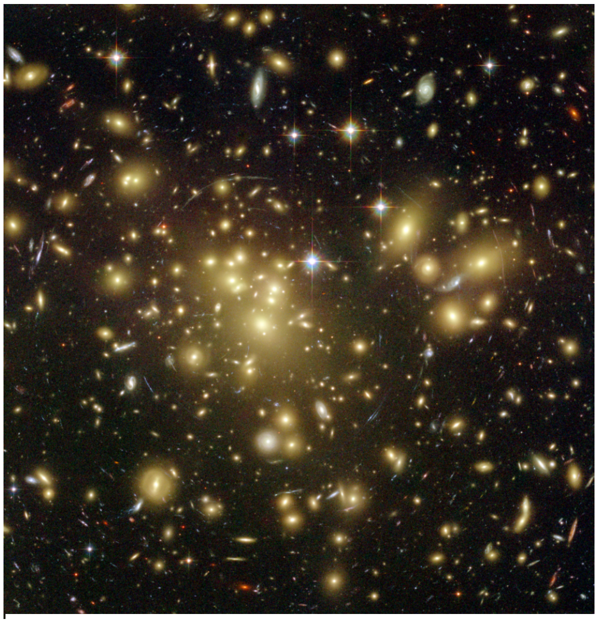
Chapter 2: The Nature of Stars



Galaxy Cluster Abell 1689 (HST Image)

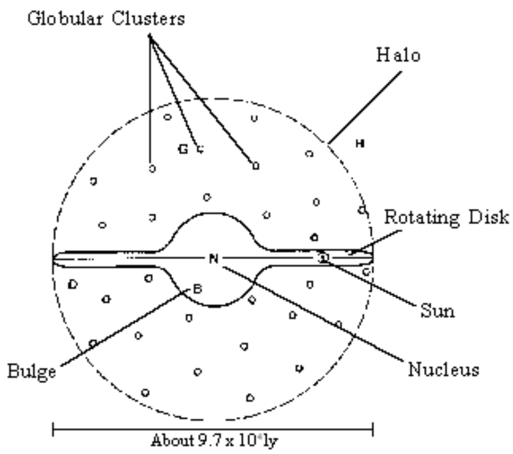
Introduction

Beyond our Sun and Solar System exist billions of other stars traveling around the center of the Milky Way Galaxy. If you go to a site away from city lights and stare up at the night sky when the Moon is not up, you will be able to see, ideally, about 3,000 of these stars during a single night of observation with the unaided eye. What can be seen or not seen depends upon the surrounding environment: light and air pollution, convection currents, weather, the brightness of the stars, and the acuity of the observer's vision. You will notice too that the stars vary in appearance.

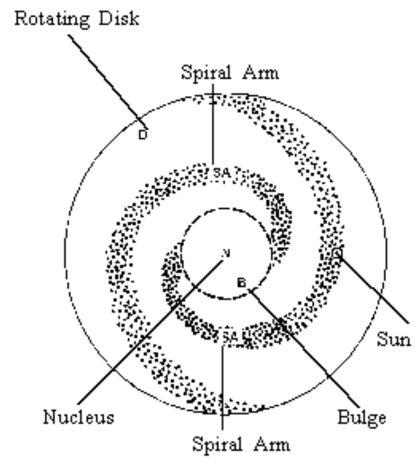
All the stars you see lie within the disk of the Milky Way Galaxy. It is a typical *spiral galaxy* with prominent arms of gas, dust, and stars (see Figure 2.1 on the next page). The nuclear bulge—a dense concentration of stars surrounding a massive black hole—lies in the direction of the constellation Sagittarius. Within the disk some stars are solitary, others are gravitationally-bound multiple star systems. There are also special groups of stars, open clusters, and globular clusters. Open clusters are located within the disk of the galaxy. They are groups of stars which were born within the same condensing cloud of gas and dust. Although they are still gravitationally associated with each other, they have their own motions and will slowly drift farther and farther apart. A familiar example of an open cluster is the Pleiades, which precede Orion into the autumn and winter sky. Globular clusters are tightly packed, spherically symmetrical groups of stars located outside the disk, within the galactic halo, and are also thought to share a common origin. However, unlike open clusters which contain young stars, globular clusters contain older stars, much older than the Sun, and are thought to have formed early in the life of the Milky Way.

