared to change, be sure `stars` is the active data group.) With a constant luminosity set, you may now toggle between them by typing `lum const` and `lum lum`.

Intrinsically Bright Stars Lie in the Milky Way Band   We have set two selection expressions in the `mw.cf` file to cull stars by their intrinsic brightness, what astronomers call the absolute magnitude. If you would like to look at the intrinsically bright stars, type

```
see bright
```

The `bright` alias has been set to show only those stars with an absolute magnitude, M_V, in the range $-10 < M_V < -3$. Remember, the smaller the number, the brighter the star. We mentioned previously that the brightness of the Sun is -26. Its absolute magnitude is around +5—rather dim.

Notice that these intrinsically bright stars lie mostly along the band of the Milky Way. Also, some of the brighter stars in the sky are missing, including Sirius, the brightest star in the sky.

Dim Stars Far Outnumber Bright Stars in the Galaxy   Now let's look at the intrinsically dim stars using the

```
see faint
```

command. Here we show those stars with $0 < M_V < 10$, and you may notice that most of the stars in the sky fall into this category. There are many more intrinsically dim stars in the Galaxy than bright stars.

Next let's explore stellar distances and see how well astronomers have determined the positions of the stars.

Tutorial: Stellar Distances

Goals: Explore the nearby stars and investigate their parallax values and uncertainties.

Before starting, turn on: stars, mwVis

You will be using: thresh command

In this tutorial, you will learn about stellar distances and parallax. Let's begin at Earth looking toward Orion (press the Home Button if necessary).

Seeing Only the Nearest Stars   First tell Partiview that you want to see only those stars within 25 light-years of the Sun (make sure stars is the active data group). Do this by using the thresh command on the data variable distly:

```
thresh distly 0 25
```

This removes all stars outside this range (their labels remain, though, an oversight in Partiview). Partiview reports that there are 103 stars in this range.

Let's see how this looks from outside the solar neighborhood. Pull away from the Sun to see all of these stars. Turn off the constellations and the visible Milky Way (mwVis). You may need to brighten the stars with the Slum Slider. You can see that Sirius, Procyon, and Altair dominate the scene.

Let's expand our scope and increase the limit to 100 light-years using

```
thresh distly 0 100
```

Now you see a nice sphere of stars surrounding the Sun. Turn on the ecliptic coordinates, `eclip`, which are traced on a 100-light-year-radius sphere. As you orbit, notice the midplane of the sphere (the sphere's "equator"). This is called the ecliptic, the plane that contains Earth's orbit around the Sun and generally defines the plane of the Solar System.

Stellar Distances Are Determined by Parallax   Return all stars to view (`see all`) and let's now look at the parallax. A detailed definition of parallax and how astronomers calculate a star's distance can be found in "Parallax and Distance." Briefly, parallax is an angle astronomers measure that is used to solve the lengths of a right triangle, thereby yielding a star's distance (which is one side of the triangle). This angle comes from Earth's path around the Sun. If a star is close, it will appear in one place with respect to the background stars (those stars that surround it in the sky but are farther away). Six months later, it will appear to have moved ever-so-slightly relative to the background stars. This motion is so small that astronomers need powerful telescopes to detect it.

In the Atlas, we can look at the distance of stars in terms of the parallax angle. The range of values shown in the report generated by the $\mathrm{datavar}$ command is 0.64 to 722.33 milliarcseconds (mas) with a mean of 8.35 mas. The closer the star, the larger this angle will be, so let's look at stars with large parallax angles:

```
thresh plx 100 800
```

There are 187 stars in this range resembling our view of the stars within 25 light-years.

Parallax Uncertainty and the Plane of the Solar System   Associated with each of these parallax measurements is an uncertainty. These uncertainties come from the methods and instruments used to measure the parallax, for no measurement is free from uncertainty. To see how this uncertainty propagates through the stellar catalog, let's look at those stars with small errors.

The parallax uncertainty ranges from $0.19 - 76.92$ mas, with a mean of 24.7 mas. Look at the stars with very little uncertainty using the command

```
thresh plxerr 0 3
```

This shows stars with highly accurate distances. As you might expect, these are nearby stars, but you'll notice they are not distributed in a sphere. The reason for this is somewhat obscure.

If you still have the ecliptic coordinates on, you'll notice that the long axis of symmetry of the star distribution intersects the ecliptic poles. Think about what astronomers observe on Earth. As Earth orbits the Sun, the parallax of a star near the ecliptic pole (not the celestial pole) will make a circle in the sky. Conversely, if you're looking at a star near the ecliptic (in the same plane), it will appear to move back and forth along a line. Between these extremes, the parallax motion is in the shape of an ellipse.

It's easier to measure the width of an angle formed by a circle than a line, so the uncertainty for a star in the ecliptic will be more than that of the same star at the ecliptic poles. Therefore, our distances are more accurate at the poles of the ecliptic coordinates than near the ecliptic itself.

Let's see how this uncertainty in the measured parallax angle translates into distance uncertainty in the Atlas.

Tutorial: Distance Uncertainty

Goals: Be aware of the underlying uncertainties in the stellar catalog.

Before starting, turn on: `stars`, `mwVis`

You will be using: `altLbl`, center and censize commands, `10ly`, `err`

You've seen how the measured parallax angle determines the distance to a star and how the uncertainty in that measurement propagates into the stellar data. Now you'll see a visual representation of these uncertainties for select stars.

Let's go home in the Milky Way Atlas (press the Home Button). (If you're continuing from the last tutorial, reset the stars back to their normal brightness and use `see all` to return all stars to view.) Instead of backing away from the Sun, let's fly forward toward the Hyades star cluster. If you don't know where the Hyades is, turn on the open clusters, `oc`, for a moment to find the cluster. Once you've centered the cluster, fly forward by moving the mouse to the right (in Orbit Flight Mode) while pressing the right mouse button. It may take a few seconds to get going since you're so close to the Point of Interest.

The Hyades forms a "V" shape. As you fly out, you'll see what appeared to be the brightest star in the cluster, Aldebaran, pass by long before reaching the cluster. At 65 light-years, it's not actually in the cluster but sits between the cluster and Earth. Once you get to the cluster, stop. You're going to change

the Point of Interest to examine the cluster more effectively. With the cluster in front of you, turn on the alternate star names (`altLbl` button) and find the star θ^2 Tauri (marked as `The2 Tau`). You may need to switch into Translate Flight Mode to get the proper perspective.

Changing the Point of Interest Location   Once you have located the star, bring it close and place the mouse pointer over it. Next press the `Shift` + `p` keys (or use `Shift` + middle mouse button for a three-button mouse). This places the Point of Interest on this star. To confirm that the Point of Interest has moved, increase the size of the Point of Interest marker by using the Censize Slider. The censize command sets the size of the Point of Interest marker in the units of the data you are viewing, which in the case of the Milky Way Atlas is parsecs. You can move it with the slider or enter a value at the command line. Make it exactly 1 light-year by entering

```
censize 0.307
```

(0.307 parsecs = 1 light-year). Now you have a measuring stick and an idea of the size and scale of the star cluster. With the Point of Interest centered in your view, switch back to Orbit Flight Mode and orbit the cluster with the left mouse button. Turn off `altLbl` to see the stars without their labels. Also turn on the 10-light-year grid (`10ly`) to give yourself a reference to the location of the Sun and Solar System.

Seeing Uncertainty   While you orbit the Hyades star cluster, turn on the stellar distance uncertainty (`err`). You will see a series of red points, some with blue labels, come on around the star Ain. This is Ain's distance uncertainty. Notice how these points line up when you look toward the Sun. Astronomers know a star's position in the sky to great certainty. It's the distance that is difficult to obtain because of the margin of error associated with it from the parallax measurement.

The star is placed at the parallax-derived distance of 154.94 light-years. However, the star could lie anywhere along the red line from 149 to 161 light-years. The red points are spaced in 1-light-year increments with the absence of a point corresponding to the published parallax distance.

Bring the Point of Interest back to the Sun. Rather than travel back to the Sun, place the mouse over it, and use the `Shift` + `p` to move the Point of Interest, it's easier to use the Command Line. The center (or interest) command sets where the Point of Interest is. Type the command

```
center 0 0 0
```

to move the Point of Interest back to the Sun so that you return to orbiting the Sun.

Pull away from the Hyades and pass near the Pleiades star cluster, with its bright stars and longer uncertainty marker (remember to turn on the open clusters if you have trouble finding the Pleiades). We highlight the distance uncertainty of Pleione, the first star in the handle of the dipper-like asterism. You will immediately notice the uncertainty has grown a lot from that in the Hyades. This increased uncertainty, about eight times greater, affects the overall shape of the star cluster. You may recall that the Hyades was a nice spherical cluster, what you might expect a star cluster to look like. The Pleiades, on the other hand, is slightly stretched along the line of sight to the Sun, parallel to the distance uncertainty. Astronomers call this radial stretching a "finger of god." Of course, this is an observational artifact—if the telescope were larger, the parallax (and resulting distance) would be more accurate and the cluster would look more spherical.

Above the Pleiades is the star Betelgeuse, the bright red giant in Orion's shoulder (you may have to pull back from the cluster to see it). If you look at its ray of uncertainty, you'll notice the star is not in the space left for the published trigonometric parallax distance, at 427 light-years. We actually placed the star a bit closer because of the parallax error. For this star, the parallax error was so high that we factored in the photometric distance (the distance derived from knowledge of the star's brightness and luminosity). With a weighted mean distance between each of these, the star ends up a bit closer.

We have chosen a handful of stars for this data group. A list appears in "The Stellar Distance Uncertainty." Deneb, the bright star in Cygnus, is the farthest star we sample. It is a distant star that is intrinsically very bright. But because it's far away, the uncertainty ranges from about 2,000 to 7,000 light-years.

All Data Have Uncertainties   From outside the stellar data group, all these lines of uncertainty point to the Sun and should remind you that all data in the Atlas have uncertainties. From the nebulae and clusters to galaxies outside the Milky Way, each point has an uncertainty that depends on the technique used to determine its distance.

 Tutorial: Sorting Stars by Color

> **Goals:** Contrast the differences in stellar color.
>
> **Before starting, turn on:** `stars`
>
> **You will be using:** `galaxy`, see and showbox commands

The color of a star is a measure of its temperature and provides astronomers with a means of classifying stars. With color as a discriminator, two stellar populations are apparent, revealing the underlying structure of our Galaxy.

Color Is Derived from Two Brightness Measurements at Different Wavelengths   In the Milky Way Atlas, we use the $(B - V)$ observed color to assign the stars their visual colors. This is the subtraction of the B and V filter brightnesses. Astronomers observe a star through many filters, then combine them to get an overall color for the star or object. In this case, the B filter is a blue light filter that sees light between about 400 nm (nanometers) and 480 nm. The V filter is roughly equivalent to the human eye and only allows light between about 500 nm and 600 nm to pass through. The difference between the measured magnitudes from each filter is the $(B - V)$ color of the star. For this color, blue stars will be high in the B filter, resulting in a lower magnitude (remember, the brighter the star, the lower its magnitude) and a negative $(B - V)$ color. Red stars will be brighter in the V filter, resulting in positive $(B - V)$ colors. Let's see this in the Atlas.

In the Milky Way Atlas, move away from the Sun so that you see most of the stars (be sure to turn the `mwVis` group off). If the stars are too dim, feel free to use the Slum Slider to increase their brightness. As you orbit the Sun from this great distance, you will select stars based on their $(B - V)$ color. The **datavar** command reports that the `BVcolor` variable ranges from -0.63 to $+2.057$, with an average value of $+0.535$.

We've set up two selection expressions to show the color differences among stars. These selection expressions are defined in the `mw.cf` file and are called `blue` and `red`.

Blue Stars Are Young, Hot Stars   First let's explore the bluer stars by typing

```
see blue
```

You should see a complete change in the data with a flat distribution along the Galactic disk. This might make sense, since the blue stars are hotter stars that have shorter lifetimes, burning their nuclear fuel at a high rate. These are the gas-guzzlers of stars. Because star formation takes place in the disk of the Galaxy, it makes sense that these short-lived stars would be found here.

As an aside, culling the blue stars better reveals a feature of larger Galactic structure called Gould's Belt. It is a local grouping of stars inclined about $16°$ to the Galactic plane. If you type `showbox 1` in

`stars` and turn the boxes on, a box will appear around the bright blue stars. Press the Box Toggle Button to turn the boxes off.

Red Stars Are Cooler Stars   Now let's see the redder stars by typing

    `see red`

The red stars are more numerous (more than 80% of the stars) and are distributed in a spherical shape. Of course, because these are observed from Earth, the distribution is centered on the Sun, but one can imagine the entire Galaxy filled with these dim stars.

Red stars are cooler stars that form throughout the Galaxy. They burn their fuel slowly and have long lifespans; some stars are as old as the Galaxy. The Sun is among these red stars, a relatively cool star with a $(B - V)$ = 0.65. It has been burning its fuel for about 5 billion years and has about another 5 billion to go before entering the end stages toward a red giant and a white dwarf star.

Stellar Color Traces Galactic Structure   These two contrasting views tell us about the structure of the stars in our Galaxy. The red stars are typically known as Population II stars and revolve around the center of the Galaxy in elliptical, sometimes highly inclined orbits. Bluer stars are referred to as Population I stars and lie in the Galactic disk, orbiting in orderly paths around the Galactic center. While we plot only the stars we have accurate distances for, you can imagine the disk (turn on the Milky Way image using the `galaxy` button) filled with blue stars with many red stars as well. Also imagine a spherical distribution around the entire Galaxy filled with cool, red stars. This is called the Galactic Halo (`halo` button), and we'll talk about it soon.

3.2.4 Building the Galaxy

Examining the objects that make up our Galaxy enables us to understand its structure and evolution. In this section, we will look at an assortment of objects from the Atlas and build the Galaxy one data set at a time. Let's start a new session of the Milky Way Atlas and begin by investigating the OB associations.

Tutorial: OB Associations

Goals: Discover how the OB associations reveal the structure of the Galaxy.

Before starting, turn on: `stars`, `ob`, `galac`

You will be using: `10ly`, `galaxy`

You've seen the night-sky view of the OB associations in the "Two-Dimensional Distributions" tutorial. Let's turn everything off in the Milky Way Atlas (`gall off`) and start with the `stars`, `ob`, and `galac` groups on.

OB Associations Are in the Galactic Disk   Again, it's easy to see that the OB associations are found in the Galactic plane. Rather than look at their distribution from Earth's perspective, let's look upon them from a point away from Earth. Fly backward from the Sun until you see all the OB associations in view, then orbit the Sun from this vantage point.

You should still see the Galactic coordinates sphere encircling the Sun. It has a radius of 1,000 light-years. If you fly back toward the sphere, you will notice a few OB associations within that distance. For scale, turn on the 10,000-light-year grid `10kly`, which is in the plane of the Galaxy and spans the OB associations. Not all the OB associations are represented in this group, only those with known distances—those in the neighborhood.

OB Associations Are Loose Groupings of New Stars   Each of these points represents 10 to 100 stars that have dispersed to the point where they are no longer held together by their mutual gravity. O and B stars are among the hottest, most luminous stars and burn their nuclear fuel quickly. Because O stars live for only 1 million years and B stars for tens of millions of years, the lifetime of OB associations is not long compared with that of other objects in the Galaxy or the Galaxy itself.

As we have discussed in previous sections, the Galactic disk is the lifeblood of the Galaxy, where the process of stellar birth and death is ongoing. As you orbit the Sun from a distance such that you see all

the associations, you can see they lie in a relatively flat plane. Turn on the Milky Way image (`galaxy`) to see how these fit into the larger picture.

OB Associations Trace Spiral Structure   Because OB associations contain young stars, they form in the spiral arms of the Galaxy and are good tracers of Galactic structure. Their color coding reflects this. The Sun is located on the inner side of the Orion Arm. Sometimes this is called the Orion-Cygnus Spur, as it may be a minor connector between major spiral arms. The OB associations in this arm are colored blue and purple. Toward the Galactic center, we look toward the constellation Sagittarius and the Sagittarius Arm of the Galaxy. The associations in this arm are olive green. Opposite this, we look away from the Galactic center toward the Perseus Arm. Here the associations are orange.

The OB associations allow you to examine the local spiral structure of the Galaxy. Now let's look at another type of star grouping called open clusters and see what they tell us about the structure of our Galaxy.

Tutorial: Open Star Clusters

> **Goals:** Explore the 3-D distribution of the open star clusters and contrast them with the OB associations.
>
> **Before starting, turn on:** `stars`, `oc`
>
> **You will be using:** `ob`, `galaxy`, `galGrid`, `galac`, see command

If you're coming directly from the last tour, turn off the OB associations and turn on the open clusters (`oc`). If you're starting the Milky Way Atlas fresh, turn on the 10,000-light-year grid (`10kly`) and fly away from the Sun until you can see the entire grid.

The open clusters are represented by green points. From out here, we can see the entire data set, but let's quickly fly in toward the Sun (at the center of the grid) to familiarize ourselves with these data. As you approach the Sun, stop and orbit. The Hyades should be visible, as should a few other nearby clusters. Let's fly over to the Hyades.

Once you reach the Hyades, turn off the open cluster's polygons so that you can see the stars in the cluster. This is the best example of an open cluster in the stellar data set; it is a spherically distributed grouping of stars. Turn on the boxes for the `stars` group to emphasize the cluster.

Open Clusters Are Relatively Young Objects   Now pull back out and turn on the open clusters again. Once you've reached the point where you see most of the data, stop there and orbit. Again, you will notice a concentration toward the disk of the Galaxy. From our discussion in "OB Associations," you may deduce that these are younger objects in the Galaxy. In fact, they range in age from those that are currently forming to the oldest known cluster, Berkeley 17, which is believed to be more than 12 billion years old. However, this is an anomaly among clusters, the majority of which are young.

The Youngest Clusters Lie in Spiral Arms   You might expect the younger clusters to trace out the present structure of the Galaxy and its spiral arms. Let's see if this is true. In Partiview, run the command

```
see young
```

This sets a threshold on the clusters such that all clusters more than 10 million years old will be removed from view. Now you see something that resembles arms. Turn on the OB associations to see if they correlate. Flash them on and off to see the similarities. You can see that they line up very well, confirming the placement of the local spiral arms.

You may return the full data set to view using

```
see all
```

Let's also gain a wider perspective by turning on the Milky Way image with the `galaxy` button, and the Galaxy coordinate grid using the `galGrid` button (turn off `10kly` for clarity). Viewing the Galaxy from afar, turn off the open clusters and turn on the Galactic coordinates (`galac`) to mark the location of the Sun (which is at the center of that 1,000-light-year sphere). Now you're ready to add other pieces to the Galaxy. Let's see what they reveal about the Milky Way.

Tutorial: HII Regions

Goals: Discover how star-birthing regions are distributed throughout the Galaxy.

Before starting, turn on: `stars`

You will be using: `h2`, `galaxy`, `galGrid`

Let's turn to one of the youngest objects in the Atlas. We've discussed OB associations as being generally older versions of open clusters, which themselves are typically between 5 million and a few

billion years old. Now let's examine where the open clusters are born, in stellar nurseries called H II regions (`h2` button).

HII Regions Are Tightly Correlated to the Galactic Disk From a perspective outside the Galaxy, turn on the `h2` group. Each of these blue points represents an area of stellar birth in the Galaxy, a giant cloud of excited hydrogen gas, glowing from the stars born within them. Like the open clusters, they are concentrated in the disk of the Galaxy, more so than the clusters.

H II regions (by the way, it's pronounced "*H-two*") are also seen to greater distances in the Galaxy. As opposed to open clusters and OB associations, which are huddled around the Sun, we see H II regions across the Galaxy. Astronomers use radio telescopes to penetrate the gas and dust, allowing them to see signature elements, such as carbon monoxide, that are used to find these clouds across the Galaxy. The only part of the Galaxy invisible to us at these wavelengths is that part opposite the Galactic center, where a high concentration of gas and dust obscures our view to those objects beyond.

When you inspect the H II regions face-on (looking down on the Galactic disk), the data form a pattern that resembles a spider. There is a concentration near the Sun, as you might expect from observed data, but beyond the Sun the H II regions form in lines, like the long legs of a spider. Turn off `galaxy` to see this more clearly. Then bring back `galaxy` for reference.

Astronomers Use HII Regions to Map the Spiral Arms These "legs" are in fact the spiral arms of our Galaxy. You may wonder why H II regions are seen to such great distances while we have distances to open clusters only near the Sun. The answer to this question involves the method for observing these objects. In the case of open clusters, we need to see the star and observe it with a telescope so that we can dissect its properties from their light. Because of the gas and dust in the Galaxy, those stars across the Milky Way are invisible to us.

H II regions mark the active part of the Galaxy, where the Galaxy rejuvenates itself through new star formation. But if stars are born in the Galaxy, that must mean they die too. Let's look at where stellar death occurs in the Galaxy.

Tutorial: Pulsars and Supernova Remnants

> **Goals:** Discuss the end of the stellar life cycle and explore where these stellar remnants are located.

Before starting, turn on: `galaxy`

You will be using: `snr`, `pul`

Up to now, we've been discussing younger stars and stellar birth in the Galaxy. Now let's turn our attention to the end of the stellar life cycle. From a point of view where you see the entire Galaxy, turn on the supernova remnants with the `snr` button.

Supernova Remnants Are the Nebulous Remains of Stellar Death   These orange points highlight the locations of the nebulous remains of a star after it has exploded. If a star is born with enough mass, it will burn through its nuclear fuel quickly and die spectacularly in the most energetic explosion in the Galaxy, called a supernova. The core of the star remains as a neutron star, while the outer layers burst out. From Earth, we see these outer layers as small nebulae or glowing gas clouds. One of the most famous examples is the Crab Nebula (Messier 1), a remnant from the supernova of 1054.

If you've read the previous tutorials in this section, you likely know why the supernova remnants are confined to the disk of the Galaxy. If ongoing star formation is a phenomenon of the disk, then this too must be where stellar death occurs. You may also wonder why a few remnants appear to be right in the Galactic center. This is due to the large uncertainties in these data. Clouds in space are among the most difficult objects to obtain good distances for. In the case of H II regions, they are extraordinarily bright and there are chemical signatures in the radio spectrum that allow their detection. For supernova remnants, astronomers must rely on other techniques.

Supernova Remnants Glow for a Very Short Time   We see very few remnants sprinkled around the disk. The reason for this is that the remnant itself, the glowing cloud that surrounds the stellar core, has a very short lifetime. The glow lasts only about 50,000 years before the gas mixes into the ambient interstellar gas, cools, and fades from view. However, the core of the former star will be around for some time.

Pulsars Are Spinning Neutron Stars   To see these stellar cores, turn on the pulsars (`pul`). A pulsar is simply a spinning neutron star, the spinning remnants of a dying star. After the star explodes, the neutron star core is spinning very rapidly. Unlike the stars that you are familiar with, like the Sun, a neutron star has been crushed by gravity to the extent that the electrons in each atom have been forced

into the atomic nucleus. This makes the material extremely dense (a teaspoon of it would weigh about 100 million tons). In time, energy is lost by its rapid spinning, and after about a million years, the star is no longer visible.

The 1-million-year lifetime of the pulsar is much longer than the 50,000 years that the supernova remnant is visible, so you would expect to see more pulsars in the Atlas. For the same reason, you might also expect a wider scatter of pulsars above and below the plane of the Galaxy. The Atlas shows both these trends in addition to outlying pulsars far above the plane and even out of the Galaxy. We will talk about those in an upcoming tutorial.

Tutorial: Globular Clusters

Goals: View the globular star clusters and investigate how their age relates to their location in the Milky Way.

Before starting, turn on: `oc`

You will be using: `gc`, `galaxy`, see command

The final data group that we will examine within the Galaxy is the globular clusters (group `gc`).

Globular Clusters Are Distributed Spherically If you orbit the Sun from outside the Galaxy, you'll see the globular clusters are not concentrated in the disk at all but are found above and below the disk. You will also see that they are distributed about the Galactic center.

In addition to their Galactic position, globular clusters differ from open clusters in other ways. For one, they are far more dense, packing 100,000 to 1 million stars into a cluster typically 30 to 100 light-years in diameter. With your new sense of scale, imagine stuffing a million stars inside Earth's radio sphere.

Globular Cluster Stars Are Older and Cooler The stars that populate these two cluster types are different as well. Open clusters are young objects filled with young stars. Globular clusters contain stars that are older and cooler and that formed as the Galaxy was taking shape.

Turn off the open clusters to see the globulars on their own. Among all the data in the Milky Way Atlas, the globular clusters are the most complete, with only a few missing that we cannot see. These are likely on the opposite side of the Galaxy.

Metallicity Is a Measure of Age   Astronomers use a quantity called metallicity to determine the age of a globular cluster. Metallicity is the fractional abundance of elements heavier than helium. In astronomy, all elements other than hydrogen and helium are "metals." A chemist would not be happy with this definition, but this is how astronomers use the word "metal." Clusters with a low metal abundance are older, while higher metal abundances imply younger clusters.

You can see where the older and younger clusters reside using the pre-defined selection expressions in the `mw.cf` file. Type

```
see oldgc
```

to see the older globulars. The distribution remains the same, but fewer clusters are present. Now look at the younger clusters with

```
see younggc
```

The young clusters are concentrated in the center of the Galaxy and are close to the Galactic plane (turn on the `galaxy` group to see this plane).

Perhaps this makes sense. Younger objects tend to be found in the spiral arms within the Galactic disk. The disk is also generally more metal-rich. Heavy elements are created inside stars, and supernovae release them into the Galaxy. These elements, then, are going to be found where the stellar life cycle is active.

The older clusters, on the other hand, are found out of the disk. This part of the Galaxy is called the halo (turn it on using the `halo` button). The stars that formed here are from an era when the Galaxy was forming. After this star formation, the hot, blue stars exhausted their fuel quickly and became stellar remnants. What we see now are the cool stars that burn their fuel slowly and have very long lifetimes. These stars are metal-poor and very faint, making them difficult to see.

If you inspect all the clusters (type `see all`), you may notice some are quite far away. Astronomers are still discovering what lies around our Galaxy. Recently there has been speculation about some of the globular clusters possibly belonging to other galaxies, or the Milky Way capturing them from passing galaxies.

In the next section, we will discuss the larger structural elements of the Galaxy and begin to talk about what is outside our Galaxy as we wrap up our discussion of the Milky Way and head into the Extragalactic Atlas.

3.2.5   The Galactic Outskirts

These tutorials cover the Galaxy as a whole, the global properties of our star system. How large is it? What are the main structural elements of the Galaxy? And how does our Galaxy measure up to neighboring galaxies? We will answer these questions in this section as we explore the outer reaches of the Milky Way Atlas.

Tutorial: The Galactic Disk

> **Goals:** Examine the disk component of the Milky Way, including the Galactic center, the bar, and the spiral arms.
>
> **Before starting, turn on:** `galaxy`
>
> **You will be using:** `center` command, `mwbar`, `h2`

If you're just starting the Milky Way Atlas, fly away from the Sun so that you see the entire Galaxy. Up to this point, we have discussed the data sets that make up the Galaxy. In this tutorial, we will discuss the Galaxy as an object itself.

Even today, astronomers are challenged to understand the structure of our Galaxy. Because we live within the Galaxy, we cannot see the entire star system. This often makes the structure of galaxies millions of light-years away easier to understand than the structure of our own Milky Way.

From your vantage point in the Atlas, you should see the two-dimensional image we use to represent our Galaxy. Of course, we have never seen the Galaxy from this perspective. This image is the galaxy named NGC 1232, a galaxy thought to resemble the Milky Way.

The Sun Is 26,000 Light-Years from the Galactic Center   The Galactic disk is just less than 100,000 light-years across. The Sun orbits 26,000 light-years (8,000 parsecs) from the Galactic center and is about 50 light-years (15 parsecs) above the disk midplane. The disk is dominated by the bright center and the outlying spiral arms.

To examine this structure, change the Point of Interest to the center of the Galaxy. Right now it is set to the Sun's position at $(x, y, z) = (0, 0, 0)$ parsecs. The center of the Galaxy is at $(x, y, z) = (8000, 0, -15)$ parsecs, so set the Point of Interest to this location with the command

```
center 8000 0 -15
```

To confirm the shift, increase the center size using the Censize Slider. You will see Cartesian axes appear at the Galactic center, as well as a half-axes element at the Sun. Upon confirmation, you can reduce the center size back to zero to hide it from view.

Now you can orbit the center of the Galaxy. Bring the Galactic center to the middle of your Graphics Window using the Fly Flight Mode if necessary, then switch back to Orbit Flight Mode.

The Galactic Center   The center of our Galaxy is tumultuous. Within the bright region on the image are billions of stars with densities approaching 50,000 stars per cubic parsec (compare that with the density around the Sun of 0.05 stars per cubic parsec). These high densities ensure stellar interactions and even collisions. Astronomers cannot see the Galactic center in the visible spectrum because of the intervening gas and dust. However, these regions can be probed in the infrared and radio, which are less susceptible to light scattering from dust.

At the core of the Galaxy, astronomers observe a swirling ring of gas only a few parsecs across with a strong magnetic field and extended filaments. The energy required to sustain this activity must come from a massive object. But because the gas features are so small, the object driving this activity must be small too. Astronomers currently believe that a super-massive black hole exists at the Galactic center. A black hole is a region of space where gravity is so high that nothing escapes, not even light.

Our Barred Galaxy   Surrounding the core is the Galactic bar. Astronomers observe noncircular orbits among the stars near the Galactic center and therefore believe our Galaxy is a barred spiral. Turn on the Galactic `bar` to see the size and shape of this feature.

The bar is an ellipsoid with a size of $(a_x, a_y, a_z) = (5500, 2050, 1350)$ light-years and its long axis tipped $14°$ with respect to the Sun. Inside this ellipsoid are billions of stars and the most active star formation in the Galaxy. This is the Galactic powerhouse, and much of the Galaxy's activity is driven from this area.

Beyond the bar, there is the Galactic disk. The image shows spiral arms with bright H II regions (star-forming regions like the Orion Nebula) sprinkled throughout them. Depending on what kind of object you consider, the disk varies in thickness. If you consider young stars, gas, and dust in the vicinity of the Sun, the disk is only 300 parsecs (978 light-years) thick. However, if you look at older disk stars in the range of 7 billion to 10 billion years, the disk is around 2 to 3 kpc $(6,500 - 9,800$ light-years) thick. These stars formed in the disk but over time found their way out of the disk from interactions with

molecular clouds and other stars.

These are the main elements in the disk component of our Galaxy. Let's now explore the spherical components of the Galaxy in the next tutorial.

Tutorial: The Spherical Component

> **Goals:** Explore the spherical component of the Galaxy, including the Galactic bulge and its halo.
>
> **Before starting, turn on:** `galaxy`
>
> **You will be using:** `bulge`, `halo`

As you've just seen, the disk component of the Galaxy is the lifeblood of the system. This is where stars are forming and where they explode into clouds of glowing hydrogen. The spherical component is from an era when the Galaxy was forming. The stars in this part of the Galaxy are older, cooler stars that formed long ago and have long lifetimes. Let's explore the structural elements that make up this component of the Galaxy.

The Galactic Bulge   The innermost component is the Galactic bulge (`bulge` button). The bulge is the brightest part of the Galaxy and contains the Galactic bar (`bar` button) and nucleus. While it contains many older stars, it also contains the active Galactic center, where stars form and orbit in the disk component. Overall, the stars in the bulge are more metal-rich and younger than those found in the halo, the region surrounding the bulge.

The Galactic Halo   The Galactic halo (`halo` button) is a large, roughly spherical volume that encompasses the entire Galactic disk. The halo is filled with old, faint stars and globular clusters. Recall that the globulars are densely packed clusters of 100,000 to 1 million stars. The stars in the halo and inside globular clusters are metal-poor, older stars that formed close to the era of Galaxy formation.

The shape is thought to be slightly flattened like the bulge but is spherical to first order. The size of the halo remains under study. In the Milky Way Atlas, we set the radius to 41,000 pc (about 130,000 light-years). If you have the globular clusters on, you'll see that most of the clusters lie within the halo but that a handful do not. Do these clusters belong to our Galaxy? Is the halo significantly larger, as some astronomers suggest? The answers to these questions will be found in two areas: in the

nature of globular clusters versus small dwarf galaxies, and with our increased knowledge of our Galactic neighbors.

Our last tutorial of the Milky Way Atlas addresses the latter topic: our Galactic neighbors.

Tutorial: Beyond the Milky Way

> **Goals:** Investigate what lies immediately outside the Galaxy.
>
> **Before starting, turn on:** `halo`, `galaxy`
>
> **You will be using:** `lgrp`, `pul`, clip and labelsize commands

Beyond our Galaxy is extragalactic space, the remainder of the observable Universe. We will cover this in the next chapter on the Extragalactic Atlas. For now, though, our last step in the Milky Way Atlas will be the Galactic neighborhood. What lies just beyond our Galaxy?

We Are a Member of the Local Group of Galaxies   Astronomers call the grouping of galaxies around the Milky Way the Local Group (`lgrp` button). Turn on the Local Group to see these galaxies. You will notice a single point for the Milky Way now. Pull away so that you see the Galaxy and its halo. Most of the nearby galaxies share their names with the constellations: Sagittarius, Ursa Major, and Draco, to name a few. Two notable exceptions are the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC), named for Ferdinand Magellan, the Portuguese explorer of the 16th century who first spotted these clouds while exploring the Southern Hemisphere. If you turn on the pulsars (`pul`, you'll see they extend beyond the Galaxy to these two satellite galaxies.

These are called satellite galaxies because astronomers believe that they have been captured by the Milky Way and are now interacting with it. It is likely that the Milky Way collided with these small galaxies and decimated them, leaving an unstructured cloud of stars, gas, and dust.

Our nearest neighbors, the Sagittarius elliptical dwarf galaxy (SgrDEG) and the Canis Major dwarf galaxy (CMa dw), were discovered in 1994 and 2003, respectively. Both of these small galaxies are being stretched by the tidal forces of the Milky Way, ripped apart like the Magellanic Clouds as they orbit the Galaxy. Because they are both near the plane of our Galaxy, they remained elusive until astronomers began observing the galaxy with infrared telescopes.

Let's do some quick Partiview maintenance. Once again, you are pushing the limits of your graphics card and need to change your clipping planes. Type `clip` and Partiview should report that the near and

far clipping planes are 0.1 and 1 million parsecs. We no longer need to see detail, so change the clipping planes using the command

```
clip 1 1e8
```

(Different graphics support will react differently, and you may need to adjust these values to suit your hardware.)

Now fly farther from the Milky Way. If you have the halo on, the sphere will reduce to a small circle on your screen. Using the Slum Slider, brighten the points for the Local Group. As you orbit from this distance, you may notice two main groupings of galaxies. One group is huddled around the Milky Way, while the other is around the Andromeda Galaxy (Messier 31). If you try increasing the labels with the Labelsize Slider, you will see that the slider is at its maximum point. Increase the label size by hand using the command

```
lsize *10
```

This will increase the size of the labels by a factor of 10. The Andromeda Galaxy is the farthest object you can see with your unaided eye. At 2.5 million light-years away, if you gaze upon it in the sky tonight, you're seeing the galaxy as it looked 2.5 million years ago.

The three large galaxies in the Local Group are Andromeda, the Milky Way, and Messier 33. All three are spiral galaxies and, Andromeda and the Milky Way in particular, have great influence on the galaxies around them. Each lies at the center of a cluster of mostly small dwarf galaxies.

There is no conclusive definition for the Local Group. You might imagine it is defined by some arbitrary distance, inside of which all galaxies are members. Or perhaps it is defined by those galaxies that share a mutual gravitation with one another. In reality, both of these criteria are used to define the size of the Local Group.

We will explore this topic more in the Extragalactic Atlas, where we discuss the local structure of the Universe and travel out to the edge of the observable Universe. Following this section are the detailed sections on each of the data groups in the Milky Way Atlas. You may choose to skip this section and continue your tutorials in the Extragalactic Atlas, but we recommend coming back to the data sections, as they contain a great deal of information that we were not able to include in the tutorials.

3.3 Milky Way Data Groups

The Digital Universe data groups fall into distinct categories. Some are 3-D data, like the stars, while others are images or graphical representations of Galactic structure. Here, we discuss each data group in the order in which they appear in Partiview.

3.3.1 AMNH Stars

Group Name	`stars`
Reference	Hipparcos, the New Reduction (van Leeuwen, 2007)
	The Hipparcos and Tycho Catalogues (ESA 1997)
	Third Catalogue of Nearby Stars (Preliminary) (Gliese+ 1991)
	General Catalog of Mean Radial Velocities
	(Barbier-Brossat+ 2000)
Prepared by	Ron Drimmel (University of Torino, Italy)
	Brian Abbott (AMNH/Hayden)
	Carter Emmart (AMNH/Hayden)
	Stuart Levy (NCSA/UIUC)
	James Adams (AMNH/Hayden)
Labels	Yes. Common star names
	(see also "Alternate Star Names")
Files	`stars.speck, stars.label`
Dependencies	`halo.sgi, colorbv.cmap`
Census	113,709 Hipparcos stars
	+49 Gliese stars
	−9244 stars rejected for their parallax values
	−3856 stars rejected for their distance values
	100,660 stars (including the Sun) and 228 labels.
	21,025 of these stars have radial velocities.

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. How do we determine these distances, though?

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 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 BC 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 remains the most successful astrometric mission to date and will only be surpassed by Gaia, which is set to launch in a couple years.

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 almost 50 such stars from Gliese in our AMNH star catalog.

Finally, we integrate data from the General Catalog of Mean Radial Velocities. The catalog contains mean radial velocities of more than 36,000 stars. The radial velocity is the velocity of the star along the line of sight, measuring how fast the star is moving toward or away from Earth in the radial direction. This value is measured from the Doppler shift in the star's spectrum.

We can also measure the star's tangential velocity, or proper motion, across the sky. 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). This velocity, combined with the radial

velocity, yields the star's overall velocity, or space velocity. We then break this velocity into its vector components and include these, in addition to the star's speed, in our catalog.

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 trigonometric and photometric parallaxes. (Photometric parallax uses a star's brightness and luminosity to derive its distance.) If the star has a measured trigonometric parallax with an uncertainty of less than 20%, the distance is based solely on that measurement. If the uncertainty is greater than this value but less than 75%, we compute the trigonometric parallax distance and the photometric parallax distance, then compute a weighted mean distance based on the uncertainties of each. If the measured trigonometric parallax uncertainty is more than 75%, then we reject the star. There are no stars in our catalog with pure photometric parallax distances.

The distance determination method is traced for each star via the dcalc data variable. 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.

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 $\mathbf{datavar}$ or the shortened $\mathbf{dv}$ command.

Data Variables for the Stars			
Number	**Name**	**Description**	**Units**
0	BVcolor	$(B - V)$ color	—
1	lum	Luminosity scaling (calculated)	—
2	absmag	Absolute Magnitude	mag
3	appmag	Apparent Magnitude	mag
4	texnum	Texture Number	—
5	distly	Distance (calculated)	ly
6	dcalc	Distance determination method	—
7	plx	Parallax measurement	mas
8	plxerr	Parallax uncertainty	mas
9	vx	X-component velocity unit vector	pc/Myr
10	vy	Y-component velocity unit vector	pc/Myr
11	vz	Z-component velocity unit vector	pc/Myr
12	speed	Speed of the star	pc/Myr
13	hipnum	Hipparcos number (-99 of not a HIP star)	—

Where mag is the magnitude, ly stands for light-year, mas is milli-arcsecond, and is a speed expressed in parsecs per million years.

Labels for the stars include the star names, 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 (Greek) and Flamsteed labels in the alternate star labels (altLbl) data group.

Selection Expressions   Using Partiview selection expressions, we have preset some "scenes" in the mw.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 -1 0	Select those stars with a $(B - V)$ color between -1 and 0, the "bluer" stars
red	thresh BVcolor 0 1	See those stars with $(B - V)$ color between 0–1, the "redder" stars
eye	thresh appmag -30 6.5	See stars that have an apparent magnitude brighter than 6.5
m75	thresh appmag < 7.5	Show all stars with an apparent magnitude brighter than 7.5
trig	only= dcalc 1	See those stars with pure trig parallax distances
weighted	only= dcalc 2	Show those stars that have weighted mean distances
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
500ly	thresh distly < 500	Display all stars within 500 light-years

Boxes   In addition to the selection statements, we have defined a few boxes in the stars group. Boxes are useful for highlighting a subset of data within the group (using the boxes command) or separating data from the group (using the clipbox command). The table shows predefined boxes in the mw.cf file.

Boxes in the Stars Data Group		
Box Number	**Dimensions (parsecs)** **(xcen,ycen,zcen xlen,ylen,zlen)**	**Description**
1	−400, −200, −200 400, 200, 100	Box around the Gould Belt
2	−42.35, −0.26, −17.12 3.5, 3.5, 3.5	Box around the Hyades star cluster
3	−100.93, 24.83, −45.95 6, 3, 3	Box around the Pleiades star cluster
clipbox	−400, −200, −200 400, 200, 100	Clip box around the Gould Belt

Pressing the Box Toggle Button in Partiview will produce two boxes around the Hyades and Pleiades; however, the box around the Gould Belt will be invisible. Use the showbox and hidebox commands to alter which boxes are displayed. showbox 1 will turn on the Gould Belt box, for example. (The Gould Belt is a grouping of bright stars inclined to the Galactic plane that demonstrate recent star formation.)

The last entry in the table is a clipbox rather than an ordinary box. It removes all data outside the box from the display. Type `cb on` while `stars` is the active group to see this box.

3.3.2   Alternate Star Names

Group Name	`altLbl`
Reference	Various
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes, but there are no specks. Use with `stars`
Files	`stars-altlbl.label`
Dependencies	none
Census	3,007 labels (1,472 Greek, 1,535 Flamsteed)

In addition to the Arabic star names in the `stars.label` file, we include another data group with star labels. These labels are a combination of Greek star names (Bayer Catalog) and Flamsteed numbers (Greek names taking 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 `mw.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."

3.3.3 The 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/Hayden)
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.

Table 3.2 – Stars selected for error analysis. The distance refers to their published trigonometric parallax distance. The uncertainty of this measurement is listed in terms of distances in the range column, and the uncertainty column lists the uncertainty in light-years.

Star Name	Other Name	Distance	Range (light-years)	Uncertainty
Ain	ϵ Tauri	155	149–161	12
Bellatrix	γ Orionis	243	226–262	36
Spica	α Virginis	262	245–282	37
Betelgeuse	α Orionis	368	352–544	192
Pleione	28 Tauri	387	351–431	80
Polaris	α Ursae Minoris	431	405–460	55
Antares	α Scorpii	469	460–876	416
Rigel	β Orionis	773	648–956	308
Deneb	α Cygni	2,150	2,063–7,409	5,346

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.

The star Ain in the Hyades star cluster in Taurus is the closest star in this sample. At 155 light-years away, it has a small uncertainty, only 12 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 80-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 non-stellar objects is far greater.

3.3.4 Constellation Connectivity Lines

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

Astronomers divide the sky into 88 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 pre-existing 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 most civilizations interpreted the heavens independently of one another, today the International Astronomical Union accepts 88 constellations, based mainly on Babylonian and Greek mythology and lore. More than half of the 88 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 BC. Around the 5th century BC, 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 12 parts of the zodiac.

In the 2nd century B.C., 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 12 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 88 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 placed arbitrarily at 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 mw.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 mw.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.

3.3.5   Nearby Stars

Group Name	`nearstars`
Reference	Lépine Shara Proper Motion Catalog
	Sébastien Lépine & Michael Shara (AMNH)
Prepared by	Sébastien Lépine (AMNH)
Labels	No
Files	`LSPMstars_100ly.speck`
Dependencies	`halo.sgi, colorbv.cmap`
Census	7,031 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 move in the sky.

All stars are in motion within the Galaxy; the Sun orbits the center of the Milky Way galaxy at approximately 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 AD, 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.

Local Stellar Density   The LSPM catalog contains over 7,000 stars. Viewing these stars 200,000 times brighter than their true luminosity reveals the sheer density of the local stellar neighborhood. For example, in the same 100-light-year-radius sphere, Hipparcos only observed 2,414 stars (Hipparcos was a targeted survey, so no new stars were expected to be discovered).

Another, more informative, comparison is illustrated using the preset selection expressions.

Selection Expressions for the Nearby Stars		
Alias	**Partiview Command**	**Description**
eye	`thresh appmag -2 6.5`	Select those stars visible to the unaided eye in the night sky
lowlum	`thresh absmag 10 25`	Select the intrinsically faint stars
hip	`thresh hipid 0 130000`	Select those stars with a Hipparcos ID
nonhip	`thresh hipid < 0`	Select all stars without a Hipparcos ID

Let's view the number of stars that are bright enough to see with our unaided eye using the `eye` selection expression. Type `see eye` and 577 of the 7,031 stars will remain. Perform the same exercise on the stars data group (activate `stars` and type `see eye`) and over 8,600 stars will remain. This tells us that over the course of one year there are about 8,600 "naked eye" stars in the night sky of both hemispheres. Only 577 of them are within 100 light-years. Therefore, about 6,500 nearby stars, right in our own astronomical backyard, remain invisible without the use of a telescope.

To see the intrinsically dim stars, we can use the `lowlum` selection expression. Now we have over 4,600 dim stars in view. These are primarily cool, red stars that are ubiquitous throughout the Galaxy.

While this catalog presents a more accurate representation of the local stellar density, fainter objects remain and astronomers are beginning to catalog them.

3.3.6   Dwarf Catalog

Group Name	`dwarfs`
Reference	Dwarf Archives
	Chris Gelino and Davy Kirkpatrick (IPAC/Caltech),
	and Adam Burgasser (MIT)
	Images by Robert Hurt (NASA/IPAC)
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes
Files	`dwarfs.speck, dwarfs.label`
Dependencies	`L-dwarf.sgi, T-dwarf.sgi`
Census	27 L dwarfs and 53 T 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 Two Micron All-Sky Survey (2MASS), 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 over-sized images that astronomers believe resemble these objects. The L dwarfs appear bright red while the T dwarfs are a dimmer red-purple color. 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`.

3.3.7   Extrasolar Planets

Group Name	`expl`
Reference	The Extrasolar Planets Encyclopaedia
	Jean Schneider (CNRS/LUTH, Paris Observatory)
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes
Files	`expl.speck, expl.label`
Dependencies	`target-blue.sgi`
Census	725 planets in 520 systems

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 520 systems consisting of one or more planets around a host star.

These planets were not discovered in the traditional sense of past planetary discoveries; they are so far away and so small that we cannot actually see them. Instead, for many of the systems, the host star's spectrum is analyzed, and an extremely small motion is inferred for the star. This tiny motion is due to the orbiting planet.

While we think of the Sun as being 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.

Many of the exoplanets were discovered with this observational technique. Other techniques include pulsar timings, measuring the periodic variation in the light arrival time; transit photometry, which measures the periodic variation in the light of the host star; and gravitational microlensing.

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 Greek 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. Each have the lowercase lettered name of the planet or planets in the system. The first planet is named "b," and subsequent planets are given letters in sequence.

Two pulsars have been found to host planets and are labeled with "PSR." The detection method used for pulsars allows their planets to be found at greater distances. The two systems in the atlas are 978 and 12,388 light-years from Earth. Compare that with the main-sequence-star hosts that are within 350 light-years (most are within 150 light-years).

The remaining handful were found by microlensing and transit surveys. These are considerably farther, ranging from 500 to 20,000 light-years from Earth.

The systems are represented by a blue target around each host star. This image is not meant to represent the orbit of the planet, it is simply a marker.

The extrasolar planets have a number of data variables to offer flexibility when visualizing these data.

Data Variables for the Extrasolar Planets			
Number	**Name**	**Description**	**Units**
0	numplanets	Number of planets in the system	—
1	discovered	Year of discovery of the first planet in the system	years
2	distly	Distance to the system	light-years
3	texnum	Texture number	—

You can use these variables in conjunction with the thresh command to see how many systems have more than one planet (thresh numplanets > 2), or how many planets were discovered between 1995 and 2000 (thresh discovered 1995 2000).

3.3.8   Open Star Clusters

Group Name	`oc`
Reference	Optically visible open clusters and Candidates
	(Dias+ 2002-2012)
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes
Files	`oc.speck, oc.label`
Dependencies	none
Census	1,041 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 the star's spectrum, we can determine the spectral type and the luminosity class, revealing the age of the star.)

Since 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 the 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.

Data Variables for Open Star Clusters			
Number	**Name**	**Description**	**Units**
0	`diam`	Angular diameter	arcminutes
1	`logage`	Log of the cluster's age	years

Exploring the Data   As previously mentioned, 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` data variable is an indication of where the most recent clusters are forming. A preset selection

expression (in `mw.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). The remaining clusters highlight the local spiral arms nicely. From outside the Galaxy, you should see three distinct arms: the Sagittarius Arm toward Galactic center; the Orion Arm, 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. These are in exact agreement with the open clusters, each providing a measure of the Galactic structure in our part of the Galaxy.