Our Sun and Solar System occupy the Orion Arm of the galaxy, 30,000 light-years away from the galactic center. As part of the Orion Arm, the Solar System orbits around the galactic center once every 250,000,000 years (one galactic year). If the spiral arms—carrying their stars, dust, and gas—orbit around the galactic center in the same manner that the planets orbit around the Sun, then the spiral arm structure should no longer exist. The farther away from the center, the slower the arms should rotate. The spiral arms should have wound up and formed a disk by now. How spiral galaxies maintain their spiral arm structure is a puzzle. Astrophysicists are still trying to solve this mystery.

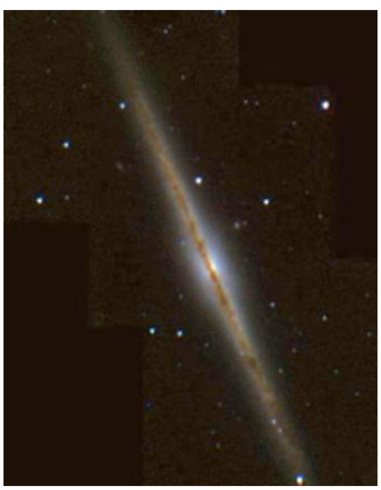
On a clear night, from the Northern Hemisphere, we can catch a small glimpse of our sister galaxy, the Andromeda Galaxy. Although Andromeda is similar in size to our Milky Way, it appears as a fuzzy patch with no individual stars discernible. Even though it is nearby, the light we see from this galaxy has traveled through space for two million years before reaching planet Earth. We always see the Andromeda Galaxy the way it looked two million years ago—we will never be able to see it the way it looks at this moment!



An edge-on schematic view
of our Milky Way galaxy



A face-on schematic view
of our Milky Way galaxy

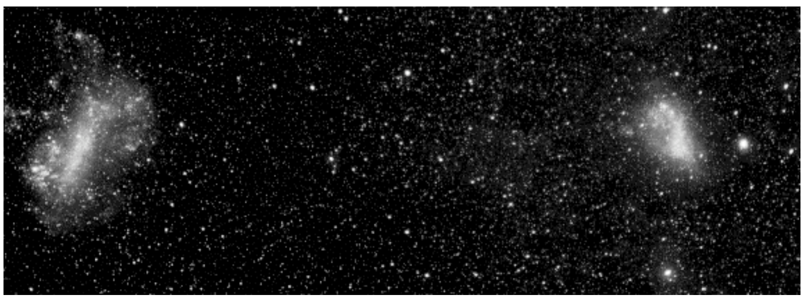


Edge-on view of NGC 891, a spiral galaxy with features simlar to our Milky Way

Face-on view of M74, a spiral galaxy with features similar to our Milky Way galaxy, (Gemini Observatory, GMOS)Team)

Figure 2.1

From the Southern Hemisphere, two more companion galaxies much closer to the Milky Way are visible, the Large and Small Magellanic Clouds, 160,000 and 195,600 light-years away, respectively. The Large Magellanic Cloud (LMC) has one-fifteenth the mass of the Milky Way, and the Small Magellanic Cloud (SMC) has one-sixth the mass of the LMC. They are ragged in appearance and classified as irregular galaxies, as they have no specific shape or structure. These galaxies were named after Ferdinand Magellan during his voyage around the world in 1512. Magellan's historian on the voyage, Ernesto Pigafetta, officially described and recorded these objects, though they had been used previously by Portuguese navigators during the 1400's to locate the direction of the South Pole. The Portuguese referred to them as Cape Clouds, because they came into view as their ships approached the Cape of Good Hope. For the next three hundred years these galaxies were thought to be clouds within our own galaxy.