Selection Expressions for the Open Clusters		
Alias	**Partiview Command**	**Description**
young	`thresh logage 6 7.3`	Show clusters that are less than 20 million years old

3.3.9   OB Associations

Group Name	ob
Reference	Various
Prepared by	Glenn LeDrew (Main-Sequence Software: Ottawa, Canada)
Labels	Yes
Files	`ob.speck, ob.label`
Dependencies	`ob.cmap`
Census	58 OB Associations
Notes	**Olive green** = Sagittarius Arm **Blue** and **Purple** = Orion Arm (or Spur) **Orange** = Perseus Arm

OB associations are groups of O and B stars that have dispersed to the extent that their mutual gravity no longer holds them together. Although they may be far apart, stars in an association share a common motion in space because they were formed from the same gas cloud. This allows astronomers to easily determine OB association membership stars, although rather than structural or gravitational, they are coupled by velocity or evolutionary properties.

Associations typically have anywhere from 10 to 100 stars. If they are young (less than 50 million years old), they will be populated with their original O and B stars (although the O stars last only about 1 million years). For each O or B star that forms, tens of cooler M stars will form.

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 data. The colors are representative of the spiral arm structure. 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 (orange), the Perseus Arm opposite Galactic center (olive green), and the Orion Arm (blue and purple). The Sun and Earth are located just on the inner edge of the Orion Arm, 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 olive green (Sagittarius Arm), blue and purple (Orion Arm), and orange (Perseus Arm) markers. The luminosity of each point is set to the association's diameter divided by 100 parsecs (326 light-years), rendering

markers whose size no longer decreases with distance but is set to a scaling of the association's physical size.

Data Variables for OB Associations			
Number	**Name**	**Description**	**Units**
0	`lumin`	Diameter divided by 100 pc	pc
1	`color`	Color based on spiral arm membership	—

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 be a blue color. To return to the settings based on the data variables `color` and `lumin`, type `color color` and `lum lumin` at Partiview's Command Line.

The Continuing Star Formation Story   In the section "HII Regions," we mention the Orion Nebula and the stars that are forming there. The stars that form from this cloud will eventually be part of a new OB association called Ori OB1d. It is the latest in a string of star formation events that have occurred in this region.

In the Atlas, you will see the OB associations Ori OB1a, Ori OB1b, and Ori OB1c in the constellation Orion. Because O stars live only about a million years before exhausting their nuclear fuel, we can place constraints on the relative time line of their formation. If the Orion Nebula (Ori OB1d) currently has O stars, then Ori OB1c must be about 1 million years old. We know this because it is the supernova explosions from Ori OB1c that likely caused the stars in the Orion Nebula to form. Ori OB1b likely followed this pattern too; its hot stars exploded and caused stars to form in Ori OB1c. This is not the end of the story either. At some point an Ori OB1e association and nebula will form and the cycle of birth and death in the Galaxy will continue.

3.3.10   Globular Star Clusters

Group Name	gc
Reference	Catalog of Parameters for Milky Way Globular Clusters (Harris 1997)
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes
Files	gc.speck, gc.label
Dependencies	none
Census	145 clusters and 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 spaced a few light-months from each other). 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 all in orbit 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.

Data Variables for Globular Star Clusters			
Number	**Name**	**Description**	**Units**
0	`metal`	Log of the metallicity	suns
1	`rcore`	Core radius	arcmin
2	`distly`	Distance	light-years

Exploring the Catalog   The globular clusters form one of the most complete data sets in the Atlas. Data for the 145 clusters in the catalog were compiled by William Harris (McMaster University, Canada) and represent almost all the clusters in our Galaxy (a few on the opposite side of Galactic center may be invisible to us).

Selection Expressions for the Globular Clusters		
Alias	**Partiview Command**	**Description**
`oldgc`	`thresh metal -2.0 -1.5`	Show the metal-deficient, older clusters
`younggc`	`thresh metal -1.0 1.0`	Display the metal-rich, younger clusters

In Partiview, it's easy to see what Shapley observed 80 years ago: that most of the clusters are located in Sagittarius near the Galactic center as seen from Earth. 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

7,200 light-years away. Some of the farthest clusters lie at the edge of the Galactic halo and perhaps even beyond it (more on this in the "The Galactic Outskirts" tutorial).

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

```
see oldgc
see younggc
```

Having formed about 10 billion to 12 billion years ago, globular clusters are among the oldest objects in the Galaxy. They were around when the Galaxy formed, 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.

3.3.11 Pulsars

Group Name	`pul`
Reference	ATNF Pulsar Catalogue
	Manchester, Hobbs, Teoh, & Hobbs,
	Astronomical Journal, v129, pp. 1993–2006 (2005)
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes
Files	`pulsar.speck`, `pulsar.label`
Dependencies	none
Census	1393 pulsars and labels

Upon death, stars leave behind one of three possible remnants: a white dwarf star, a neutron star, or a black hole. Stars that are 1.4 to about 3 solar masses will 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 on Earth a teaspoonful would weigh about 100 million tons.

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, a pulsar in the Large Magellanic Cloud, and the pulsar PSR 1939+2134 are all 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. For this reason, you will notice there are many more pulsars in the southern sky. 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.

3.3.12 Planetary Nebulae

Group Name	pn
Reference	Strasbourg-ESO Catalogue of Galactic Planetary Nebulae (Acker+ 1992)
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes
Files	planneb.speck, planneb.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.

Planetaries 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 remains at the center, and often it appears green because of an abundance of ionized oxygen (OIII), which radiates in the green part of the visible spectrum.

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 planetaries 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 H II regions. We also see more planetaries toward the Galactic center, as well as an increased amount above and below the plane at Galactic center.

3.3.13 HII Regions

Group Name	h2
Reference	CO Radial Velocities Toward Galactic H II Regions (Blitz+ 1982) Georgelin, Y. M. and Georgelin, Y. M. 1976, Astronomy & Astrophysics, 49, 57
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes
Files	h2region.speck, h2region.label
Dependencies	none
Census	261 H II Regions and labels

H II (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, heating 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.

H II 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 call a Strömgren sphere. An O5 star can excite hydrogen up to 65 light-years from the star.

The result is a glowing nebula that is seen from great distances. One local celebrity among H II regions is the Orion Nebula (M42). About 1,500 light-years away, the wispy cloud can be seen with 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). It is also 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 10^{19} atoms per cubic

centimeter.

Source Catalogs Our catalog of H II regions is composed of two main surveys. The main catalog combines observations of molecular cloud complexes made in the Northern and Southern hemispheres. Observations from the Southern Hemisphere were made between 1975 and 1976 with the Anglo-Australian 3.9-meter optical telescope at a frequency of 115 gigaHertz (or a wavelength of 2.6 millimeters). They were then added to the Northern Hemisphere data in the early 1980s.

The catalog is composed of many characteristics of these clouds, such as temperatures, optical diameters, and carbon monoxide (CO) radial velocities. The CO molecule is important because it acts as a tracer of molecular hydrogen and radiates at an atmospherically transparent region in radio, so we can observe it from Earth. CO is rare in the Universe (relative to hydrogen), as it is broken apart by the ultraviolet light from stars. We observe CO only deep within molecular clouds, where it is protected by dust from the destructive interstellar radiation.

We use additional data from a paper published in 1976 by Y. M. Georgelin and Y. P. Georgelin at the Observatoire de Marseille. This paper is a study of molecular clouds in the Galactic plane and has a table of 100 H II regions. While the table gives Galactic longitude and the distance, it does not give the Galactic latitude, as the clouds all lie close to the plane of the Milky Way. For this reason, we place them all *in* the Galactic plane. This is not entirely correct from Earth's point of view, but it is valid when you are viewing them from outside the Galaxy, where this difference would translate into less than one pixel on the screen.

Labels H II regions are described by blue polygons. We designated labels from the Georgelin and Georgelin catalog to have a `GG` prefix. Because this is not strictly a catalog, there was no naming convention. The Blitz catalog retained the naming convention from the Sharpless catalog of the 1959. Most of the data have Sharpless identifiers indicated by an `S` followed by the object number.

Tracing Galactic Structure From Earth's perspective, you'll notice that the H II 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 H II regions.

3.3.14   Supernova Remnants

Group Name	snr
Reference	Galactic Supernova Remnants Catalogue (Ilovaisky+ 1972)
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes
Files	sn_remnant.speck, sn_remnant.label
Dependencies	none
Census	116 supernova remnants and 83 labels

A supernova remnant is the nebulous gas left over from a supernova explosion. During a supernova, one-fifth the mass of the original star can 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 and 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 `Cyg Loop` for 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.

3.3.15   Orion Nebula Star Cluster

Group Name	`oricl`
Reference	Orion Nebula Cluster Population (Hillenbrand 1997)
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	No
Files	`ori_clust.speck`
Dependencies	`halo.sgi, colorbv.cmap`
Census	813 stars
Notes	The distance for each star is statistically generated.

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

We built the Orion Nebula star cluster for our model of the Orion Nebula that was used in the reopened Hayden Planetarium's premiere space show, *Passport to the Universe*. In creating a 3-D model of the nebula, we needed to place the stars of the cluster within 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 in the catalog.

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.

Viewing the Cluster   Because the cluster is so small, it can be difficult to see. One way to see it is to use Partiview to simulate a telescopic view. Center your view on the cluster as best you can (the cluster is in the sword of Orion—you will see it flash as you turn it on and off). With the cluster centered, use the FOV Slider to decrease your field of view. The cluster stars should come into view.

3.3.16 The Orion Nebula Model

Group Name	`orineb`
Reference	A Three-Dimensional Model of the Orion Nebula,
	Wen & O'Dell, *The Astrophysical Journal*, v438, p784
	Image: NASA, ESA, M. Robberto (STScI/ESA),
	Hubble Space Telescope Orion Treasury Project Team
Prepared by	Carter Emmart, Erik Wesselak,
	Brian Abbott, Ryan Wyatt (AMNH/Hayden)
Labels	No
Files	`orion_nebula.obj`, `orishocks.obj`,
	`oribay.obj`, `proplyds.obj`
Dependencies	`orineb.sgi`

The Orion Nebula (also known as M42) shows up in the H II regions (`h2`) and its associated stars are represented in the Orion Nebula star cluster (`oricl`), the open clusters (`oc`), and the OB associations (`ob`), but it receives special treatment here as a three-dimensional model recreated from Hubble Space Telescope observations of the nebula.

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 emission we detect 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 H II regions that we see lie close to the edge of dense clouds of molecular hydrogen (H II regions embedded inside such clouds remain invisible at optical wavelengths). The Orion Nebula has entered what some call the "champagne phase" of an H II 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, some 1,500 light years away from us, can be determined through careful observation and a knowledge of the laws of atomic physics.

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 H II 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 H II 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.

3.3.17 Oort Cloud Sphere

Group Name	oort
Reference	—
Prepared by	Brian Abbott (AMNH/Hayden)
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.

3.3.18   Equatorial Coordinates Sphere

Group Name	`radec`
Reference	—
Prepared by	Carter Emmart, Brian Abbott (AMNH/Hayden)
Labels	Yes
Files	`radec.speck`
Dependencies	none
Notes	Also represents Earth's radio sphere (see below).

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 $+90^\circ$ 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.

Drawing the Sphere   From Earth's perspective, the wire-frame sphere perfectly represents the equatorial coordinates. If you examine the `radec.speck` file, you'll see four main sections. The first section is the ellipsoid command that draws the main sphere:

```
0 0 0 ellipsoid -s line -c 1 -r 20.245 -n 24,19
```

The second part contains a mesh statement that draws a line around the celestial equator; this has a color index of 2. Following this is another ellipsoid statement that draws lines every 15 arcminutes in

right ascension and every 2 degrees in declination. This ellipsoid has a color index of 3 and is initially set to black in the `mw.cf` file. If you have zoomed into a small portion of sky by adjusting the field of view, you can make these visible by setting the color index to a color, such as:

```
cment 3 0 0 0.2
```

Finally, there is a series of labels for the data group in hours for right ascension and degrees for declination.

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 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 and those early signals that left in 1940 have reached the 72-light-year mark.

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. Looking into space is looking back in time to a younger Universe.

3.3.19   Ecliptic Coordinates Sphere

Group Name	`eclip`
Reference	—
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes
Files	`eclip.speck`
Dependencies	none

Ecliptic coordinates are based on the imaginary line 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 $23.^{\circ}5$ to this plane, the Sun appears to move in declination throughout the year (see "Equatorial Coordinates Sphere" for definition). 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 $23.^{\circ}5$ north and $23.^{\circ}5$ 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 [$(RA, Dec) = (0, 0)^{\circ}$] and the ecliptic north pole is in the constellation Draco ($23.^{\circ}5$ 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 $23.^{\circ}5$.

A New Horizon   In the Atlas, the ecliptic sphere is similar to the celestial sphere but is given a radius of 100 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 ($62.^{\circ}87$ 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. In fact, the Sun and all its planets are orbiting the center of the Galaxy once every 225 million years. Picture the Sun and its planets tipped 60°, orbiting in the Galactic plane at 220 km/sec (or just less than 500,000 miles/hour). We now see there's a more significant horizon to obey, that of our home Galaxy. Are there any horizons

beyond this?

3.3.20   Galactic Coordinates Sphere

Group Name	`galac`
Reference	—
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes
Files	`galac.speck`
Dependencies	none

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.

3.3.21 Visible All-Sky Survey

Group Name	`mwVis`
Reference	Axel Mellinger (Universitaet Potsdam)
Prepared by	Ryan Wyatt (AMNH/Hayden)
Labels	No
Files	`mw-visible.speck`
Dependencies	`mellinger-optmw.sgi`
Wavelength	400 nm − 700 nm
Frequency	750,000 GHz − 430,000 GHz

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 star system. It was not until the 20th century, though, that astronomers began to understand the nature and structure of our Galaxy, by looking at that band of light across our sky and comparing it with other "island universes," like the Andromeda Galaxy.

Image Features   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 $(l, b) = (0, 0)^\circ$ to center screen]. In this direction, looking toward Scorpius and Sagittarius, is the center of the Galaxy. 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 (see group `bulge` for size), whereas the rest of the band appears thinner.

If you turn to look in the opposite direction, toward Orion $[(l, b) = (180, 0)^\circ]$, 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.

3.3.22 Atomic Hydrogen Survey

Group Name	`mwH`
Reference	Atlas of Galactic Neutral Hydrogen (Hartmann+, 1997)
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	No
Files	`mw-21cm.speck`
Dependencies	`02-21cm-512.sgi`
Wavelength	21 cm
Frequency	1.42 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.

The false colors in the survey represent the density of atomic hydrogen along a line of sight. White and red represent highly dense regions of hydrogen gas, while blue and purple are regions of lower density. These measurements, combined with the Doppler shift of the light, give us an idea of the structure of the Milky Way's hydrogen gas clouds.

3.3.23   Carbon Monoxide All-Sky Survey

Group Name	`mwCO`
Reference	Composite CO Survey of the Milky Way (Dame et al. 1987)
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	No
Files	`mw-CO.speck`
Dependencies	`03-115GHz-512.sgi`
Wavelength	2.6 mm
Frequency	115 GHz

Carbon monoxide (CO) 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. The observations used to compose this image were made with the Columbia/GISS 1.2-meter telescope in New York City as well as telescopes at Cerro Tololo in Chile.

CO is used to trace molecular hydrogen (H_2). Normally, CO molecules would be broken apart by the ultraviolet radiation from stars. However, the CO molecules remain shielded from the harmful UV rays deep inside dense, dusty molecular clouds of hydrogen.

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 white 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.

3.3.24 Far Infrared Survey

Group Name	`mwFIR`
Reference	IRAS Sky Survey Atlas Explanatory Supplement
	(Wheelock, S. L., et al. 1994)
Prepared by	Ryan Wyatt (AMNH/Hayden)
Labels	No
Files	`mw-iras100um.speck`
Dependencies	`mw-iras100um-1024.sgi`
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.

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 very, very small 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 in the 100-micron far infrared (FIR) survey. Astronomers consider far infrared light to be in the range of a few tens of microns to about 300 microns. 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 can be seen too, like the Andromeda Galaxy and the Small and Large Magellanic

Clouds.

3.3.25   IRAS Composite All-Sky Survey

Group Name	`mwIRASc`
Reference	IRAS Sky Survey Atlas Explanatory Supplement
	(Wheelock, S. L., et al. 1994)
Prepared by	Carter Emmart (AMNH/Hayden)
Labels	No
Files	`mw-iras.speck`
Dependencies	`iras.sgi`
Wavelength	Composite of 12, 60, and 100 microns
Frequency	Composite of 25,000, 5,000, and 3,000 GHz

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 at 12, 25, 60, and 100 microns. This all-sky survey is a composite of the 12, 60, and 100 micron observations. (More information on IRAS can be found in "Far Infrared Survey.")

Because heat is infrared radiation, it was necessary to cool the telescope to temperatures below 10 Kelvin (-440°F). This cooling was achieved with liquid helium; however, the coolant ran out a little early, causing the detector to become saturated by the telescope's own heat. These "missed orbits" are seen in this all-sky image as two slits of missing data. Astronomers have since filled in these regions with other data, but we leave the empty regions in this composite survey to preserve the original IRAS data.

Image Features   The most obvious feature in the IRAS all-sky is the missing data from those lost orbits (discussed above). Another, more subtle artifact is present as two purple bands running perpendicular to the swaths of missing data. If you turn on the ecliptic coordinates, you will notice that these purple bands are along the ecliptic, which marks the plane of our solar system. These bands result from the subtraction of the zodiacal light. The plane of the solar system is filled with particulate matter, dust grains that absorb sunlight and radiate in the infrared. In order to see the infrared light from the Galaxy, astronomers subtracted the light from within our solar system, producing these two bands.

Toward Galactic center in Sagittarius, the infrared light is tightly constrained to the Galactic plane. In the opposite side of the sky near Orion, the infrared light seems to break up, becoming more clumpy. Here we are looking away from the center of the Galaxy.

Some objects glow in this part of the sky, though. 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.

3.3.26 Two Micron (2MASS) All-Sky Survey

Group Name	`mw2MASS`
Reference	Two Micron All-Sky Survey
	(UMass, IPAC/CalTech, NASA, NSF)
Prepared by	Tom Jarrett (IPAC/CalTech),
	Brian Abbott (AMNH/Hayden)
Labels	No
Files	`mw-2mass.speck`
Dependencies	`mw-2mass-1024.sgi`
Wavelength	1.24, 1.66, 2.16 microns
Frequency	241,936, 180,723, 138,889 GHz

The Two Micron All-Sky Survey (2MASS) is an infrared (IR) survey of the sky. Because it is looking in the IR 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 IR 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 IR detectors that could observe 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). You will see some distortion artifacts toward the Galactic poles. This is from the process of wrapping the image on a sphere.

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.

3.3.27 Hydrogen-Alpha All-Sky Survey

Group Name	`mwHalpha`
Reference	Doug Finkbeiner (Princeton)
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	No
Files	`mw-halpha.speck`
Dependencies	`mw-halpha.sgi`
Wavelength	656 nm
Frequency	457,000 GHz

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 feature 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 about 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. This H II region, Sharpless 264, is one of many that glow brightly in the spiral arms of our Galaxy. Zeta Ophiuchi is another hot star, about 450 light-years away.

Other nebulae and H II 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.

3.3.28 Gamma-Ray All-Sky Survey

Group Name	`mwGamma`
Reference	Compton Gamma-Ray Observatory
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	No
Files	`mw-gamray.speck`
Dependencies	`08-gamma-512.sgi`
Wavelength	4.17×10^{-15} m
Frequency	$> 7.2 \times 10^{13}$ GHz

Gamma-ray light is the highest energy radiation in the electromagnetic spectrum. Gamma-rays have very short wavelengths and high frequencies and it can penetrate solid objects. Radioactive decay of atoms produce high-energy particles, such as alpha, beta, and gamma particles. An alpha particle is a positively-charged helium nucleus. It is the least energetic radioactive particle and is stopped by a sheet of paper or the skin. Beta particles are similar to electrons and can travel in air for a few feet before losing their energy. They are shielded by aluminum or glass and penetrate only a fraction of an inch in our skin. Gamma particles are the most energetic, requiring several inches of lead or concrete for protection from burns, cancer, and genetic mutations.

Because our atmosphere shields us from cosmic gamma-ray light, gamma-ray astronomy did not develop until we were able to place balloons or satellites above the atmosphere. The first gamma-ray space telescope was carried aboard the Explorer 11 satellite in 1961. Subsequent missions detected gamma-rays in the Galaxy and in the Universe. Gamma-rays are produced in massive explosions and high-speed collisions, suggesting the Universe is more violent than astronomers once thought.

A breakthrough came in the late 1960s and early 1970s when the United States placed a series of satellites in orbit to detect gamma-rays from nuclear explosions. They detected flashes of bright gamma-ray radiation, but these were coming from space. In April 1991, NASA's Compton Gamma-Ray Observatory (CGRO) was launched into space by the Space Shuttle Atlantis. Before being de-orbited in June 2000, the telescope discovered gamma-ray bursts, cataloged gamma-ray sources, and surveyed the sky.

This all-sky survey is from the Energetic Gamma-Ray Experiment Telescope (EGRET) on the CGRO. The rainbow-colored map indicates gamma-ray bright areas (white, red) and dimmer areas (blue, indigo). The brightness along the Galactic plane is due to gamma-rays interacting with interstellar gas. Several bright sources appear as white spots on the map. These include the Crab, Geminga, and Vela pulsars in the Galactic plane. The brightest source above the plane, 3C 279, is a quasar that lies

about 4 billion light-years away.

3.3.29 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/Hayden)
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.

Object type	Messier objects included
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
M8	Lagoon Nebula
M16	Open cluster (in the Eagle Nebula)
M17	Omega Nebula
M20	Trifid Nebula
M27	Dumbbell Nebula
M31	Andromeda Galaxy
M57	Ring 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, you can 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 to the left of the slider is the field of view (in degrees) of your window in the up-down direction. A value of 5–10 degrees might simulate a pair of binoculars while a value less than 0.5 replicates a telescopic view.

Of course, you can also exaggerate the size of the images by changing the polygon size of the data group, but we don't recommend this as a means of seeing the images since it grossly misrepresents these data. However, if you do increase the polygon size by choosing `polysize` from the Slider Menu, a polygon size of 1.0 will bring them back to their actual size.

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, which will be challenging if you have a lot of data in your view. For example, if you zoom in on M27, the Dumbbell Nebula, and hit the p key while your mouse is over the image, you will see the following one-line report in the Console Window:

```
[g28]Picked -121.574 -217.853 -16.117 (w121.574 217.853 -16.117)
"M27 (Joe and Gail Metcalf/Adam Block/NOAO/AURA/NSF)"
@250 (of 2); texture 27 radius 0.2568
```

The first numbers describe the location of the object selected, followed by the object name and image credit in quotes, followed by other metadata values associated with the data point.

3.3.30 Galaxy Image

Group Name	`galaxy`
Reference	European Space Agency
Prepared by	Carter Emmart (AMNH/Hayden)
Labels	No
Files	`mwpoly.speck`
Dependencies	`ngc1232.sgi`

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. Even today, 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.

This debate and its outcome gave astronomers a better idea of how the Galaxy was structured. With other galaxies as examples, it soon became clear that we were inside a spiral galaxy like Andromeda.

The Galaxy in 2-D   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.

You can adjust the brightness of the Galaxy using the Alpha Slider. Its size is specified in the speck file but is also affected by commands in the `mw.cf` file.

The features you see in the image, of course, do not represent our Galaxy 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, as it 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.

3.3.31 Galactic Bar

Group Name	bar
Reference	Merrifield, M. & Binney, J. 1998, *Galactic Astronomy* (Princeton: Princeton University Press)
Prepared by	Carter Emmart & Brian Abbott (AMNH/Hayden)
Labels	No
Files	bar.speck
Dependencies	halo.sgi

The Milky Way has two main structural elements: the disk and the spherical components. 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, bulge and halo groups, respectively. 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. In 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 $14°$ 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.

3.3.32 The Galactic Bulge

Group Name	`bulge`
Reference	Merrifield, M. & Binney, J. 1998, *Galactic Astronomy* (Princeton: Princeton University Press)
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	No
Files	`bulge.speck`
Dependencies	none

Astronomers refer to the large, bright glow from the Galaxy's center as its bulge. Most of the Galaxy's mass and luminosity are within the bulge. In the Milky Way, the bulge is roughly 20,000 light-years across the disk of the Galaxy and extends 13,000 light-years off the Galactic plane.

In the Atlas, the bulge is represented by a yellow ellipsoid centered on the Milky Way. If you view the bulge from Earth, you'll see that it almost perfectly encompasses that part of the Milky Way toward Galactic center. (Increase the alpha on mwVis using the Alpha Slider).

The bulge is the inner element of the spherical component of the Galaxy. This spherical component is populated mostly with older, dimmer stars. However, the bulge lies in the disk of the Galaxy, so it contains a mixture of older stars and new stars from the disk component of the Galaxy. The outer parts of the spherical component are called the Galactic halo, and we will discuss that data group next.

3.3.33   The Galactic Halo

Group Name	`halo`
Reference	Merrifield, M. & Binney, J. 1998, *Galactic Astronomy* (Princeton: Princeton University Press)
Prepared by	Brian Abbott (AMNH/Hayden)
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 very 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.

3.3.34 Local Group of Galaxies

Group Name	`lgrp`
Reference	Students for the Exploration and Development of Space (SEDS)
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes
Files	`localgroup.speck, localgroup.label`
Dependencies	none
Census	46 galaxies and labels

The Local Group refers to the few dozen galaxies in our Galactic neighborhood. While these are outside the Milky Way, we include them here to provide a transition to the Extragalactic Atlas portion of the Digital Universe. The group consists of three large spiral galaxies (in order of size): Andromeda, the Milky Way, and M33. The remaining members of the group are dwarf spheroidals, dwarf ellipticals, and irregulars.

The galaxies occupy a space of about 6 million light-years (1 Mpc) in diameter. The Andromeda Galaxy and the Milky Way dominate, each with a host of small dwarf galaxies huddled around them.

Colliding Galaxies   Several galaxies in our neighborhood are interacting with our Milky Way. Astronomers believe that galaxy interactions and mergers are far more common than once thought. For some time, we have understood the involvement of the Large and Small Magellanic Clouds (LMC and SMC) with our Milky Way. These galaxies are irregular galaxies that are about 160,000 light-years from the center of the Milky Way. Both galaxies contain active star formation as well as older stars and globular clusters. Radio observations also show the possibility of a stream of gas connecting them to the Milky Way.

The LMC was considered to be our nearest neighbor until 1994, when the Sagittarius dwarf elliptical galaxy (SgrDEG) was discovered. The SagDEG lies opposite the center of the Milky Way and is interacting with our Galaxy. As it orbits the Milky Way, it is stretched apart, leaving streams of stars in its wake. It's not entirely accurate representing the Sagittarius spheroidal as one point in the Atlas, since these streams are believed to stretch across the Galactic plane over tens of degrees in our sky. The SgrDEG lost the title of closest galaxy in November 2003, when the Canis Major dwarf galaxy was discovered. The Canis Major dwarf is about 25,000 light-years away from the Sun in the constellation Canis Major.

3.3.35 Planetary Orbits

Group Name	`solsys`
Reference	Jet Propulsion Lab's HORIZONS
Prepared by	Brian Abbott, Ryan Wyatt (AMNH/Hayden)
Labels	No
Files	`solsys-mw.speck`
Dependencies	`halo.sgi`
Census	9 orbits

Because the Solar System is among the most familiar and widely understood aspects of astronomy, we have included the paths of the planetary orbits in the Milky Way Atlas. This is a bit unnatural, since the scale of the Solar System is so small when compared with the nearest star to the Sun. But with a few modifications, you can see how the Solar System fits in the overall scale of the Milky Way Atlas.

This is not a "working" Solar System. There are no planets that move along these trajectories. Only the orbits themselves are present for context within the Atlas.

The orbits' color coding is loosely based on the planets' colors. Mercury is gray, Venus is yellow, Earth is blue, Mars is orange, and so on for the outer planets. The data set also includes what we call the mini-sun. This is a smaller Sun exactly like the Sun in the `stars` group but far less luminous.

Recall that the average Earth-Sun distance is defined to be 1 astronomical unit (AU) and equals 149.6 million kilometers (93 million miles). (Yes, that small distance between the Sun and the blue orbit is 93 million miles.) We can also express this distance in light-travel time as 8.3 light-minutes. Light-travel time is the time it takes light to traverse some distance in space. It takes the Sun's light a little more than 8 minutes to reach Earth. It takes more than 4 hours to reach Neptune. For more on light-travel time, see "Light-Travel Time and Distance."

Seeing the Solar System Group   The scale of the Solar System is so small compared with the parsec-scaled Milky Way Atlas (Earth is 0.00000485 parsecs from the Sun) that you must alter the display characteristics of Partiview to see the `solsys` (and `probes`) data group. Once you bring up the Milky Way Atlas, follow these steps to view the orbits:

1. Turn on the `solsys` data group.

2. Change Partiview's clipping planes using the command `clip 1e-5 1e5`. You should see the orbits appear. If you see nothing, see the "Troubleshooting" paragraph below.

3. Turn off the star polygons. Make sure `stars` is the active data group and press the Poly Toggle Button. This is necessary because the Sun's polygon will be too bright on the scale of the Solar System, so we must turn it off.

4. Fly backward away from the Sun using the right mouse button and moving the mouse to the left.

5. Now you can orbit the Solar System and view it from outside. Once you leave the Solar System and begin flying away from the Sun, remember to switch your clipping planes back to their preset values using the command `clip 0.1 1e6` and return the stars' polygons.

What Are Clipping Planes?   In any 3-D graphics software, the program needs to know what to draw and where to draw it. When you look into Partiview's Graphics Window, imagine you're looking down onto a pyramid from its apex. The sides of the pyramid are represented by the four sides of the window, which is set by the field of view. A small field of view will make your pyramid narrow, resulting in a narrow sightline and less data in view; a large field of view will expand the range for drawing, resulting in a pyramid with a wide base.

The location of the base and apex of the pyramid are set using clipping planes. There is a near clipping plane, the apex, in front of which nothing is drawn, and a far clipping plane, the base, behind which nothing is drawn. The Milky Way Atlas is initialized with the command `clip 0.1 1000000`, meaning objects will be drawn only when they are between 0.1 and 1 million parsecs from your position. Anything closer than 0.1 pc and farther than 1 million pc will not be drawn. The Solar System is very small on the parsec scale, so we must bring the near clipping plane closer to us to see it. Hence the 1e-5 (0.00001 pc) setting.

Troubleshooting   Depending on your computer and graphics support, you may have problems with these clipping-plane values. On most systems, you will see flashing and blinking of data with such small values and large differences between planes. There are some graphics cards that draw nothing when you enter a near clip of less than 1. Some cannot handle a large range between the near and far planes. If you are having trouble, experiment with the values to see if you can make something work. Because Partiview has never been rigorously tested on various graphics cards, we cannot provide any hard, fast rules for its performance.

3.3.36   Spacecraft Trajectories

Group Name	`probes`
Reference	Jet Propulsion Lab's HORIZONS
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes
Files	`pioneer10.speck, pioneer11.speck,` `voyager1.speck, voyager2.speck`
Dependencies	none
Census	Pioneer 10 & 11, Voyager 1 & 2 trajectories

This data group consists of the trajectories of the Pioneer 10 and 11 (green) and the Voyager 1 and 2 (yellow) spacecraft. These are the four farthest objects man has sent into space. To view them, follow the instructions on altering your clipping planes in "Planetary Orbits."

The Pioneer program was the first large-scale planetary exploration mission undertaken by NASA. We highlight Pioneer 10 and Pioneer 11 missions because they are traveling into interstellar space. However, these are but two probes in the program. Pioneers 6–9 were launched between 1965 and 1968 and were sent into orbit around the Sun. Pioneer 6 is the oldest NASA spacecraft in working order. The last successful communication with the craft occurred on December 8, 2000, to commemorate its 35th anniversary.

On March 2, 1972, Pioneer 10 was launched to fly by Jupiter. It was the first spacecraft to fly through the asteroid belt and made its closest approach to Jupiter on December 3, 1973. Pioneer imaged the planet and its moons and sent back measurements of Jupiter's magnetic field and atmosphere. The last signal was received from Pioneer 10 on January 23, 2003, before its radioisotope power source decayed to levels too low to send signals strong enough to detect.

Pioneer 11 was launched on April 5, 1973, and followed Pioneer 10 to Jupiter, then went on to image Saturn. Its last transmission was received on September 30, 1995. The spacecraft's antenna is now out of Earth's view, and, with no communication possible, the craft cannot be moved to point its antenna back toward Earth. The probe may continue to transmit a signal today, but it is not possible to receive it.

After the Pioneer 10 and 11 probes, the Voyager program began its "grand tour" of the Solar System. Voyager 2 was launched on August 20, 1977, with Voyager 1 following 15 days later. Midyear 1979, the spacecraft made their closest approach to Jupiter. In November 1980, Voyager 1 flew by Saturn and then, with a boost from Saturn, was ejected from the plane of the Solar System, beginning its interstellar mission phase.

Voyager 2 visited Saturn in summer 1981 and was the first spacecraft to visit Uranus, in January 1986, and Neptune, in the summer of 1989. Neptune then boosted Voyager 2 out of the Solar System's plane.

The interstellar mission involves the investigation of the outer reaches of the Sun's influence. As the Sun moves through space, it is plowing into the gas that surrounds it. This sets up a shock whereby the particles streaming from the Sun ram into the particles of the interstellar gas. The Voyager spacecraft will one day encounter that shock and return data on the nature of this interstellar gas unaffected by the Sun. The spacecraft should begin entering this region in the next five years and cross it entirely 10 to 20 years after reaching the shock. Beyond this, Voyager will continue to sail into the Milky Way. In about 296,000 years, Voyager 2 will pass within 5 light-years of the bright star Sirius in Canis Major.

Scientists continue to communicate with the Voyager craft. Both are traveling at about 3.5 AU/year. On February 17, 1998, Voyager 1 surpassed Pioneer 10 to be the farthest man-made object.

The Trajectories   Each of the four trajectories begins from Earth's orbit, and their point of departure marks the location of Earth when the probes were launched. The trajectories extend to the year 2050. Labels appear either at planetary encounters or every 10 years once the spacecraft leave the planetary plane. Alongside each year, we include the light-travel time in light-minutes (`lm`) or light-hours (`lh`).

If you turn on the 1-light-month grid (`1lmo`), you will see that the probes will be about 1 light-day from Earth in 2050. One light-day is about 26 billion kilometers, or 16 billion miles, the distance light travels in one day.

3.3.37   Sun-Centered Coordinate Grids

Group Name	`1lmo, 1ly, 10ly, 100ly, 1kly, 10kly`
Reference	—
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes

Files	`target1lweek.speck, target1lmonth.speck,`
	`grid1lmonth.speck;`
	`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-day scale (in `1lmo`) to the 10,000-light-year scale (in `10kly`). The grids are placed in the Galactic plane.

Using the Grids   Each grid is centered on the Sun and covers a size scale that is well suited for particular data sets in the Atlas. The units are in light-travel time and appear as `lw` for light-weeks, `ly` for light-years, and `kly` for kilo-light-years (1,000-light-year units).

1lmo   The light-month grid extends to 4 light-weeks, or 1 light-month. Lines of constant radius are drawn for the first 7 light-days, after which lines are drawn each light-week. The overlying grid has increments every two light-weeks.

1ly   Beyond the light-month grid is the light-year grid. It 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 year. Viewing the grid face-on along with the stars, one is able to see the locations of those nearby stars close to the plane. While this is not an exact measuring tool, it's easy to see that Alpha Centauri (Proxima) is just more than 4 light-years and Sirius is between 8 and 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 72 light-years with many of the extrasolar planetary systems (`expl`).

1kly   A 1,000-light-year (1-kilo-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 Arm (the Sun is located on the inner edge of the Orion Arm, sometimes called a 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 (`ob`) are found within the grid, as are data from the open clusters (`oc`), supernova remnants (`snr`), and H II regions (`h2`).

3.3.38 Galaxy Coordinate Grid

Group Name	`galGrid`
Reference	—
Prepared by	Brian Abbott (AMNH/Hayden)
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 midpoint is at the Galactic center. The grid lies in the plane of the Galaxy, which is about 50 light-years "below" the Solar System. 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`), some pulsars (`pul`), and galaxies in the Local Group (`lgrp`). The grid is complemented by the Milky Way image (`galaxy`), the Galactic bar (`mwbar`), the Galactic bulge (`bulge`), and the Galactic halo (`halo`), which diagrammatically highlight some of the Galaxy's structural features.

3.3.39   Sloan Stars

Group Name	`sloanstars`
Reference	Sloan Digital Sky Survey
	John Bochanski & Suzanne Hawley (U Washington),
	Kevin Covey (Harvard CfA),
	Neill Reid (Space Telescope Science Institute),
	Andrew West (UC Berkeley),
	Sloan Digital Sky Survey Collaboration
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	No
Files	`sdssMstars.speck`
Dependencies	`halo.sgi`
Census	1,000,000 M stars

In the Digital Universe, the `stars` data set contains stars for which relatively accurate distances exist. It is not an accident that these are located close to Earth. However, these stars represent a mere drop in the bucket when we consider the few hundred billion stars in the Milky Way.

The Sloan stars are a sampling of one million stars from the Galactic halo (`halo`). Because these stars are so far away, astronomers cannot use trigonometric parallax to determine their distance. Rather, they must use the starlight itself—its photometric properties—to obtain a distance to the star (see "Parallax and Distance" for a detailed discussion on these techniques). While this distance is not as accurate as a geometrically obtained trigonometric parallax distance, it is informative and, frankly, the best technique astronomers have for normal stars at this distance.

The Sloan Digital Sky Survey's primary goal was to map galaxies and quasars that lie beyond the Milky Way (see the Sloan galaxies, `SloanGals`, and the Sloan quasars, `SloanQSOs`, in the Extragalactic chapter). They accomplished this over one-quarter of the sky using a dedicated, 2.5-meter telescope at Apache Point Observatory in New Mexico. A byproduct of this project is the detection of millions of stars, 28 million of which are cool, M dwarf stars. This data group contains 1 million randomly sampled stars from this larger, 28-million-star data set.

M dwarfs, also known as red dwarfs, are relatively small, cool stars. They have less than half the Sun's mass and emit less than 10% of the Sun's luminosity. Their surface temperature is about 3,500 Kelvin (3,200°C or 5,800°F), compared to the Sun's 5,800 Kelvin. M stars are so dim that even those close to the Sun remain invisible to the unaided eye.

Taking a census by number, M dwarfs comprise about 75% of all stars in the Galaxy. One reason for

this is that they have incredibly long lifetimes. The Sun, a G dwarf, has a lifetime of around 10 billion years. After this time, its primary source of fuel, hydrogen, is exhausted and the star enters into the final stages of its existence. M dwarfs live for tens of billions and perhaps even trillions of years, meaning most M stars that were ever created in the Galaxy are still around. While the hotter, brighter, more massive stars come and go, the cooler, red dwarfs remain.

The Bow Tie Effect   By now, you may have noticed that these stars, as seen from outside the Galaxy, appear to form the shape of a bow tie whose center is at the Sun. These wedges describe the patches of sky observed by the telescope. If you return home to the Sun, you will see where these stars were observed in the night sky. The stars are not everywhere, but in select patches in the sky. As you move away from the Sun, you can see these patches transform from a 2-D view to a 3-D distribution. If the telescope were to observe the entire sky, we would see a spherical distribution of stars around the Sun, rather than the triangular shapes presently seen.

Galactic Structure   Astronomers study these stars to understand the structure of our Galaxy. Because we are in the midst of the Milky Way's disk, it is difficult to grasp the true shape and configuration of our own Galaxy.

From a point where you see all these stars (you may have to brighten them), notice the contours of this data set. Stars at the "edge" of the data set, i.e., those stars farthest from the Sun, form a circular arc. Conversely, the higher density region closer to the Sun has an asymmetric shape. If you do not see this shape, jump directly to this point:

```
jump -9000 12000 1500 -50 -80 -100
```

From this vantage point, you will see a distinct increase in the stellar density parallel to the Galactic disk and in the direction of the Galactic core. This rising profile reflects the vertical structure of the Milky Way. You may also notice a small increase in density in the lower half of the data, less pronounced because there is less data in this part of the survey.

Astronomers use 3-D star counts to realize the structure of the Galaxy. While we call the Milky Way our home, we still know remarkably little about the overall structure of the galaxy. Knowledge of these star counts in various locations allow us to map the disk, bulge, and halo, and better understand the Galaxy we live in.

3.3.40 Stellar Orbits

Group Name	`starorbits`
Reference	Sébastien Lépine (AMNH)
Prepared by	Sébastien Lépine (AMNH),
	Brian Abbott (AMNH/Hayden Planetarium)
Labels	Yes
Files	`starorbits.speck`
Dependencies	none
Census	7 star orbits

Everything in the Universe moves. We experience the rotation of Earth when day turns to night, and we experience Earth's orbit around the Sun as the seasons change. Unbeknownst until the 20th century, the Sun and its family of planets, dwarf planets, asteroids, and comets move through the Milky Way galaxy at about 500,000 miles per hour. We orbit the Milky Way in a relatively stable orbit, one circuit around—our "galactic year"—takes about 225 million years. The last time the Sun was in the same spot in the Galaxy, dinosaurs ruled the Earth.

In this data group, we illustrate orbital trajectories for seven stars with varying speeds and directions. There are a few hundred billion stars in our Galaxy, and here we see how seven of them will move over the next one billion years.

The Sun, our host star, is the most stable of the seven. It travels in a fairly consistent orbit in the disk of the Galaxy. Currently, it is heading in the direction of the constellation Cygnus and lies about 50 light-years above the plane of the Galaxy. The Sun's position oscillates above and below the plane every 32 million years, reaching a maximum of about 260 light-years above or below the plane. Imagine how our night sky changes due to this periodic motion. When we are centered on the plane of the Galaxy, the band of light across the sky will be at its thinnest. Conversely, when we are 260 light-years above or below the plane, the band of light will appear a little thicker, occupying a little more sky. Beyond the appearance of our night sky, some scientists believe that our position above or below the Galactic plane may even cause mass extinction events on Earth.

Barnard's Star, the fourth-closest star to the Sun, has the highest proper motion of any star in the night sky (see the `nearstars` data group for more on proper motion). While its path generally remains in the Galactic disk, its radius from the Galactic center varies greatly. Currently, the Sun and Barnard's star are moving toward one another as we travel along our Galactic orbit. In about 10,000 years, Barnard's star will be only 3.8 light-years away, making it the closest star to the Sun.

Not all stars are so well behaved. Some move wildly above and below the Galactic disk. Imagine how your night sky will appear under these circumstances. If we were living on a planet whose host star was high above or below the disk, we would have a magnificent, face-on view of the Galaxy. The star PM J13420-3415 is an example of such a star. At its maximum distance above the Galactic disk, the night sky on a planet similar to Earth would appear fully illuminated by the Galaxy for part of the year, and appear dark the remaining time as we look away from the Galaxy.

PM J13420-3415 is only one of billions of stars that orbit the Galaxy in this fashion. The Milky Way contains a population of old, mainly dim, stars that are distributed spherically about its center. Astronomers call these *halo stars*. We cannot see many of these stars, let alone derive accurate distances to them. The most visible objects in the Galactic halo (`halo`) are the globular clusters (`gc`), which are dense concentrations of halo stars.

Hidden Orbits   For clarity, we show only 4 trajectories by default. To display the other three stars, open the `mw.cf` file and follow the instructions in the `starorbits` group. Alternatively, you can change the color of the trajectories and labels in Partiview. For example, to see the seventh star LSR J0822+1700, type `cment 7 1 1 1` and `textcment 7 1 1 1`. The "7" represents the seventh star's orbit, and the "1 1 1" is the red-green-blue color, which in this case is white. Frankly, it is easier to open the config file in a text editor and decide what you want to see, just scroll to the `starorbits` group in the `mw.cf` file.

3.4   Optimizing the Milky Way Atlas

While technology is quickly catching up with the graphics power our Atlas demands, some people still find that the Atlas runs sluggishly on their computers. There are a few things you can do to reduce your computer's strain.

Threshold the Stars   The most common culprits in the Milky Way Atlas are the stars. We distribute a star catalog with more than 100,000 stars, mostly from Hipparcos and a few from the Gliese Catalog. Many computers cannot handle all of these stars with their points and textures. Using the Partiview command `thresh`, you can remove many of the stars from view, improving the performance.

We have placed many preset threshold statements for the stars in the `mw.cf` file. Some threshold distance, others the star's color. One threshold useful for eliminating most of the stars without altering the night sky view is a threshold on the stars' brightness, called the apparent magnitude.

The system of stellar magnitudes has its roots in ancient times. The scale is such that the brighter the object is, the smaller its apparent magnitude is. The brightest object in the sky, the Sun, has a magnitude of -26; the moon's is -12. The brightest star in the sky other than the Sun, Sirius, has a magnitude of -1. Our eyes can see to about $+6.5$ magnitude, so thresholding the stars that are dimmer than this will preserve the night sky while cutting out many of the dimmer stars.

We have set up a threshold statement in the `mw.cf` file that removes all stars over 7.5 apparent magnitude. To activate it, type

```
see m75
```

at Partiview's Command Line. Alternatively, you could enter the command by typing `thresh appmag < 7.5`. This leaves you with about 25,000 stars and, we hope, improved performance. If you are still having troubles, though, please read on.

Save Your Changes   Once you have the settings configured for your system, open the `mw.cf` file in a text editor and alter the file to suit the improved custom configuration.

4

The Extragalactic Atlas

The word "extragalactic" means everything outside the Milky Way, our home galaxy. Extragalactic space consists mainly of galaxies, the building blocks of the Universe. Within the observable Universe (that part of the Universe visible to us), astronomers estimate there to be 40 billion to 100 billion of them. Imagine, 40 billion galaxies with billions of stars each. If even a tiny fraction of those stars are host to planets, there would be trillions and trillions of planets in the Universe.

The Digital Universe allows us to view these galaxies in three dimensions, revealing the weblike distribution of galaxies in our Universe. In the Milky Way Atlas we adopted the notion of a solar neighborhood. In the Extragalactic Atlas we expand on that idea and discuss our Galactic neighborhood. Beyond the neighborhood, you may wonder whether we are located in an action-packed region of the Universe or on the outskirts looking in. You may even contemplate some age-old questions: How big is the Universe? Where are we in the Universe? Is there other life in the Universe? These and other questions will be addressed in this chapter. Some will be answered, while others remain beyond our reach.

We will start this chapter with a review of the objects found in extragalactic space and briefly discuss the origin and structure of the Universe. We will then turn to a series of tutorials in "Extragalactic Atlas Tutorial," where we discuss the issues specific to the Atlas. Finally, we present an overview of each data set in "Extragalactic Data Groups."

4.1 Extragalactic Atlas Overview

The Extragalactic Atlas has fewer groups than the Milky Way Atlas, mostly because there is less variety of objects outside galaxies than inside them—galaxies and quasars make up much of the data available for the Extragalactic Atlas. In the table below, we list these data groups along with a brief description and a reference to a detailed description. The order of the groups is the same as one finds in the Digital Universe.

Table 4.1 – Extragalactic Atlas data groups with brief descriptions. Refer to the associated page number for a detailed description of each group.

Group Name	See Page	Description
stars	169	The observed stars (on a fixed sphere)
constel	170	Constellation connectivity lines
mwVis	171	Visible all-sky survey
radec	172	Equatorial (RA/Dec) coordinates
galac	173	Galactic coordinates
galaxy	174	An image for the Milky Way
halo	175	The Galactic halo
local	176	Galaxies near the Milky Way
Tully	180	Tully Galaxy Catalog
isoDensity	183	Tully's smoothed density surfaces
2MASS	185	2MASS Galaxy Catalog
Abell	191	Abell galaxy clusters & nearby superclusters
2dFgals	193	The Two-Degree Field Galaxy Survey
SloanGals	196	The Sloan Digital Sky Galaxy Survey
2dFQSOs	198	The Two-Degree Field Quasar Survey
SloanQSOs	200	The Sloan Digital Sky Quasar Survey
wmap	201	WMAP all-sky survey (cosmic microwave background)
100kly	204	A 100,000-light-year grid centered on the Sun
1Mly	204	A 1-million-light-year grid centered on the Sun
10Mly	204	A 10-million-light-year grid centered on the Sun
100Mly	204	A 100-million-light-year grid centered on the Sun
1Gly	204	A 1-billion-light-year grid centered on the Sun
20Gly	204	A 20-billion-light-year grid centered on the Sun

In the following sections are a series of primers for those new to extragalactic astronomy. Addressing questions like, 'What is a galaxy or quasar?' or 'What is large-scale structure?', these sections will bring you up to speed on galaxies and cosmology.

If you know about galaxies, quasars, and cosmology, you can skip ahead to "Extragalactic Atlas Tutorial," where we explore these groups in the context of the Atlas and the Universe.