The Magellanic Clouds are satellite galaxies, close enough to the Milky Way Galaxy to be severely affected by its gravitational field. Both have had close encounters with the Milky Way, and the Small Magellanic Cloud has been seriously disturbed by these interactions. Both the LMC and the SMC are embedded in a loop of hydrogen gas that extends into the Milky Way from a recent encounter. As a result of these interactions, the SMC is deteriorating, not having enough mass to hold onto its gas and dust, which are necessary ingredients for manufacturing new stars. The SMC will eventually be absorbed by both the LMC and the Milky Way—the price a low-mass galaxy pays when it strays too close to its more massive companions. The tranquil appearance of our galaxy is indeed misleading, as it is even now in the process of obliterating one of its own neighboring galaxies. The Milky Way Galaxy and the Magellanic Clouds are locked into a cosmic dance with gravity.

Galaxies are bound together in clusters. The Milky Way, Andromeda, the LMC and SMC, are only four of the approximately twenty-four galaxies that comprise the cluster known as the Local Group. Clusters of galaxies are gravitationally bound into the largest associations in the universe—superclusters. The Local Group belongs to the Virgo Supercluster. Sky surveys show that superclusters are not uniformly spread throughout the universe, but cluster around the edges of large spherical empty spaces.

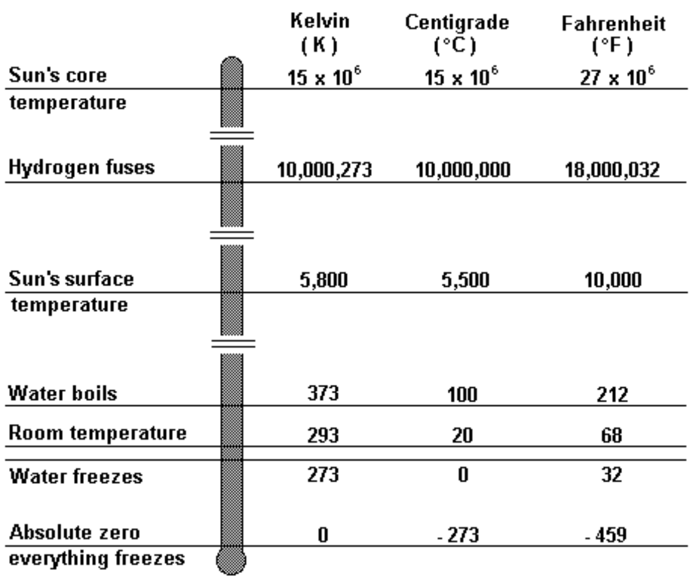
Investigation 2.1: The Properties of Stars

Look at the slide of a star field in Cygnus below. Do all the stars in the field look the same? What are some differences? Make a list. What properties of stars do you think would cause these differences?

Star Field in Cygnus

Core Activity 2.2: Understanding the Temperature Scales

Temperature scales are constructed by assigning numbers to certain points where, for example, water freezes or boils. The most common scale used in the United States was developed by Gabriel Fahrenheit in 1714. This scale was originally standardized by assigning the value 98.6 to the normal temperature of the human body and establishing this as the high end of the scale. The lower end was established by assigning a temperature of zero to an ice water solution that contained salt, as salt water has a lower freezing temperature than pure water. The Fahrenheit scale has been modified so that the upper limit is standardized as the point at which pure water boils at sea level (212 degrees) and the lower limit at 32 degrees, the freezing point of pure water. The Celsius scale, commonly used throughout the world, was developed by Anders Celsius in 1742. This scale assigns 100 degrees as the boiling point of pure water at sea level and zero degrees as the freezing point.



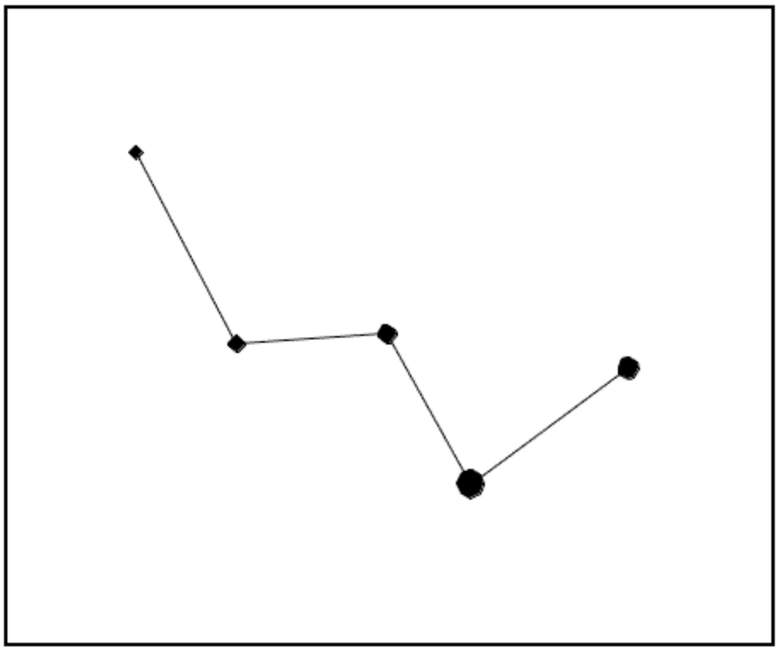
A different scale is used by scientists, called the *Kelvin (K) scale*. This scale is not arbitrary: the zero point of the Kelvin scale is -273^{o}C or absolute zero—the point at which all molecular motion (kinetic energy) ceases. This is the lowest possible temperature an object can reach. Since the zero point of the Celsius scale is the freezing point of water, and the zero point of the Kelvin scale is absolute zero, and these two scales are separated by 273, the conversion from one of these scales to the other is simply the addition or subtraction of 273. (From ^{o}C to K, add 273; and from K to ^{o}C, subtract 273.) NOTE: The Kelvin scale is based upon kinetic energy, a measure of molecular motion, and therefore does not have a “degree” symbol

Temperature Conversion Relationships

From	**To**	**Formulae**
Fahrenheit	Celsius	$T_c = 5/9(T_f - 32)$
Celsius	Fahrenheit	$T_f = (9/5\ T_c) + 32$
Celsius	Kelvin	$T_k = T_c + 273$
Kelvin	Celsius	$T_c = T_k - 273$

1. The average body temperature for humans is 98.6 °F. What is this temperature in Kelvin?
2. Determine the temperature of your room in Fahrenheit, Celsius, and Kelvin.
3. The Moon's temperature on its bright side is 100 °C and on its dark side is –173°C. What are the corresponding temperatures in Fahrenheit and Kelvin?
4.
   a. The surface temperature of the Sun is 5770 K. What is the equivalent temperature in Fahrenheit?
   b. This temperature may seem very high indeed. However, the bright star Rigel in the constellation of Orion the Hunter is a hot, bright white star with a surface temperature of ~12,000 K. How much hotter is Rigel than the Sun?
5.
   a. The hottest stars in the night sky shine with a bluish color and have temperatures in the range of 30,000–60,000 °C. Express this temperature range in Kelvin and Fahrenheit.
   b. Cool red stars have temperatures of about 3250 °C. Express this value in Kelvin and degrees Fahrenheit.
6. Outer space is filled with huge voids between individual stars, and even between galaxies and between clusters of galaxies. The temperature within these voids is essentially 3K, which is the temperature of the cosmic background radiation. Convert this temperature to Celsius and Fahrenheit.
7. Some variable stars pulsate through a range of temperatures. One such star, the omicron star from the constellation Cetus the Whale, varies from ~4500 K to 2400 K. What is the corresponding change in °F?
8. Why is the Kelvin scale useful? Why is it used instead of Celsius for stellar atmospheres? Would the Kelvin scale be useful instead of the Fahrenheit scale for everyday purposes? Why don't our thermometers use this scale?

Given below is a sketch of the five brightest stars in the constellation Cassiopeia. In this sketch, as in other star charts, the stars are represented by points of different sizes. Although we cannot discern the relative sizes of the stars in the sky, this method of representing stars by different point sizes is used to indicate the relative brightness of the stars. The larger the point, the brighter the star is in the night sky. In the sketch below, rank the stars in order of brightest to dimmest on a scale of one to five with one being the brightest, and five being the dimmest.