4.1.1 Galaxies

As we travel away from our Milky Way, objects in the Digital Universe become less familiar. This is partly because only three objects from the extragalactic realm are visible to the naked eye. In the Northern Hemisphere, the Andromeda Galaxy is visible as a blurry smudge in the night sky. In the Southern Hemisphere, the Large and Small Magellanic Clouds are prominent satellite galaxies visible as dim patches of light that resemble the band of the Milky Way.

Once telescopes were put to use scanning the skies, more faint smudges were seen. Even with a pair of binoculars we can see many extragalactic objects. But are they part of the Milky Way, or do they lie outside our Galaxy? We know the answer to that question today, but it was not until 1923, when Edwin Hubble estimated the distance to what was then called the Andromeda Nebula to be around 1 million light-years away (less than half its actual distance). Astronomers had determined the dimensions of the Milky Way only a few years prior, and this distance was well outside the Galaxy. This put to rest the cosmological debate between those who believed the Milky Way was the entire Universe and those who felt that there was a Universe outside our Galaxy. Hence the Andromeda Nebula was renamed the Andromeda Galaxy and extragalactic astronomy was born.

Astronomers find that galaxies come in a wide variety of shapes, sizes, and colors, from giant, red ellipticals shaped like a watermelon to bluer spirals like our Milky Way. Galaxies that do not fit the elliptical or spiral mold are deemed irregular. These are typically smaller and have bluer stars than spirals or ellipticals. There are even dwarf spiral and dwarf elliptical galaxies. The distinction between objects is not always clear—some astronomers believe a few of the Milky Way's globular clusters could be dwarf galaxies.

Despite this complexity, galaxies, including our Milky Way, have one thing in common: they are composed of stars. Some, like our Galaxy, have hundreds of billions of stars, while others have fewer,

less diverse stellar populations. Some have active, ongoing star formation, and others are relatively inactive, dead galaxies.

The variety of galactic shapes and colors was categorized by Hubble in the early 1930s. Formulating three main branches, Hubble identified elliptical galaxies (E0–E5, S0, SB0), spiral galaxies (Sa–Sd) and barred spiral galaxies (SBa–SBd), along with the separate group of irregular galaxies (Irr). Each has a range of types within the main branch (noted in parentheses) that refer to the shape or other observed attributes of the galaxy. For example, an E0 galaxy is rounder, while an E5 galaxy is oblong. An Sa galaxy has a large bulge with tightly wound spiral arms, while an Sd galaxy has a small bulge with looser arms.

The Milky Way is among roughly three dozen galaxies called the Local Group. Most of the galaxies in this group are small dwarf or irregular galaxies, with the exception of three spirals: Andromeda, the Milky Way, and M33, a face-on spiral in Triangulum. Andromeda is about 2.5 million light-years away (that's about 15,000,000,000,000,000,000 miles) and is the farthest object you can see without the use of binoculars or a telescope. Beyond these neighboring galaxies, it becomes difficult to see the individual stars that make up the galaxy, even with a telescope. Instead, astronomers see a smooth distribution of light, bright at the galactic core and dimming toward its edges.

Looking out to 100 million light-years, we begin to see how these galaxies are constructed to form our Universe. Galaxies do not appear to be haphazardly placed in the Universe. They are organized into clusters and superclusters. The Milky Way is in the Local Group, and the Local Group is part of the Virgo Supercluster. Galaxies also form in filaments, connecting galaxy clusters with strands of galaxies. Large voids occupy space like the inside of a bubble, where space is relatively empty. The clusters, superclusters, and filaments of galaxies are collectively referred to as the "large-scale structure" of the Universe, and astronomers have spent much of the past three decades coming to understand it.

4.1.2   Quasi-Stellar Objects (Quasars)

If you look at the Andromeda Galaxy tonight (assuming it's visible), you are looking at a galaxy that is 2.5 million light-years away. The light that reaches your eye left the galaxy 2.5 million years ago, so in a sense, you are looking at the galaxy when the Universe was 2.5 million years younger. That's a short time on cosmic scales, but what about the farthest objects we see that are billions of light-years away? At that distance, even galaxies become too dim to see easily.

In 1960, astronomers discovered mysterious, starlike objects that emitted radio waves. Previously, radio light was observed from clouds of gas or supernova remnants in our Galaxy, but this was the first instance in which radio light emanated from what astronomers thought was a star. Everything about the object was strange; even its spectrum was unrecognizable. Two years later, a second similar object was discovered, and in 1963 astronomers realized that they were looking at the familiar hydrogen spectral lines. But the lines were shifted toward the red end of the spectrum by 16%, the largest shift to the red that had been observed to date.

This shift of light into the red is called redshift, and it is a measure of the speed with which an object is moving away from us. Like a train whistle that changes pitch as the train pulls away from us, light is Doppler-shifted to the red (or blue) end of the spectrum if the object is moving away from (or coming toward) us.

Forty years later, astronomers have deduced that these quasi-stellar objects, or quasars, are just tremendously bright galaxies. The energy source responsible for this incredible luminosity is the heating and colliding of gas as it spirals into a supermassive black hole at the core. A quasar, then, is just a galaxy with a supermassive black hole at its core, generating immense amounts of energy hundreds of times more luminous than the Milky Way.

Just as we see a slightly earlier Universe when we look to Andromeda, we see a much younger Universe when we look at quasars, which lie billions of light-years away. Could the active quasars represent an era in the earlier Universe when all galaxies were more active and luminous? Astronomers are answering these questions as they study the origin of our Universe.

4.1.3   The Cosmic Microwave Background

Most objects in the Universe emit radiation that is proportional to the temperature of that object. This type of light is called blackbody radiation and is emitted by stars, galaxies, and the Universe itself. Even humans emit a blackbody spectrum. If you put on some night-vision goggles (ones that are tuned to the wavelengths in which humans glow), you see a glow around a relatively warm person with respect to the cooler surroundings. At our body temperature, we radiate most of our energy in the infrared. Stars, galaxies, and the Universe radiate much of their energy in different regions of the spectrum—see "Electromagnetic Spectrum" for more information.

In modern cosmology, the Big Bang Theory best describes the origins of the Universe. Briefly, the

theory suggests that origins of space and time, matter, and energy come from a time when the Universe was extremely hot and dense. About 13.7 billion years ago, the Universe exploded, forming space itself, which would later be populated with the galaxies we see today.

Very soon after the Big Bang, matter in the Universe was so hot that it formed a plasma, a state in which atoms are separated into nuclei and free electrons, similar to the Sun's interior. These free electrons prohibit the free flow of light in the Universe. The Universe was opaque to light in these early times. Later, as the Universe expanded and cooled, the electrons combined with the nuclei and formed hydrogen atoms. With few free electrons, light was now free to travel the Universe. This transition took place about 379,000 years after the Big Bang, ushering in a new era in the Universe.

The Universe was then transparent to light as photons, which traveled freely across the Universe, encountering few collisions that would absorb or scatter the light. If we could have seen it, the Universe would have been about 3,000 Kelvin and would have glowed orange in visible light. In fact, the peak intensity of the Universe at that time was around 1 micron (in the infrared). Since that time, the Universe has expanded 1,000-fold and the light waves have expanded along with space. The light, then, appears redshifted as space itself expands. Today, the peak intensity of the Universe is 1,000 times lower than it was then, so the wavelength is 1,000 times greater and is close to 1 millimeter
(1 micron $\times$ 1,000 = 1 mm). This peak intensity corresponds to a gas temperature 1,000 times less, or 3 Kelvin (3,000 K $\div$ 1,000 = 3 K). Light at 1 mm is in the microwave portion of the EM spectrum, and this is where we see the remnant light from the Big Bang, called the Cosmic Microwave Background radiation, or CMBR.

The CMBR pervades the Universe. It is an imprint of the time of recombination in the Universe, when protons and electrons combined to form hydrogen, when light began to travel in space unimpeded. When we look at that light, we are looking back in time to that event, 379,000 years after the Big Bang. Before that time, the Universe was opaque, like looking through a fog, so we will never see the Big Bang event itself.

The CMBR, then, defines that part of the Universe that we can see, what we call our *Observable Universe.* While the CMBR is everywhere in the Universe, we can also think of it as our outer limit, that which we cannot see beyond.

The best observations of the CMBR come from the Wilkinson Microwave Anisotropy Probe (learn more about this space telescope in the "Microwave (WMAP) All-Sky Survey" section). The image is a snapshot, a baby picture if you will, of the early Universe, tracing out the farthest reaches of the

observable Universe. It shows the minute variations in temperature that were present in the Universe during that early era. These temperature variations are on the order of millionths of degrees around the average temperature of 2.725 Kelvin. In the next section, we will see just how important these minute fluctuations are in determining the structure and evolution of the Universe.

4.1.4 Cosmological Structure Formation

The minute temperature fluctuations in the CMBR are directly responsible for the complex large-scale structure in today's Universe. Scientists are still on the quest toward understanding how these small fluctuations evolve into the galaxy clusters and filaments we see today.

The temperature fluctuations in the WMAP may be thought of as density fluctuations in the early Universe. These slight differences in density become amplified by gravity. Regions that are more dense, even by tiny amounts, will gradually collapse because of this excess gravity. This process, called gravitational instability, worked slowly over billions of years until galaxies formed. Those galaxies are now hundreds of times denser than the nearly empty space that surrounds them.

In addition to galaxy-sized objects, this process gave rise to clusters and filamentary strands of galaxies. The structure of the Universe is akin to human settlement in the world. We settle in towns of various sizes (a galaxy) and these towns often cluster around each other (a galaxy cluster). Connecting these towns are trails, rivers, and highways, along which smaller towns or groups of towns are found (galaxy filaments).

While galaxy groups and clusters are gravitationally bound systems such that no galaxy can escape, superclusters have not yet settled into this state. In our analogy, this would be similar to the major cities in the Northeast United States. From Washington, D.C., to New York, one can travel from town to town almost without leaving an urban area. Interstate 95 connects them all as one area. But this urban region has not yet merged into one large megalopolis, just as a supercluster has not yet become gravitationally bound.

4.1.5 The Distance Scale

The Universe has been expanding continuously, although not linearly, since the Big Bang, about 13.7 billion years ago. Its expansion gradually slowed because of the total gravity of matter in the Universe. However, it was recently discovered that during the past few billion years the expansion has

increased. This acceleration is attributed to something astronomers call *dark energy.* Dark energy is the mysterious force that is causing the expansion of the Universe to speed up, overcoming the force of gravity.

In 1998, astronomers looked at Type Ia supernovae—exploding stars with predictable brightness—and found that supernovae observed in distant galaxies were dimmer than they should have been, meaning they are farther than predicted and the Universe must be expanding faster than previously thought. Astronomers don't know what dark energy is, but they do know some force is overcoming the gravitational pull within the Universe, speeding up its rate of expansion.

For the Digital Universe, we use this information to compute distances to the galaxies and quasars in the Extragalactic Atlas. This provides you with the size and scale of the Universe at the present epoch. This distance scheme sets the scale of the Universe so that the quasars can be found past 20 billion light-years, while the CMBR is fixed to a sphere with a radius of 42 billion light-years. Of course, these objects were much closer when their light left. If we plotted the Universe according to where an object's light left from, then the CMBR would be 13.7 billion light-years away. However, we have opted to plot the Universe at its current state, lending reality to the Atlas and one's impression of the Universe.

4.2   Extragalactic Atlas Tutorial

While the topics of astrophysics and cosmology are more complex in the extragalactic realm, the tutorials are less elaborate than those in the Milky Way Atlas. The homogeneity of the data at this scale, where we are limited to discussing galaxies as single objects, puts constrains on the types of data sets we have, as opposed to the zoo of objects one finds in the Milky Way.

Our tutorials will take you on a journey from the Galactic neighborhood out to the edge of our observable Universe. Along the way, we will discuss scale and structure in the Universe. Let's start by exploring our Galactic backyard.

4.2.1   Tutorial: The Galactic Neighborhood

Goals: Explore the Milky Way's nearest neighboring galaxies.

Before starting, turn on: `galaxy`, `local`

You will be using: cb command

In our first tutorial, you will explore the Galactic neighborhood, discovering what lies outside our Galaxy and how these objects are arranged around us. Let's launch the Extragalactic Atlas and begin exploring.

Starting from Home   Upon launching the Atlas, you are just outside the Milky Way looking back on our home Galaxy. The image you see beside the Home label is not our Milky Way but NGC 1232, a galaxy that is believed to resemble the Milky Way.

Barely detectable from this distance is the Point of Interest marker, the multicolored Cartesian axes that mark the location of the Sun and its planets within our Galaxy. Each half-width is 1,500 light-years, about the distance to the Orion Nebula. You may have to fly in closer to see the axes clearly.

Begin by slowly orbiting this point where the Sun is located. You will notice some nearby galaxies with large labels and other, more distant galaxies that appear as green points. Focus on those near the Milky Way. At Partiview's Command Line, type

```
cb on
```

to temporarily remove the more distant galaxies.

Our Nearest Neighbor   The nearest object to the Milky Way was discovered in 1994. The Sagittarius galaxy is represented by a point, but this belies the nature of this mysterious object.

You may have figured out that the object is called Sagittarius because it is seen in that constellation in the night sky. However, parts of this galaxy have been seen on both sides of the Galactic disk. So representing it with one point is really not too accurate.

The Sagittarius is a dwarf spheroidal galaxy that has been stretched and warped by our Milky Way. A dwarf spheroidal (dSph) galaxy appears as a smudge on the sky in even the largest telescopes. With a low star density, these galaxies often resemble star clusters rather than galaxies. The first dSph, Sculptor, was discovered in 1938 by Harlow Shapley.

Astronomers have come to realize that galaxies interact with one another more often than once thought. The Sagittarius dSph is in fact in the midst of an interaction. As it orbits our Milky Way, our Galaxy slowly rips the Sagittarius dSph apart, stripping away streams of stars on each pass near the Milky Way's disk. The same thing once happened with two other nearby companions, the Large and Small Magellanic Clouds.

The Magellanic Clouds   The Magellanic Clouds (labeled `LMC` and `SMC` for Large and Small), are irregular galaxies. They do not fit into the spiral or elliptical classes observed by Hubble and published in *The Realm of the Nebulae* in 1936. Galaxies that were outside these two common types were called irregular. These are seen in the southern sky and appear as two isolated patches of faint light, similar in appearance to the light in the band of the Milky Way as seen from Earth.

They are actually small galaxies that contain star formation, globular clusters, and the famous supernova of 1987 (in the LMC). These two galaxies are likely in the process of colliding with our Milky Way. Because our Milky Way is far more massive than either of these galaxies, they have been ripped apart by our more dominant Galaxy. Astronomers may even see a trail of gas connecting the two galaxies, but this remains uncertain.

All the galaxies in this clip box are dwarf spheroidals except the Milky Way, which is a large spiral, and the LMC and SMC, which are irregulars. What lies beyond, though?

The Local Group   Pull out farther so that you see the entire clip box, then turn the clip box off by typing

```
cb off
```

at the Command Line. Turn on another box (the non-clipping variety) by pressing the Box Toggle Button. This box surrounds the galaxies of the Local Group. The Milky Way is at the center of this box, and it now encompasses another grouping of galaxies. If you inspect this group, you will find it surrounds the Andromeda Galaxy (M31).

Similar to the Milky Way, Andromeda commands attention from its smaller, nearby companions. At 2.3 million light-years, Andromeda is the largest galaxy we've seen thus far, just slightly larger than the Milky Way, and is the king of the hill among Local Group galaxies. It is the farthest object we can see with our unaided eye in a dark sky.

Like the Milky Way grouping, most of the galaxies around Andromeda are smaller dwarf spheroidals or dwarf ellipticals. One exception, M33, is the other spiral galaxy in the Local Group.

All the galaxies in this box are part of a group of galaxies that interact with one another under the group's mutual gravity. Many of the nearby galaxies are interacting with the Milky Way, but Andromeda is also on a collision course. In 3 billion to 5 billion years, the two galaxies will collide. By then, our Sun will be in its late stages, expanding its envelope as it evolves into a white dwarf star.

4.2.2   Tutorial: The Local Universe

Goals: Understand the distribution of galaxies around the Local Group.

Before starting, turn on: `galaxy`, `local`

You will be using: $only=$ and $thresh$ commands

If you're continuing from the previous tutorial, go to the next paragraph. If you're starting a new session, once the Extragalactic Atlas is up, pull away so that you can see all the data in the local galaxies (`local`) and turn on the boxes to see the Local Group.

Exploring the entire data set, you may notice that most of the galaxies are in bunches about the size of the Local Group. These bunches typically have a large spiral or elliptical galaxy that attracts smaller galaxies.

Galactic Census   How many galaxies like the Milky Way are in the neighborhood? If you threshold the data according to type, you can see. A report on the Milky Way (place the mouse over the Milky Way and press the p key) reveals that it has a type of 5. According to the table in "Local Galaxies," this corresponds to an Sc spiral galaxy. Sc galaxies have small central bulges and loosely wound spiral arms. To see these galaxies in the data, type the command

```
only= type 5
```

Only eight galaxies remain and only two in the Local Group. Andromeda is an Sb type, having a larger central bulge and a tighter arm structure (there are three Sb galaxies). To see all the spirals, type the command

```
thresh type 1 8
```

Still only 48 galaxies out of about 250, amounting to 19% of the data. In this way, you can perform a census on the data and visually explore the results in the Galaxy Morphology Codes table.

The Brightest Galaxies   Now let's see the most luminous galaxies. Type the command

```
thresh lum 0.5 6
```

The `lum` data variable ranges from 0 to 5.7, with an average of 0.177. So with this statement, you are looking at the brightest galaxies. As you might expect, intrinsically bright galaxies are fewer in number

than dimmer ones. Only 11 galaxies are bright enough to make this cut. They include the Milky Way, Andromeda, M33, M81, and the giant elliptical Centaurus A. Within a galaxy, the luminous stars are few and far between compared with the number of dimmer stars. Galaxies appear to follow this trend, as most of the nearby galaxies have low luminosities.

This picture of the nearby galaxies is the best science has to offer. Of course, there are many small, dimmer galaxies that we cannot see, even in our own backyard. Let's look at other galaxy surveys that map galaxies out to greater distances.

4.2.3 Tutorial: Local Large-Scale Structure

Goals: Explore the local structure of the Universe.

Before starting, turn on: `galaxy`, `local`, `Tully`

You will be using: clipbox, polysize commands

In the previous sections, we described the Local Group of galaxies and the groups of galaxies that surround the Local Group. Now you will explore the structure of the local Universe and see what lies beyond the surrounding galaxy groups.

Fly out of the local galaxies (`local`) and turn on the Tully Galaxy Catalog (`Tully`). Tully's multicolored points now occupy the rest of your view. Look only at the nearest galaxies by setting a clip box for these data. Run the command

```
clipbox 0,0,0 30,30,30
```

This shows only the galaxies within 30 megaparsecs, about 100 light-years. Now fly outside of this box so that you have a view of the entire data set. Brighten the galaxies if necessary.

The most dominant feature is the dense red cluster near the center. Fly to this galaxy cluster. This dense cluster could be considered "downtown" for our region of the Universe, the center of our local supercluster. This is the Virgo Cluster.

The Virgo Cluster   Sixteen of Messier's galaxies are members of the Virgo Cluster, but this is a mere fraction of Virgo's 2,000-plus galaxies. While it is about 50 million light-years away, the immense gravity of the cluster affects our Local Group galaxies and pulls other galaxies toward it.

Now turn off the points and labels and turn off the `local` data group. If you fly right into the cluster, you may notice the faint glow of a few bright galaxies. In fact, the Tully Catalog has images placed on each point that represents the type of galaxy it is. These images are given the proper size and orientation, and the luminosity of the points is accurate. If you wish to see these images more prominently, increase their polysize. Because their slum value is fixed according to the galaxy's size, you will have to use the polysize command to increase the size of the polygons. Choose `polysize` from the Slider Menu and adjust the slider to your liking.

Turn on the labels for the Tully data set. You may see labels like M31, which refer to the Messier Catalog, or NGC 4429, which refer to the New General Catalog. At the center of the Virgo Cluster is M87, a massive elliptical galaxy extending out more than half a million light-years. Its most peculiar feature is the long, knotty jet of material streaming out from its center.

Reduce the polysize back to normal (the Polysize Slider should be at its left-most setting) and turn the points back on. If you orbit the Milky Way with the Virgo Cluster in sight, you will notice a stream of light-blue galaxies extending up toward the Virgo Cluster. This is the Ursa Major filament that, in the 2-D sky, traces a path from the constellation Virgo up to Ursa Major.

The scientist who compiled these data sets into one consistent catalog, Brent Tully of the Institute for Astronomy in Hawaii, color-coded the galaxies according to a group membership. All galaxies belonging to dense clusters are red, while the galaxies in the Local Group and other nearby groups are green. Galaxies belonging to the Ursa Major Filament are light blue.

Many more clusters, filaments, and spurs are out there. Within this 100-light-year box are more than 6,800 galaxies. Let's look at the entire data set by typing

```
cb off
```

removing the clip box and revealing the remaining 20,000 or so galaxies. We discuss this larger view of the Universe in the next section.

4.2.4 Tutorial: Tully's Nearby Galaxies

Goals: Discuss the structure of the nearby Universe.

Before starting, turn on: galaxy, local, Tully

You will be using: see command

Beyond those local features like the Virgo Cluster and the Ursa Major Filament, the Tully galaxies reveal the grand structure of the nearby Universe. Fly to the outer edge of the data and orbit. From this view, you will see the major structural elements: clusters, filaments, and voids.

Before we begin, let's first discuss the shape of these data. If you are orbiting far enough away, you will notice that the data appear to form a cube. In fact, they are confined to a cube. This is an artificial boundary that samples data within about 150 million light-years of the Milky Way.

Following from the previous tutorial, the colors are randomly assigned to a structural element, except for red, which is assigned to dense clusters. Within this cube are about 30,000 galaxies that cover a range of 300 million light-years. The Milky Way lies at the center of this observed data set.

Dense Clusters   As with many phenomena in nature, it is common to find galaxies in clusters. Some are small, loose agglomerations of galaxies, while others are massive, dense clusters of thousands of galaxies. Let's examine the dense clusters by typing

```
see abell
```

at the Command Line. Now you should see the green points, which represent the `local` data group, and the dense, red clusters of galaxies surrounding us. Virgo is the closest, at about 50 million light-years, but many more are present in this data set. Often these clusters do not have an accurate number of galaxies within them. The see command tells us that there are about 1,700 galaxies showing; however, we know the Virgo Cluster alone has more than 2,000 galaxies.

Filaments and Voids   The other structures one sees in the nearby Universe are the filaments and voids. Filaments are strings of galaxies that often connect larger clusters. We discussed the Ursa Major Filament in the previous tutorial, and now we see that Virgo and the Ursa Major Filament are part of a large network of clusters and connecting filaments.

Follow the Ursa Major Filament up to the Virgo Cluster and beyond, to another red cluster of galaxies. This is Abell 3526, located in the constellation Centaurus in our 2-D sky. Looser than Virgo, it seems to have a yellow line of galaxies extend over to it. These lead to the Antlia Cluster, at which point the yellow galaxies seem to take a right turn, where the filament connects up to another group of galaxies.

The yellow strands of galaxies define an edge, inside of which you see few galaxies until the aqua

strand that seems to connect with the Virgo Cluster on the opposite side of Ursa Major. That large area where few galaxies are found is like the inside of a bubble. These regions of few large galaxies are called voids. The overall density of these regions is low relative to that of the galaxy-rich filaments. However, there are likely small dwarf galaxies that we cannot see in these regions.

The local Universe seems to resemble a bubblelike form, where filaments of galaxies reside on the bubble surface and vast voids exist between them. These filaments connect large clusters of galaxies and make larger superclusters.

4.2.5   Tutorial: The 2MASS Galaxies

Goals: Investigate the structure of the nearby Universe using 2MASS; Learn to manipulate the enormous 2MASS data group.

Before starting, turn on: `galaxy`, `Tully`

You will be using: 2MASS, `galac`, see, thresh, color, and lum commands

Adding to our knowledge of the nearby Universe, the Two Micron All Sky Survey (2MASS) has recently released the most complete picture of our cosmic surroundings. The data set consists of whopping 1.14 million galaxies within about 2 billion light-years. Let's explore what this data group reveals about the structure of the Universe.

Press the Home Button. You should be looking at the Milky Way with the `Tully` Virgo Cluster in the background. Turn off `Tully` and turn on the 2MASS group.

In the previous tutorial we introduced the elements of structure in the Universe: galaxies, filaments, and voids. With the 2MASS galaxy data, you see a more complete picture of the local Universe than what you see in the `Tully` group. In fact, within the same volume, 2MASS contains 32% more galaxies than `Tully`.

From your current view, you should see the Virgo Cluster and strands of multi-colored points. Like `Tully`, those galaxies in dense clusters are given the color red, but, unlike `Tully`, color in 2MASS describes galaxy density rather than the randomly assigned colors Tully assigned to filaments. In 2MASS, red regions have the highest density, followed by orange, yellow, green, and aqua for the lowest density regions.

Fly backward (Home and Virgo should move away from you) until you see the Fornax Cluster, then orbit from that point. We've lost the Milky Way, so turn on the galactic coordinates sphere (`galac`) to

mark from where we came. You should see the large labels delineating the Virgo Cluster, Fornax Cluster, and you may possibly see the Centaurus and Hydra Clusters too. These are the nearest galaxy clusters to Earth.

Continue moving away from the Milky Way to see the entire data set, then adjust the brightness so the structure of the Universe pops out—the red clusters, orange and yellow filaments, out to the faint blue galaxies. From this vantage point, let's orbit around the Milky Way. (You will need to adjust the brightness of these data using the Slum Slider throughout this tutorial.)

Seeing the Forest Through the Trees   First, let's see the entire 2MASS data set so we know what this picture really looks like without filtering. Type

```
see all
```

and all 1,140,931 galaxies are displayed. Here you have a sense of just how dense the Universe is. And, 2MASS only observed relatively bright galaxies. With this view, we no longer see the structure of the Universe so easily. To return to our filtered view showing the large-scale structure, type

```
see lss
```

The Proximity Factor   The lss selection is set using a data variable called the proximity factor. The 2MASS data come with two proximity factors, one for $R = 2$ Mpc and one for $R = 5$ Mpc (Mpc means megaparsecs with 1 Mpc = 1,000,000 pc and 1 pc = 3.26 light-years). These factors describe the density of space around a particular galaxy. Specifically, the $R = 2$ Mpc and $R = 5$ Mpc factors, called prox2 and prox5, respectively, are high when there are many galaxies within the specified radius, and they are low when a galaxy is by itself in space.

The sheer number and density of galaxies in 2MASS demands that we use creative ways to view these data. By default, we use the lss selection set in the extragalactic.cf file with the command only= prox5 > 0.7. This command tells Partiview to display only those galaxies with prox5 > 0.7, resulting in only 15% of total number shown. Removing 85% of the data may not seem logical, but allows us to see structure.

Dense Clusters   We have also defined a selection expression to display the dense clusters. Type the command

<pre><code>see clusters</code></pre>

and you will see the most dense regions of the nearby Universe. This selection is defined using the `prox2` proximity factor in the command `thresh prox2 1.3 3`. Increase the label size to see the names of these clusters. Type `see lss` to return to the normal view.

Color Schemes   Type `color` and Partiview will report that colors are mapped to these galaxies using the `prox5` data variable. We have defined a color map file and several color schemes to highlight various aspects of these data.

First, and most obvious, we can view the galaxies at a constant color. Type

<pre><code>color const</code></pre>

and the galaxies will change to an aqua color. Sometimes, a constant color is good for seeing structure and puts all the galaxies on common ground. Of course, you can change this constant color to any red-green-blue values you like, for example, make the points gray by typing

<pre><code>color const .5 .5 .5</code></pre>

The galaxies may also be colored by distance using either

<pre><code>color distMly</code></pre>

or

<pre><code>color redshift</code></pre>

These set the innermost galaxies to aqua, then continues to green, yellow, orange, and red for the farthest galaxies.

Coloring by proximity is the best way to highlight structure in the data set. The default color for the data group is

<pre><code>color prox5</code></pre>

which, as mentioned above, sets the color of each point based on the $R = 5\,\mathrm{Mpc}$ proximity factor. We have also defined a similar color map for the `prox2` proximity factor

```
color prox2
```

Both of these show dense regions in red, then, as the density decreases, the colors change to orange, yellow, green, and aqua.

Luminosity Settings   Normally, the 2MASS galaxies are given a constant luminosity, which is to say all points are given an equal intrinsic brightness. Of course, the actual brightness you see in Partiview is a function of the galaxy's intrinsic brightness plus your distance from that galaxy.

If you want to highlight the structure a little, you can assign luminosity as a function of the proximity value, so higher values of `prox5` will have a higher intrinsic luminosity. We have preset such a scenario which you can see by typing

```
lum prox5
```

After issuing this command, you may see the galaxies go dim or bright; just adjust the Slum Slider (remember, each **lum** setting has its own **slum** value). This **lum** setting pumps up the brightness just a tad on the clusters and filaments so that they stand out a little. Return to the default constant luminosity with

```
lum const
```

so that all galaxies have equal intrinsic brightness.

The 2MASS galaxies have given us a comprehensive look at the structure of the nearby Universe. Next, we'll explore galaxy clusters more closely and take a look at the nearest superclusters.

4.2.6   Tutorial: Galaxy Clusters and Superclusters

Goals: Observe the distribution of galaxy clusters and superclusters

Before starting, turn on: galaxy, Tully

You will be using: Abell, see command, censize command, 1Gly

Let's begin this tutorial by looking at the entire Tully galaxy catalog. Fly outside the Tully data set so you can see the entire cube; you may need to brighten up the data set.

Now, type the command

```
see abell
```

to remove all the Tully galaxies except those inside dense clusters. These clusters are called Abell clusters after George Abell (1927–1983), who first cataloged them. Now you are left with a few dozen galaxy clusters that contain red-colored galaxies. Turn up the center size using the Censize Slider so that we know where the Milky Way is.

Turn on the `Abell` data group. Each point in this data group represents a cluster of galaxies. Some points may represent tens of galaxies, others may stand in for hundreds or even thousands of galaxies.

The first thing you should do is turn off the labels, you won't need them yet. Notice that those red clusters from `Tully` now are accompanied by a single point in `Abell`. Pull out to see the entire data set and turn on the `1Gly` group for scale.

As you orbit the Milky Way, you will see immediately that, unlike `Tully`, the `Abell` clusters do not readily show large-scale structure. In fact, the galaxy clusters do not appear to cluster or form connecting filaments with one another. However, some of the Abell clusters are grouped, and these groupings are indicated by the various non-gray points and the labels (turn on the labels now).

The color of the points represents their membership in superclusters. A supercluster is a cluster of galaxy clusters. By now, you know that the Virgo Cluster is the nearest galaxy cluster to the Milky Way. It's about 60 million light-years away, 15 million light-years in diameter, and contains over 1,000 galaxies. A supercluster contains many galaxy clusters and is on the order of 300 million light-years across.

Those galaxy clusters with a color other than gray are considered to be members of a supercluster. Let's filter the data set to see these clusters on their own. `Abell` has a data variable attached to it called `notable` (that's "notable", not "no table"). If `notable = 1`, then the galaxy cluster is part of a supercluster. So, use the **only=** command to see these notable galaxy clusters by typing

```
only= notable 1
```

(note: there is no space between the word "only" and the equal sign.)

Now you see the largest superclusters around our Local Supercluster, which is also called the Virgo Supercluster. Most of these superclusters are named for the constellations they appear in. Our supercluster contains the mighty Virgo Cluster and many other smaller groups such as the Ursa Major Group, the M51 Group, the M81 Group, and our group, the Local Group, among others. Now you see similar systems in the Universe, representing at least hundreds of thousands of galaxies.

Bring back all the Abell clusters by typing `see all`. The gray points, which are the majority of points, are not connected to any major supercluster, but remain as a nexus between the filaments and galaxies that must be present, but remain invisible in these data sets.

Next, we explore two partial galaxy surveys, the Two Degree Field Survey and the Sloan Digital Sky Survey.

4.2.7   Tutorial: Galaxy Surveys

Goals: Understand the extragalactic data from Earth's perspective; begin exploring the 2dF and Sloan galaxies.

Before starting, turn on: `galaxy`, `stars`, `constel`, `mwVis`, `galac`

You will be using: `2dFgals`, `SloanGals`, `1Gly`, `20Gly`

If you're continuing from a previous tutorial, quit Partiview and restart the Extragalactic Atlas for a fresh start. Once the Atlas appears, turn off the `local` group. You should be left with the Point of Interest marker. Fly toward it until it disappears. Now you should see nothing.

We're first going to look at these surveys from Earth. Turn on the `stars`, `constel`, `mwVis`, and the `galac` groups so that you see the stars, constellations, visible all-sky image, and the constellations for reference.

Viewing Galaxy Surveys from Earth   Turn on the 2dF Galaxy Redshift Survey (`2dFgals`). As you pan around the sky, you will see one strip of yellow toward the northern Galactic latitudes and another strip surrounded by circular patches in the south Galactic polar region. Each of these patches of galaxies shows the actual telescope footprint on the sky. If you look at each closely, you will see they are two degrees wide and contain many galaxies.

Now turn on the `SloanGals` group to see the Sloan Digital Sky Survey galaxies. You will see more coverage on the sky, particularly in the northern Galactic hemisphere. These are two major galaxy surveys that astronomers have completed. As you can see, they cover only a portion of the entire sky, often in narrow strips.

Now turn off the Sloan galaxies so that you're left with only the 2dF survey. Position yourself so you're looking toward the random fields (circular patches) in the south Galactic pole. Begin flying away and, as you do, notice the random fields appear to be pulled in toward the Milky Way. You may also

notice that the stars, Milky Way all-sky, constellations, and coordinates all lie on a fixed sphere. Because the distance to the stars would be extremely small on this scale (megaparsecs), we placed the stars and related data groups on a fixed sphere with a radius of 1 Mpc (1 million parsecs).

Flying Away from Earth   As you pull back, you'll be out of the data set in no time. Once you see most of the galaxies, stop and orbit.

From out here, you can see the large-scale structure of the Universe: dense clusters of galaxies connected by strands of galaxies, and areas where there are fewer galaxies, called voids. Turn on the 1-billion-light-year grid, `1Gly`, and the 20-billion-light-year grid, `20Gly`, to see the scale of these galaxies. The random pointings now appear as pencil beams that extend out billions of light-years from the Milky Way.

The bow-tie shape of these data indicates the patches of sky that were surveyed. Imagine if the entire sky were surveyed, you would see similar data surrounding the Milky Way in a spherical distribution. The Sloan Digital Sky Survey's original goals were to do just that. Let's turn the `SloanGals` back on and see them in 3-D.

You may want to adjust their brightness using the Slum Slider. The Sloan galaxies also show the large-scale structure, that pattern of clusters, filaments, and voids. This is the structure of the local Universe. Remember, for a galaxy 3 billion light-years away, the light traveled for about 3 billion years to reach the lens of the observing telescope. Does the evolution of the Universe affect this view? How far do you have to look before the large-scale structure you see currently is nonexistent or is in an unrecognizable phase?

We will continue exploring these questions in subsequent tutorials. For this scale, we are still looking at objects generally in the same cosmic era. Yes, when we look at a galaxy 3 billion light-years away, we're seeing it as it was 3 billion years ago. However, this is a relatively short time, cosmically. Next we'll discuss quasars, objects that we see at greater distances.

4.2.8   Tutorial: Quasar Surveys

Goals: Explore the characteristics of the quasar surveys.

Before starting, turn on: `2dFgals`

You will be using: `2dFQSOs`, `SloanQSOs`, `20Gly`, `alpha` command

As we look farther out into space, we are looking further back in time. Quasars are the farthest objects we see. The nearest quasar is 1 billion light-years, but most are more than 10 billion light-years away. Reflecting a greater abundance at an earlier time in the Universe, quasars provide evidence that we live in an evolving Universe where objects change over time.

What Is a Quasar?   Quasars are violent, extremely luminous galaxies. There are many types of active galaxies (Seyfert galaxies and radio galaxies for two), but quasars trump them all in power and brightness. The light we see from a quasar is from synchrotron radiation and occurs from electrons moving close to the speed of light in a strong magnetic field.

Quasar Distribution   Let's look at some quasars in the Atlas. Begin from a vantage point where you see all the 2dF galaxies. If you're continuing from the previous tutorial, then you should be set if group `2dFgals` is on.

As we mentioned in the previous tutorial, the 2dF galaxies extend to about 3 billion light-years and the bow-tie shape of these data reflects those parts of the sky that were observed by the telescope.

Now turn on the 2dF Survey quasars (`2dFQSOs`). As you can see, they appear like a natural extension to the galaxy survey. Nearby, there seems to be less density and the number of quasars increases as the distance increases toward their average distance of 13.4 billion light-years. By about 15 billion to 20 billion light-years, the density of quasars begins to fall off. This fall-off is due to the limiting magnitude of the telescopes—their cut-off is set by brightness, typically around 20th magnitude—and objects dimmer than this will not be detected.

Turn off the 2dF quasars and turn on the Sloan Digital Sky Survey quasars (`SloanQSOs`). If you turn on the 20-billion-light-year grid, `20Gly`, you can see that these quasars have the same properties as those in 2dF. If you want to see the grid throughout the data, you can make it completely opaque by increasing its `alpha` value to 1. We like the grids semitransparent, though, so they don't dominate the scene.

While quasars are the farthest objects we can see, there is light from an earlier epoch that pervades the Universe, called the cosmic microwave background. We will discuss this light in the next tutorial.

4.2.9   Tutorial: Edge of the Observable Universe

Goals: View the cosmic microwave background radiation in context with the quasars.

Before starting, turn on: `galaxy`, `local`, `SloanQSOs`, `20Gly`

You will be using: `wmap`

The Cosmic Microwave Background Radiation   Astronomers believe that the Universe was born from the Big Bang, when space expanded from an extremely hot and dense condition. You might imagine that this event was spectacular in its energy and luminosity output. If we think quasars are bright, the creation of the Universe must have been incredible. Given that, wouldn't you expect to see something from this energetic event?

In fact, astronomers do see the light from just after the Big Bang. At that time, the Universe was very hot, so hot that atoms could not form. Instead, there were free electrons and protons and neutrons that made up the primordial Universe. Light could not travel very far before it collided with a free electron. Thus we say the Universe was opaque, as radiation and matter were constantly interacting. As the Universe expanded, the temperature of the plasma dropped and, after 379,000 years, the Universe was cool enough to allow electrons and protons to combine, forming hydrogen atoms. Once this occurred, the light from the Big Bang was free to traverse the Universe, since the free electrons were captured by atomic nuclei.

Bring up the Extragalactic Atlas and load the `galaxy`, `local`, `SloanQSOs`, and the `20Gly` data groups. Now fly away from the Milky Way but remain within the quasar data, somewhere around 15 billion light-years away.

The WMAP All-Sky Survey   From this perspective, turn on the `wmap` group and begin orbiting the Milky Way [see "Microwave (WMAP) All-Sky Survey" for information on the WMAP image]. The image is a false-color mapping of the tiny temperature fluctuations in the microwave light: red for the warmer regions, blue for the cooler regions. These minute differences represent temperature fluctuations in the primordial Universe. While the Universe was remarkably uniform in temperature at 379,000 years old, the seeds of structure were present. These seeds would one day grow to become the galaxy clusters and large-scale structure we see in the nearby Universe.

Astronomers do not yet understand what happened in the Universe between that point and now. How structure formed remains a topic at the forefront of science.

Our Observable Universe   This is the entire observable Universe for Earthlings. We have seen in these tutorials that the local Universe consists of galaxies, galaxy clusters, and superclusters of galaxies. These elements are the wave crests in the large-scale structure of the Universe. Between these galaxy-rich strands are voids, where we see a lack of bright objects. Deeper into space, we look to earlier epochs in the Universe where we see quasars, early forms of galaxies with active cores perhaps from the continual interaction between galaxies in the early Universe. Beyond, we see the light left over from the Big Bang itself, this cosmic microwave background.

4.3 Extragalactic Data Groups

In this section you'll find a dossier on each data group in the Extragalactic Atlas. Each profile will have a listing of the data files, their sources, and the data variables associated with each group. For data groups that also appear in the Milky Way Atlas, we will refer you to those previous sections rather than reiterate them here.

4.3.1 AMNH Fixed Stars

Group Name	`stars`
Reference	Hipparcos, the New Reduction (van Leeuwen, 2007) The Hipparcos and Tycho Catalogues (ESA 1997) Third Catalogue of Nearby Stars (Preliminary) (Gliese+ 1991)
Prepared by	Ron Drimmel (University of Torino, Italy) Brian Abbott (AMNH/Hayden) Carter Emmart (AMNH/Hayden) Stuart Levy (NCSA/UIUC) James Adams (AMNH/Hayden)
Labels	Yes
Files	`stars.speck, stars.label`
Dependencies	`halo.sgi, colorbv.cmap`
Census	24,676 stars, 226 labels

The stars appear in the Extragalactic Atlas to provide us with a familiar context within the extragalactic data. With the stars, we can go back to a night-sky view and see where particular galaxies are located relative to the stars we see in the sky.

In the Extragalactic Atlas, we place the stars at a fixed distance of 1 megaparsec from the Milky Way. From the Point of Interest, the stars take on their proper night-sky appearance, but they are all 3.26 million light-years from the Sun's position in the Extragalactic Atlas.

A detailed description of the stars may be found in "AMNH Stars" in the Milky Way Atlas, where the stars are properly placed in three-dimensional space.

4.3.2 Constellations

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

In the Extragalactic Atlas, we provide the constellation lines along with the stars for night-sky context. They, too, are fixed on the 1 Mpc sphere and have a single color (unlike the Milky Way Atlas). For a full description of these lines and their meaning, please refer to "Constellation Connectivity Lines" in the Milky Way Atlas.

4.3.3 Visible All-Sky Survey

Group Name	`mwVis`
Reference	Axel Mellinger (Universitaet Potsdam)
Prepared by	Ryan Wyatt (AMNH/Hayden)
Labels	No
Files	`mw-visible.speck`
Dependencies	`mellinger-optmw.sgi`
Wavelength	400 nm − 700 nm
Frequency	750,000 GHz − 430,000 GHz

The visible Milky Way shows the Milky Way Galaxy from Earth's perspective, our night-sky view. This all-sky image shows the gas and dust visible to us from our own Galaxy.

Because we cover this image in greater detail in the Milky Way Atlas, we will forgo discussing it here. Instead, we will refer you to "Visible All-Sky Survey" for a thorough description of the image.

Like the objects in the Milky Way Atlas, the all-sky images in the Extragalactic Atlas are placed at a fixed distance. Of course, the Extragalactic Atlas's megaparsec scale is much larger than that of the Milky Way Atlas's parsec scale. You may recall in the Milky Way Atlas that the visible all-sky image is placed at an arbitrary distance of 1,000 parsecs (or 3,260 light-years). In the Extragalactic Atlas, we place the all-sky image on a sphere with a radius of 1 Mpc, or 3.26 million light-years. This distance corresponds with that of the `stars` group, `constel` group, and the coordinate spheres.

4.3.4   Equatorial Coordinates

Group Name	radec
Reference	—
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes
Files	radec.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. A detailed description of the equatorial coordinates can be found in "Equatorial Coordinates Sphere" in the Milky Way Atlas.

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.

4.3.5 Galactic Coordinates

Group Name	galac
Reference	—
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	Yes
Files	galac.speck
Dependencies	none

The Galactic coordinates are similar to the equatorial coordinates in that they are provided in the Extragalactic Atlas for context. The fundamental plane of the system is defined by the Milky Way's disk, acting as the Galactic equator in our sky. The Galactic poles point directly out of the plane of the Galaxy. For more information, see "Galactic Coordinates Sphere."

4.3.6 Galaxy Image

Group Name	galaxy
Reference	European Space Agency
Prepared by	Carter Emmart (AMNH/Hayden)
Labels	No
Files	mwpoly.speck
Dependencies	ngc1232.sgi

We use an image of the galaxy NGC 1232 to represent the Milky Way Galaxy in the Extragalactic Atlas. Since we cannot see the Galaxy from the outside, astronomers must make some assumptions about what it looks like. Many scientists agree that NGC 1232 is a good representation for the Milky Way. For more information on this data group, please see "Galaxy Image" in the Milky Way Atlas section of this guide.

4.3.7 Milky Way Halo

Group Name	`halo`
Reference	Merrifield, M. & Binney, J. 1998, *Galactic Astronomy* (Princeton: Princeton University Press)
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	No
Files	`halo.speck`
Dependencies	none

The Milky Way is surrounded by a large, spherical halo. The most prominent objects in this halo are the globular clusters (`gc`), the bright, compact star clusters of hundreds of thousands of stars. The halo is also filled with dimmer, cooler stars that formed around the time the Galaxy was forming. We include the halo here to see its scale among our neighboring galaxies. It is 41,000 parsecs, or about 134,000 light-years, in radius. For more information about our Galactic halo, see "The Galactic Halo" in the Milky Way Atlas chapter.

4.3.8 Local Galaxies

Group Name	`local`
Reference	Revision on the Nearby Galaxies Catalogue, Cambridge University Press (Tully, 1988; revised 2003)
Prepared by	R. Brent Tully (U Hawaii) Stuart Levy (NCSA/U Illinois)
Labels	Yes
Files	`g8local.speck, g8local.label`
Dependencies	none
Census	247 galaxies

The galaxies in the `local` data group represent the best picture we have of the galactic neighborhood. These 247 objects compose a collection of galaxies that is more complete than other galaxy surveys, which typically show only larger and brighter galaxies.

These galaxies were compiled by Brent Tully at the University of Hawaii. Known for discovering the Tully-Fisher relation, a correlation between the luminosity and the rotation period of a spiral galaxy, Brent dedicates his time toward understanding the structure of the Universe.

Data Variables   The nearby galaxies have data variables that describe their brightness, size, and orientation. We list these variables in the following table.

Number	Name	Description	Units
**Data Variables for the Local Galaxies**			
0	`type`	Galaxy Morphological Type	—
1	`diamkpc`	Galaxy diameter	kpc
2	`Mblueneg`	Negative absolute B magnitude	mag
3	`lum`	Galaxy luminosity scaled to `Mblueneg`	—
4	`txno`	Texture number	—
5	`cloud`	The cloud (grouping) number	—
6	`pgc`	Principal Galaxies Catalogue number	—
7	`hicnt`	References for a grouping catalog	—
8–13	`orient0`	Unit vectors for the polygon orientation	Mpc

The galaxy morphological `type` variable 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. For an overview of galaxy classification, see "Galaxies" in the extragalactic overview.

Galaxy Morphology Codes and Census			
Number	**Hubble Type**	**Galaxy Type**	**Census**
-5	E	Elliptical	20
-3	E/SO	Elliptical/Lenticular[1]	3
-2	SO	Lenticular	2
0	SO/a	Lenticular/Spiral	39
1	Sa	Spiral	0
2	Sab	Spiral	3
3	Sb	Spiral	3
4	Sbc	Spiral	1
5	Sc	Spiral	8
6	Scd	Spiral	9
7	Sd	Spiral	12
8	Sdm	Spiral	12
9	Sm	Spiral/irregular	15
10	Irr	Irregular	117
12	S	Spiral/irregular[2]	0
13	P	Peculiar	0

This table also describes the population of galaxies in the data set. Most of them are irregular galaxies, with SO/a spirals (mostly dwarfs) are the second-highest population in the data set. Most of the galaxies around us are small, but is this true elsewhere in the Universe? Turns out the answer is probably yes, and we happen to live in a large galaxy.

Other data variables describe the galaxy's size, brightness, and orientation. `diamkpc` is the diameter of the galaxy in kiloparsecs (the Milky Way is 100,000 light-years in diameter, which equals 30 kpc). `Mblueneg` is the negative value of the intrinsic B magnitude of the galaxy. The luminosity is a linear scaling of the intrinsic B magnitude, with `lum` = 1 corresponding to `Mblueneg` = 19.

In this data set, a galaxy is often a member of a group, a cluster, a cloud, and a supercluster. Many groups and clusters of galaxies form a cloud, and many clouds form a supercluster. For example, the Milky Way belongs to the Local Group, which is in the Virgo Supercluster, which is part of the Pisces-Cetus Supercluster Complex.

The `pgc` variable is the Principal Galaxies Catalogue number, and the `hicnt` is a cross-referencing

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[1]classification uncertain

number for a galaxy grouping catalog. Following that, the next six columns beginning with `orient0` specify the orientation of the galaxy.

Structure Within the Local Galaxies   Each of these green points is a Galactic neighbor. We have defined three boxes (see table below) that highlight the galaxies in this data group.