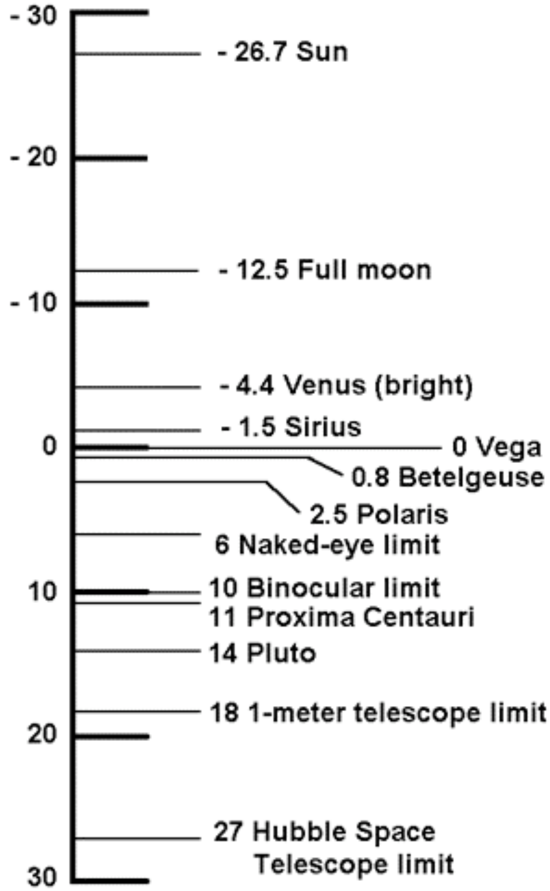


Repeat this activity with a slide of Cassiopeia. If you are able to observe this constellation at your location, you may wish to rank the stars by direct observation.

Measuring the Brightness of Stars

If you have observed the night sky, you have noticed that some stars are brighter than others. The brightest star in the northern hemisphere winter sky is Sirius, the "Dog Star" accompanying Orion on his nightly journey through the sky. In the constellation of Lyra the Harp, Vega shines the brightest in the summer sky. How bright is Sirius compared to its starry companions in the night sky? How does it compare to Vega, its counterpart in the summer sky? How bright are these stars compared to the light reflected from the surface of the Moon? From the surface of Venus?

The method we use today to compare the *apparent brightness* of stars is rooted in antiquity. Hipparchus, a Greek astronomer who lived in the second century BC, is usually credited with formulating a system to classify the brightness of stars. He called the brightest star in each constellation "first magnitude." Ptolemy, in 140 AD, refined Hipparchus' system and used a 1 to 6 scale to compare star brightness, with 1 being the brightest and 6 the faintest. Astronomers in the mid-1800's quantified these numbers and modified the old Greek system. Measurements demonstrated that 1st magnitude stars were 100 times brighter than 6th magnitude stars. It has also been calculated that the human eye perceives a one magnitude change as being 2½ times brighter, so a change in 5 magnitudes would seem to be 2.5^5 (or approximately 100) times brighter. Therefore a difference of 5 magnitudes has been defined as being equal to a factor of exactly 100 in apparent brightness.



Magnitudes of Selected Objects

It follows that one magnitude is equal to the fifth root of 100, or approximately 2.5; therefore the apparent brightness of two objects can be compared by subtracting the difference in their individual magnitudes and raising 2.5 to the power equal to that difference. For example, Venus and Sirius have a difference of about 3 magnitudes. This means that Venus appears 2.5^3 (or about 15) times brighter to the human eye than Sirius. In other words, it would take 15 stars with the brightness of Sirius in one spot in the sky to equal the brightness of Venus. Sirius, the brightest apparent star in the winter sky,and the Sun have an apparent magnitude difference of about 25. This means that we would need 2.5^{25} or about 9 billion Sirius-type stars at one spot to shine as brightly as our Sun! The full Moon appears 10 magnitudes brighter than Jupiter; 2.5^{10} equals 10,000, therefore it would take 10,000 Jupiters to appear as bright as the full Moon.

On this scale, some objects are so bright that they have negative magnitudes, while the most powerful telescopes have revealed faint 30th-magnitude objects. The Hubble Space Telescope can “see” objects down to a magnitude of about +30. Sirius is the brightest star in the sky, with an apparent magnitude of –1.4, while Vega is nearly zero magnitude (–0.04).

Core Activity 2.4: The Apparent Colors of Stars in the Night Sky

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You will be shown some constellations, star fields, or other pictures of the night sky. You will be given three different colored filters. For each picture, write your observations in the table below of how the pictures appear when looking through each filter.

1. Look at one of the color slides or prints. Describe the brightness and colors of the objects it shows.

2. What types of stars or features of the pictures are more visible with the red filter? Why?

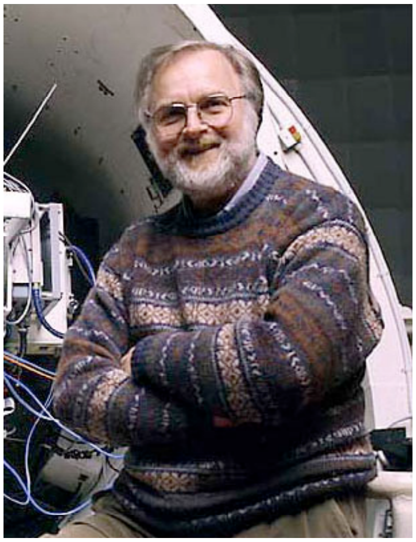
3. What features of the picture are more visible with the blue filter? Why?

4. Which filter changes the pictures least from your non-filtered view?

5. Human eyes are most sensitive to yellow, so red or blue objects appear dimmer to us when we observe them in the sky. Do you think humans have evolved in such a way that there is a relationship between this sensitivity and the color of the Sun?

SLIDE NAME	Red	Blue	Yellow
1.			
2.			
3.			
4.			
5.			

David Malin - The Man Who Colors the Stars



Like other great artists before him, David Malin is a great experimenter. Utilizing photographic film as his canvas, wielding a prime focus camera mounted in a cage attached to the Anglo-Australian Telescope as his brush, and with the entire cosmos displayed before him as his subject, David Malin has changed forever the way that we view the universe. The masterpieces in his cosmic portfolio adorn and beautify our world in books, and on posters, coffee cups, T-shirts, postcards, bookmarks, television, and postage stamps. Who has not seen his Horsehead Nebula image? It is captivating-the Mona Lisa of astronomical photography-luring us to contemplate what lies behind the seemingly calm exterior. David Malin is the world's foremost astrophotographer. He has given us a gift of rare and wondrous insight into the breathtaking beauty that otherwise would remain invisible to human perception.

Malin's legacy is one of color. His pictures are not only beautiful, but also valuable, full of priceless science. Utilizing glass plates 14 inches square, Malin takes three black and white exposures through separate colored filters of red, green, and blue. These are then superimposed onto photographic film, resulting in images of stars with their actual colors, thus giving an indication of their age, size, temperature and evolutionary history. Malin's images of nebulae and galaxies are a veritable feast of color and detail, painstakingly extracted from the glass plates with techniques he has developed. "There's color out there that explains the cosmos," Malin declares. The aim of his work is to unlock the information hidden within and behind the cosmic clouds of dust and gas to reveal a wealth of scientific insights.

David Malin's artistic ability to paint the universe is a powerful tool for scientific study. Science is the objective; the art only a delightful result. But it is a result which helps make the cosmos more understandable for us all.

Malin, sitting inside his prime focus cage with his back to the stars, listening to the music of Bach and Beethoven, bestows upon science an almost spiritual experience placing the details of rigorous research into the context of humankind's incessant search into cosmic distances for answers to ancient questions.

David Malin portrays the messages from the stars as scientist, artist, and astronomical historian. By producing images of the light echoes from the 1987 supernova in the Large Magellanic Cloud, Malin allows us to see in rich detail an event which occurred 160,000 years ago before Neanderthal Man emerged in southern Germany. Being able to see those light echoes, we are able to measure the rate of expansion of the supernova's resulting shockwave. Malin's paintings of starlight tell stories of ancient catastrophes, such as gas shell remnants around galaxies which show that two galaxies, trapped in gravitational warfare, have long since reconciled their fates and merged into one.

M20, The Trifid Nebula.
David Malin's photographic works brings out structures that no other techniques reveal. (Photo courtesy of David Malin, Anglo-Australian Observatory)

Bok globules seen against the faint nebula IC2944. These globules are small, dark, cool clouds of gas and dust which may produce low-mass stars.