Boxes for the Local Galaxies		
Box Number	**Dimensions (Mpc)** **(xcen,ycen,zcen xlen,ylen,zlen)**	**Description**
1	0, 0, 0 0.85, 0.85, 0.85	Local Group box
2	0, 0, 0 3.75, 3.75, 3.75	Box around the entire data set
Clipbox	0, 0, 0 0.18, 0.18, 0.18	Milky Way group of galaxies

The smallest box encloses those galaxies around the Milky Way. This is a clip box and is activated with the command `cb on` in the Partiview Command Line. Within this box are 12 galaxies, our nearest neighbors.

To see those galaxies that live around the block, turn off the clip box (`cb off`) and turn on the normal boxes by pressing the Box Toggle Button. Inside this dark yellow box are the three dozen or so Local Group galaxies. We discussed this group in the Local Group section (`lgrp`) and in "Beyond the Milky Way" in the Milky Way Atlas, but now we have a greater appreciation for the context of these galaxies among the other nearby galaxies in the local Universe.

Within the Local Group, the two major players are the Andromeda Galaxy (M31) and the Milky Way. These are large spiral galaxies that have a bevy of smaller galactic companions clustered around them. Another, less concentrated grouping is found near the galaxy NGC 3109, on the outskirts of the group.

Membership in the Local Group is based on two criteria: the mutual gravitational attraction of the galaxies and their distance from us. While the former seems sensible and the latter somewhat arbitrary, this is the historical evolution behind selecting the galaxies of the Local Group.

Finally, we have the adjacent neighborhoods that, in this data set, surround the Local Group. Upon inspection, you may see that these galaxies tend to clump into groups that rival the Local Group in size and number. Most of these groups have dominant galaxies that tend to influence their evolution, just as Andromeda and the Milky Way influence the smaller dwarf galaxies in the Local Group. These include NGC 5128, or Centaurus A, a large (500-kpc-diameter), peculiar elliptical galaxy in Centaurus with a large, irregular dust lane and strong radio-emitting gas lobes emanating from its nucleus (not shown in

the Atlas). These peculiar features are likely the result of a galaxy collision some 500 million years ago. Also, M81, the large spiral in Ursa Major, dominates the Ursa Major Group, and NGC 253, a large spiral near the South Galactic Pole, is the largest member of the Sculptor Group.

Some of these adjacent groups around the Local Group appear more concentrated than others, but they all tend to have similar properties. Dominated by one or a few large galaxies, the majority of galaxies tend to be small dwarf and irregular galaxies.

4.3.9 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	Various images (sgi format)
Census	28,364 galaxies

The Tully Galaxy Catalog is an extension of the Local Galaxies (`local`) data group. While `local` has only about 250 galaxies, the full Atlas has about 30,000 galaxies. The two remain separate because the `local` data group is more complete than this larger data set and includes smaller, dimmer galaxies.

Many details of the Tully galaxies are described in "Local Galaxies." Please see that section for a description of the data variables for this data group.

Size and Scale of the Data   This data group differs from the local galaxies in that it provides coverage over a larger volume of the Universe. The 28,364 points are distributed over about 2.7×10^{25} cubic light-years. The data are distributed in a cube that is about 300 million light-years per side. Because this is all observed data, the Milky Way, of course, lies at the center of this cube. The cube shape of the entire data group is completely arbitrary and has no physical significance.

Colors   The colors of the data points are based on galaxy membership to various structures. All galaxies that belong to dense clusters are colored red. Beyond this, galaxies that belong to a grouping, whether it is a smaller cluster or a strand of galaxies, get one color to signify their membership. For example, the line of galaxies that extend up from the Virgo Cluster (according to our 2-D view in the sky) belong to the Ursa Major Filament and are all colored blue. The galaxies in each structural part of the Universe have received a color based on what element they belong to.

Galactic Census   The following table is equivalent to the census table in the previous section, except we have updated the numbers for the larger data set. Please see an explanation of this table in the previous section.

Galaxy Morphology Codes and Census			
Number	**Hubble Type**	**Galaxy Type**	**Census**
-5	E	Elliptical	990
-3	E/SO	Elliptical/Lenticular[2]	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[5]	0
13	P	Peculiar	0

The census reveals the differences between the `local` data group and this data group. In the `local` data group, most of the galaxies are irregular, while here irregulars make up fewer than 2% of the total. The bulk of the galaxies in this catalog are spirals. This is just the opposite of the `local` galaxies, where most of the galaxies are irregular or dwarf galaxies. We cannot see dwarf galaxies out this far, so their numbers are artificially reduced by this observational limitation. The observational bias leans toward the big, bright galaxies, so spirals dominate the population in this data group.

Galaxy Images   Each galaxy in this data group is represented by a point and a polygon. These polygons are properly sized and have an orientation matching that of the galaxy. Placed upon each polygon is an image representing its galaxy type (spiral, elliptical, etc.). Most of these come from *The Galaxy Catalog*.

A handful of images for nearby galaxies were taken 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.

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[2]classification uncertain

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.

For a description of the cluster, filament, and void structure in these data, we direct you to the associated tutorials: "Local Large-Scale Structure" and "Tully's Nearby Galaxies."

4.3.10   Tully's Smoothed Density Surfaces

Group Name	`isoDensity`
Reference	Tully 8,000 km/s Galaxy Catalog
Prepared by	R. Brent Tully (U Hawaii)
	Stuart Levy (NCSA/U Illinois)
Labels	No
Files	`d16_100_u02_50k.obj, d16_200_u02_10k.obj`
Dependencies	none

Accompanying the Tully galaxy catalog (`Tully`) is a model of the density of the 28,000 galaxies in that catalog. These appear as 3-D surfaces surrounding the most dense regions of galaxies. Each surface represents points of constant density. After smoothing the galaxy data, that is, averaging these data to compensate for random fluctuations, a 3-D mapping of the overall density may be displayed as surfaces of constant value.

The surfaces represent two values of constant density. The blue, inner surface is a relatively high density, while the aqua, outer surface represents a lower density. The blue contours mainly show dense galaxy clusters, like the Virgo Cluster, Fornax Cluster, and most of the Abell clusters in the `Tully` data group. These are the regions of highest density in our local Universe.

Some of the aqua contours resemble the blue contours in shape, but more often they reveal larger structures that connect blue contours together. The largest feature appears on the edge of the data cube and is called the Great Wall. Brighten up the Tully galaxies and, while it's still the active group, type `see gw`. This removes all the galaxies except those in the enormous Great Wall structure, which follow the density contours closely. Type `see all` to return all the Tully galaxies to view.

Isolating the Isosurfaces   If you desire to see just one of the isosurfaces, then you must change the color of the surface you wish to remove. In the `extragalactic.cf` file, the blue and aqua colors have a color index of 1 and 2, respectively, and are assigned these default red-green-blue colors:

```
cment 1 0 0 1 (blue)
cment 2 0.0 0.2 0.35 (aqua)
```

To see the aqua contours alone, change the blue contours to black with the command `cment 1 0 0 0`. Then, to emphasize the aqua contours, increase their $alpha$ value using the Alpha Slider. The higher the value, the more opaque the surfaces become. Set $alpha$ to its maximum value of 1 and the surfaces

will appear solid. If you fly inside, you will notice the smaller, black density contours are now visible. To return the higher density surfaces to blue, type `cment 1 0 0 1`.

4.3.11   2MASS Galaxy Catalog

Group Name	2MASS
Reference	The Two Micron All Sky Survey
	The Two Micron All Sky Survey Galaxy Redshift Catalog v13
	Tom Jarrett (CalTech)
Prepared by	Tom Jarrett (CalTech)
Labels	Yes
Files	various
Dependencies	2mass.cmap
Census	1,140,931 galaxies

The Two Micron All-Sky Survey, abbreviated 2MASS and pronounced "*two-mass*," is an image survey of the entire sky. Between 1997 and 2001, two automated 1.3-meter telescopes, one on Mount Hopkins, Arizona, and another on Cerro Tololo, Chile, scanned the sky in three near-infrared wavelengths resulting in over four million images and information on over 470 million objects. However, a survey of images does not yield distances to the objects identified within them.

To determine distances, we need the object's redshift. (The definition of redshift and its relationship to distance is discussed in "Redshift and Distance.") The 2MASS Galaxy Redshift Catalog assembles redshift data from many surveys, including 2MASS, ZCAT, Sloan, 2dF, 6dF, and others, and includes redshifts derived from photometric (i.e., brightness) and velocity data.

Combining the 2MASS galaxies and these various redshift surveys results in the most complete all-sky census of galaxies, including more galaxies in the "zone of obscuration," where the bright optical band of the Milky Way blocks our view of the galaxies beyond. The resulting catalog contains an impressive 1.14 million galaxies that surround the Milky Way.

The impact of 2MASS has been tremendous for astronomy and astrophysics. Not only has the survey enabled this galaxy data set, giving us one of the best pictures of the local Universe, but scientists are finding many new objects, including L-type and T-type dwarf stars (included in the `dwarfs` data group).

Why Use Infrared Telescopes?   Astronomers use infrared detectors to reveal parts of the Universe that remain hidden in visible light. These regions are embedded in dense clouds of gas and dust which glow brightly in visible light. Infrared light passes through these dense clouds, allowing astronomers to see objects within them. For example, we see "deeper" toward the Galactic center in

infrared light, and when we look at the Orion Nebula in the infrared we see stars within the gas that we cannot see in visible light. Furthermore, Earth's atmosphere is relatively transparent to infrared light at the wavelengths used in the survey (J = 1.25 microns, H = 1.65 microns, and K = 2.17 microns), so the light passes freely to Earth's surface.

Data Variables   The sheer density and coverage of the 2MASS presents a challenge when trying to see the structure within the data set. For this reason, we have defined several variables to hone your view of these galaxies.

Data Variables for the 2MASS Group			
Number	**Name**	**Description**	**Units**
0	distMly	Distance	light-years (millions)
1	redshift	Redshift	—
2	zcatalog	Redshift source catalog	—
3	prox2	Proximity factor for R = 2 Mpc	—
4	prox5	Proximity factor for R = 5 Mpc	—
5	rahrs	Right Ascension	hours
6	decdeg	Declination	degrees

The most useful of these data variables are the proximity factors, prox2 and prox5. These numbers describe the likelihood that within a given volume surrounding a particular galaxy there exists another galaxy. The more galaxies in that volume, the higher the proximity factor. For example, prox2 is the proximity factor for a spherical volume with a radius of R = 2 million parsecs (or 6.52 million light-years). Similarly, prox5 is the factor corresponding to a radius R = 5 million parsecs (or 16.3 million light-years). Low values of the proximity factors indicate that the galaxy in question is not near other galaxies—that it's out on its own. The higher the proximity values, the more concentrated the area around the galaxy will be. And, since the radius is smaller for prox2, these concentrations will be more dense than those for prox5.

By default, only those 2MASS galaxies with prox5 $<$ 0.7 are displayed, removing 85% of the galaxies. You might think this is crazy, but it's the only way to see the forest through the trees. If you type see all while 2MASS is active, you will see the full-up catalog of 1.14 million galaxies. Seeing the density of galaxies surrounding us is certainly impressive, but the vast number of galaxies prevent us from seeing any structure.

Two data variables describe the distance to each galaxy. One variable, called distMly, is the

distance expressed in millions of light-years and ranges from about 2 million to 3,000 million (or 3 billion) light-years. For example, type `thresh distMly 0 100` to see the 3,478 galaxies within 100 million light-years of the Sun. The Virgo Cluster is the most prominent cluster in view, while the smaller Fornax Cluster lies opposite the Milky Way from Virgo.

Similarly, because redshift is directly related to distance, we can use it to produce subsets of data. For example, `thresh redshift 0 0.007` is approximately equal to the 100-million-light-year threshold we set above.

To parse these data on yet another parameter, the 2MASS galaxies include a redshift source catalog identifier called `zcatalog`. This data variable is an integer that describes the redshift source, allowing you to cull the component catalogs from the larger data set. Naturally, we have set selection expressions for these redshift sources (see below).

Redshift Source Catalog ID	
zcatalog	**Catalog Name**
1	Tully's Nearby Galaxies
2	Six-degree Field Galaxy Survey
3	Sloan Digital Sky Survey
4	NASA/IPAC Extragalactic Database (NED)
5	ZCAT, which includes the CfA Redshift Survey
6	Lyon-Meudon Extragalactic Database (LEDA)
7	Two-degree Field Galaxy Survey
9	Photometric redshift

Using these data variables will help you see the structure of our local Universe through the overwhelming density of galaxies in this data set. Use these parameters creatively and in combination with one another to show any slice of galaxies you would like to see.

Selection Expressions   We have predefined several selection expressions in the `extragalactic.cf` file that make it easier to view the 2MASS galaxies. We summarize these in the table below.

Selection Expressions for the 2MASS Galaxies		
Alias	**Partiview Command**	**Description**
lss	only= prox5 > 0.7	The default setting showing large-scale structure and removing many of the isolated galaxies
d100	thresh distMly 0 100	All galaxies within 100 million light-years
d372	thresh distMly 0 372	All galaxies within 372 million light-years, roughly the same volume as Tully
zbest	only= redshift < 0.06 only- prox5 < 0.7	Galaxies with lower redshift uncertainty
clusters	thresh prox2 1.3 3	Dense clusters of galaxies
tully	only= zcatalog 1	Redshifts from Tully's Nearby Galaxy Catalog
6df	only= zcatalog 2	Redshifts from the Six-degree Field Survey
sdss	only= zcatalog 3	Redshifts from the Sloan Digital Sky Survey
ned	only= zcatalog 4	Redshifts from NED
zcat	only= zcatalog 5	Redshifts from ZCAT
leda	only= zcatalog 6	Redshifts from LEDA
2df	only= zcatalog 7	Redshifts from Two-degree Field Survey
photoz	only= zcatalog 9	Photometric redshift used
nophotoz	thresh zcatalog 1 8	Removes all galaxies with photometric redshifts

The lss expression is the default setting when you launch the Extragalactic Atlas. It selects all galaxies with an $R = 5$ Mpc proximity factor greater than 0.7. This leaves only 15% of the total 2MASS galaxies, but allows you to see the large-scale structure of galaxy clusters and filaments.

The d100 and d372 settings allow you to see all galaxies within 100 million light-years and 372 million light-years, respectively. We chose 372 million light-years because it represents the same volume as the Tully data group.

To see galaxies with relatively good redshift data, use the zbest expression. This displays galaxies with high redshift confidence. As the distance increases, accurate redshifts become more difficult to measure, so the uncertainty in distance increases. However, redshifts less than 0.06 are known with higher certainty.

The clusters expression culls out clusters of galaxies, the most dense regions around the Milky Way.

The remaining expressions show portions of the data set based on the redshift source. Perhaps the most useful of these is the nophotoz expression, which removes all the galaxies that have a photometric redshift. Spectroscopic redshifts are more accurate than a photometric estimation, so these

galaxies' distances are more accurate.

Luminosity Settings   In addition to the selection expressions, we have supplied several luminosity settings for the data group that enable you to emphasize aspects of the massive data set.

In Partiview, it is possible to define many luminosity settings using the **lum** command, each with its own scaling factor defined by the **slum** command. We typically use a constant luminosity for 2MASS (`lum const 1`), and this is the setting in effect when you launch the Digital Universe. However, to emphasize the structure of these data, we also supply a luminosity setting according to the $R = 5$ proximity factor, prox5 (`lum prox5 0 1`). This sets the luminosity of the points such that the regions of higher density appear brighter. You can toggle between these two states by typing `lum prox5` and `lum const`. Use the Slum Slider to set separate **slum** factors for each.

Color Settings   Color is a helpful tool in visualizing data and plays an important role with these 1-million-plus galaxies. In the `extragalactic.cf` file, we've defined five color settings which are set according to the 2MASS color map file, `2mass.cmap`.

Color by	Description
`const`	All galaxies receive one color (doesn't use the color map file).
`redshift`	Color according to redshift. Aqua at low redshifts, then green, yellow, orange, and red at high redshifts.
`distMly`	Similar to `redshift`, but colors mapped over the `distMly` range.
`prox2`	Colors mapped over the `prox2` data range.
`prox5`	Colors mapped over the `prox5` data range. This is the default.

The default color map uses the `prox5` data variable. The low values receive an aqua color, while increasingly dense regions receive green, yellow, orange, and red for the most dense regions. Experiment with the other color settings, or try setting some of your own.

Radial Stretching   You may notice some radial stretching in the 2MASS galaxies, short lines of galaxies that appear to point toward Earth. In fact, this is common in all the galaxy surveys, including 2dFgals and SloanGals. To emphasize this effect, you can display all the 2MASS galaxies then filter the galaxies by the `prox2` factor

```
see all
thresh prox2 0.5 3
```

The data appear to form lines that point toward Earth. Astronomers call this radial stretching effect a "finger of god." Throughout history, astronomers have shown just how ordinary we Earthlings are by disproving our position in the center of the Solar System, the Galaxy, and even the Universe. When, in the 1980s and 1990s long lines of galaxies pointing radially toward Earth were discovered, we had reason to believe we were special again. However, it was quickly apparent that this was an artificial result.

Astronomers realized these radial effects are a product of velocity dispersions that differ from the overall expansion of the Universe. Within a cluster of galaxies, an individual galaxy could be heading toward Earth (blueshifted), away from Earth (redshifted), or there may be no radial component at all in its motion (no shift in the light). These dispersions cause the distances of galaxies within clusters to be stretched radially. In fact, the mapping of large-scale structure is stymied by this effect—the more concentrated the area, the more uncertainty there will be in the galaxy's distance.

For a more realistic view of the Universe, this stretching must be removed. For large clusters in `2MASS`, the stretching has been removed, resulting in a statistically accurate representation of a galaxy cluster. In the mid-range densities, the radial stretching remains—you will see many long lines of galaxies that point toward Earth. As the density decreases, the stretching will not be as prominent.

Let's go back to our normal view for `2MASS` by typing `see lss`.

Labels   The `2MASS` data group has two sets of labels. One set is a local label, showing the names of individual galaxies when you fly close to them (with the default label size). Another set of labels in the `2MASSclusters.label` file, identify galaxy clusters and structure. These labels are 20 times larger than the individual galaxies, so they will be visible from greater distances. Adjust the Labelsize and Labelminpixels Sliders to suit your label taste.

4.3.12 Abell Galaxy Clusters and Nearby Superclusters

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` group is composed of all the 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 data analysis was conducted by R. Brent Tully of the Institute for Astronomy, to determine the distance and three-dimensional distribution of these galaxy clusters.

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.

The Shapley concentration, named after the American astronomer Harlow Shapley (1885–1972), is one of the closest rich superclusters to us. Six hundred million light-years distant, the supercluster is composed of about 25 rich galaxy clusters, amounting to 10,000 Milky Ways.

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 supercl`, and 313 galaxy clusters in about two dozen superclusters will remain. Type `see all` to return all the galaxy clusters to view.

Labels   Two sets of labels describe the `Abell` data group, the supercluster labels and the individual cluster labels. The handful of large, white labels describe supercluster positions. Approach a particular Abell cluster and you will see a blue-green label pop on, revealing its Abell catalog number. Of course, you can adjust the appearance and visibility of these labels using the $\mathrm{labelsize}$ and $\mathrm{labelminpixels}$ commands.

4.3.13 Two-degree Field Galaxy Survey

Group Name	2dFgals
Reference	2dF Galaxy Redshift Survey (Colless+ 2003)
Prepared by	Eric Gawiser (Rutgers University)
Labels	No
Files	2dfgals.speck
Dependencies	none
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 2-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. For information on converting redshift to distance, please see "Redshift and Distance."

Data Variables   The 2dF galaxy survey has the following data variables available (note that these are the same for the 2dF quasars and the Sloan galaxies and quasars):

Data Variables for the 2dF and Sloan Surveys			
Number	**Name**	**Description**	**Units**
0	`Rmag`	R magnitude	mag
1	`redshift`	Object's redshift	—
2	`Tlookback`	The Lookback Time	Gyr
3	`distMpc`	Distance	Mpc
4	`distMly`	Distance	millions of light-years
5	`radeg`	Right Ascension	degrees
6	`decdeg`	Declination	degrees

The zeroth data variable, `Rmag`, is the apparent R magnitude of the object. The R filter peaks at 658 nm, which is in the red end of the visible spectrum. In the 2dF galaxy survey, the magnitude has the range $11.69 \leq$ `Rmag` ≤ 21.7 mags, so we're looking at dim objects indeed.

The redshift ranges from 0.0016 to 3.5, with a mean value of 0.118. The look-back time, how long ago an object emitted the light, should not exceed the age of the Universe, which is currently thought to be 13.7 billion years. The look-back time ranges from 0.02 billion to 11.7 billion years, meaning the oldest galaxies in these data date back 11.7 billion years. To see them, you must increase the brightness of the data set.

Following these, we have two distance variables, one in megaparsecs and the other in light-years. We also include their position on the sky, which is useful in setting a threshold for the data if you want to display only one part of the data set.

If you turn on the `20Gly` group, you will see that most galaxies extend to about 2.5 billion light-years before the data become sparse. As mentioned in "The Distance Scale," the distance for each galaxy reflects the present location of that galaxy, not where its light left from. For example, a galaxy around 3 billion light-years in the Atlas has a look-back time of 2.7 billion years; the galaxy was 2.7 billion light-years away when the light we observe today left the galaxy. This discrepancy comes about from the expansion of the Universe; the farther an object is from us, the larger this discrepancy becomes.

Out to about 2 billion light-years, the 2dF galaxies show the large-scale structure of the Universe. Even in these thin slices, the pattern of clusters, connecting filaments, and voids is present in these data. Imagine if the 2dF were to look at the entire sky, we would be surrounded by galaxies that form this pattern. This is the goal of the Sloan Digital Sky Survey (SDSS), and we will discuss its latest

results next.

4.3.14   Sloan Digital Sky Galaxy Survey

Group Name	SloanGals
Reference	Sloan Digital Sky Survey
Prepared by	Eric Gawiser (Rutgers University)
Labels	No
Files	sdssgals.speck
Dependencies	none
Census	696,417 galaxies

The Sloan Digital Sky Survey (SDSS) is an ambitious project to map one-quarter of the sky. The survey will measure the position and brightness of more than 100 million objects and measure redshift (which yields a distance) to 1 million galaxies and quasars.

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 data variables (see p. 194) associated with the SDSS galaxies are the same as those in the 2dF galaxies, except for the data variable called `release`, which describes the data release (see below). The SDSS galaxies are also 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 (like the 2MASS galaxies). Right now, we see only a few select slices from that sphere.

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.

Look at the nearby galaxies using the command

```
thresh distMly 0 2500
```

showing galaxies out to 2.5 billion light-years. Now view the distant galaxies using the command

```
thresh distMly 3000 8000
```

Now you're looking at galaxies between 3 billion and 8 billion light-years, and the lack of structure is easy to see.

Seeing Structure In order to see any structure among the almost 700,000 galaxies, it helps to remove some of the galaxies from your view. To accomplish this, you can filter these data by their position in the sky (right ascension and declination), or by data release. For example, you can single out a "slice" of galaxies by selecting data between a narrow declination range, like:

```
thresh decdeg -5 5
```

As always, type `see all` to return all the galaxies to your view.

You may also follow the evolution of the Sloan Digital Sky Survey by selecting galaxies based on their data release. The first data were released in 2003, followed by five more releases through 2007. Because data release 1 and 2 were released jointly, we include them both in data release 2. Try using the thresh command and see how the SDSS evolved over the past few years. For example: try typing `thresh release 2 2` to see release 1 and 2. Or type `thresh release 6 6` to see the latest release.

Is this the farthest out we can see? Continue to the next data group to find out.

4.3.15   Two-degree Field Quasar Survey

Group Name	2dFQSOs
Reference	The 2dF QSO Redshift Survey (Colless+ 2003)
Prepared by	Eric Gawiser (Rutgers University)
Labels	No
Files	`2dfqsos.speck`
Dependencies	none
Census	22,431 quasars

If you are familiar with the Two-degree Field (2dF) survey, you may know that the 2dF also surveyed quasars, the farthest objects in the Universe. For details on the 2dF survey and instrument, please see "Two-degree Field Galaxy Survey." The data variables associated with the 2dF quasars are the same as those in the 2dFgals.

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 spectra 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 our 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 look-back times for the 2dF quasars range from 1 billion to more than 11 billion years. Consider a quasar with an 11 billion-year look-back 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.

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. 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.

4.3.16   Sloan Digital Sky Quasar Survey

Group Name	`SloanQSOs`
Reference	Sloan Digital Sky Survey
Prepared by	Eric Gawiser (Rutgers University)
Labels	No
Files	`sdssqsos.speck`
Dependencies	none
Census	90,509 quasars

The Sloan Quasar Survey contains over 90,000 quasars that extend beyond the `SloanGals`. This makes sense, as they come from the same observations that were made to compile the Sloan galaxy catalog.