Even the world's foremost astrophotographer has to settle for his own small allotment of precious telescope time, usually 5–8 nights a year, and sometimes some of those nights are cloudy. In the twenty years that David Malin has been at the Anglo-Australian Telescope, he has produced fewer than 200 pictures, some of which have taken years to produce. Malin produces spectacular images even with an ordinary hand-held camera because he is constantly experimenting, exploring, and developing new techniques. His star trails are brilliant; some, which have been progressively defocused, show the stars as trailing plumes of stellar colors. David Malin gives us visual proof that color helps to explain the cosmos.

David Malin grew up in a cottage without electricity in England's Lake District. His mother worked in a cotton mill, and Malin worked as a projectionist at the local movie house and as a caller in a bingo parlor. At the age of 15, Malin dropped out of school. Eventually he became a lab apprentice with the Swiss Chemical Company, where he re-established an abandoned photography darkroom. Malin took classes in physics, chemistry, and math at a technical college to maintain his position with the company, and used his knowledge to experiment with photography.

He had no formal education in astronomy and few qualifications for employment when he applied for work at the Anglo-Australian Telescope on Siding Spring Mountain, Coonabarabran, New South Wales, Australia. However, his self-acquired knowledge and expertise with photographic plates gained him the position. Always experimenting with different techniques to produce better and better images, never being completely satisfied, and forever seeking ways to extract more and more information from his glass plates, have earned David Malin his international reputation as the world's foremost astrophotographer.

David Malin is now at a photographic crossroads. Eastman Kodak has stopped making the 14-square inch glass photographic plates which Malin uses for his astrophotography. The world has become more technological and now CCD (Charge Coupled Device) cameras have replaced glass plates. We are all familiar with the beautiful CCD images provided by the Hubble Space Telescope (HST). Many would say that Malin and his glass plates are now outdated and old-fashioned. But Malin is not in competition with HST; his work, is complementary. As yet, CCD images cannot compete with Malin, cannot render the fine detail delivered by his special techniques. Yet CCD cameras are rapidly improving, and soon will have that ability.

The rapid advances in technology have resulted in an explosion of astronomical knowledge in the last two decades. Sometimes old methods must give way to new methods, and scientists must keep up with changing technologies. And so Malin has started producing images with CCD cameras. The reluctance of leaving behind the familiar is overshadowed by the excitement of new possibilities. Whether by glass plates or by CCD images, Malin will continue to bring us stunning views of the universe, and his images will have many cosmic stories to tell.

David Malin's photography reveals subtleties in the reflection nebula that is illuminated by the stars of the Pleiades.

(Photos courtesy of David Malin, Anglo-Australian Observatory)

So far only robot eyes have seen any farther than the Moon. As the Voyagers travel to the farthest reaches of the Solar System and beyond, they will eventually stop transmitting information and silently drift into interstellar space, no longer able to communicate with the hopeful civilization that launched them. If we were traveling with Voyager 1, now on its way past Pluto's orbit, the **apparent brightness** (**apparent magnitude**) of the Sun would be greatly diminished—even though its **actual brightness**, or **absolute magnitude**, would be the same. From this distance the Sun would be just another star, its life-sustaining energy too faint to impact the frigid outer reaches of the Solar System.

Voyager 1 has been traveling at 59,346 kilometers/hour for 20 years; however, that is an incredibly slow speed compared to the speed at which light travels. The six o'clock morning news broadcast would reach Voyager by three o'clock that same afternoon—traveling in 9 hours the same distance covered by Voyager in 20 years!

The Light-Year:
A Unit of Cosmic Distance

Because there is nothing known to travel faster than the speed of light, the light-year is the most convenient way in which to describe the very large distances and sizes we find in the universe.

The light-year is a unit of distance equal to the distance that light, radio waves, or any other form of electromagnetic radiation, travels through space in one year.

All electromagnetic radiation in a vacuum travels at the speed of light, 299,792 km/s. So at this rate, one light-year 12 equals 9.4605 x 10^{12} km (9.4 trillion kilometers, or about 6 trillion miles.) Distances expressed in light-years give the time that radiation would take to cross that distance. There are other ways of measuring distance in space, but the light-year is the unit of measurement used in most cases.