The SDSS quasars have the same data variables listed in the section describing the `2dFgals` group, with the exception of the `release` variable describing the data release (see "Sloan Digital Sky Galaxy Survey"). Of course, the range of these variables is dramatically different from that of the SDSS galaxies. Generally, the objects are dimmer from our perspective; their average distance is 12.5 billion light-years, compared with 1.8 billion light-years for the galaxies. And the look-back time, the length of time the light has been traveling, is 8 billion years on average, while it is only 1.7 billion years for the galaxies.

These differences are not at all surprising given that quasars are thought to represent galaxies in their early stages of evolution. If we could travel instantaneously to a Sloan 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.

The SDSS quasars appear to have no obvious signs of large-scale structure. There is a pattern that depends on distance, which we might expect to see since this is an observed catalog and the brightness of objects falls off with distance. Around 16 billion light-years, the data begin to "fade out," or become sparse. You'll notice too that the 2dF quasars cut off at this same distance, around 20 billion light-years. However, the lack of structure within the data results from the fact that quasars are relatively rare and represent only a sparse sampling of the large-scale structure that exists.

Quasars are among the farthest objects we see, but they do not take us all the way back to the beginning of the Universe. To peer into the earlier Universe, we look to the cosmic microwave background light seen in the WMAP all-sky survey (`wmap`).

4.3.17 Microwave (WMAP) All-Sky Survey

Group Name	`wmap`
Reference	Wilkinson Microwave Anisotropy Probe (2003)
Prepared by	Brian Abbott (AMNH/Hayden)
Labels	No
Files	`wmap.speck`
Dependencies	`wmap1024blue.sgi`
Wavelength	13.0 mm, 9.09 mm, 7.32 mm, 4.92 mm, 3.23 mm
Frequency	23 GHz, 33 GHz, 41 GHz, 61 GHz, 93 GHz

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 (see "Electromagnetic Spectrum" for information on microwave light).

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 cosmic microwave background radiation (CMBR) was a blackbody (thermal radiation). 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 CMBR 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 CMBR to greater resolution was proposed to NASA. Called MAP (Microwave Anisotropy Probe), 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.

The WMAP observations have a much higher temperature resolution than COBE, allowing astronomers to see these temperature fluctuations in more detail. At present, WMAP provides the best image of the CMBR, and the results from the mission have narrowed down many of the open questions in cosmology, including the age of the Universe and its ultimate fate.

Origin of the CMBR   In the beginning, the Universe was very hot and free electrons (those not attached to any atom) prohibited radiation from traveling freely. 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 379,000 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.

When this recombination event 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. Today, the peak wavelength is close to 1 mm (1 micrometer $\times$ 1,000 = 1 mm) and corresponds to a gas temperature around 3 Kelvin (3,000 K $\div$ 1,000 = 3 K).

The WMAP Image The WMAP results show the CMBR to be 2.725 Kelvin and resolve temperature fluctuations that vary by millionths of a degree. In the image, red patches are warmer by the slightest deviations from the 2.725 K average, while blue patches are cooler by the same slight difference. Remember, though, that the overall temperature would appear uniform to our eyes. If we could see in microwave wavelengths, the sky would be a uniform brightness everywhere, for our eyes cannot see such small fluctuations.

The red regions are the seeds of the large-scale structure we see in today's Universe. The WMAP data give astronomers another piece in the puzzle of the evolution of the Universe. Astronomers continue to ponder how these small temperature fluctuations from 379,000 years after the Big Bang ultimately became the galaxy clusters and filaments we see in the present Universe.

Currently, we miss much of the universe's childhood. The WMAP is the baby picture taken when the Universe was 379,000 years old. Our next picture is not until the Universe is about 900 million years old, when quasars and galaxies appear. What occurred between those times is under the microscope—or telescope, in this case—of astronomers the world over.

Placement of the WMAP The WMAP all-sky image is a two-dimensional image taken from a space telescope in orbit around Earth. We place the image on a sphere whose radius represents the furthest extent of light from the recombination era. This is a bit deceiving, since the CMBR is everywhere in the Universe; however, the sphere marks the farthest reaches of the Universe as seen from Earth, where hydrogen formed 379,000 years after the Big Bang. Currently, this places our horizon at about 42 billion light-years in all directions. Beyond this distance, the Universe will forever be opaque to us.

4.3.18 Extragalactic Coordinate Grids

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

As was the case in the Milky Way Atlas, 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 most of the nearby galaxies in the `local` data group.

100Mly   The 100 million-light-year grid begins to cover the close galaxies in the 2dF and Sloan galaxy surveys.

1Gly   The 1 billion-light-year grid is an intermediate step to our largest grid.

20Gly   The largest grid extends to 20 billion light-years from the Sun and spans the majority of the quasars.

4.4   Optimizing the Extragalactic Atlas

There are several ways to improve performance in the Extragalactic Atlas. Chances are that the large galaxy surveys will be the heaviest burden on your system. You can ease this burden by setting thresholds on these data sets, relieving your computer's processor.

Thresholding on Brightness   The data variable that reflects the galaxy's brightness in the 2dF and Sloan surveys is Rmag. For each survey, the range will be different. If you get a report on each in Partiview (using the datavar command), the result will be

```
datavar 0 Rmag 11.688..  21.731 mean 17.5139
datavar 0 Rmag 14.4315..  28.3567 mean 18.648
```

for the 2dF and Sloan surveys, respectively. Of course, the lower the number, the brighter the galaxy, so the brighter galaxies will be under the mean value.

For the 2dF survey, which has more than 229,000 galaxies, try setting a threshold around 17.5 mag using the command

```
thresh Rmag 11 17.5
```

which displays all data with an Rmag value between 11 and 17.5, the brightest galaxies. This leaves about 96,000 galaxies. If this is too many, set the range to 11–17.0 and you'll be left with only 50,000 galaxies. If you can handle more, set your range to 11–18.

The Sloan galaxy survey has more than 374,000 galaxies. Thresholding on the same data variable, first try the range 14–18. This leaves 66,000 galaxies. Keep adjusting the upper limit on the range until you reach a suitable number of galaxies for your display.

Thresholding on Distance   Rather than selectively display data based on brightness, you can show galaxies within a given distance, thereby cutting down the number of particles to display while retaining a complete data set for those areas shown. For the 2dF and Sloan galaxy surveys, a good cutoff that allows you to see the large-scale structure is around 2 billion light-years. If you execute the following command for both surveys, you will be left with 70% of the galaxies.

```
thresh distly < 2e9
```

Lowering this threshold to 1×10^9 shows about 25% of the data, so find a suitable number in between these for your display (1.5×10^9 shows about 50%).

A Random Subset   Partiview will take a random subset of the data using the every command. This command takes an integer argument based on the number of points you want to show. For example, `every 1` shows all points, `every 2` shows 50% of the data, and so on. The points are chosen at random, and their total brightness is kept constant. So the smaller the sample, the brighter the particles become to compensate. For the Sloan galaxies, every fourth particle tends to be the limit before the structure in the data set disappears. Type

```
every 4
```

to see the random subset.

We recommend using the every command as a last resort, seeing as it changes the structure of the data. Better to view a complete data set thresholded on some value rather than a data set that is complete nowhere.

With these tricks, you should be able to find a suitable display for your computer. Once you have the settings that you like, open the `extragalactic.cf` file and add them to the appropriate groups. Remember the eval command, though. For example, these commands in the `extragalactic.cf` file need to be placed in their appropriate data group and would appear:

```
eval thresh Rmag 11 17.5
eval thresh distly < 2e9
eval every 4
```

If you continue to have trouble displaying these data sets, please email us for more ideas.

Appendix A

Light-Travel Time and Distance

The Digital Universe measures distance in light-travel time rather than in kilometers or miles. Light-travel time refers to the distance light travels over a given time. We know light travels at 299,792 km/sec (186,322 miles/sec). At that speed, the light-year becomes a convenient unit of distance in the Milky Way. In this appendix, we list common conversions between light-travel times and distances that we're familiar with.

Table A.1 – Conversion between light-travel time distances and astronomical units (AU), kilometers, and miles. (1 AU = Earth-Sun distance)

Light-travel Time	Distance (AU)	(kilometers)	(miles)
1 light-second	0.0020	299,792.458	186,322.224
1 light-minute	0.1202	17.98 million	11.18 million
8.3 light-minutes	1.0	149.6 million	93 million
1 light-hour	7.2143	1.08 billion	670.76 million
1 light-day	173.14	25.9 billion	16.098 billion
1 light-week	1212.0	181.3 billion	112.69 billion
1 light-month (30 days)	5194.3	777.06 billion	482.95 billion
1 light-year	63240.2	9.46 trillion	5.89 trillion

Table A.2 – Light-travel distances to some familiar objects in the Universe, as
measured from the Sun.

Object	Light-travel distance
Mercury	3.22 light-minutes
Venus	6.01 light-minutes
Earth	8.32 light-minutes
Mars	12.7 light-minutes
Jupiter	43.3 light-minutes
Saturn	1.32 light-hours
Uranus	2.66 light-hours
Neptune	4.16 light-hours
Farthest comets	1.58 light-years
Proxima Centauri (nearest star)	4.3 light-years
Orion Nebula	1,500 light-years
Center of the Milky Way	26,000 light-years
Andromeda Galaxy (farthest naked-eye object)	2.36 million light-years

The table above lists some light-travel-time distances to a few well-known places. These are
measured from the Sun. Included are the major Solar System objects, including Earth, which is about
8 light-minutes from the Sun. Think about this for a minute. If the Sun's light takes 8 light-minutes to
reach Earth, then something catastrophic could happen on the Sun and we would not know for
8 minutes. The nearest star to the Sun is more than 4 light-years away. Look to that star in the sky
tonight and you're seeing it as it was 4 years ago. The center of our Galaxy is 26,000 light-years away.
The light we see from there left when our ancestors were painting primitive scenes in caves. The
farthest object we can see with our eyes, in a dark sky without the aid of a telescope, is the Andromeda
Galaxy, more than 2 million light-years away. What was happening on Earth 2 million years ago?

Appendix B

Parallax and Distance

One of the most important breakthroughs in astronomy was the development of accurate distance determination methods for the nearby stars. Distances in astronomy are elusive, and astronomers use many methods to determine them. Our knowledge of the size and scale of the Universe is based upon some fundamental distances, and the distances to the nearby stars are one pillar upon which many theories rest. How certain are we about the distance to a nearby star?

To find the distance to a nearby star, astronomers measure something called the parallax angle of a star. Generally, parallax is the apparent shift in an object's position resulting from the observer's changing perspective. We experience this effect just by closing one eye, then viewing the same scene with only the other eye open. Of course, the scene must be nearby, as our eyes can perceive depth only when objects are relatively close to us.

We know that stars are very far away, so we cannot use our eyes to see the parallax of stars. We need a larger baseline than the separation between our eyes. The longer baseline that allows us to see parallax in stars is the motion of the Earth around the Sun. Six months from now, Earth will have moved through half its orbit and will be located opposite the Sun from where it is today. The baseline between these two points is 2 times the Earth-Sun distance, or 2 astronomical units.

This baseline, which is almost 300 million kilometers (186 million miles), still does not reveal the apparent motion of the stars to our eyes. However, using a telescope, astronomers can measure these tiny apparent motions throughout the course of the year. But what do we observe?

Let's think about the situation. We have the Sun, Earth in orbit around it, and a distant star. The Sun-Earth distance, *R*, is known to be 1 AU, and the angle between the line connecting the Sun and star and the line connecting Earth and the star, *p*, is the parallax angle that is measured. Given these two quantities, we can solve the triangle for the distance, *d*, between the Sun and the star.

If you recall your trigonometric equations, you can express the solution to the triangle in this equation:

$$\tan(p) = \frac{R}{d}$$

When the angle *p* is very small, as it is here (the parallax angle to the nearest star, Proxima Centauri, is only 0.75 arcseconds = $0.°00021$), $\tan(p)$ is nearly zero, which means that *d* must be much, much greater than *R*. And indeed it is! When the parallax angle is one arcsecond, the distance to the star is defined to be one parallax-second, or parsec, a fundamental unit of distance in astronomy. A star that is 1 parsec from the Sun appears to subtend 1 second of arc in the sky as Earth orbits the Sun. A star of 10 parsecs, like the star Pollux in Gemini, has a parallax angle of about $1/10$ arcseconds (in fact, it is 0.0967 arcseconds, close to 0.1).

This very simple relation yields insight toward the scale of the nearby stars. This understanding came in 1838 thanks to the observations of Friedrich Bessel at the Prussian Observatory in Berlin, Germany. He measured the parallax angle of the star 61 Cygni to be about a third of an arcsecond, yielding the first reliable distance to a nearby star (which turns out to be 3.2 parsecs, or about 10 light-years).

You might think that this solves all of our problems in understanding the distance to objects, but it does not. Just as the baseline for the human eye is too small to see the effects of parallax, or depth, the baseline of Earth's orbit is also minute compared with the scales of the Milky Way, let alone the Universe.

Photometric Parallax   For stars that are too far away to measure their parallax angle, astronomers derive a photometric parallax for use in determining their distance. The photometric parallax is not an angle and is not even based in geometry. Rather, it is based on an analysis of the light of the star.

For stars with a trigonometric parallax that can be measured with little uncertainty, astronomers look at the light from the stars and classify them by spectral types according to the absorption and emission lines that appear in their spectra. If the star has a measured apparent brightness, *m*, as seen from Earth, and its distance *d* is known from its trigonometric parallax, then its intrinsic brightness, or

absolute magnitude *M*, can be calculated with this equation:

$$m - M = -5 + 5\log(d)$$

From these classifications, astronomers can determine whether it is a hot, intrinsically bright star or a cool, dimmer star. Then the star's intrinsic brightness and its spectral type can be calibrated for stars with known distances.

Astronomers use this calibration to determine the distance to stars that are too far away to measure trigonometric parallax angles. By observing the star's spectrum, they infer intrinsic brightness. This, along with the apparent magnitude of the star, is used in the previous equation, which, rearranged to solve for the distance, is given by

$$d = 10^{\frac{m-M+5}{5}}$$

The notion of photometric parallax, assuming the intrinsic brightness of an object, is common in astronomy for determining distances to stars, molecular clouds, and supernovae. It is plagued by large uncertainties, but in some cases, it is the best clue we have to determine an object's distance.

AMNH Star Distances   In the AMNH star catalog, a star's distance is derived from a weighted mean value of the trigonometric and photometric parallax. The uncertainties of each are factored in, and then a final distance is computed. If the trigonometric parallax measurement is of high quality, then it will be the primary measurement used in determining the distance. If the measurement has a high uncertainty, then the photometric parallax will be brought in for comparison. For about 45% of the stars, the final distance is a combination of the trigonometric and the photometric parallax.

Appendix C

Redshift and Distance

For objects on extragalactic scales, we use something called the redshift to determine the object's distance. Redshift refers to the Doppler shift in the light of an object as it moves away from us.

Consider an approaching train. If the train is blowing its whistle as it approaches you, passes you, and speeds away from you, the pitch of the whistle will change. This is the Doppler shift of the sound waves as the train travels toward you and then away from you. Another way to describe this change in pitch is to indicate the alteration in wavelength, or frequency.

Similar shifts happen to light as an object travels toward or away from you. The wavelength or frequency of the light changes. The electromagnetic (EM) spectrum spans all light and runs from short wavelengths, where energetic gamma rays exist, to long wavelengths in the radio part of the spectrum (see "Electromagnetic Spectrum" for more information). In general, the gamma rays are said to be on the blue end of the spectrum and the radio waves are toward the red end. These red and blue labels come from the visible spectrum, where red light within the visible spectrum is on the radio side of the EM spectrum and blue and violet are on the gamma-ray side of the spectrum.

If an object is moving away from us, we observe the wavelength of the light to increase and the light appears to decrease in energy. This is called redshifted light. Conversely, if an object is approaching us, its light is shifted to shorter wavelengths and appears more energetic. This is called blueshifted light.

From the section "Extragalactic Atlas Overview," we know the Universe is expanding. In 1912, Vesto Slipher discovered that all the spiral galaxies he observed had a redshifted spectrum. In the 1920s, Edwin Hubble began plotting the redshift, or recessional velocity, of galaxies versus their distance and

discovered that there was a linear correlation. We now know this relationship as Hubble's Law. It is simply stated

$$v_{recessional} = H_0 \times distance$$

where the redshift yields the $v_{recessional}$ and H_0 is the constant of proportionality called Hubble's constant.

Mathematically, Hubble's constant is just the slope of the straight line relating the velocity and the distance. Physically, it is the rate of expansion of the Universe and is one of the most important quantities in astrophysics. It dominated astrophysical discussions in the 20th century, but is known with more certainty now. The units of the constant are in speed over distance and are typically in km/sec/Mpc (kilometers per second for each megaparsec).

Using various methods, astronomers narrowed the value of this constant down to the range $45 - 90$ km/sec/Mpc. Some believed it to be closer to 50 km/sec/Mpc, while others were in the 90 km/sec/Mpc camp. The latest results from the WMAP mission derives the Hubble constant from the fluctuations in the cosmic microwave background. Their results accurately determine the value to within 5% and place its value at 71 km/sec/Mpc.

Redshift is measured by the literal shift in an object's light toward the red end of the EM spectrum. Astronomers first observe the spectrum of a far-off galaxy. Then they compare the wavelengths of the spectral features (absorption lines) from where they would be for an object at rest. This shift determines the recessional velocity as a percentage of the speed of light. If the redshift of a galaxy is 0.2, then it is moving away from us at 20% the speed of light.

This presents a problem, since the highest redshifts observed are more than 8.0. Is the object speeding away at 8 times the speed of light? No, nothing can travel faster than the speed of light. Large redshifts are called cosmological redshifts, and they require us to factor in relativity.

The Doppler formula, which assumes the velocity is much less than the speed of light, is not correct for quasars that appear to be moving away from us at close to or more than the speed of light. For these objects, we must take into account the expansion of the Universe itself. This is why astronomers have introduced the look-back time, which is a measure of how long ago the light was emitted from the object. For nearby objects, the look-back time and the distance are equal. For more distant objects, the look-back time and the distance diverge because the Universe is expanding. Light from the edge of the observable Universe has a look-back time of about 13 billion years; however, the distance to the horizon is now 42 billion light-years, due to the expanding Universe. The simple equations for Doppler shift and

Hubble's Law do not apply at these great redshifts, where astronomers must use relativistic versions of the equations to account for the expanding Universe.

Appendix D

Electromagnetic Spectrum

The entirety of light, or radiation, in the Universe spans more than just the light we see with our eyes. This continuous range of light is called the electromagnetic (EM) spectrum and includes radiation at every frequency or wavelength. The EM spectrum has been broken into regions (see Table D.1) ranging from the highest-energy gamma rays to the lowest-energy radio waves.

Table D.1 – Regions of the electromagnetic spectrum. Ranges are expressed as wavelengths (in meters) and frequencies (in Hertz). The corresponding blackbody temperature is the average over the range (or the upper or lower limit) and is in Kelvin.

Region	Wavelengths (m)	Frequencies (Hz)	Temperature (K)
Radio	$> 1 \times 10^{-1}$	$< 3 \times 10^{9}$	< 0.029
Microwave	1×10^{-3} to 1×10^{-1}	3×10^{9} to 3×10^{11}	$2.9 - 0.029$
Infrared	7×10^{-7} to 1×10^{-3}	3×10^{11} to 4×10^{14}	$4,140 - 2.9$
Visible	4×10^{-7} to 7×10^{-7}	4×10^{14} to 7×10^{14}	$7,245 - 4,140$
Ultraviolet	1×10^{-8} to 4×10^{-7}	7×10^{14} to 3×10^{16}	$290,000 - 7,245$
X-ray	1×10^{-11} to 1×10^{-8}	3×10^{16} to 3×10^{19}	$290,000,000 - 290,000$
Gamma-ray	$< 1 \times 10^{-11}$	$> 3 \times 10^{19}$	$> 290,000,000$

In addition to its usefulness in astronomy, each region of the EM spectrum is important for everyday uses as well. On the high-energy side of the EM spectrum, we use gamma rays to power nuclear reactors and for medical testing involving radioactive isotopes. In space we observe gamma-ray bursts. These result from a collision between a black hole and a neutron star and produce enough energy that

they are easily seen across the Universe.

On Earth, we use X-rays to check for broken bones and decay in our teeth. In astronomy, X-rays are used to study neutron stars and black holes in our Galaxy and to find quasars throughout the Universe. Astronomers also observe X-rays in the winds of hot stars in the Milky Way.

Most of the ultraviolet (UV) radiation is absorbed in the atmosphere before it reaches the ground. The little that does make it through can be harmful to humans, causing skin cells to mutate and become cancerous. In astronomy, UV light is used to study active star formation and for probing the atmospheres of cooler stars.

The visible part of the spectrum is that region of the EM spectrum where the Sun emits its peak intensity. This is the main reason that humans have evolved to see in this region of the spectrum. Our eyes can simply be thought of as filters that see only in the visible part of the EM spectrum. With a prism, this region can be split into its component colors from red to violet. Visible light reveals the main stellar populations in galaxies.

Infrared (IR) light is used to track cloud cover in meteorology and for seeing objects in the dark with night-vision goggles. Humans radiate in the IR (about 9,300 nm) with a body temperature of about 36°C (98°F). In the Galaxy, infrared light is emitted by dust, which can absorb a huge fraction of incoming starlight before re-radiating it. IR telescopes can penetrate this dust to see stars and planets embedded in clouds of star-forming regions, like the Orion Nebula.

Microwave radiation is used to heat food and for cellular communications. Astronomers observe microwave light in galaxies and quasars, but for the most part, the microwave bands are dominated by the cosmic microwave background, the light emitted shortly after the Big Bang.

Finally, the least energetic form of light is radio. On Earth, we receive radio light for AM and FM broadcasts (wavelengths of AM are around 1 kilometer, while FM lies near 10 meters), television (UHF and VHF signals are around 0.1 to 1 meter), and radar. Astronomers use radio telescopes to detect the locations of large hydrogen clouds where stars form, revealing the size and structure of the Galaxy.

Astronomers use the EM spectrum to probe objects at varying depths. Some regions, like the visible and parts of the radio spectrum, are observed on Earth. Most regions are absorbed by our atmosphere, requiring us to build space telescopes to see these wavelengths.

Appendix E

Constants and Units

In addition to the meter (m), kilogram (kg), and second (s), there are several units commonly used in astronomy. We list these and provide some conversions, astronomical constants, and the metric prefix converter.

Table E.1 – Commonly used quantities in astronomy.

Astronomical Units		
Name	**Symbol**	**Value**
astronomical unit	AU	149.6×10^6 km = 93 million miles
light-year	ly	9.46×10^{12} km = 5.88 trillion miles
parsec	pc	3.26 ly = 206,265 AU
Ångstrom	Å	10^{-10} meters
micron	μ	1 micrometer = 10^{-6} meters
Kelvin	K	$^\circ$C + 273

Table E.2 – Some constants in astronomy.

Astronomical Constants and Measurements		
Name	**Symbol**	**Value**
Speed of light	c	3×10^8 meters/sec
Mass of the Sun	$M_\odot$	1.989×10^{30} kilograms
Radius of the Sun	$R_\odot$	6.96×10^8 m = 432,494 miles
Luminosity of the Sun	$L_\odot$	3.83×10^{26} J/sec
Mass of Earth	$M_\oplus$	5.98×10^{24} kg
Mass of Jupiter	M_J	317.03 $M_\oplus$
Radius of Earth (equatorial)	$R_\oplus$	6,378.2 km = 3,963.4 miles

Metric Prefixes   These prefixes are used before fundamental units like meter, Hertz, or second. Factors with positive exponents increase the number of zeros after the number. For example, a kilometer, km, is 1,000 meters; a gigaHertz, GHz, is 1 billion Hertz or 1,000,000,000 Hertz. Prefixes with negative factors are less than unity. A nanometer (nm) is a billionth of a meter or 0.000 000 001 meter; a millisecond (ms) is a thousandth of a second or 0.001 second.

Table E.3 – Prefixes for metric units including the prefix name, its symbol, and the multiplying factor. **Bold** prefixes are used commonly in astronomy.

Metric System Prefixes		
Name	**Symbol**	**Factor**
yotta	Y	10^{24}
zetta	Z	10^{21}
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	**G**	10^{9}
mega	**M**	10^{6}
kilo	**k**	10^{3}
hecto	h	10^{2}
deka	da	10
deci	d	10^{-1}
centi	**c**	10^{-2}
milli	**m**	10^{-3}
micro	μ	10^{-6}
nano	**n**	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}
zepto	z	10^{-21}
yocto	y	10^{-24}

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