The light-year is the ideal way to describe astronomically large distances, but it can be applied to smaller distances as well. For example, the distance from the Sun to the Earth is about 8 light-minutes.

Speed of	km/s	Unit of Distance	Distance Travelled in 1 year
Light	299,792	1 light-year	9.4 X 10^{12} km
Voyager-1	16.485	1 Voyager-1 year	5.2 X 10^{8} km
Sound	0.331	1 sound year	1.0 X 10^{7} km
Jet Plane	0.223	1 jet year	7.0 X 10^{6} km
Fast Car	0.030	1 fast car year	9.4 X 10^{5} km
Person Walking	0.00089	1 person year	2.8 X 10^{4} km
Snake	0.00022	1 snake year	16.9 X 10^{3} km
Skunk	10.00002	1 skunk year	6.3 X 10^{2} km
Snail	0.0000004	1 snail year	1.2 X 10^{1} km

The nearest star is Proxima Centauri, 4.2 **light-years** away. At this distance, anybody listening to radio signals coming from Earth would be learning about the events taking place on this planet a little more than four years ago. But near Pollux, one of the twins in the constellation Gemini 35 light-years away, the news of John Glenn's orbit around the Earth in 1962 is now rushing past. Anyone near 13 Ceti, a 5th-magnitude star in the constellation Cetus, 53 light-years away, would now be hearing about D-Day, the beginning of the end of WWII when the Allies landed on the beaches of Normandy, France. Signals from Orson Welles' famous Halloween Eve broadcast of "The War of the Worlds" in 1938 are only now reaching tau Cygni, in the constellation Cygnus. (Do listeners on other worlds think that somewhere a planet called Mars is invading a planet called Earth?) Aldebaran, the very bright reddish-orange star in Taurus the Bull, is hearing about the stock market crash of 1929 marking the beginning of the Great Depression. 16 Cygni is now receiving the message that Charles Lindbergh is the first person to fly solo across the Atlantic Ocean in an airplane. Somewhere, some star 77 light-years distant is hearing America's first radio broadcast from 1920. Will anyone receiving these signals be able to understand them? And if so, will they know what an ocean is, or a stock market, or a war?

The **interstellar medium** between stars is so thin and tenuous that it is nearly a perfect vacuum. The few atoms and molecules that comprise the medium inhabit a frigid environment with a temperature of only 3 **Kelvin**—having so little kinetic energy that they barely move. It is also a silent environment, since sound requires a medium through which to travel. Light, which needs no medium, travels through the dark and cold, carrying its messages to and from distant stars and planetary systems hundreds and thousands of light-years apart. In places, great clouds of gas and dust, called **nebulae**, emit, reflect, or absorb radiation.

Leaving the plane of the **galaxy** with its huge spiral arm structure of rotating clouds of gas, dust, and stars, and traveling above or below the disk, we encounter an even less-occupied region of the Milky Way. Here is where the **globular clusters** reside. These clusters do not have enough mass to retain their gas and dust, and supernova explosions carry material away from the clusters. As globular clusters wander around the galactic halo, sometimes they travel through the disk, and lose even more material. Consequently the dust and gas necessary for making new stars is absent. Eventually the globular clusters will become galactic ghost towns, filled with the cores of dead and dying stars. Imagine living on a planet orbiting a star in a globular cluster and having a full-face, close-up view of the Milky Way Galaxy lighting up the entire night sky!

Virgo Supercluster

(Creekside Observatory, Embry Riddle Aeronautical University)

Light traveling through the Milky Way would take 100,000 years to get from one end to the other; 30,000 years to get from the center of the galaxy to the Sun; two million years to reach the shores of the Andromeda Galaxy from the Earth. To reach the edge of the Local Group **cluster** of galaxies, the light from the Milky Way Galaxy would take more than three and a quarter million years, and in excess of 65 million years to reach the heart of the Virgo **supercluster**. Light is the ultimate cosmic voyager, traveling for hundreds, thousands, millions, and billions of light-years to deliver ancient messages from the stars and galaxies to those with the ability to read them.